Terrestrial Process Research Using a Multi-Scale Geographic Approach

Abstract

Earth systems are interrelated in complex ways which are inadequately understood. An improved understanding of these systems is necessary to develop effective policies for the stewardship and management of our planet. The natural and human systems must be studied together to understand the processes that cause changes on global and regional scales. The understanding gathered must be communicated in a meaningful way to managers and decision makers.

The United States Global Change Research Program (USGCRP) has developed a priority framework for global change research that is designed to meet the above concerns. The U. S. Geological Survey (USGS) is one of the agencies conducting research into global change with an emphasis on the terrestrial environment. The USGS addresses critical Earth processes using a multiscale geographic approach. This approach has been successful in making significant scientific findings of use not only for modeling of global change but also to support decision making about hazards, resource use, and other environmental issues. It has also supported a strong effort in data management to ensure the diffusion of data and information throughout the scientific and management communities.

Introduction

The synthesis of Earth science understanding required to meet the program goals of emerging science and policy activities reflects a heightened awareness of the interconnectivity of Earth systems that rivals the revolutionary changes that have taken place in the histories of other scientific disciplines. In philosophy, Aristotle's development of a formalized synthesis of natural philosophy in his encyclopedia paved the way to future developments in science. Copernicus' brilliant insight that moved the sun to the center of our model of the solar system and Kepler's breaking with traditional Greek adherence to "perfect" geometric forms for orbital paths simplified our concept of the cosmos, and opened the way to modern scientific cosmologies. Darwin developed theories of evolution that revolutionized our concept of the development of life forms. Einstein changed our view of space and time, and redefined our cosmology. There have been other such concepts and technologies that have led to revolutions in science and incredibly rapid increases in our understanding of the world around us. Each of those was based on a synthesis of knowledge and resulted in a new world view.

In Earth science that type of synthesis is only now taking place. There have been major revolutions in the understanding of the solid Earth, for example, plate tectonics. However, the larger synthesis of geology, hydrology, climatology, and biology must be completed. These must be linked to the social sciences to understand and predict the effect of major environmental changes on the future of the human condition.

The United States Global Change Research Program (USGCRP), in conjunction with other coordinated international programs, endeavors to make that interdisciplinary link. The goal of the USGCRP, as defined by the Committee on Earth and Environmental Sciences (CEES), is "to establish the scientific basis for national and international policy making related to natural and human induced changes in the global Earth system" (Committee on Earth Science, 1989).

The CEES is made up of eleven U.S. agencies conducting focused global change research (Committee on Earth and Environmental Sciences, 1992a). Each agency provides specific research which is part of the integrated whole. This whole is based on a synthesis or reconstruction of Earth science.

For example, the U.S. Geological Survey (USGS), as part of the Department of the Interior (DOI), has a significant responsibility to provide fundamental terrestrial process research. This research must help to better understand the integrated Earth system and provide information and understanding to support management and policy decisions that must be made by DOI and the rest of the Federal government. This is a highly complex need which requires addressing the management and policy issues, the scientific concerns, and the communication of the information between the scientists and the management and policy decision-makers.

Earth System Understanding and Policy Information Needs

It is now well established that humans can make changes to the Earth system on local, regional, and global scales. These changes can be very long lasting, yet relatively benign to the physical system as is evidenced by many of the archeological ruins that exist worldwide. They can also be long lasting and locally significant, such as the salting of the city of Carthage in Northern Africa by the Roman commander Scipio Aemilianus.*

It is becoming clear that humankind can affect the global environment in ways that can have significant long term effects on physical and biological systems. The depletion of stratospheric ozone, the cumulative affect of degradation and depletion of water supplies, and the alteration and fragmentation of the landscape are examples of these effects. In human terms these effects can be negative, as with stratospheric ozone depletion, positive, or even mixed, as with altering land-cover characteristics by agriculture to increase food productivity.

*In 146 BC the Roman commander Scipio Aemilianus, during the bitter Third Punic War, conquered Carthage and destroyed the city. His army sowed salt in the fertile soil near the city, effectively destroying highly productive agriculture in that area to this day.

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There is inherent variability and change in both human and natural systems at all scales from local to regional to global. These changes are both causes and effects and are often interactive and iterative (see Table 1).

Because changes can be caused by human activity and can affect human interaction with the natural system and thus, human well-being, it is important to have a sound understanding of the interactions of the natural and human systems. This is particularly important if we are to understand how humans can best adapt to natural or human induced Earth system variability. Often, policy and management decisions affect the environment at various scales. Therefore, decision makers must rely on information about the environment so that the impact of the decisions is the one that is intended, or the tradeoffs that will be made are well understood. This requires effective information transfer among the policy and management decision makers and the scientists conducting research and data acquisition. A management and policy oriented geographically based strategy for terrestrial effects research has been presented elsewhere (Kelmelis and Ragone, 1992). The strategy is designed to ensure that adequate linkage takes place between the needs of resource managers and scientific researchers. That strategy is based on the understanding that most adaptive measures to global system change must be made at the regional and local scales. It also notes that many global system changes are the result of aggregates of processes that take place at regional and local scales.

Program

The member agencies of the USGCRP conduct both contributing and focused research. Contributing research is conducted for a purpose other than the Global Change Research Program but provides data and information that are necessary or useful to meet the goals of the USGCRP. The contributing programs are examined with respect to the goals of the USGCRP and, where there are gaps in the existing contributing programs, new research efforts are planned. These efforts are called focused research. Thus, each agency that is conducting focused global change research does so in accordance with its mission and in accordance with needs of the USGCRP.

USGS Global Change Research Program

Agency goals in the USGCRP must be consistent with their missions. For example, the goals of the USGS Global Change Research Program are:

> "to acquire and synthesize scientific information into an integrated understanding of the terrestrial environment, to link that with knowledge of other portions of the environment to build an integrated understanding of the entire Earth system, and to provide that Earth science information to policy makers and resource managers as the scientific foundation to help meet their management and stewardship responsibilities" (Kelmelis, 1992).

To accomplish these goals the USGS must meet the following objectives:

- Document past and current changes in the Earth system;
- improve the understanding of key Earth system processes—particularly those related to the exchange of water, energy, carbon, and nutrients between the terrestrial system and the atmosphere and between the terrestrial system and the oceans;
- contribute to improved models of Earth system processes by developing better characterizations of water, energy, and biogeochemical exchanges between the land, atmosphere, and oceans, by providing data sets for model development and verification, and by modeling efforts within its areas of expertise; and
- manage terrestrial scientific data and provide improved scientific information and understanding to aid in the management, policy, stewardship, and scientific responsibilities of the Department of the Interior and the government as a whole.

TABLE 1. EXAMPLES OF SOCIAL AND NATURAL SYSTEMS THAT VARY OR CHANGE ON GLOBAL OR REGIONAL SCALES. NOTE THAT THESE SYSTEMS ARE INTERACTIVE AND ARE BOTH CAUSES AND EFFECTS OF OTHER CHANGES.

Social	Natural
Population	Biologic Evolution
Geopolitics	Solid Earth Processes
Economics	Resources
Technology	Climate Variability and Change
Cultural Concepts	Biodiversity
Land Use	Atmospheric Trace Gas Concentrations

Individual research projects and subprograms are proposed and accepted based on how well they fit the goals and objectives. The individual program contents will change over time as we improve our understanding of the processes involved and the needs of the sub-program. However, current research efforts specifically focused on global change meet at least one of the objectives directly and may meet more either directly or indirectly.

Strategy

The USGS adopted a strategy which can be applied to any natural science agenda. Its elements are to

- identify the research activities for which a critical mission requirement and national need exists;
- select those research needs for which the agency has the mandate and has or can develop the capability;
- conduct the research and analyze the results within the resources available; and
- provide the resulting information to the policy and management decision makers in the appropriate form.

Within the USGCRP, the USGS focuses the majority of its efforts on the terrestrial portion of the environment and its interconnections with the oceans and atmosphere.

The USGS strategy is realized by developing research programs that address Earth processes in and geographic regions at various scales to meet critical scientific and management needs for information. The USGS is concentrating on three major process research areas: (1) water, energy, and biogeochemical cycles; (2) land surface transformations; and (3) climate variability and change.

Process Studies

WATER, ENERGY, AND BIOGEOCHEMICAL CYCLES

Improving the understanding of the interactive physical and biogeochemical processes that govern the exchange of water, energy, carbon, nutrients, and other important chemical constituents between the atmosphere, oceans, and the terrestrial environments is basic to understanding how (1) the terrestrial environment acts as a force in the global system, (2) the atmosphere and oceans respond to that force, and (3) the terrestrial system responds to forcing functions from the rest of the Earth system. This research program (a) examines the basic water and carbon cycles and their linkage to climate and hydrologic systems; (b) improves the understanding of basic climatic and hydrologic diagnostics; (c) includes realistic hydrologic processes in global modeling; (d) improves understanding of the contribution of natural processes such as terrestrial and submarine volcano emissions to the global system; (e) increases understanding of global biogeochemical cycling of carbon, phosphorus, nitrogen, sulfur, and other elements that are essential to maintain life and/or compo-

nents of the Earth's atmosphere; and (f) examines historical variation in system fluxes.

Land Surface Transformations

The interaction of natural and human processes affects the character of the land surface from patch to global scales. Examining the natural and human processes independently and integrating the understanding of these processes is critical to understanding the nature of the response of the land surface to global changes (see Table 1). Part of this effort is aimed at developing an understanding of how sensitive regions interact with or to global changes. Solid Earth processes, geomorphic processes, land-use activities, land-cover responses, biologic system interactions, and human interactions are examined. The spatial distribution of surficial characteristics sensitive to climate and other global change variables are determined. The processes that change these characteristics are examined and the sensitivity of these characteristics are studied. Information is developed for researchers and resource managers. Some of the sensitive regions examined include arid and semi-arid regions, high altitude and high latitude regions, and coastal regions. Characterizations are made on broader scales as well, including national, continental, and global. These broader characterizations look at land surface characteristics such as greenness (i.e., seasonal variation and intensity of vegetative growth), land use and land cover, susceptibility to destabalization, and others.

Some of the historic questions that are addressed include: What was the response of the environment (e.g., ecosystems) to past climate changes, especially abrupt climate change? How have relatively climate-sensitive areas responded to past climate changes (e.g., climate zone boundaries, and ecotones)? How has sea level responded to past climate changes (e.g., magnitudes, rates, and impacts)?

Climate Variability and Change

Developing detailed histories of past climates and environments and providing synoptic reconstructions of past climate conditions from evidence preserved in the geologic record are the focus of this process research. Questions being addressed include: What is the natural range of climate variability on all time scales (interannual, to millions of years)? How rapidly has climate changed in the past? How can paleoclimate and other paleoenvironment data sets be used effectively to test and improve general circulation models (GCMs) or other climate models? What insights can be gained from the geologic record that may contribute to the understanding of climate change?

Part of the paleoclimate research in the USGS Global Change Research Program is to provide critical scientific information to test the results of global climate models through hind-casting (climate variability and change). Verifying past climates helps identify the level of reliability that exists for predictive modeling, and ultimately helps improve the model output for use in policy and management decision making. This work is done at a global scale. Other paleoclimate activities examine the land surface environment under different climatic regimes in the past (i.e., a land surface transformation). Still others examine the hydrologic responses to past environmental changes and the relationships among changes in the climate system and changes in terrestrial biogeochemical processes (e.g., water, energy, and biogeochemical cycles). This research adds the temporal dimension to the understanding of many processes. It can be thought of as adding "the history of" to the understanding of processes. This is of critical importance to determining whether a particular variation from the norm of the recent past is merely a normal variation or truly a change.

Another example is the sensitivity of water resources research which meets both scientific and management information needs. These studies develop a capability to predict the water resources responses to climate variability and change across the range of environmental conditions existing in the United States. These studies examine the response of a resource to natural variability and potential change in climate. An integrated river basin assessment was recently completed in the Delaware River Basin (Ayers *et al.*, in press). Methods were developed to assess daily weather types and relate these patterns to known stream-flow response patterns. This is a valuable tool for water resource managers in that river basin. These regional scale studies are of direct value to managers and also provide information and use in understanding the river system response to changes in climatic variables. This is important regardless of whether the climate is changing due to anthropogenic factors or varying naturally. Thus, water resources managers are more able to plan for changes in water availability and ensure a more secure water supply.

Geographic Regionalization

A geographic approach helps identify management/policy concerns as well as helping ensure that process studies are well planned to address appropriate variables and ensure comparability among data and information gathered. For instance, there is a set of management concerns in a geographic region characterized by arid and semi-arid climatic conditions. In such a region special emphasis must be placed on, among other things, water availability, dry land agricultural practices, and potential destabilization of the soil. While similar issues are of concern in humid regions, other issues may take precedence. By identifying the management concerns on a regional basis, the process studies can be focused where they will provide the greatest benefit. In addition, many processes are studied in different regions, and the results are compared to determine the effect of regionally significant variables on the processes. By using a regional approach, appropriate sites for the field research can be better identified. The processes are studied at different scales—global, continental, regional, landscape, patch, and laboratory. Of course, at scales less extensive than global, geographic organization becomes important. Regions are defined in several ways according to the major issues being addressed. For instance, arid, semi-arid, and cold regions are primarily climatic designations; tropical forests, temperate forests, or grasslands are based on vegetation cover type or potential vegetal cover type; agricultural, rural, suburban, and urban indicate a high level land use classification scheme; country, state, province, county, etc., represent a political scheme; and eastern United States, high latitudes, or Southern Hemisphere indicate a geolocational or mixed system. There are many other regionalization schemes as well.

Because there is no "perfect" regionalization scheme, regionalizations are based on topically relevant variables. Geographically referencing research activities and relating them to various regionalization schemes is an effective method to ensure that specific research projects can meet the research needs of at least one principal scientific or policy concern while contributing information to help with the understanding of others. Tables 2 and 3 illustrate the use of the process and geographic region approach for research. Note that these matrices are highly abstracted and used for illustrations only; most USGS Global Change Research projects are not presented in the matrices in this paper.

TABLE 2. AN EXAMPLE OF RELATING SOME USGS PROJECTS TO PROCESSES AND REGIONS BASED ON CLIMATE ZONES. NOTE: THIS IS ONLY AN EXAMPLE AND DOES NOT REPRESENT THE FULL RANGE OF USGS GLOBAL CHANGE RESEARCH PROJECTS.

Climate Regions	Critical Processes		
	Water, energy, biogeochemical cycles	Land surface transformations	Climate variability and change
Global	Greenness Mapping	Greenness Mapping; Land Character	Paleoclimates Research
Highland	Glacier Studies	Glacier Studies	Sensitivity of Water Resources
Polar	Methane Studies; Glacier Studies	Glacier Studies	
Boreal	Methane Studies		
Temperate	Water, Energy, & Biogeochemical Budgets		Sensitivity of Water Resources
Sub-tropical	Water, Energy, & Biogeochemical Budgets		
Sub-tropical	Water, Energy, & Biogeochemical Budgets		
Tropical Humid	Water, Energy, & Biogeochemical Budgets	Coastal Erosion and Inundation	
Dry	Water, Energy, & Biogeochemical Budgets	Arid and Semi-Arid Research;	Sensitivity of Water Resources

On one axis, the abscissa in this case, the major processes to be examined are identified. The other axis represents the regionalization scheme. Based on topically relevant variables, this can be a climate scheme as illustrated in Table 2 or continental land masses as in Table 3 or other schemes as described above. The schemes are logical hierarchies.

Using a geographic information system to store and retrieve information about the research can provide a flexible approach to determine if the research is being conducted to address a variety of policy, management, or scientific issues.

Georeferencing research activities and comparing them to overlays of variables identifies whether and where additional related research should be conducted as well as where research can be combined to be conducted more efficiently and effectively.

Crosscutting Activities

There are several activities that are not specifically process or geographically based studies. These are techniques development, data management, and data presentation. The USGS is pursuing activities in each of these areas and, as with the research activities, is tightly linked with other Federal and non-Federal organizations. In some cases, such as developing techniques to transfer information from one scale to another using statistical techniques to multifractals (De Cola, 1991), the work is being done with data from a specific geographic location but the techniques being developed are transportable. In other cases, such as developing a Global Land Information System, the activity cuts across many scales, all regions, and many processes. Both of those activities are outside of, but still support, the general policy and process related research activities.

Accomplishments

This approach to planning and executing research to meet the research and management goals has provided important data and understanding. From basic scientific premises to applied activities, research results have been important. For example, in the process category of Water, Energy, and Biogeochemical Cycles at the global scale, general circulation models (GCMs) have been evaluated. Calculations show that, by including empirically developed evaporation and soil moisture processes, a more realistic water and energy flow through the models will result (Milly, 1992). This has helped improve the reliability of the GCMs, an important consideration for policy decision making.

At the regional scale, both tropical and arid regions have been studied to determine the cycling of methane in the soils. Methane cycling in the tropical regions was found to be consistent with expectations. However, in arid regions conventional wisdom indicated that there was no or nearly no methane cycling in the soils. New information indicates that soils in some arid regions do sequester methane (Striegl *et al.*, 1992). This is altering our understanding of the global carbon cycle.

A network of small area research sites have been established in a variety of hydorclimatic zones to study Water Energy and Biogeochemical Budgets (WEBB). These WEBB sites are providing data to help understand the cycling of various chemical constituents through the unsaturated zone of the soils, an

TABLE 3. AN EXAMPLE OF RELATING SOME USGS PROJECTS TO PROCESSES AND REGIONS BASED ON GEOGRAPHIC LOCATION. NOTE: THIS IS ONLY AN EXAMPLE AND DOES NOT REPRESENT THE FULL RANGE OF USGS GLOBAL CHANGE RESEARCH PROJECTS.

Continental Regions	Critical Processes		
	Water, Energy, Biogeochemical Cycles	Land Surface Transformations	Climate Variability and Change
Global	Greenness Mapping	Glacier Studies; Greenness Mapping	Paleoclimates Research
North America	Methane Studies; Glacier Studies; Water, Energy, & Biogeochemical Budgets; Greenness Mapping	Arid and Semi-Arid Regions; Coastal Erosion and Inundation; Land Character; Glacier Studies; Greenness Mapping	Sensitivity of Water Resources; Paleoclimates Research
South America		Glacier Studies	
Antarctica		Glacier Studies	
Europe		Glacier Studies	
Asia	Methane Studies	Glacier Studies	
Africa		Glacier Studies; Arid and Semi-Arid Research	
Australia & New Zealand		Glacier Studies	
Islands	Water, Energy, & Biogeochemical Budgets	Glacier Studies; Coastal Erosion and Inundation	

important link to understanding the transfer of trace gases between the terrestrial environment and the atmosphere.

Land surface transformation is a major process in the terrestrial environment that is of importance to global change research and environmental management decisions. This includes examining current status of the system and changes that have or are occurring. A global scale project, the Satellite Image Atlas of Glaciers of the World, is nearing completion with several volumes already published (Williams and Ferrigno, 1988, 1989, in press).

The development of vegetation indices and land characterizations based on AVHRR and other data for conterminous United States (Eidenshink, 1992a) and at the continental scale (Eidenshink, 1992b) can be used for time series analysis to determine changes in greenness inter and intra annually (Loveland *et al.*, 1991). These data have significant potential for both extending our understanding of local processes to regional and global scales as well as providing a tool to support operational activities such as weather prediction modeling and forest fire fuels modeling. This has direct management payoff as well as long-term benefit to global change policy making. To extend these capabilities to a global scale, worldwide AVHRR data sets are being gathered (Sturdevant *et al.*, 1991). To add a retrospective view to the land surface transformations, Landsat Pathfinder activities are identifying previously collected Landsat data of different years to provide higher resolution representations of environmental change due to a variety of causes (Benjamin *et al.*, 1992). To provide the next step in linking terrestrial models, an interagency group—made up initially of the Agricultural Research Service, U. S. Forest Service, and USGS—has established the Terrestrial Regional Research and Analysis laboratory (TERRA). The benefit of TERRA's land surface transformation research to both scientific understanding and management and policy decision-making is that, at regional scales, studies of the various systems are linked and studied interactively.

Climate variability and change studies provide knowledge of past changes which help us understand present processes. For instance, new evidence has raised serious questions about the widely accepted Milankovitch theory (Winograd, 1988: Winograd *et al.*, 1992: Broker, 1992) which holds that the timing of ice ages is driven by periodic variations in the Earth's orbit. Whether Winograd's findings provide evidence of a global signal that differs from the currently accepted climate reconstruction or argue for regional variation that mask the global pattern is a serious research issue. However, they indicate that the climate system is even more complicated than previously believed. This indicates the need for closer study of both global and regional processes with retrospective analysis as well as ongoing monitoring and observation.

Relevant retrospective analysis is conducted for time periods that predate the ice ages. Findings from reconstruction of the global temperature distribution at regional scales for the Middle Pliocene, approximately 3.0 million years before present (Dowsett *et al.*, 1992), indicate that ocean currents transported heat from equatorial regions to polar regions. Thus polar regions were warmer than they are today while equatorial regions had temperatures similar to current conditions. This is similar to the projections made by equalibrium GCM $2 \times CO_2$ simulations (Dowsett and Poore, 1991). These findings provide an opportunity to test general circulation

models of the climate through hind-casting, thus gaining an understanding of the reliability of the models which will feed the land management and policy decision making process in the long run.

For applied research activities to be of value to the current decision making process, GCM output is combined with empirical knowledge of regional climate variability and well understood hydrologic models to provide scientific tool kits tuned to specific river basins for water resource managers (Ayers *et al.*, in press). A modular hydrologic modeling system has been designed to assemble the appropriate modules to simulate water, energy, and biogeochemical processes on a river basin scale (Leavesley *et al.*, 1992).

In the final analysis, for all of these activities to be relevant, adequate data and information management are necessary. For many terrestrial data sets, the Global Land Information System (GLIS) is a major cataloging and search system. It is part of a larger, more comprehensive data management activity called the Global Change Data and Information System (GCDIS), planned "to make it as easy as possible for researchers and others to access and use global change data and information" (Committee on Earth and Environmental Sciences, 1992b). For the data and information to be particularly valuable to managers and other decision makers, research must be conducted not only to develop methods to make the data and information more accessible, but also to make it more understandable and easy to use, and to give a clear indication of the reliability of the analysis conducted with the data.

Conclusion

Using a geographically based, policy and management linked approach to the planning and execution of the process oriented scientific research and data gathering activities provides an effective means to identify research needs and ensure a research program that maintains scientific validity. This is because the geographic approach shows whether the research is being done in the locations that are appropriate to the variables and issues being addressed. It also helps to identify the multiple values of various scientific activities because of spatial overlap of regions established based on the aggregation of variables important to different topics.

Results of research conducted using this approach have been significant for both the basic science and the management of resources in a changing and varying environment. Ongoing research is constantly redirected and refocused as scientific understanding increases and policy and management needs evolve.

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