1988 PROPOSAL FOR CREATING THE CU
"CENTER FOR THE STUDY OF GLOBAL CHANGE"
(now the CU Environmental Program)

Center Director: Robert E. Sievers, Director of the Coooperative Institute for Research in Environmental Sciences (CIRES) and Professor of Chemistry

Center Associate Director: Mark Meier, Director, Institute of Arctic and Alpine Research (INSTAAR) and Professor of Geological Sciences

Other faculty and senior investigators:
John Andrews
Richard Armstrong
James Avery
Susan Avery
Ben Balsley
Robert Barkley
Roger Barry
Peter Birkeland
John Birks
Maurice Blackmon
Ronald Brunner
Radford Byerly
Robert Chase
David Crumpacker
J. DeLuisi
Ray Fall
Fred Fehsenfeld
Alexander Goetz
David Greenland
Robert Hamm
Howard Hanson
Charles Howe
Siri-Jodha Khalsa
William Lewis
Lawrence MacDonnell
Vera Markgraf
Alfred McLaren
Gifford Miller
Russell Monson
Jame Peterson
Tad Pfeffer
William Riebsame
James Saunders
Steven Schmidt
Russell Schnell

Center for the Study of Global Change
at the
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5. RATIONALE FOR THE CENTER

5.1. Why a Center for the Study of Global Change?

Ozone depletion, acid deposition, greenhouse warming, sea-level rise, desertification: we now recognize that the environment of Earth is changing, that these changes may affect the future habitability of Earth, and that the changes may be caused in part by human action. We also now know that our environment - atmosphere, hydrosphere, and earth surface - is a product of both living and non-living processes that are tightly coupled in a delicate balance. Improved understanding of these interactive processes and how they are integrated to form our global environment will provide the basis for a more rational management of our resources and will increase our ability to predict and ameliorate the impact of future environmental changes. Without this understanding, the economic development and the health and well being of our nation and civilization may be at serious risk. Insuring the economic competitiveness of the United States can best be achieved by developing the knowledge base that characterizes the resiliency or vulnerability of the Earth's ecosystems.

The realization that a concerted scientific attack on the problems of global change is needed, and that the tools to permit such a study are now available, has led to major international and national initiatives. But a fruitful accomplishment of these initiatives will require a new structure of scientific endeavor - a new paradigm of science - that will require a global view and a trans-disciplinary approach to the interactions between physical, chemical, and biological phenomena and processes. The scientific disciplines, essential as they may be, must in this endeavor be considered as tools rather than ends in themselves. This integration of disciplines calls for a new academic structure - a

Center.

We propose to form a Center for the Study of Global Change that will unite disciplines in a concerted effort to improve our understanding of the changing global environment, and how we might better avoid, manage, or respond to these changes.

5.2. Why at Colorado?

The University of Colorado at Boulder is widely recognized as a leader in many of the individual disciplines involved in studies of the geosphere and biosphere, especially in regard to ecology, biochemistry, atmospheric chemistry and dynamics, the history of environmental change and a wide-ranging program in space science and technology. Furthermore, the University has made a commitment to interdisciplinary studies in general, and to earth system science in particular. The commitment to interdisciplinary studies is evident by a number of flourishing interdisciplinary institutes and centers within the University, such as the Institute of Arctic and Alpine Research, the Center for the Study of Earth from Space, the Center for Astrophysics and Space Astronomy, the Center for Space and Geosciences Policy, the Office of Space Science and Technology, and the Laboratory for Atmospheric and Space Physics; as well as interdisciplinary institutes operated jointly by the University and a government agency such as the Cooperative Institute for Research in Environmental Sciences (CIRES). Commitment to the concept of Global Change as a University-wide theme is evident by a Distinguished Lecture Series on this subject and new courses on Global Change offered at the beginning as well as at more advanced levels, as well as by the active participation of faculty in planning for the national and international Global Change agendas. For instance, the Director and the Associate Director of this proposed Center are or were members of the Global Change committees of the National Academy of Sciences. The general competence of the faculty, the emphasis on interdisciplinary research, and the specific interest in Global Change suggests that this University could mount a strong and productive effort in this field.

In addition to this strength within the University, there is unusually-productive cooperation between the University of Colorado and with Federal laboratories in Boulder and nearby. The National Oceanic and Atmospheric Administration (NOAA) has, in its Boulder laboratories, active research programs in atmospheric chemistry, climate, polar/global interactions, and related fields, as well as World and National Data Centers for environmental research. There is a long history of cooperation between the NOAA laboratories and the University of Colorado, especially through the joint institute CIRES. The National Bureau of Standards' Boulder laboratories also cooperate with the University, as does the U.S. Geological Survey in Denver The University, through its Space Science and Technology Program, cooperates extensively with many programs of the National Aeronautical and Space Administration. Informal but highly effective cooperation in the field of Global Change, occurs between the University and the National Center for Atmospheric Research, and the Office of Interdisciplinary Earth Sciences. This cooperation will improve the advancement of science and the transfer of knowledge to federal laboratories and to the public.

5.3. Impact of this Center

Global Change is recognized nationally and internationally as such a significant emerging issue that many universities and other bodies will be doing research on the subject. This Center will actively cooperate with these other efforts, through the interchange of data, results, and personnel. The impact of this Center on the total effort will include several facets:

- The Center will develop a new methodology of integrating broadly-multidisciplinary research, of application elsewhere.

- The Center will advance knowledge in certain specific themes, including biogeochemical cycles (especially the nitrogen cycle), in the dynamics of the physical environment (especially polar/global and tropical/global interactions), in the record of environmental change, in global observations, and in human/environmental interactions and impacts.

- Education in Global Change will be advanced, providing a new supply of students and entry-level scientists to participate in the emerging effort.

- New technology will develop in instrumentation, observation, and the assembly of large observational data sets for meaningful analysis and conclusions in order to better know and predict changes in environmental variables.

- The Center will define and clarify the policy implications of global change and bring these to the attention of those involved in governmental and private-sector decision making.

- Through a number of outreach activities such as workshops for scientists, science teachers, and decision makers, the results of the expanding knowledge on Global Change will be widely disseminated.

6. DESCRIPTION OF INTELLECTUAL FOCUS AND RESEARCH

6.1. INTRODUCTION

The complex problem of Global Change — the interactions between the geosphere and the biosphere — is conceptually very broad. We propose to focus our research on the two major themes that are most central to an understanding of global interactions: *biogeochemical cycles* and *environmental dynamics.* By environmental dynamics we mean the physical system of the geosphere that interacts with the biosphere through biogeochemical cycles. These two themes are, of course, intimately inter-related. In order to mount an effective research effort on these broad themes, we include the study of new *techniques, instruments and systems for global observations, and we require the perspective given by knowledge of the record of past environmental change.* In order to apply the results of this study of global change, we need to study the science and policy issues involved in *human/enviromental interactions and impacts.* These interdependent research activities, inseparable in the context of global change, make up the scientific theme of our proposed Center. Underpinning this scientific activity will be a concerted effort to solve the problem of cross-disciplinary communication and cooperation, which is essential to success in such an interdisciplinary endeavor. BIOGEOCHEMICAL CYCLES

6.1.1. Introduction

Biogeochemical cycles are driven by the integrated environmental functions of the biosphere, and thus provide a strong conceptual foundation for analyzing and forecasting global change This explains the increasing emphasis of national and international organizations on global biogeochemical cycles (NAS 1986a). Specific advantages of biogeochemical cycles as a basis for studying global change include: (1) applicability of concepts and methodology across a wide range of spatial and temporal scales, (2) integration of physical, chemical, and biological processes, and (3) compatibility with the need for modelling and prediction. For these reasons, the Center for Study of Global Change at the University of Colorado will place major emphasis on the study of biogeochemical cycles.

The study of biogeochemical cycles for all elements would be impractical for any specific group of investigators. At the same time, studies of the biogeochemistry of an arbitrarily selected element might fail to encompass many aspects of global change that are at present most urgently in need of study. There is an informal concensus within the environmental sciences that the cycles of carbon, nitrogen, sulfur, and phosphorus are of special importance to the analysis of global change (Bolin et al. 1983, Mooney et al. 1987); of these four, the cycles of carbon and nitrogen unquestionably show the greatest number of connections to global environmental change. At the present time, the global carbon cycle has received more attention than the global nitrogen cycle. Preliminary evidence suggests, however, that the nitrogen cycle may be just as important in relation to global change as the carbon cycle. The nitrogen cycle is directly connected to problems of ozone depletion, biological productivity, environmental damage through acidic deposition, and global greenhouse effects. Because direct linkages between the nitrogen cycle and natural or anthropogenic aspects of global change are impressive in number and scope, sustained and comprehensive studies of the nitrogen cycle will be particularly productive.

Studies of the global nitrogen cycle require especially great multidisciplinary breadth (Figure 1). The multiplicity of stable oxidation states for nitrogen under natural conditions on the surface of the earth, and the abundant distribution of nitrogen compounds throughout the gaseous, aqueous, and solid phases of the biosphere cause the nitrogen cycle to be dependent on an exceptionally large number of environmental linkages (Delwiche 1970). Analysis of these linkages as an interactive system requires expertise from a wide range of disciplines.

Present research capabilities at the University of Colorado, supplemented by those of nearby federal agencies that have a close and existing relationship to research on the Boulder Campus, show excellent strength relevant to studies of the biogeochemical cycling of nitrogen on a global scale (Table 1). To a large extent, this combination of expertise is fortuitous because it reflects clusters of specific research interests that have evolved separately. The possibility for uniting these separate research efforts through their common focus on the nitrogen cycle is a major aim of the proposed Center for Study of Global Change at the University of Colorado. Given the past independent productivities of these research programs, the integration of their efforts toward a common understanding of the global nitrogen cycle provides excellent prospects as a central theme for the Center, and would incorporate strong scientific motivation for the individual investigators. For these reasons, the global nitrogen cycle (Figure 1) will be the focus of the biogeochemistry component within the Center for Study of Global Change.

6.1.2. Global Change in Relation to the Nitrogen Cycle

Studies of the nitrogen cycle by the University of Colorado Center for Study of Global Change will have a sufficiently broad base to be applicable to a number of recognized environmental problems. It is also the intent of the Center to anticipate the need for a basic foundation of knowledge relevant to important aspects of global change that may not yet be fully appreciated or recognized, just as many problems of present concern were unknown one or two decades ago. The fundamental and practical significance of the Center's studies of the nitrogen cycle can be illustrated by brief descriptions of some of the presently recognized connections between global change and the nitrogen cycle. In order to illustrate the impressive scope of regulatory mechanisms involving the nitrogen cycle, these examples begin with the stratosphere, and then pass through the troposphere and finally to the earth's surface. The means by which some of these phenomena can be studied will be described in greater detail in connection with the proposed scope of work.

Connection of the Nitrogen Cycle to the Earth's Ultraviolet Radiation Exposure

The stratosphere, which is the primary atmospheric reservoir of ozone, controls the exposure of the earth's surface to ultraviolet radiation (WMO 1985). The ozone inventory of the stratosphere is subject to anthropogenic alteration by a number of mechanisms. For example, it is now well known that passage of chlorinated hydrocarbons to the stratosphere is capable of causing depletion of ozone. The connection between chlorinated hydrocarbons, ozone, and industrial societies is relatively straightforward because there are no significant natural sources of chlorinated hydrocarbons. More complex, but perhaps equally important, are the fluxes across the tropopause of other gases that are known to influence the concentrations of ozone but whose effects are difficult to assess because they originate from diverse sources, some of which are subject to anthropogenic influence. One of the most important of these is N2O, which is produced at the earth's surface by combustion (Hao et al. 1987) and by biological mechanisms (primarily denitrification: Bowden 1986). N2O is essentially inert in the troposphere, but assumes significance after passage into the stratosphere because of its potential photochemical conversion to NO. NO in the stratosphere affects the formation of ozone, and thus is an important factor regulating the radiation shield provided by the stratosphere.

The sources of N2O, unlike those of chlorinated hydrocarbons, are both natural and diverse; the natural sources are subject to multiple kinds of anthropogenic perturbations that are poorly understood (Bowden and Bormann 1986). Thus studies of steps in the nitrogen cycle leading to the production of N2O and of its passage to the stratosphere are essential to an understanding of changes in ultraviolet radiation exposure of the earth's surface. In addition, NO produced in the stratosphere is a source of NO for the troposphere, although other sources are probably larger than the stratospheric source.

The Nitrogen Cycle as a Regulator of Atmospheric Chemistry

In the troposphere, the oxides of nitrogen play a critical role in the regulation of atmospheric chemistry. For example, NO of terrestrial or marine origin controls the amount of ozone in the troposphere. While the amount of ozone in the troposphere is far less than the amount in the stratosphere, and is thus relatively unimportant with respect to ultraviolet radiation, ozone in the troposphere is significant as a phytotoxin and as a regulator of tropospheric chemical reactions. The critical role of nitrogen oxides is well illustrated by the responsiveness of ozone to NOx concentrations: at concentrations exceeding approximately 10 pptv NOx, ozone is produced; at concentrations of NOx below 10 pptv, ozone is consumed (Crutzen 1983).

Connection of the Nitrogen Cycle to Global Heat Balance

Global heat balance is subject to change on a geologic time scale through natural mechanisms, and on a much shorter time scale through anthropogenic mechanisms.

While changes in the CO_2 concentration of the atmosphere were first considered to be the cause of global temperature changes, it is now clear that the composite effect of other radiatively-active gases probably equals the effect of CO_2 (NOAA 1986). Important among these additional radiatively- important gases are N_2O and ozone, both of which are components of the nitrogen cycle.

Effect of Fixed Nitrogen on the Acidity of Atmospheric Deposition

Nitric acid originating from nitrogen oxides strongly influences the acidity of atmospheric deposition (Stensland et al. 1986). Extensive anthropogenic alteration of nitric acid in atmospheric deposition has contributed to large changes in the chemistry of deposition and is expected in some situations to influence the chemistry of soils and surface waters, or to damage vegetation (NAS 1986b). However, ammonia, which is also mobilized in response to both natural and anthropogenic processes, may either raise or reduce the acidity of a receiving system, depending on its metabolic fate, and thus complicates the interpretation of both natural and anthropogenic alterations in the deposition of fixed nitrogen compounds.

The Influence of Nitrogen on Global Productivity

Aside from its potential significance in relation to acidity, deposition of fixed nitrogen compounds from the atmosphere may play a significant role in the nitrogen balance of some ecosystems, particularly where nitrogen fixation in situ is small, and thus may be an important long-term regulator of biological productivity.

Inorganic nitrogen is a major limiting nutrient in terrestrial (Chapin 1980), marine (Parsons et al. 1984), freshwater (OECD 1982), and agricultural (Loomis 1976) ecosystems. Thus the biotic productivity of the globe is strongly influenced by fixed nitrogen;

alterations in the distribution and concentration of nitrogen on a global scale can be expected to influence the productivity of biological systems. To a large extent, increases in global agricultural productivity have been achieved through nitrogen application: nitrate application rates in developed nations range from 20 to 250 kg/ha/yr, or substantially in excess of the highest natural accumulation rates (Degens 1982). Agricultural applications have strongly perturbed natural fluxes (e.g., Figure 2). As much as 108 t/yr of carbon may be fixed in world oceans as a result of anthropogenic increases in river nitrogen transport (Kempe 1982).

Sensitivity of Nitrogen Inventories to Ecosystem Disturbance

Largely because of the high mobility of nitrate in soils, nitrogen is lost in large amounts when biological sequestering mechanisms are disrupted through ecosystem disturbance (Vitousek et al. 1979). Massive alteration of the earth's vegetative cover will greatly increase the movement of nitrogen through runoff, as well as altering the fluxes of nitrogen compounds from vegetation and soils to the atmosphere.

6.1.3. Basis for Proposed Studies of the Nitrogen Cycle

Past and present studies of the nitrogen cycle principally fall into three categories: process-oriented, site-oriented, and global/synthetic. The process-oriented studies, which have been particularly prominent in the atmospheric sciences, have dealt with specific phenomena, such as reaction kinetics. Site-specific studies, which are more common among ecologists, but which have also been conducted by some groups of atmospheric chemists, deal with multiple fluxes at a particular site, but typically focus either on the atmospheric compartment or the terrestrial and aquatic compartments, and seldom include both. Global/synthetic studies have been done by a number of individuals and by international groups (Bolin et al. 1983), but are almost entirely limited to the use of scattered data from the literature to approximate global fluxes and compartment sizes.

The three kinds of studies, which differ in their balance of detail and generality, are the foundation of our present understanding of the nitrogen cycle. However, yet another kind of study, which may be termed "integrated" in the sense that it combines within a single group of investigators some features of all three of the existing approaches, could be especially effective in accelerating our progress toward a confident grasp of the cycles of nitrogen or of other elements on a global scale. This integrated approach, which includes selected elements of process studies, geographically broad empirical data collection, and global synthesis, has not yet emerged because of the traditional ways in which the environmental sciences are institutionalized and compartmentalized. The Science and Technology Center program of the National Science Foundation provides the essential financial and organizational superstructure upon which such an approach can be based.

An integrated approach to the study of a nitrogen cycle is inherently multidisciplinary because it requires meaningful collaboration of specialists from disciplines that deal with all major compartments and fluxes that regulate the global nitrogen cycle. It also requires collaboration of individuals who are reductionist by inclination and experience with individuals who work on problems of broader scope. The group that has been assembled by the University of Colorado for integrated study of the nitrogen cycle reflects this essential breadth of disciplinary specialization and conceptual approach (Table 1).

An integrated program for study of the global nitrogen cycle, under which the

Center's research group is to be unified, has three components: (1) development of methods and measurement technologies for the estimation of rates or concentrations for which satisfactory measurements do not yet exist, (2) application of existing methodologies across a broader range of ecosystem types in cases where this breadth is now lacking, and (3) screening and synthesis of existing and new information culminating in the creation of a global mass flux compartment model for nitrogen. Process studies or studies of methodologies are to focus on linkages in the nitrogen cycle that are poorly understood and yet are critical to an understanding of the global cycle. The following sections of the proposal illustrate how the three components of the program will function.

6.1.3.1. Development of New Methods and Instrumentation

Some aspects of the nitrogen cycle are poorly studied simply because adequate methods are not yet available, or have only recently become available, for measurement of the critical concentrations or fluxes (e.g., Fehsenfeld et al. 1988). The University of Colorado has particular strength in the development of instrumentation and measurement methodologies for environmental substances critical to the global nitrogen cycle, and has broadened its capabilities by collaboration with the NOAA and NCAR laboratories in Boulder. Thus the development of methods and techniques for the study of critical nitrogen fluxes that are not yet adequately measured will be an important component of the work to be performed by the Center. The Center will support four primary areas of methods and technology development related to the nitrogen cycle: 1) enhancement of chemiluminescence detection methods for nitrogen species, 2) improvement of methods for using organic substances as a basis for air-mass signatures, 3) development of methods for improving the interface between biogeochemical studies and remote sensing, and 4) application of stable isotope methodology to the biogeochemical cycling of nitrogen.

Chemiluminescence Detection Methods

Chemiluminescence of nitrogen oxides in the presence of ozone provides a highly sensitive and rapid method for the analysis of NOx in the atmosphere. This methodology has been broadly used because of its great practical importance in the monitoring of polluted air masses. Although this use of chemiluminescence detectors will continue to be important in the future, the chemiluminescence principle has much greater potential that yet remains to be developed. The University of Colorado's Cooperative Institute for Research in the Environmental Sciences (CIRES) and NOAA's Aeronomy Laboratory, which works in close collaboration with CIRES, have pioneered the development of chemiluminescence technology and are continuing to develop new applications and instruments for exploitation of this technology.

One major area of development for chemiluminescence technology is improvement in the sensitivity of detectors. The older detectors function well only above the ppbv range. However, for the study of background concentrations, sensitivity below the ppbv range is needed. Detectors with these capabilities are available (Fehsenfeld et al. 1988) but need to be more widely used; validity of the chemiluminescence method at low concentrations has now been confirmed by laser-induced fluorescence (Hoell et al. 1987). Improvements in chemiluminescence instrumentation will be part of the Center's program.

Chemiluminescence detection may also be extended to nonvolatile species. This can be accomplished by coupling of chemiluminescence detection to liquid chromatography.

This is an active interest of the analytical chemistry group within CIRES, and will serve the Center's interest in global nitrogen cycling by offering the possibility of greatly broadening the scope of analytical capabilities for nitrogen compounds in the environment. For example, as much as 25% of the total nitrogen flux from the atmosphere to terrestrial surfaces can be accounted for by filterable organic nitrogen (e.g., Lewis 1981, Grant and Lewis 1982). The identity of these compounds, their cycling mechanisms, and their participation in atmospheric reaction systems is very poorly known, primarily because of inadequate analytical methods.

Ammonia detection is also a high priority for methods development. Detection of ammonia at natural concentrations may be practical on the basis of the chemiluminescence principle following the conversion of atmospheric ammonia to nitrogen oxide. Prototype detectors based on this principle are presently being used by the NOAA Aeronomy Laboratory.

Air-mass Signatures

Through the use of gas chromatography and mass spectrometry, it may be possible to develop sophisticated methods for the identification and tracking of air masses. Development of such methods is a high priority for the CIRES analytical chemists who will be involved in the global nitrogen-cycle studies. An example of this approach is a recent identification of 42 separate organic compounds in air masses of the Front Range area, followed by factor analysis capable of segregating distinctive sources for these compounds (Greaves et al. 1987). This work has shown that it is easily possible to distinguish air masses of the Denver region and Front Range Urban Corridor, which contain substantial amounts of oxidation products ("brown cloud" constituents), from air masses that pass into the Front Range from the west. Air masses originating from the west contain much lower amounts of oxidation products and much higher amounts of biogenic volatile organic compounds such as terpenes. Methods of this type are an essential step toward segregating the anthropogenic and natural components of the biogeochemical cycle for nitrogen.

Remote Sensing

Observations from satellite-borne sensors provide by far the most comprehensive synoptic data collection system in support of global studies. However, because of certain intrinsic limitations on remote sensing technology, it is unlikely that remote sensing will ever displace fully the collection of data by other methods. In addition, ground verification is essential for the calibration and checking of remote sensing data. Despite these limitations, it is clear that the use of remote sensing for the analysis of global phenomena has by no means yet been fully exploited. Advances can be anticipated in part because of the improvement of the sensors themselves, and in part because of the discovery of novel and creative uses of remote sensing data. The University of Colorado has dedicated considerable resources toward these two objectives through its establishment of the Center for the Study of the Earth from Space (CSES). One objective of the proposed Center for Study of Global Change will be to use expertise and technology that are available in the CEOS in the study of problems of interest to the Center.

The proposed Center for Study of Global Change will draw upon the data collection capabilities of the existing Solar Mesosphere Explorer Program, which collects quantitative spectrographic information on the concentrations of NO2 in the upper atmosphere and studies relationships between solar cycles and upper atmosphere constituents (Barth et al. 1983). However, the primary new technological thrust associated with the Center's activity will lie at the interface between ecosystem function and remote sensing. The Center proposes to participate in the development of a recently described approach for deriving nutrient cycling data from remote spectral reflectance observations of tree canopies (Wessman 1987). Specifically, we propose to broaden the application of this technique to other biomes, as described elsewhere in this proposal, and to correlate satellite and airborne imaging spectrometer measurements with measurement of fluxes in situ.

The capability of airborne imaging sensors has advanced significantly with the introduction of airborne visible and infrared imaging spectrometry (AVIRIS: Goetz et al. 1985). This system is capable of acquiring image data over an 11-km path and 224 spectral bands in the region 0.4-2.5 um. The extension to global measurements will come from a high resolution imaging spectrometer (HRIS), which is capable of acquiring images over a 30-km path with 30-m pixils and 192 spectral bands (Goetz and Herring 1987). This system is scheduled for incorporation in the earth observation system instrument complement on the Polar Orbiting Platform (Butler et al. 1984, 1987). If the full analytical power of these sensors is to be applied to biogeochemical phenomena, hypothetical connections between spectral information and ecosystem fluxes must be explored and tested at a much faster rate than at present. The University of Colorado has made a commitment to this type of research through establishment of a postdoctoral position linking biology and remote sensing (filled in 1987-88 by C. Wessman), and by designation of a tenure-track faculty position linking autotrophic functions of ecosystems with remote sensing (search in progress, 1988).

Potential linkages between the remote sensing capabilities under development at COES and the biogeochemistry of nitrogen include relationships between spectrallyobservable properties in vegetation canopies and nutrient cycling rates or constraints on vegetation that arise through nutrient availability. Recent work with airborne sensors shows that forest canopy nitrogen and lignin concentrations can be estimated with sensors of high spectral resolution (Wessman et al. 1987). In addition, relationships between leaf reflectance and leaf chlorophyll and nitrogen concentrations have been demonstrated (Thomas and Oerther 1972, Tsay et al. 1982, Everitt et al. 1985, Nelson et al. 1986). Remote sensing of canopy nitrogen and the change in canopy nitrogen over time are potential indicators of the regulation of plant growth by soil nutrients. Leaf nitrogen concentration and photosynthetic rate are highly correlated (Mooney 1972, Mooney and Gulmon 1982). Lignin content is considered potentially related to decomposition and mineralization, which may in turn be related to nitrogen availability at specific sites (Melillo et al. 1982, Vitousek et al. 1982, Schimel et al. 1985, Parton et al. 1987). Wessman et al. (1988a) present evidence of a strong relationship between canopy lignin and nitrogen availability in seven undisturbed forest sites in Wisconsin, but the breadth of biome representation in studies of this type needs to be extended.

Stable Isotopes

Stable isotopes of nitrogen, carbon, and sulfur are increasingly used as a means of tracking element pathways in ecosystems (Fry and Sherr 1984, Peterson and Fry 1987). However, the application of stable isotope methodology has been limited to some extent by the availability of analytical facilities. The University of Colorado has dedicated a new faculty position (J. White, Geological Sciences), as well as the essential facilities and support for the development of a stable isotope analysis facility. We propose to incorporate stable isotope signatures, particularly those related to nitrogen, in the studies of nitrogen cycling.

Analysis of nitrogen isotopes in support of ecological studies has been less common than the analysis of carbon isotopes. Although the interpretation of stable isotope signatures for nitrogen is more complex than that of carbon because of the higher likelihood of multiple microbial transformations of nitrogen (Heaton 1986), we believe that much unexploited potential remains in the use of stable isotopes to identify sources and fates of nitrogen in specific ecosystems where stable isotope signatures can be identified with specific compartments.

6.1.3.2. Empirical Studies of Globally-representative Ecosystems

One of the greatest present deficiencies in studies of the global nitrogen cycle is the lack of an organized system for assessing the fluxes that are characteristic of a broad diversity of ecosystems, and for establishing quantitative methods for weighting these fluxes according to their representation within the biosphere. A major portion of the effort of the Center for Study of Global Change at the University of Colorado will be directed toward these two ends.

It is probably not feasible or cost-effective for investigators from a specific institution within the United States to work across numerous international boundaries as would be required for direct representation of the diversity of biomes that must be studied if global element fluxes are to be understood. International study groups do exist (e.g., Degens and Kempe 1982, WMO 1985), and perform an important role across international boundaries, but often are handicapped by logistical difficulties and inability to make coordinated and detailed sets of empirical measurements, as would be possible for a group of investigators working together directly from a given location.

The United States and its territories contain a very broad representation of global biomes (Figure 3). By the use of these biomes, particularly if supplemented in a few instances by studies outside the United States where research collaborations already exist, it is possible to establish a reasonable surrogate for global diversity of ecological systems at the biome level. A major activity of the Center for Study of Global Change at the University of Colorado will be to assemble comprehensive data sets on the nitrogen cycle for global biomes through a network of sites situated mainly within the territorial United States. While such a program will by no means represent the full diversity of fluxes found in ecosystems of the world, it will constitute a significant step forward from the present state of knowledge concerning global nitrogen fluxes. This approach will provide coordinated data sets representing the breadth of variation in fluxes and the probable range of reasonable values to be used for specific fluxes in accounting for the global nitrogen cycle. Furthermore, representation of a broad diversity of biomes may allow the development of correlations involving vegetation types, moisture, or other well documented variables that could be used in formulating indirect estimation techniques for specific nitrogen fluxes.

Documentation of nitrogen fluxes over a network of sites representing a wide range of biomes will require three approaches: (1) assembly of the existing information on the nitrogen cycle from the sites, and conversion of this information to a standard format, (2) development of a means for estimating statistical uncertainty in annual flux measurements associated with physiographic or ecological diversity within each biome, and (3) direct measurement of fluxes that have not been measured for each site as a means of completing the nitrogen flux data set across all sites. The work will progress through three stages. The first stage will focus on nitrogen fluxes of undisturbed ecosystems, and will lead to the creation of a background nitrogen flux model for the earth. The second stage will encompass land-use variation within the biomes, and the third stage will concentrate on the use of the information from the first two stages to construct a mass-flux model that can be used for predictions based on changes in anthropogenic sources and sinks of nitrogen.

6.1.3.3. Development of a Site Network

Distinctive ecosystems such as tropical rain forests and temperate grasslands are expected to differ greatly in specific nitrogen fluxes because the nitrogen fluxes are under strong climatic and biotic control (Mooney et al. 1987). At a coarse level, characterization of global diversity in nitrogen flux can be accomplished by choice of a suitable world classification of ecosystems followed by the quantification of nitrogen fluxes in each of these ecosystem types. Udvardy (1975, 1976) has identified and mapped fourteen major ecosystem types, or biomes (Figure 3). Extensive examples of all but two of these biomes occur in the United States. Tropical humid forests and tropical grasslands are represented in only minor quantity within the United States and its territories, but are extensively represented in Costa Rica, Peru, and Venezuela, where collaborative studies involving the University of Colorado are already in progress. Thus a cost-effective assessment of global diversity in nitrogen fluxes could be obtained on the basis of a network of sites limited to the United States and possibly one or two other countries.

There is great regional diversity within each of the biomes (e.g., see Bailey and Hogg 1986), the full assessment of which would require a far more extensive network of sites than is proposed here. However, assessment of the degree of diversity itself can be approached statistically, as outlined below. We propose to obtain comprehensive data sets from at least one site in each biome, and a quantitative estimate of the degree to which such a single estimate represents the biome.

Udvardy's classification scheme is especially useful in our proposed studies of nitrogen flux because his biogeographical provinces (biomes) are serving as a framework for the selection of both U.S. and world biosphere reserves (Fernald et al. 1983, Harrison et al. 1984). The latter form an international network of protected areas designed to conserve representative samples of world ecosystem diversity and to provide large sites for environmental baseline studies and monitoring (Anonymous 1979). As of 1985, there were 51 biosphere reserves in 23 U.S. states and Puerto Rico (Figure 4). Examples include the Jornada experimental range in New Mexico (warm desert and semi-desert), Niwot Ridge in Colorado (mixed mountain and highland systems), and Coweeta hydrologic lab and experimental forest in North Carolina (temperate broadleaf forest).

Two advantages of using U.S. biosphere reserve sites include the existing data bases on many of these sites and the emphasis on site comparison that is inherent in the network system. Many of the biosphere reserve sites were chosen partly because they have been a focus of research for many years. These sites will provide existing measurements of a number of important nitrogen fluxes without any further data collection, and will also provide perspective on year-to-year variability and give information on ancillary influences such as net primary production that may be very important in predictions or causal interpretations. In addition, it may be feasible to establish collaborative arrangements by which essential measurements are simply incorporated into existing monitoring programs at the sites, without direct physical involvement of the group at Colorado. In this way, the data base could be expanded at minimal cost.

Within the U.S. biosphere reserve system, a number of sites are designated as Long-term Ecological Research sites of the National Science Foundation (Halfpenny and Ingraham 1984). The Niwot Ridge site, an LTER site operated by the University of Colorado Institute of Arctic and Alpine Research, is an example. We propose to incorporate the Long-term Ecological Research sites into the network wherever possible because intensive documentation of environmental fluxes is one of the purposes for extended study of these sites, which are representative of the Biosphere Observatory concept emphasized in the International Geosphere/Biosphere Program.

The emphasis of the site measurement program is on fluxes involving terrestrial systems, either through exchange with the atmosphere or through runoff to the world oceans. Exchanges between the atmosphere and the oceans are not a subject of direct empirical study by this project. However, through the existing close collaboration between NOAA and the University of Colorado, we propose to represent the marine-atmosphere component on the basis of the NOAA marine network monitoring program.

6.1.4. Choice of Fluxes for Study

Figure 1 summarizes the fluxes that are of major interest to the Center for Study of Global Change. For convenience, these fluxes are divided in Table 2 into two groups: fluxes between compartments (land, atmosphere, ocean), and fluxes within compartments. For fluxes passing from terrestrial surfaces to the atmosphere, particular emphasis will be placed on the release of nitrogen oxides and ammonia. Such releases are as yet poorly studied at specific sites. They are not only relevant to the nitrogen balance of terrestrial ecosystems but, even more importantly, are the major source of fixed nitrogen compounds for the lower atmosphere. Lack of emphasis on terrestrial releases of nitrogen oxides or of ammonia is in part related to inadequate methods for detection and sampling of these substances. However, a new generation of detection methods has greatly improved the feasibility of making measurements under realistic field conditions. A number of new methods are being developed jointly by the University and NOAA. A broadening of the measurement base for these techniques across diverse ecosystems is badly needed as a means of establishing greater confidence in the nitrogen cycle fluxes, and as a basis for understanding the mechanisms that control release.

6.1.4.1. Organic Compounds in the Atmosphere

Methane has received within the last decade a great deal of attention as it has become evident that methane is an important regulator of photochemical reactions in the atmosphere and an important greenhouse gas (Khalil and Rasmussen 1984), and that its concentrations are increasing. Because methane is being intensively studied by other groups in connection with the carbon cycle, methane will be represented in the Center's work primarily through linkage with the NOAA Carbon Cycle Group located in Boulder (P. Tans, group leader). However, considerable emphasis will be placed on nonmethane hydrocarbons, which have been much less studied and which have some critical interactions with the nitrogen cycle, and on other organic compounds.

The emission of non-methane hydrocarbons (NMHC) from vegetation has been known for over two decades (Rasmussen 1981, Duce et al. 1983, Altshuller 1983). Interest in these volatile organic compounds is increasing in light of recent work showing that they interact with nitrogen gases and oxidants in the troposphere in a series of photochemical reactions that generate important tropospheric gases such as ozone (Liu et al. 1987, Trainer et al. 1987). The following simplified reaction scheme shows the catalytic role of NMHC in ozone generation in the presence of nitric oxide (NO):

(1) NMHC + HO + O2 ----> RO2 + H2O

(2) RO2 + NO + O2 ----> NO2 + HO2 + CARB

(3) HO2 + NO ----> NO2 + HO

(4) 2(NO2 + hv + O2 ----> O3 + NO)

Net: NMHC + 4O2 ----> 2O3 + CARB + H2O

In this scheme "CARB" refers to carbonyl compounds such as aldehydes generated from NMHC; these carbonyl compounds themselves can also participate in a similar sequence of reactions, generating more ozone and ultimately carbon monoxide. Thus NMHC are direct precursors of carbon monoxide, and are an important link in balancing the global carbon cycle (Chameides and Cicerone 1978, Zimmerman et al. 1978), and also affect oxidant concentrations. Since the reaction rates of NMHC, such as isoprene, with hydroxyl radical are much higher than similar reactions with methane or carbon monoxide, Crutzen (1982) has concluded that NMHC are important regulators of tropospheric OH concentration. In addition, NMHC such as isoprene are direct precursors of organic peroxides, organic nitrates, aldehydes and ketones, and organic acids such as formic and acetic acid (Gaffney et al. 1987, Jacob and Wofsy 1987).

The products of these photochemical reactions of NMHC contribute to regional air pollution and may also induce damage to exposed crops and forests. It is estimated that increased tropospheric ozone alone results in several billion dollars loss per year in the U.S. due to diminished agricultural crop yields (Adams et al. 1985). Ozone uptake by plants leads to various types of tissue damage and significant decreases in photosynthetic capacity, and it is estimated that the ambient ozone levels typical of the eastern U.S. are leading to reductions in net photosynthesis over that entire region of the country (Reich and Amundson 1985). In addition, ozone alone and in combination with sulfur dioxide or nitrogen oxides is causing major damage to forests on a worldwide basis (Ashmore et al. 1985).

Surprisingly little is known of the environmental variables that regulate NMHC emissions from vegetation. In addition, there is uncertainty about the chemical identification of a large fraction of biogenic hydrocarbons and the biochemistry of plant hydrocarbon production. Major goals of studies proposed here are to a) establish the sources and chemical speciation of biogenic NMHC; b) provide more accurate regional and global estimates of the magnitude of NMHC emissions from the biosphere; c) characterize whole plant emissions of NMHC and the role of oxidant stress in promoting these emissions; d) establish the biochemical pathways of NMHC synthesis; e) clarify the reasons for NMHC production by plants and the regulation of these processes; and f) assess the disruption of oxidative cleansing processes in the atmosphere by organic compounds of natural and anthropogenic origin.

6.1.4.2. Atmospheric Deposition

Measurement of inorganic nitrogen compounds and wet deposition by the use of standard collectors is now routine, largely because it is incorporated into the national network programs for deposition monitoring in the United States and European nations (NAS 1986b). This provides a firm foundation for judging the rates and variabilities of inorganic nitrogen flux from the atmosphere to terrestrial surfaces. There remain, however, a number of great uncertainties concerning the total flux of fixed nitrogen compounds to ecosystems. These uncertainties fall generally under three headings: (1) the deposition of organic nitrogen in either soluble or particulate forms, (2) differentiation of transport distances for various forms of nitrogen, and (3) quantification of dry deposition rates. All three of these questions need to be approached with the best available methodology in a broad variety of ecosystems.

Organic and particulate nitrogen can account for a significant amount of the mass flux of nitrogen from the atmosphere to a given terrestrial site, as measured with a standard collector (e.g., 47% of total deposition at Niwot Ridge in Colorado: Grant and Lewis 1982). However, such measurements have not been made sufficiently often to indicate the probable magnitudes and variabilities of nitrogen deposition by this pathway. Nitrogen in these forms is, of course, not of direct significance to the acidity of deposition, but may be important to the nitrogen balance of ecosystems, or to the global inventory of fixed nitrogen in the atmosphere.

The origin of fixed nitrogen compounds deposited through wet or dry atmospheric deposition in an ecosystem may be of great interest with respect to its nitrogen balance. Estimates of sedimentation coefficients, particularly if conducted in connection with synoptic studies tracking specific air masses, may demonstrate typical transport distances. However, such studies are outside the scope of work proposed here. More meaningful in the present context is a comparison of the nitrogen influx from the atmosphere with the efflux to the atmosphere at the same site. Differences in these two sets of fluxes will determine the degree of influence of the atmosphere on the nitrogen balance of the terrestrial system. We propose detailed site-specific measurement of fluxes into and out of the atmosphere for fixed nitrogen compounds across the diversity of biomes.

One of the greatest difficulties in isolating the atmospheric component of element budgets for terrestrial surfaces is the estimation of deposition rates under dry conditions, when substances are removed from the atmosphere by impaction and gravity sedimentation at the surfaces themselves, rather than by wet precipitation (Sievering 1984). There are basically two lines of research related to this problem: (1) modelling of the deposition process, and (2) development of methods for empirical measurement of deposition. We propose to focus on empirical measurements because of the compatibility of this approach with our other studies, and because of the paucity of direct information on deposition rates for nitrogen fluxes from the atmosphere under dry conditions across a wide variety of sites.

Dry deposition is currently estimated by a combination of methods, none of which is completely satisfactory. Given that each of these methods presents interpretational difficulties of some type, it seems best to rely on multiple methods that can be checked against each other. Lindberg and co-workers (Lindberg et al. 1982) have pioneered methods for the estimation of dry deposition by the use of standard surrogate surfaces. However, these surfaces may produce inconsistent results (Sievering and Ton 1985). Comparisons of throughfall with deposition incident on the canopy surface have been used, but are also subject to some interpretational difficulties. The multiple regression approach of Lovett and Lindberg (1985) appears to be a promising extension of this method that is likely to improve its reliability. Eddy flux or gradient techniques may also be appropriate, and in fact may be the most frequently used of current methods. The quality of such estimates made by these methods depends to a large degree on the speed and accuracy of the underlying empirical measurements.

6.1.4.3. Runoff

Large amounts of fixed nitrogen are removed from ecosystems along with runoff. Nitrate is typically the dominant inorganic constituent and has been thoroughly analyzed in the surface waters and groundwaters of industrialized countries, although good series of measurements from some of the world's largest uninhabited drainages are still surprisingly few (Meybeck 1982). The information on ammonium, which is typically the second most abundant inorganic species in solution, is much less abundant, and a large portion of the existing information on ammonium is unusable because of unsatisfactory analytical methods. Although ammonium has sometimes been judged an insignificant component of transport for inorganic nitrogen, its importance may have been underestimated, particularly for certain poorly studied but globally important biomes such as tropical moist forest (Lewis 1986). Transport of soluble organic nitrogen and particulate nitrogen has been documented even less satisfactorily, largely because of analytical difficulties. However, the existing data show clearly that the transport of these species through rivers can easily account for 50% of the total nitrogen transport by water. These deficiencies need to be remedied for a full range of biomes.

6.1.4.4. Biotic Processing

As a step toward a mechanistic understanding of the fluxes between compartments, some within-compartment analyses also need to be included in the program. As shown by Table 2, the terrestrial compartment includes a number of important biologically-mediated processes that ultimately govern nitrogen fluxes. Although some of these processes have been studied for decades, coverage is uneven across the processes and across the intersections between processes and ecosystems. Special emphasis will be given to denitrification, which is the least well understood of the processes listed in Table

2, and which is likely to be directly connected to the release of fixed nitrogen from terrestrial environments.

Biogeochemical cycling of nitrogen is highly dependent on the activity of soil microorganisms. It has been estimated that 90 million metric tons of nitrogen is fixed every year by soil bacteria, and that anthropogenic sources of fixed nitrogen are of about the same magnitude (Mooney et al. 1987). The largest drain of nitrogen from the soil environment may be denitrification, which leads to the loss of approximately 140 million metric tons per annum (Burns and Hardy 1975).

Denitrification, in the strict sense, refers to the reduction of nitrate (NO3-) and nitrite (NO2-) to nitric oxide (NO) and nitrous oxide (N2O), both of which may be further reduced to dinitrogen (N2)(Knowles 1982). Denitrification takes place primarily under anaerobic conditions, but recent work has shown that N2O can be produced by nitrifying bacteria under aerobic conditions (Anderson and Levine 1986, Aulakh et al. 1984, Belser 1979, Yoshida and Alexander 1970). In addition, aerobic chemoautotrophic bacteria can produce small amounts of N2 (Poth 1986). Although some denitrification can take place under aerobic conditions, it

s generally believed that most of the N2O, NO, and N2 leaving the soil is derived from anaerobic denitrification (Atlas and Bartha 1987). Loss of these compounds is therefore greatly stimulated at high soil moisture levels, as would occur after a rain (Craswell 1978). This observation has obvious implications for the variability of denitrification in the field.

The evolution of nitrogen oxides from the soil can be measured by gas chromatography (Payne 1981). Measurement of N2, however, is hindered by the high background levels of this gas in the atmosphere. To get around this problem, acetylene can be used to inhibit the microbial conversion of N2O to N2; this allows denitrification to be quantified in terms of N2O. The main disadvantage of this technique is that acetylene also interferes with nitrification and other microbial processes in the soil (Mosier and Heinmeyer 1985). This interference can eventually deplete the NO3- that feeds the denitrification process. Despite these problems, this technique has led to meaningful results from field studies. The main advantages of the acetylene inhibition technique are that it (1) is simple and inexpensive; (2) can be used without fertilizer additions or other soil disturbances, and (3) is very sensitive, having a N2O detection limit of 1 g N ha-1d-1 (Mosier and Heinmeyer 1985).

The other commonly used method for quantifying denitrification is the 15N technique (Knowles 1982). The major disadvantages of this method are that it requires disturbing the soil via the addition of 15NO3-, and that its lowest level of sensitivity is ca. 5 g N ha-1d-1 (Mosier and Heinmeyer 1985).

For most of the sites, direct or indirect estimates of assimilative uptake and decomposition will be available as a result of biologically-oriented ecosystem studies. Specific estimates will sometimes also be available for nitrogen fixation and nitrification. Where these are not available, existing methods will be used to make site-specific estimates.

6.1.5. The Atmospheric Compartment

Within the atmospheric compartment, the reactions of greatest interest include those involving ozone, nitrogen oxide, and organic carbon. Models exist for the interaction of these substances based on reaction rates for specified radiation environments and the presence of other moderating chemical species or particles in the atmosphere.

However, measurements of all of the important reaction system components have been limited to very few sites, or, if done across a geographical range, have been limited to synoptic sampling. We propose to broaden this base of information by collecting site-specific information on the atmospheric reaction components.

6.1.6. Quantifying Variation in the Fluxes

Global flux measurements are typically reported without formal assessments of error. In fact, error assessments are typically impossible because they are not incorporated in the measurement schemes upon which the global estimates were based. We believe that this deficiency can be circumvented to a large extent by incorporation of statistical estimates of uncertainty in the network approach.

A components of variance approach can be taken for the decomposition of variance in any environmental measurement that varies simultaneously through time and space (e.g., Lewis 1978, Robertson 1987). This requires only replication through time (in this case, years) and across sites within a given biome. Such a scheme can even take into account interaction between time and space components. We propose to use a components of variance approach for the quantification of individual fluxes within each biome. Although ideally this would involve a full suite of measurements at multiple sites within each biome, for practical purposes we limit ourselves to the use of multiple sites on only a few dates, with appropriate extrapolation of variance from that base. For measurements that show extreme temporal or spatial variability, it will also be possible to add components of variance to account for variation on differing temporal or spatial scales.

We believe that an important result of the site-specific empirical assessment of fluxes will be quantification of the relative variance of each flux. This will in turn help prioritize for the future the study of fluxes, and will help identify the fluxes that need to be studied more extensively in order to improve confidence in global extrapolations.

6.1.7. Logistics for Sampling

Data on specific fluxes will be taken from existing data records or existing monitoring programs whenever possible, given reliable and relevant data, and will be converted into a form that is useful for our own analysis of fluxes. Where such measurements are not available, the first choice will be to obtain these measurements by collaboration with resident scientists who may be making related measurements. The final choice, which we expect to use most often in relation to fluxes that are seldom measured but that are of special interest for this program, involves the use of two mobile field crews equipped for making site-specific measurements or for collecting samples for shipment to Boulder. Measurements at specific sites will be made bimonthly for the number of years necessary to quantify interannual variation (at a minimum, three, but preferably more). The field crew will also make measurements at supplementary sites to provide the basis for estimating interbiome sources of variation for fluxes.

6.1.8. Synthesis

Synthesis, which need not be restricted to the end of any particular study interval, will be based upon a global flux model. The global flux model will basically be algebraic in design, i.e., it will not attempt to provide process-level simulation of all fluxes, although process-level simulation of selected fluxes is not precluded. The main function of the global flux model will be to serve as an organizational tool that can assimilate the information on fluxes and biome types; the model can be visualized as a two-dimensional matrix that yields all possible combinations of biome types and fluxes. The final objective is to provide quantitative estimates for each of these intersections, and then to weight the contribution of fluxes across biomes according to the areal representation of each biome type.

In addition to being an organizational tool, the flux model will be used in error analysis for global fluxes. Provided that empirical estimates of error are available for each compartment in the matrix, error propagation can also be estimated for the summation of fluxes.

The principal aims of the synthesis will be as follows: (1) to establish the background nitrogen fluxes for the biosphere, to estimate the degree to which each of these fluxes has been perturbed anthropogenically, and to make projections of future perturbations; (2) to demonstrate whether the present understanding of fluxes is sufficent to account for the observed quantities within the major global pools of nitrogen; (3) to provide a general framework that can incorporate future improvements in measurement of specific fluxes; (4) to show which fluxes and which ecosystem types are most urgently in need of intensive study, as a result of their unusual flux patterns or their high variability; (5) to provide the basis for establishing correlations between nitrogen fluxes and environmental variables that are more easily and more economically measured; (6) to provide a focus for the use of new technology in the measurement of specific nitrogen fluxes.

6.2. ENVIRONMENTAL DYNAMICS

6.2.1. INTRODUCTION

By environmental dynamics we mean the dynamics of the physical environment that interacts with the biosphere through biogeochemical exchanges. Environmental dynamics pertains to the atmosphere, snow and ice, oceans, and land surface, including the couplings and exchanges between these and with the various elements of the biosphere.

Earth's environmental dynamics have been studied for many decades, and the atmospheric and oceanic sciences have developed into rich, diverse disciplines. However, the notion of Earth *as a unified system* as a topic of study is quite recent, one that has evolved from the realization that the physical environment cannot be dealt with in isolation from the biosphere.

The complete environmental dynamics of Earth is a subject of great breadth, and is probably too broad for efficient study by andy single institution. The Center for the Study of Global Change will concentrate its effort on three of the most critical aspects of environmental dynamics relevant to global change, and the Center will undertake to foster those areas and broaden them to investigate their relationships to other facets of the physical and biological world. The first two of these areas are *polar/global* and *tropical/global and interaction studies* In each of these fields, theoretical and observational research activities at the Center will be aimed at understanding the relationships between processes in the climate system and environmental change. Complementing this activity, the *record of enviromental change* as deduced from past environments will provide an inter-hemispheric section to tie the tropical and polar regions together.

6.2.2. Polar/Global Interactions

6.2.2.1. Introduction

The polar regions play a key role in global change. They serve as primary sink regions of global energy transported by the atmosphere and oceans and they may also serve as sinks for anthropogenic aerosols in the Arctic and for trace gases in both polar stratospheres. Both polar oceans play important roles in the world ocean circulation and contribute to climatic change through their variable sea ice covers. Polar ice masses also play a key role in global sea level trends through changes in their mass balance. Further, the polar regions have been shown by empirical evidence and by modeling assessments to be especially sensitive to climatic change. Consequently, improved knowledge and understanding of polar environments is critical to monitoring and predicting global change. Finally, polar areas contain important evidence of past environmental history from ice cores, ocean and lake sediment cores, and from pollen evidence.

The organization of polar research has traditionally been characterized by interdisciplinary endeavors and for this reason it offers special opportunities for global change/global geoscience. This is as reflected in the recent UCAR/University of Colorado/Royal Society of Canada workshop on Arctic Interactions (UCAR, 1988). The University of Colorado has a tradition of high-level accomplishment in polar sciences, and with its collaborating agencies afford the possibility of a coordinated focus on polar environmental dynamics. Organizational strengths include the presence of the Cooperative Institute for Research in Environmental Sciences with programs in atmospheric and climate dynamics, environmental chemistry, remote sensing (Center for the Study of Earth from Space), and the contractual operation of the National Snow and Ice Data

Center (NSIDC)/World Data Center-A for Glaciology; the Institute of Arctic and Alpine Research with programs in geochronology, glaciology, Quaternary studies, and paleoenvironmental analysis; and other institutes and departments involved in polar research. NOAA entities located in Boulder with polar interests include the Global Monitoring for Climate Change (GMCC) program and the Aeronomy Laboratory of the Environmental Research Laboratories, and the National Geophysical Data Center of the National Environmental Satellite Data and Information Service.

Specific polar research already underway at the University includes (1) an ONR university Research Initiative 5-year grant for Arctic Ocean atmosphere-ice system studies (Barry, McLaren and Schnell, CIRES); (2) NASA supported studies of polar cloudiness (Barry); (3) DOE support for studies of ice sheet contribution to global sea level change (Meier and Pfeffer, INSTAAR), (4) NSF supported Quaternary research in Svalbard and the eastern Canadian Arctic (Miller, Andrews); (5) NASA support for Arctic and Antarctic sea ice products from the Defense Meteorological Satellite Program Special Sensor Microwave Imager (DMSP SSM/I) by the National Snow and Ice Data Center (Weaver and Barry); and (6) Arctic Gas and Aerosol Sampling Program encompassing 38 PIs from across the United States and supported by ONR, NASA, NOAA, and DNA. This ground and aircraft project covers the Arctic from Alaska to Norway and is a joint CIRES/NOAA research effort. The new Center for Global Change will provide a focal point for the proposed interdisciplinary collaboration.

The primary topics for the first phase of the Center's activity in these areas are shown in Table P.1; their significance is outlined in Table P.2. These themes address issues identified in numerous reports of the Polar Research Board (1984, 1985a, 1985b), as well as the U.S. Arctic Research Commission (1987), Interagency Arctic Research

Policy Committee (1987), and the National Science Board (1987). For example, the PRB Committee on the Role of the Polar Regions in Climatic change (1984) identified the polar regions as: (1) "sources of climatic unrest". They play a key role in the physical processes responsible for global climatic fluctuations through energy transfers, ice-albedo feedback, and production of water masses; (2) "Windows on the Past", through ocean sediment cores, ice cores, terrestrial pollen records and glacial-geologic evidence of past ice cover; (3) "uniquely vulnerable to climatic changes of the kind projected to occur in the coming century as a result atmospheric increases of CO_2 and other 'greenhouse gases'". Study of "the sources, transport pathways and chemical signatures, conversion processes and effects" of anthropogenic pollutants and of their climatic, hydrologic and biological effects in tundra areas is recommended in the PRB "National Issues and Research Priorities in the Arctic" (1985). That same report also recommended as its highest priority study of the Arctic Ocean (including sea ice) and of how the ocean and atmosphere operate as coupled components.

Investigation of the full scope of problems implied by Table P.1 will require a decade-long endeavor. Theme 1 addresses the high-latitude phenomena of global significance; theme 2, the physical processes which make polar regions vulnerable to change; and theme 3, the environmental evidence of the sensitivity of high latitude to natural and anthropogenic change. Specific questions that would provide the focus of the initial phase of study are as follows: (1) What is the sensitivity of the ice covers of the Arctic and Antarctic to climatic perturbations due to anthropogenic activity over the next century and what will be the consequences for global climate? Is a seasonally-ice-free Arctic Ocean possible? What consequences for the production of ocean bottom-water and ocean chemical tracer transport arise? What have been the respective contributions of polar ice masses and alpine glaciers to recent global sea level change and what are they likely to be over the next century? (2) What improvements can be made in our understanding of polar region surface energy budgets by integrating the various ground-based, aircraft and satellite measurements in a systematic way? Based on these improvements, how far can simulations of the global atmospheric circulation and climate in a general circulation model be improved by more realistic treatment of snow cover and sea ice distribution and properties? (3) How do trends of trace gases and aerosols in polar latitudes compare with those in mid-latitudes and what are the implications? What is the role of Arctic haze in perturbing the Arctic climate and snow/ice cover? (4) What environmental parameters in polar regions are most suitable as indicators of global scale climatic change and how might their regional responses differ to a uniform forcing?

6.2.2.2. Research Themes

Topic 1. Polar Ice Stability and Climatic Effects

The possibility of an ice-free Arctic Ocean due to global warming or changing hydrologic conditions has been postulated by both meteorologists (Donn and Shaw, 1967) and oceanographers (Aagaard and Coachman, 1975). The date of inception of an ice cover in the Arctic Ocean is uncertain and the possibility of seasonally ice free intervals during the late Quaternary is controversial (Herman, 1985; Clark, 1982; Barry, in press). Some modeling studies indicate the feasibility of such a condition for warming anticipated as a result of CO_2-doubling (Manabe and Stouffer, 1980). However, other model studies contradict these findings and indicate that the Arctic ice cover is fairly stable (Semtner, 1987). Experimentation with current sea ice models is considerably hampered by the limited availability of validation data on ice characteristics. Some of the more critical data limitations include: snow cover and its seasonal melt, ice thickness frequency distribution and its geographical characteristics, and the distribution of leads (fractures) and first year/multiyear ice and their interannual variability. Substantial progress has been made at CIRES in using satellite data to map snow melt and lead distribution (Scharfen *et al.*, 1987), and new ice thickness data are being extracted from submarine sonar records (McLaren, 1987).

These data allow improvements to be made in parameterizations of sea ice and snow cover used in both sea ice models (*e.g.* Hibler, 1979) and climate models (*e.g.* the NCAR CCM) They also provide validation data against which to test model results. Through extension of our existing collaborations with Hibler at Dartmouth College, and with Warn-Varnas at NORDA, under an ONR/URI program, simulation studies for various future greenhouse gas and other scenarios will be made. Interactions of the ice and synoptic weather systems will be analyzed extensively, building on the case studies of McLaren *et al.* (1987) as the new SSM/I passive microwave data become available for ice mapping. NOAA AVHRR data will be used to obtain cloud cover information using image analysis and classification techniques. These results will be compared with global climate model simulations described below.

Sea-ice variability as a consequence of global change is but one manifestation of polar/global interactions. High latitude processes affect global change in many ways; another obvious interaction is the effect of glacier and ice sheet wastage on sea level. The current rate of rise in global sea level has been estimated at 1 - 1.5 mm a^{-1} after removal of coastal uplift or depression effects from tide-gage records (Peltier, 1985). Part of this rise is undoubtedly due to thermal expansion, although there is little consensus on the actual amount (NRC, 1985). Meier (1984) estimated that about 0.4 - 0.5

mm a^{-1} of rise is due to wastage of the small glaciers of the world; the contributions of the Greenland and Antarctic Ice Sheets to current sea level change are thought to be relatively small, but even the sign of the contribution is in doubt (NRC, 1985).

This modest current rise in sea level is creating problems of beach erosion and storm surge damage in many parts of the world, but is overshadowed by what is likely to happen in the future due to a "greenhouse" warming of the climate. Estimates of the total sea level rise in the next 100 years range over wide limits, from a few tens of centimeters to well over one meter (NRC, 1984; Robin, 1986; EPA, 1983). Clearly, we need to understand better the causes of current sea-level rise, and then to refine estimates of future rise due to a changing climate.

We propose to improve our definition of the present contribution of land ice wastage to sea level by carrying on mass balance or volume change studies at selected sites to augment the current global observation net, and to develop improved mass balance models to extend the data over regional areas. The field studies will include *in situ* observations in several areas that are critical to sea-level change but are poorly known, such as the icefields bordering the Gulf of Alaska and in Southern Patagonia.

In addition, image-analysis techniques will be used to define the snow facies, and thus the extent of the accumulation and ablation areas, in these and other areas including the Greenland Ice Sheet and arctic ice caps. This work will supplement and extend the results of a current study under the sponsorship of the Department of Energy that is looking into how these snow facies will be affected by increased meltwater percolation into cold snow caused by climatic warming.

These results will improve our understanding of the current flux of water mass from ice on land to the ocean, and thus will provide a basis for estimating what will occur in the future with a changed climate change predictions (monthly precipitation, air temperature, radiation, pressure gradients) to estimation of meltwater runoff and thus sea-level rise. This will allow planning, which will be critically important to ameliorating the social and economic costs of sea-level rise.

Both sea- and land-ice in polar regions, and changes thereof, play significant roles in the dynamics of the world's oceans. The polar regions are the locations of deep-water production zones of the oceans, and freshwater runoff associated with ice melt can be important in this process. Also, dynamical effects at the seaward edge of an ice sheet may cause bottom-water formation (Haakinen, 1987). Deep-water formation and its relationship to climate change is central to biogeochemical cycling problems. The net amount of heat stored in the deep oceans is thought to be a factor in climate change on the glacial/interglacial time scale.

To investigate these interactions, the ocean model described below will be used. The model's capability for air-sea interaction studies will be particularly valuable in these studies. In this role, the ocean model will serve as an important diagnostic tool to complement the data analyses proposed here. These analytic studies can provide the insight needed to understand *what* is happening to the climate, and the modeling efforts will allow *how* it is happening to be understood.

Specific research questions to be addressed include:

- How does the seasonal cycle of upper ocean forcing due to varying solar radiation and winds interact with similar cycles of ice melt and freeze-up in the marginal ice zone?
- How is deep water formation in the North Atlantic affected by these interactions?

- To what degree will these processes be modified by the trend toward less multi-year ice (i.e., as the ice cap shrinks)?

- How will the poleward heat transport by the oceans be modified by these changes?

- What are the implications of these changes in the ocean circulation for redistribution of chemical substances in the ocean?

Topic 2. Polar energy budget and its climatic significance.

The polar regions serve as the energy sinks for the global heat engine, their surrounding oceans are the major sites of deep water formation for the global ocean, and the ice margins are zones of great marine biological productivity. The physical processes that effect temporal variability in this ice — climate system, which in turn influences mid-latitude weather and climate, are, with exceptions, poorly understood. The snow-ice/albedo feedback is a significant amplifying feedback of small perturbations in global climate (Robock, 1983; Hansen *et al.*, 1984). Climate model simulations of CO_2 warming point to the largest response in polar latitudes (Schlesinger and Mitchell, 1987). The ozone hole is becoming recognized as a possible manifestation of global climate change.

The polar energy budget involves radiative fluxes, which are influenced by clouds, aerosols and surface conditions, horizontal transports of energy in the atmosphere and oceans, and heat transport between the two media. Net radiative heat loss to space is offset by the horizontal transports. Therefore, a changes in the patterns of these processes represent fundamental changes in the climatic state. New data sets afford the possibility of calculating many of the terms in the energy budget more accurately than previously and of testing numerical models of the heat transfers. Satellite data, for example, enables the spatio-temporal variability in surface and planetary albedo, cloud cover, and outgoing infrared radiation to be determined consistently. Results of satellite studies will be used as validation data for GCM simulations of the type described in below.

The methodology for this project involves analysis and modeling using both satellite and ground data. Satellites presently observe the albedo and outgoing infrared (IR) radiation over the poles. Data for South Pole daily-averaged incoming solar radiation measured by GMCC display very definite characteristics that can be related to weather systems and cloudiness. Since there is no radiant heat source from the sun during austral winter, nearly all heat is advected to the pole. This warm-air advection, which is accompanied by a rapid increase in downward IR flux, is also often accompanied by large bursts of aerosols of marine origin measured at South Pole observatory (Ref).

These observations demonstrate the feasibility of attempting long-term observations of the energy budget of a polar region. Other non-United States (e.g. Japan, USSR, Italy) stations are also making measurements and their data are available for our use to gain greater regional coverage and to correlate with satellite data sets. Both Arctic and Antarctic regions will be included in this study. Ground based observations will be made at South Pole, McMurdo, and several other United States sites in Antarctica. In the Arctic, measurements will be made at Barrow and, possibly through Bilateral Working Group VIII, collaboration will be sought with scientists in Canada, Scandinavia, and U.S.S.R. Measurements will include: downwelling IR and solar and, when feasible, trace gases (O_3, CO_2, CH_4, etc.), and water vapor.

The results of the observations will be assimilated into a descriptive model of approximately 1000 km resolution for each polar region with higher resolution near the observing stations. A physical model of the energy exchange processes will be developed to account for the observed features of the descriptive model and to explain changes in observed patterns from physical principles.

This descriptive model will be complemented by more comprehensive simulations using the new version of the NCAR CCM outlined below. In particular, we propose to carry out a set of simulations to investigate the effects of changes in the snow cover and ice extent in polar regions. An obvious first experiment would be to run CCM-1 with a distribution of ice and snow cover specified from a modern climatology. The new distribution of ice and snow should produce a new distribution of heating in the atmosphere and thereby change the model climate. If the results are interesting, the experiment can be continued by reducing the extent of snow and ice in a reasonable way. The result should be of assistance in assessing the importance of global climate warming on local and regional climates of the earth.

Topic 3. Changes in Composition of the Polar Atmosphere.

The NOAA Geophysical Monitoring for Climatic Change (GMCC) program operates the four United States baseline observatories for long-term atmospheric trace species monitoring. Two of these observatories are located in polar latitudes. The northern site is at Barrow, Alaska; the southern is at the geographic South Pole. The locations of the sites purposefully were selected to be remote from significant anthropogenic sources of the species. NOAA has two full time employees at each site to operate instruments, perform calibrations and provide regular maintenance.

At these sites (and others maintained by Canada at Alert, NWT, and Norway at Ny Alesund, Svalbard) regular measurements are made of aerosols, carbon dioxide, methane, carbon monoxide (proposed), ozone (in situ, total column and vertical profiles) and solar and infrared radiation. The GMCC group also regularly obtains globally-processed upper air meteorological data for calculation of air mass trajectories. Such back or forward air trajectory calculations are very useful for interpretation of trace gas and aerosol measurements.

As part of this proposal NOAA will make its baseline observatories at Barrow and South Pole available to investigators at no cost. The NOAA employees at these sites also can provide modest support to investigators at no cost; their salaries are covered from NOAA base funds. The historical data sets, some more than 15 years long, provide a unique record of trends in atmospheric composition. These data will be analyzed to develop global-scale budgets of the measured species by a post-doctoral scientist working with the NOAA/CIRES group. The observations will be compared with theoretical calculations of ambient concentrations as a function of species source/sink distributions and scenarios.

Additionally, scientists in CIRES conceived, organized and directs the Arctic Gas and Aerosol Sampling Program (AGASP) which is determining the distribution, transport, chemistry and radiative effects of the pollution known as 'Arctic haze'. The results of this airborne and ground measurement program from spring 1983 and 1986, involving over 100 participants from six countries, have been extensively reported (*Geophys. Res. Letters*, v. 11, no. 5, 1984; *Atmos. Environ.*, v. 19, no. 12, 1985; *J. Atmos. Chem.*, 1987, in press). One of the main findings of the AGASP research is that the Arctic atmosphere can be as polluted as air immediately downwind of the industrial regions of the United States. These year around air pollution events are especially rich in soot carbon, methane, and CO_2 — all thought to be contributing to anthropogenic warming of the earth's atmosphere.

An illustration of Arctic air pollution is presented in Fig. P.4 for vertical profiles of condensation nuclei, aerosol light scattering, and soot carbon in a haze layer over the Barrow baseline station. The associated methane and CO_2 profiles shown in Fig. P.5 indicate that these gases are concentrated within the haze and just above the Arctic surface temperature inversion.

The scale of the air pollution is shown in Fig. P.6 where the path of a haze event and the outline of the United States are superimposed on the Arctic. This haze event was tracked from Central Europe across the Arctic Basin to Barrow, Alaska, then to Alert, NWT. On the scale of the United States, it is equivalent to air pollution originating in the Ohio Valley travelling east to New York City, then on south to Miami, Florida, west across the continent to Los Angeles, north to Seattle, then back to Ohio for a total travel distance of ~10,000 km. Over Barrow, Alaska, this pollution event was still as dense as any measured off the east coast of the USA during the WATOX Program.

The biogeochemical effects of such pollution will be studied in a third AGASP program in the vicinity of Svalbard during winter-spring of 1989. This University of Colorado-led aircraft program, involving 150 participants, will focus on the effects of the haze on the Arctic solar radiation budget including planetary albedo and infrared effects.

Topic 4. Environmental indicators of climatic change.

The amplified response of polar regions to a change in global climatic forcing has been widely noted; it is apparent in both observational data and model simulations. An important issue remaining to be resolved is what minimal set of environmental parameters must be monitored for detection and assessment purposes. Candidate variables include for the cryosphere: sea ice extent and thickness, snow cover extent, lake freeze-up/break-up, ice sheet and glacier mass balance (Barry, 1985), and for the atmosphere: surface radiation balance, static stability, low-level moisture content, cloud cover and type. Techniques to monitor these variables on a continuing basis are available in most cases although data for several of them do not exist in with adequate spatial and temporal coverage, or observational consistency to meet the requirements stated by the National Science Board (1987).

Data to monitor the extent of snow cover and sea ice regardless of weather and light conditions have been provided by passive microwave radiometry (ESMR and SMMR) on Nimbus 5 and 7. The SMMR data will be extended by the newly-launched SSM/I sensor on a DMSP satellite. These data will be archived and routinely processed at the National Snow and Ice Data Center in CIRES (Weaver *et al.*, 1987) as shown in Fig. P.9. The SMMR data are currently being regridded to the same format so that consistent data sets will be available from November 1978. We plan to utilize these data to produce sea ice and snow cover indices using appropriate algorithms. The capability of such data to determine the onset of snow melt on sea ice has already been shown (Anderson *et al.*, 1985) and confirmed by analysis of visible imagery (Scharfen *et al.*, 1987).

In order to accelerate the data processing for sea ice and incorporate the maximum amount of data possible for regular analysis and production of sea ice change indicators, we propose to develop a duplicate of the soon-to-be operational Navy/NOAA Joint Ice Center Digital Ice Forecasting and Analysis System (DIFAS) to support research at the University and elsewhere.

The JIC DIFAS will produce the only high quality, integrated digital data set encompassing sea ice and related atmospheric data which is available through a unified computer based data management system. The Joint Ice Center will use the system to make operational ice forecasts. Through the University of Colorado duplicate system, the same data ingested for the operational forecasts can be accessed by the research user. This will give the CU Center for Global Change and other researchers greater scope to study sea ice processes and time trends of ice extent and concentration.

NSIDC will develop a system to archive and distribute JIC digital data and products by acquiring a scaled down version of DIFAS. To this system NSIDC will add high capacity digital data storage devices (*e.g.* optical laser disk or digital magnetic tape cartridge systems). These devices will permit NSIDC to store the large volume of data produced by the DIFAS over the next ten years in a compact and easily retrievable manner.

A data management structure will be created to catalog the incoming data and produce products, including updated time series, on a daily basis. If feasible, the data will be integrated with the existing Cryospheric Data Management System (CDMS) for SSM/I data. In 1990-91 NSIDC will investigate ways of integrating SAR products collected by the Alaska SAR Facility form E-ERS-1 and J-ERS-1 into the CDMS and DIFAS environment. The latter effort is planned for NOAA funding.

The resources necessary to install the DIFAS at NSIDC will come from both this NSF proposal and from the NOAA Global Change Initiative. Resources necessary to service the wider user community and to integrate DIFAS with NSIDC's existing CDMS have been requested through the National Ocean Survey portion of NOAA's Global

Change Initiative (Dr. G. Flittner, NOS contact).

Lake freeze-up/break-up has been shown to be a valuable integrated index of temperature in the transition seasons in data-sparse areas (Palecki and Barry, 1986) and the feasibility of mapping these events by satellite remote sensing has been tested (Maslanik and Barry, 1987). Cloud cover data can be processed from AVHRR combined with passive microwave data and compared with station reports. Radiosond data will be used to extract stability and moisture content values. Further refinement and application of the technique for other areas and time intervals is required. The assessment of mass balance on icefields is discussed in topic 6 above.

These indices need to be calculated routinely and compared statistically with climatic and oceanic variables provided by the COADS data set (Woodruff *et al.*, 1987) and with the records of atmospheric composition, obtained under the NOAA program (topics 3 and 4).

The organization of polar research has traditionally been characterized by interdisciplinary endeavors and for this reason it offers special opportunities for global change/global geoscience. This is as reflected in the recent UCAR/University of Colorado/Royal Society of Canada workshop on Arctic Interactions (UCAR, 1988). The University of Colorado has a tradition of high-level accomplishment in polar sciences, and with its collaborating agencies afford the possibility of a coordinated focus on polar environmental dynamics. Organizational strengths include the presence of the Cooperative Institute for Research in Environmental Sciences with programs in atmospheric and climate dynamics, environmental chemistry, remote sensing (Center for the Study of Earth from Space), and the contractual operation of the National Snow and Ice Data

Center (NSIDC)/World Data Center-A for Glaciology; the Institute of Arctic and Alpine Research with programs in geochronology, glaciology, Quaternary studies, and paleo-environmental analysis; and other institutes and departments involved in polar research. NOAA entities located in Boulder with polar interests include the Global Monitoring for Climate Change (GMCC) program and the Aeronomy Laboratory of the Environmental Research Laboratories, and the National Geophysical Data Center of the National Environmental Satellite Data and Information Service.

Specific polar research already underway at the University includes (1) an ONR university Research Initiative 5-year grant for Arctic Ocean atmosphere-ice system studies (Barry, McLaren and Schnell, CIRES); (2) NASA supported studies of polar cloudiness (Barry); (3) DOE support for studies of ice sheet contribution to global sea level change (Meier and Pfeffer, INSTAAR), (4) NSF supported Quaternary research in Svalbard and the eastern Canadian Arctic (Miller, Andrews); (5) NASA support for Arctic and Antarctic sea ice products from the Defense Meteorological Satellite Program Special Sensor Microwave Imager (DMSP SSM/I) by the National Snow and Ice Data Center (Weaver and Barry); and (6) Arctic Gas and Aerosol Sampling Program encompassing 38 PIs from across the United States and supported by ONR, NASA, NOAA, and DNA. This ground and aircraft project covers the Arctic from Alaska to Norway and is a joint CIRES/NOAA research effort. The new Center for Global Change will provide a focal point for the proposed interdisciplinary collaboration.

6.2.3. Tropical/Global Interactions

6.2.3.1. Introduction

The tropics and subtropics, lying approximately between the 30-degree latitude parallels, contain half the Earth's surface area and intercept about two-thirds of the incoming solar radiation that the planet receives. Some three-quarters of the tropics and subtropics are oceans, and it is the solar energy stored in these oceans that ultimately provides the driving force for the atmospheric circulation of the planet. The rich diversity of the ecosystems of the tropical rain forests is well-known, and concern over habitat destruction in the tropics is based not only on the potential for climate change but also on the potential for extinction of plant and animal species not yet recorded. It seems clear that any study of global change must involve, as an important component, studies of the interactions between the tropics and the rest of the Earth.

The research topics discussed here are concerned with how the atmospheric and oceanic processes in the tropics and subtropics influence the climate of the remainder of the Earth. The research focuses on patterns and variability of tropical convection, analysis of large-scale data sets to attempt to correlate the behavior of the tropics with the mid-latitude climate, and modeling studies of the atmosphere and oceans with reference to their sensitivity to the changes in climatic forcing that are revealed by data analyses. The tropical convection research will involve a significant field component and, in the process, substantial technology transfer to the third world and within the United States.

This research into tropical/global interactions has many connections to the other research activities at the Center. Biogeochemical cycling research, for example, necessarily involves studies of transport of chemical substances in the atmosphere and oceans (as well as between the two media). Because tropical convective activity links the ocean surface directly to the stratosphere, it can have an significant effect on transport of trace species important to atmospheric ozone chemistry. The chemical reservoirs in the deep oceans are strongly affected by changes in wind forcing and deep water production at the poles, and upwelling in the tropics (which brings the deep reservoirs into contact with the surface) is also affected by changing climate. These interconnections among the various research activities at the Center are an important part of the research into tropical/global interactions.

6.2.3.2. Scientific Rationale

Latent heat release in deep organized convection in the tropics is one of the primary mechanisms by which global atmospheric circulations are forced at the Earth's surface. As such, it constitutes a primary means through which the environment interacts with the oceans, the biosphere, and man in particular.

Centers of tropical convection, such as Indonesia, the Amazon basin, and central Africa, are the primary heat engines of the atmosphere, transporting sensible and latent heat from the oceans to the tropical atmosphere. Some of this heating generates global-scale circulation anomalies in the troposphere (the so-called teleconnection patterns), which propagate into midlatitudes where they influence the general circulation and weather. However, the involvement of tropical convection in the environment is far more pervasive, maintaining tropical circulations which transport momentum, heat, and moisture around the globe (Gill, 1980), and generating equatorial waves which propagate vertically into the stratosphere (Lindzen, 1971; Holton, 1973; Salby and Garcia, 1987; Garcia and Salby, 1987) where they play key roles in global circulations such as the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO) (Holton, 1976;

Dunkerton, 1981).

Much of the water released in midlatitude synoptic storms, perpetuating man's habitat and agriculture, originates in the warm tropical oceans. This moisture is introduced into the atmosphere by organized tropical circulations driven by convective heating. In addition to water vapor, anthropogenic species such as CO_2 and methane are transported by these global circulations. In this way, tropical convection is implicitly involved in the transport of ozone and other radiatively and biologically important trace gases. Methane and water vapor, also important in the photochemistry of the stratosphere, enter through the tropical troposphere. This upward flux from the troposphere is dictated to a large extent by tropical convection.

El Niño Southern Oscillation (ENSO) events, which occur when the normal convective pattern is upset, are perhaps the best known examples of climate anomalies that are forced by tropical convection and that influence the global circulation. Equally important, however, are shorter term anomalies, such as the 40-day Kelvin wave (Madden and Julian, 1971), which modulates the tropical circulation and is thought to act perhaps as a trigger mechanism for ENSO (Lau, 1984). All of these anamolous circulations derive their energy from latent heat carried aloft from the ocean surface and deposited in the atmosphere as a result of condensation and precipitation. In addition, there is an important exchange of angular momentum between the tropical atmosphere and oceans, which drives the oceanic circulation through surface wind stress (Gill, 1982).

Apart from transferring energy from the oceans to the atmosphere by latent heat release, tropical convection, through its role in the Earth's albedo and IR exchange, is central to the radiative budget of the planet. Estimates of radiative heating of the atmosphere associated with the presence of clouds are as high as the contribution from latent heat release.

Changes in the tropical convection and resulting circulation changes can be brought about by anthropogenic sources. These sources include activities such as the clearcutting and/or burning of the tropical rainforest and the increase in carbon dioxide. It is widely recognized that, for tropical landmasses such as the Amazon basin, the interaction of atmospheric convection with the biosphere, e.g. through plant transpiration, and with the hydrology is essential in controlling the development and maintenance of organized convection. By clearing such areas through deforestation, man risks altering this interaction and thereby the overall character of organized convection and its impact on the global environment.

A similar impact can be realized by the burning of tropical rainforest. In this case, however, there would be the potential detriment of adding enormous quantities of CO_2 to the environment. The confirmed systematic increase in carbon dioxide concentration in the atmosphere has an important consequence for tropical convection and its many related phenomena. Because of the intimate relationship between organized convection and the latent heat release, and because the moisture transfer from the sea surface to the atmosphere varies exponentially with temperature, even modest changes in surface temperature can lead to significant changes in moisture and energy transfer between the oceans and the atmosphere. An important research topic is therefore the behavior of the tropical oceans, with particular reference to changes in the tropical sea-surface temperature patterns.

Over relatively short time scales (days to seasons), the oceans (because of their immense thermal inertia) are known to moderate temperature fluctuations in the atmosphere. They do so by redistributing heat from equatorial regions to colder polar climates. The redistribution process itself proceeds via two avenues: first, by the direct transport of sensible heat in the gyre-scale circulation of each ocean basin and second, through vertical fluxes of both latent and sensible heat between the ocean and atmosphere. Given the coupled nature of this two-fluid problem, it is reasonable to expect that variability in oceanic transport and heat flux patterns are coherent with and form a principal component in the variance of terrestrial climate on seasonal to inter-annual time scales.

The moderate coastal climates, in both the tropics and, for example, western Europe, are well known. The seasonal cycle of hemispherically-averaged temperature lags the solar cycle by about a month and is far less extreme than it would be on a dry planet. On longer scales, it is suspected that the induced climate warming that should accompany the increase of atmospheric CO_2 has not yet been unequivocally observed because of this moderation of climate change by the oceans. Significant interaction between ocean and atmosphere occurs and plays a major role in the short-term climate variability that is within the collective societal memory. The 1982-83 El Niño event remains notorious for its concurrent droughts and other weather extremes around the globe.

The primary objectives of the research into tropical/global interactions to be conducted at the Center for the Study for Global Change are the study of i) tropical convection and transport of constituents, ii) the changes in the circulation of the tropical oceans, its relationship to changes in patterns of deep atmospheric convection and the role of changing equatorial upwelling in the cycling of chemicals through the global system, and iii) the fundamental role of large- scale, low-frequency oceanic variability in the Pacific and Atlantic basins and its influences on terrestrial climate.

6.2.3.3. Proposed Work

We have divided the proposed work two sections. In the first section we describe the measurements and analysis of several types of data sets that will be used in studying tropical convection and the oceans and their relation to climate variability. In the second section we describe two modeling efforts that study the effects of oceans and surface fluxes on the climate variability.

6.2.3.3.1. Measurements and Data Analysis

Tropical Convection

The Intertropical Convergence Zone (ITCZ) is the region of intense convection and rainfall associated with the convergence of the southern and northern hemisphere Hadley circulation. While the ITCZ appears as a smooth and continuous feature on maps of seasonal or annual cloudiness, on shorter time scales it is seen to represent only the preferred location for deep convection (Salby and Garcia, 1987). The reality, the ascending motions that make up the vertical branch of the Hadley circulation occur intermittently in deep convective towers that are part of mesoscale convective complexes.

The impact of deep convection within the ITCZ on the thermodynamic structure of the atmosphere is not well understood. Many studies of the ITCZ at various parts of the world have produced conflicting results (Simpson, 1947; Estoque, 1975; Godbole and Ghosh, 1975; Frank, 1983; Fernandez-Partagas and Estoque, 1985). It is not clear whether the discrepancies are due to differences in instruments and methods or whether the balance between cooling by adiabatic ascent and latent heat release within cumulonimbus clouds does in fact vary with time and location. Radiation may also figure heavily in the energy budget. The intermittent nature of convection within the ITCZ may be related to the alterations of the environment by convection.

As part of the Center, we propose to examine the thermal structure of the ITCZ on a global scale using the Special Sensor Microwave Temperature (SSM/T) instrument on the Defense Meteorological Satellite Program's F-7 polar orbiters. Using visible and IR imagery to locate the ITCZ, we will composite all soundings within a set of latitude bands centered on the ITCZ axis. Composites would be made for different seasons and different continental and oceanic regions. Once a clear picture of the mean state was in hand, conditions on finer spatial and temporal scale would be examined for insights into the factors determining the variability of the ITCZ.

An important complement to the satellite investigations of tropical convection will be to analyze contemporaneous ground based measurements made by Doppler radar. Conventional 3-5 cm radars can provide continuous information of the tropospheric precipitation and aerosol field using a volume scan over an area of approximately 300 km in diameter (Gamin *et al.* 1985). Line of sight velocities can be used to infer the local motion field. A mobile Doppler unit, operated by the Department of Atmospheric Science at Hebrew University in Jerusalem, is capable of making such ground based measurements in remote regions. At the same time, it can be relocated economically to investigate regional differences such as plateua and lond/ocean effects. The 4-dimensional data provides a comprehensive and detailed picture of precipitation activity within the convection complex.

In addition to a volume scanning Doppler radar, a network of VHF Doppler wind profilers and UHF boundary layer radars will provide measurements of the fluxes of energy and momentum, and the three-dimensional wind fields, important in diagnosing the exchange between the surface and the atmosphere. The beginnings of this network are shown in Figure x. The existing network is operated by the Aeronomy Laboratory of NOAA/ERL.

We propose initially to improve the network by installing a more sensitive 50 MHz wind profiler radar at Piura, Peru as part of the research at the Center for the Study of Global Change. This radar upgrade would provide wind and turbulence data into the lower stratosphere and mesosphere and would augment the data obtained from the rest of the tropical chain. We would do this in order to study the coupling of waves between the troposphere, stastosphere and mesosphere. The data will be analyzed to study ENSO effects and the propagation of Kelvin and mixed Rossby-gravity waves to South America, vertical and horizontal energy and momentum transfer in the atmosphere wave sources (mountain versus convection) and convection patterns.

Together these radars can be used in conjunction with simultaneous satellite imagery of the cloud field to concretely diagnose the convective field over limited areas but at a variety of longitudes. Through this combined ground-based/remote sensing analysis, a correspondence between the spatial and temporal statistics of convection as inferred from space and the actual convective behavior can be established, making future and ongoing satellite monitoring of the earth's convective field directly interpretable for a variety of studies relevant to climate.

When satellite measurements of methane and other important constituents become available from the Earth Observing System (EOS) polar-orbiting platforms, these ground based measurements will be of great value in understanding the production of such species and their dispersion by the large-scale circulation.

Future plans include expanding the radar network across the Andes into the Amazon Basin using local expertise gained during the initial phases of this study. We hope to expand into the tropical Atlantic regions at a future date.

Stytems Studies of Low-Frequency Oceanic Variability

The topic of tropical/global interactions has been a subject of considerable interest (principally within the meteorological community under the topic of teleconnections) during the past decade. The large-scale character of features such as the Southern Oscillation has been known for over half a century (Walker and Bliss, 1932), and the linkage of this three-dimensional atmospheric mass transport to oceanic surface structure was documented nearly two decades ago (Bjerknes, 1969). In polar regions, the correlation of atmospheric action centers with tropical anomalies (both atmospheric and oceanic) is unmistakable (Trenberth and Paolino, 1983; van Loon and Madden, 1981). Similarly, deep convective oceanic mixing in polar regions may be enhanced by anomalous regional atmospheric warming (Broecker *et al.* 1979), which is correlated to atmospheric anomalies in tropical regions.

On interannual to decadal time scales, anomalous atmospheric heating in the tropical Pacific during ENSO events affects the global atmospheric circulation (Philander and Rasmusson, 1985). Although Bjerknes (1960) provided one of the first dynamical analyses of this linkage, Sir Gilbert Walker's correlation patterns (Walker and Bliss, 1932) suggest the existence of this relationship. Bjerknes suggested that the regional intensification of the Aleutian Low during ENSO winters was a manifestation of enhanced Hadley cell circulation. The regional enhancement in turn increases the northward transport of angular momentum in the troposphere, resulting in stronger westerlies and an increase in the meridional pressure gradient. Downstream circulation over the North American continent is altered in response to the inlet and outlet conditions (this triplet of North Pacific — North American anomalies has been referred to as the Pacific — North American teleconnection; Wallace and Gutzler, 1981). During these events, anomalous conditions develop more or less simultaneously in both the oceanic and atmospheric domains, suggesting that the interactions of these fluid systems may be a key factor.

Research to date has focused principally on the interaction of large-scale oceanic features with the atmosphere. Some evidence exists (Robinson, 1986; Gill, 1986) to suggests that the oceanic mesoscale field may plan an equally significant role in the environmental dynamics. The oceanic mesoscale may, for instance, contribute to the zonal placement of atmospheric pressure anomalies over both the North Pacific and North Atlantic basins, particularly during Northern Hemisphere winter intensification. Anomalous sea surface temperature patterns are well correlated with atmospheric convection (Gill, 1980· Webster. 1981) and there is a growing body of literature (cf. Robinson, 1986) which suggests that mesoscale structures may be of equal importance (relative to the gyre-scale circulation) in the transport and redistribution of heat. Consequently, a reasonable question to ask becomes: is there a correlation between mesoscale oceanic features (in the North Pacific and North Atlantic) and seasonal to interannual terrestrial climate variability (of the North American continent)?

We propose to examine this question using the following data sets:

1. SSM/1 from the DMSP F-8 spacecraft (for precipitation and SST) [these data

are being acquired by Roger Barry/NSIDC]

2. AVHRR from the NOAA Polar Orbiters (for SST) [a subset of these data are being acquired by NOAA]

3. Altimetry from the Navy Geosat spacecraft (for the geostrophic velocities) [this data set is being acquired by CU/CCAR]

Data analysis will be based upon a combination of empirical orthogonal function analysis and spectral analysis (cf. Davis, 1976: Trenberth and Paolino, 1981).

6.2.3.3.2. Modeling Studies

Equatorial Ocean-Atmosphere Interaction Studies

Much remains to be understood about the behavior of the equatorial oceans and how they interact with the atmosphere. Such large-scale phenomena as the ENSO are a manifestation of ocean-atmosphere interaction processes. While great progress has been made toward understanding the ENSO, its secular variability is not understood. Long-term records of ENSO variability clearly show that it is not merely a quasi-periodic phenomenon on the 3-5 year time scale, but that it also has a strong variability on the scale of decades. Whether this is due to (or a cause of) secular global climate variability is unknown. Further, the role of changes in the oceans is also not known.

The dynamics of the tropical oceans and atmosphere are traditionally studied by simplifying the governing equations using a equatorial beta-plane projection. With this simplification, the large-scale wave modes reduce to eastward-propagating equatorial Kelvin modes and westward- propagating Rossby modes, and much of the current understanding of ENSO is based on this approach. In particular, the oceanic response to varying wind forcing has been observed to contain these modes. It has been shown, using a simple analytical model, that ocean-atmosphere heat exchange can affect the propagation speeds of these modes, which also depend strongly on the ocean's stratification (Hanson and Kraus, 1982; Hanson, 1983).

Climate variability will affect both the oceanic stratification and the ocean-atmosphere interaction in the tropics, and the changing behavior of the equatorial oceans needs to be understood. In addition, the changes in equatorial upwelling have the potential for a profound effect on the ocean-atmosphere exchange of chemical substances as well as oceanic productivity. Further, the links between changes in tracer distribution in the oceans as forced by changing deep water production near the poles and upwelling of the tracers in the tropics is an unexplored aspect of global variability.

Questions to be addressed under this modeling study include:

- What is the relationship of the behavior of the numerical ocean circulation model to the analytic equatorial dynamics?
- How does ocean-atmosphere heat transfer affect the propagation of waves in the numerical model?
- How are both the equatorial waves and the mean equatorial current systems affected by atmospheric forcing that varies on decadal time scales?
- What changes in equatorial upwelling patterns may be expected in conjunction with this variability?
- How are the global budgets of atmospheric chemical species likely to be changed by this variability?
- What are the implications of changing patterns of deep water production for the equatorial oceans' dynamics?

The model to be used for this work incorporates a thermodynamically active mixed layer atop an isopycnal deep ocean model (i.e., in which the vertical coordinate is density). The air-sea exchange in the model is handled using, essentially, the mixed-layer approach discussed in Niiler and Kraus (1977). In this approach, mixing due to wind stirring and (negative) buoyancy input at the ocean surface is assumed to create a mixed layer in which momentum, temperature, salinity and tracers are invariant with depth; the depth of the mixed layer is calculated from turbulence kinetic energy considerations. When there is heating at the surface of a sufficient magnitude to overcome the effects of the wind stirring, the mixed layer becomes shallower and leaves behind, in the layers below, water that was previously in contact with the atmosphere. In this way, the effects of air-sea exchanges are transmitted to the deep ocean.

The lower part of the hybrid model — the deep-ocean part — is based on the isopycnic coordinate model developed by Bleck and Boudra (1981, 1986). In this formulation the vetrical coordinate of the model is mapped onto the density field, and the thickness of the layers of constant density is a dependent variable. This approach is particularly well suited to the problems of tracer transport in the oceans because the deep oceanic flow tends to lie along surfaces of constant density (isopycnic surfaces). A description of the methodology used to match the upper and lower halves of the hybrid model is contained in Kraus *et al.* (1988). Experiments with the model to date have involved spin-up tests and simulations of the annual cycle of the North Atlantic and further papers describing these results are in preparation.The model's mixed layer undergoes a dramatic annual cycle in the north of the basin, with wintertime depths in excess of 1000 m and summertime depths less than 50 m. This allows injection of tracers into the deep ocean, and they subsequently spread southward in the large-scale gyres. Figure 1 (from

Kraus *et al.*, 1988) shows tracer concentrations in the ocean layer at about 1100 m (relative to a maximum value of unity) after 34 years of spreading through the gyres. The value is maintained at unity in the mixed layer, and the annual cycle injects the tracer into the deep ocean where it slowly spreads.

NCAR Community Climate Model

NCAR's Community Climate Model (CCM) is a general circulation model of the atmosphere which has fairly elaborate treatment of processes within the atmosphere but quite simplified treatment of processes at the boundary. For example, the parameterization of the interaction of infrared radiation and the atmosphere is quite detailed. Cumulus convection, cloud formation and the interaction of radiation and clouds are also treated in considerable detail. On the other hand, the fluxes from the surface to the atmosphere are treated by bulk empirical formulas. Furthermore, surface properties, such as soil moisture, albedo, snow cover and ice extent are specified.

A new version of the Community Climate Model, CCM-1, has been under development for several years. In this new model, for example, the clear sky radiation parameterizations and the treatment of clouds have been improved. The numerical algorithms have been made more accurate as well. Some of the surface properties have also been improved, but not in a comprehensive way. For example, the soil moisture is still prescribed, but it varies by region. Snow cover is prescribed and varies by season, but the snow extent is simply prescribed to be a function of latitude, which is clearly incorrect. Furthermore, some of the boundary specifications come from data which are quite old. An experiment is presently being carried out which examines the changes in the model's simulations as a response to changing the specified distribution of sea surface temperatures from an old climatology to a new climatology which incorporates only measurements after 1950 and which includes satellite data toward the end of the record. In general, the performance of CCM-1 is markedly superior to the earliest version of the climate model (CCM-0).

Although more completely interactive subroutines for various surface processes are under development for inclusion in future versions of the CCM, the existing CCM-1, with its prescribed surface properties, is still a valuable research tool. Because the surface processes are specified, it is relatively easy to change the surface properties in an orderly fashion, and to design experiments which examine the atmospheric sensitivity to these changes. Changes in the sea surface temperature affect the circulation through changes in the latent and sensible heating of the atmosphere. Changes in other surface properties can perhaps have similar effects. Changes in soil moisture and albedo in the tropics can change the fluxes and therefore the atmospheric circulation. Changes in the snow cover and ice extent in polar regions can possibly change the circulation as well. We propose to carry out a set of simulations to investigate some of these effects.

One set of experiments would be concerned with the relative importance of changes of albedo in near desert regions relative to the changes in climate induced by changes in tropical sea surface temperatures. Charney hypothesized that changes in surface properties in arid regions would change the circulation in such a way as to make the dry regions even drier-desertification. This general idea has been discussed by a variety of social scientists, but it has not been demonstrated conclusively by any general circulation model experiment. On the other hand, general circulation model experiments have suggested that sea surface temperature anomalies in the tropical Atlantic and the tropical Pacific can affect precipitation in some tropical arid regions, such as the Sahel of Africa.

The model results seem to be confirmed by observational studies, but it seems fair to say that confirmatory experiments are needed. We propose to examine the relative importance of local changes in land properties versus more remote changes in sea surface temperatures by changing each set of boundary conditions individually in experiments with CCM-1.

6.2.4. Record of Past Environmental Change

6.2.4.1. Introduction

The current concerns about future climatic change, and their consequences on the biotic and physical components of the atmosphere/biosphere/cryosphere system has received considerable press (e.g., National Academy of Science, 1986; Time Magazine, 1987). Valid estimations of the magnitude of changes in temperature and precipitation require better knowledge of the mechanisms causing environment change, including the possibility of rapid switches in environmental dynamics. This knowledge cannot be developed or tested without knowledge of the global systems' natural variability on time-scales of decades to millenia. In particular, information for the last 15,000 years will provide crucial information against which the validity of climatic models can be evaluated (cf Kutzbach and Guetter, 1986).

In the global context there is a consensus that the most sensitive areas for climatic change are the polar regions, the heat sinks of the earth's climate system (Polar Research Board, 1984; National Science Board, 1987). However, to balance this there is a need to understand the role of climatic and environmental change in the equatorial region, the heat source areas. These two regions, the poles and tropics, provide a geographic focus for the University of Colorado's study of environmental dynamics in the context of

Global Change.

The University of Colorado has an international reputation in the fields of paleoclimatology and the reconstruction of past environments. This experience is focused mainly on high latitude and high altitude environments and includes research in both hemispheres. This research reputation has been built on close interdisciplinary ties between departments and institutes (Fig. 1). Note that this network also includes active participation between the University and NOAA researchers in the arena of paleoclimatology (e.g., Diaz et al., in press).

We identify two major paleoenvironmental problems that are critical. The first is to determine whether there are any fundamental frequencies in the climate system that are intermediate between the Milankovitch orbital frequences and those associated with sunspots. This lack of apparent periodicities between ca. 19,000 and 22,000 yrs (Mitchell,1976) is termed "the spectral gap" (Fig. 2), although some evidence for a 2,500 year periodicity exists. A solution to this problem will entail the examination of high-resolution proxy climate records that span all or part of the last 15,000. Such records need to be well-dated and have a temporal sampling interval of <100 years/sample and, ideally, <20 years/sample.

The second problem is the need to understand the structure of environmental change. This requires that a variety of proxy records be examined - records that include different components of the ocean/terrestrial/cryosphere system (Fig. 3). The solution to this problem requires recognizing that different biotic and abiotic components will have different thresholds in their response to a climate change, and leads and lags in the system of response, but it also includes the question of whether there are analogs for climate over the last 10,000 (and the future 10 ka??) within the period of instrumental record. Statistically the question is: how representative has the last 100 years been when compared with the last 300, 3000, or 10,000 years? Indeed, one critical climate question that must be addressed is the possibility of rapid switches in climate, such as the discrete warm events of about 800 years duration 45,000 to 25,000 years and the even more rapid transitions in the last 12,000 years that appear to have been detected in Greenland Ice Cores. These data were discussed by Broecker et al. (1985) who asked : does the ocean-atmosphere have more than one stable mode of operation? In addition, we will also actively pursue the questions of i) whether the sudden climatic oscillations at the end of the last glacial period (the Younger Dryas stade) is global and, therefore, a recognizable climate event in the North American Arctic and in the southern hemisphere (cf Rind et al., 1986), and ii) whether the major readvance of the Laurentide Ice Sheet at ca. 84,000 years ago (Falconer et al., 1965; Andrews, 1987) was climatically forced.

Our study of the record of environmental variability within the context of Global Change builds on our existing funded research programs and, furthermore, concentrates our efforts to those geographic regions where we have field and logistic experience in working in these remote areas. These field areas constitute a north-south transect through the Americas, and an east-west transect in the Arctic, both identified by Porter (1987) as being key elements in Quaternary paleoclimatic reconstructions. This will provide an integrated, interdisciplinary approach to the interpretation of high-resolution proxy records that will add the perspective needed to interpret results in the modeling of environmental dynamics. In the process, we will build links between climatologists/paleoclimatologists, researchers dealing with the proxy records, and experience on dating and chronology.

6.2.4.2. Specific Research Problems and Areas

We will focus our research on critical areas and time periods that have been identified in several national and international policy documents (e.g. NAS, 1986; Polar Research Board, 1984; National Science Board, 1987; French (ed), 1986; Risser (compiler), 1986), as well as recent workshops, e.g. Arctic Interactions (UCAR, in press), and Role of Arctic Lake Sediment Records in the reconstruction of environmental changes (Andrews and Colinvaux, 1987). Particularly in the high-latitude and high-altitude areas, the critical elements in the proxy record of climatic variation will be changes in the distribution of ice and snow, in all forms, including the responses of ice sheets, glaciers, lake ice and sea ice.

6.2.4.3. Arctic Transect

In the Arctic we focus our attention on providing high-resolution proxy records to complement and test conclusions that are being drawn from ice-core records from Greenland and the Canadian Ice Caps. The Arctic transect will extend from Baffin Island, an area with a severely depressed summer temperature, to Northern Norway and Spitzbergen which have depressed elevated summer temperatures caused by the penetration of the North Atlantic Drift Current to near 80 N latitude.

The western part of this transect is especially important because it lies upwind of the Greenland Ice Sheet. Considerable national attention is being placed on the Greenland Ice Sheet Project (GISP). The University of Colorado, Boulder, will be involved in GISP with a lead role being played by White, Chairman of the Scientific Working Group on Stable Isotopes, Conductivity, and Particulates. In addition, Short has proposed to study the pollen content of ice. We argue that it is also important to critically examine the implications of the ice core record in terms of both terrestrial and marine responses. Such a critical examination is evident in the NAS (1986) statement, and it is implicit in the Broecker et al. (1985) publication.

Glacial/Interglacial Records, NE North Atlantic - We propose to produce high-resolution stratigraphies from marine and lake cores up-wind from the GISP sites (Fig. 7). Previous Holocene proxy climatic records from this region were reviewed by Williams and Bradley (1985) (see Fig. 8). Lake cores were collected in 1987 by parties from INSTAAR with NSF-DPP and NSF-EAR support. Additional cores will be collected in 1988 from both northern and southern Baffin Island. These cores, and one peat deposit, span the last 8,000 to 16,000 years (e.g. Short and Andrews, in press). Preliminary, coarse-resolution studies on the palynology, sedimentology, and diatoms of the cores collected in 1987 is underway. In 1988, lakes will be cored where lake records should span the last 11 ka (Miller, 1980; Osterman et al., 1985). High resolution analyses will be needed from these cores as part of the Global Change effort.

Marine piston cores from the eastern shelf and fiords of Baffin Island have been obtained cooperatively with the Canadian Atlantic Geosciences Center (Halifax, N.S.). They vary between 3 and 12 m in length and have radiocarbon dated chronologies that span the last 24,000 to 8,000 years (cf. Andrews et al., 1985; Praeg et al., 1986; Short et al., subm.; Andrews, unpubl. radiocarbon dates). Preliminary, coarse-resolution results on the isotopic composition of foraminifera (Andrews et al., 1987), on foraminiferal, diatom, ostracod, and pollen assemblages (Osterman, 1982; Praeg et al., 1986; Williams, 1984, 1988; Short et al., subm.; Briggs, unpubl.) exist for several cores (Fig. 8). These cores need to be analysed in detail.

Greenland Ice Sheet The study of ice cores from the Greenland Ice Cap, and the ice caps in the Canadian Arctic, will constitute a critical source of information for evaluations of past atmospheric conditions. Much of this research will be funded from exisiting or new National Science Foundation programs. However, there is one area of research that has been neglected- there is a critical need to understand the processes controlling the present day isotopic variations (both O and D). A study which seeks to map and understand the atmospheric processes controlling the geographic variations in stable isotopes in solid precipitation will be critical to understanding polar/global interactions. Isotopic measurements on a network of shallow cores will provide both spatial and temporal data to compare with meteorological stations. Surprisingly, such a systematic study has ever been done. Existing surface and near-surface isotopic data tends to cluster about the deep-drilling sites, and important considerations, such as proximity to ocean moisture sources and prevailing wind directions have not been specifically addressed. We would use the deuterium excess method for this study. We would with Canadian colleagues to provide data on a much larger regional basis.

Spitzbergen-Glacial/Interglacial Transition Spitsbergen lies on the tail-end of the North Atlantic Drift. The Late Quaternary climatic history of the Archipelago reflects the presence/absence of this current in several dramatic ways that appear to be at variance with current concepts of the the late Quaternary history of the Northwestern North Atlantic (e.g. Kellogg, 1976; Lehman, 1987). Miller and his associates have been working on Spitsbergen for several years in conjunction with both the University of Bergen, Norway, and the Norwegian Polar Institute (NPI). Long lake cores (6 to 14 m) were recovered in 1986, and marine cores were obtained through NPI in a fall 1987 cruise. Research on the sedimentology and geochemistry, palynology, ostracodes and diatoms is currently underway; initial 14C dates have been obtained on mollusc shells in the cores; accelerator 14C dates are pending for the remainder of the cores.

The lake sediments contain a high resolution record of glacial and circulation change; sedimentation rates range from 0.2 to 0.8 m/1000 years. Sedimentological and geochemical analyses suggest a dramatic shift occurred during the middle Holocene, from a relatively warm, low amplitude seasonality into Neoglacial conditions and strong seasonality (Miller and Werner, unpublished data). Major fluctuations occurred during the Neoglacial, the most severe corresponding to the Little Ice Age, but even the climate of the present is significantly more severe than during the early Holocene climatic optimum. A detailed palynological investigation is in progress with the goal of reconstructing the frequency of southerly airflow (exotic pollen) at the site (Short, in progress).

Marine cores of 3.5 to 5 m length recovered by NPI off the west coast of Spitsbergen late in 1987 are expected to contain a complete Holocene record and to extend back into the last glaciation. We expect the cores to contain a high resolution record of oceanic circulation changes that can be compared to detailed local records of ice-marginal changes derived from ice-proximal marine sediments now raised above sea level. Both records can be independently dated on the accelerator. Our goal is to reconstruct two independent records of environmental change; one of the marine circulation, the other of the glacier activity on adjacent landmass. Combining the two should elucidate important leads and lags in the system.

6.2.4.4. Americas Transect

A study of the record of environmental change along a north-south profile spanning the Americas will provide the necessary perspective necessary for improved understanding of both the polar/global and tropical/global interactions. This can be accomplished in a cost-efficient manner by building on existing University of Colorado research programs in the Rocky Mountains, Central America, and South America. The northern end of this transect is the Arctic Transect described above.

Colorado Front Range The program of Global change in the geosphere-biosphere mimics, in many critical respects, the NSF funded Long Term Ecological Research (LTER) program. The University of Colorado, Boulder, and its Mountain Research Station (Fig. 7), is the site for the alpine LTER biome program. The program undertakes fundamental ecosytem/landscape research on a variety of space and time-scales. To complement the research undertaken on the alpine tundra of the Front Range under the LTER program, we plan to expand sampling of tree ring records at both upper timberline which is temperature-sensitive and at lower timberline which is moisture sensitive (Kreb, 1970; Drew, 1974; Kienast and Schweingruber, 1986; Veblen and Ogden unpublished). We are currently working on the climatic calibration of high quality tree-ring chronologies recently produced for subalpine forests (Veblen and Ogden unpublished). The Colorado Front Range is an ideal site for dendroclimatic reconstruction due to the availability of long instrumental records of climate over the full elevational range from lower to upper timberline (Barry, 1973; Losleben, 1986). Responses of the forests to disturbance by fire and insect epidemics are well understood along this elevational gradient (Veblen, 1986, Veblen and Lorenz, 1986; Swetnam, 1987) which is essential in distinguishing climatic from non-climatic signals in tree ring as well as pollen records.

We will also to expand our current sampling of alpine lake sediments (Andrews et al., 1986; Short, 1986; Harbor, 1984; Davis, 1987), in order to obtain high-resolution records that will allow a comparison between the tree-ring indexes and lake sediment proxy data. The lake records from the Front Range have basal radiocarbon dates of between 12,000 and 8,000 years ago with sediment thicknesses of between 1 and 5 m. However, sampling intervals have been relatively coarse (5-10 cm) and only 1-3 dates per core have been obtained. We will increase the numerical age control per core by a factor of at least 5 and decrease the sampling interval to obtain <20 yrs/sample resolution. Of specific interest in these records will be evidence for increased deposition of wind-blown dust (loess) (Andrews et al., 1986; Birkeland et al., 1987).

Lake Valencia, Venezuala - The Center for Limnology, University of Colorado has obtained lake-sediment cores from Lake Valencia in tropical South America (Lewis and Weibezahn, 1981; Bradbury et al., 1981). The record has been interpreted in terms of basin hydrology and regional precipitation trends. We will plan renewed coring in this lake, with co-operation from Venezuala, to better understand the climatic record in this area.

Peruvian Andes As part of the University of Colorado Rio Abiseo National Park project Birkeland, Short, and Rodbell (graduate student) investigated the glacial geology of the central Peruvian Andes (Fig. 10) and cored a series of high-altitude lakes. An initial basal date from a lake dammed by the terminal moraine, at 3600 m asl, was ca. 12,100 years ago (Fig. 11). Prominent white beds in the lowermost core are composed entirely of diatoms. These cores are moderately close to the Quelccaya Ice Cap (Thompson et al., 1985, 1986), thus our study will complement the stable isotope and microparticle analyses from this high-altitude ice cap. Our series of lake cores, in combination with the glacial moraines, will provide a closely dated sequence which we will examine for evidence of the Younger Dryas cold interval, and for significant environmental changes during the Holocene. In the summer of 1988, we anticipate additional similar work in the nearby Cordilleras Rosko and Blanca. One topic we hope to address is the age and source of wind-blown dust, as loess mantles the landscape. A student working on a soil-El Nino project on the coast will collaborate with this part of the project.

Southern South America Late Quaternary paleoenvironmental records from the highly diverse environments in southern South America (Markgraf, 1983, 1984, 1987)(e.g. Fig. 12) have demonstrated a great sensitivity to different types of climatic change. Comparison of 10,000 to 14,000 years old records across the steep climatic gradients, especially at high southern latitudes, suggest a link to the changing extent of Antarctic sea-ice, which in turn would be associated with changes in sea surface temperatures and thus global climate. Detailed analysis (<50 yr resolution) of the glacial to interglacial transition (12,000 and 8,000 years ago) will give invaluable information on the global significance of Antarctic sea ice variations and causal links. Of especial interest in terms of global synchoneity and mechanics of climate change is the short-term Younger Dryas cold episode. Although generally assumed to represent a North Atlantic phenomenon, it is reported to be present in records from southern South America (Heuesser and Rabassa, 1987). So far, however, the evidence for this event in the southern hemisphere is ambiguous. If it could be confirmed in the existing lake core records that are being studied by Markgraf then this would necessitate a rethinking of the spatial extent of this dramatic cold interval and its global significance.

Of particular concern in interpreting biological proxy records from the southern Andes is the distinction of climatic-induced vegetation change from changes induced by both large-scale natural disturbances such as volcanism and earthquake-triggered mass movements (Veblen et al., 1980), and by burning by the aboriginal populations (Veblen and Lorenz, in press; Heusser et al, in press). Thus, to allow appropriate interpretation of pollen records, studies of plant succession following fire and geological disturbances are essential (e.,g. Veblen and Lorenz, 1987; Veblen and Ashton, 1978) and will be continued and expanded. Tree-ring studies are also proposed for the purposes of recording climate fluctuations over the past 800 to 1000 years using conifer species growing both at the drought-controlled lower timberline (Austrocedrus chilensis) and near the temperature-controlled upper timberline (Araucaria araucana and Fitzroya cupressoides). We propose expansion of our current sampling of tree rings and will also make use of the abundant tree-ring chronologies published for southern Chile and southern Argentina by LaMarche et al. (1979). Long instrumental records (i.e., 1906 to present) from numerous sites near the sites sampled for tree-ring chronologies (recently made available to us by Argentine National Park authorities) will allow climatic calibration of the tree-ring records.

6.2.4.5. Summary

We propose to investigate lake and marine cores that have chronologies that extend from 15 ka to the present, and tree ring records that span the last 4,000 years. The major funding needs for such an effort are: i) to drastically increase the detailed C-14 chronology for the selected cores by submitting several samples per core (ca. 1 date per 1,000 years) to the AMS facility at the University of Arizona, with whom we have excellent working relations (e.g. Andrews et al., 1985); ii) to resample the cores at 1 cm intervals so as to obtain extremely detailed records of variations in floral and faunal abundances; iii) to research the methodology of a laser-logger (combined with X-radiography and densitometry) for better than 1 mm resolution of changes in grain-size/shape parameters, iv) continue to expand and improve our dendroclimatology data base; and v) to develop our ability to work on the stable isotopic record of ice cores (Fig. 3).

Figure 13 illustrates our view of the various climatic proxies that we will study. We distinguish between variables that record primarily local (i.e. basin-wide) changes, and those that integrate over a larger, regional scale.

6.3. HUMAN-ENVIRONMENT INTERACTION

6.3.1. Introduction

Current policies and population pressure on forests, energy, agriculture, water, and other resources have brought us to the point where human-environment interactions are critical, and serious adverse impacts are projected. In principle, policy based on sound scientific research can mitigate adverse environmental changes or reduce the human costs of adjustment, but the policy implications of global change are not necessarily obvious to managers, nor are practical policy limitations necessarily obvious to natural scientists. Thus we propose to study the role of policy in global change, including how information on global change can be used to enhance the quality of policy decisions.

Ideally, United States policies will keep the Nation growing economically while preserving a healthy environment. To approach this ideal we must understand the interaction between economic activities and the environment, and plan and manage so as to minimize adverse impacts.

For example, sustained utilization of natural resources associated with forests, scrublands, and grasslands depends in part on people's perceptions of, and adjustments to, stability and change in these systems. As vegetation assemblages change due to environmental forcing, especially climate change, use and management strategies--both traditional and modern/scientific--may have to change in order to provide resources to sustain local, regional, and national development.

The work proposed in this section is action-oriented, i.e., it is intended primarily to advance the application of the policy sciences, not the disciplines themselves. The payoff from this research will be an improved national ability to mitigate or adapt to adverse global change with minimum economic, social, and ecological disruption.

6.3.2. Justification

The importance of global change to society has been recognized in some research communities (Kates, et al, eds. 1985). Global changes that may occur as a result of man's activities could be larger and more rapid than previous natural changes (NAS, 1983), and may be surprisingly drastic if certain Earth systems turn out to be unstable (Broecker, 1987). Natural variability of the global environment, e.g. from El Nino, can have serious socioeconomic impacts (Glantz, et al, eds. 1987) leading to the conclusion that even if anthropogenic change cannot be predicted, we should strive to develop the capability to mitigate the impacts of whatever environmental change may occur.

Vegetation change has been a crucial element of environmental problems during the past two decades: desertification in the African Sahel (Glantz, 1977; Van Ypersele and Verstraete, 1986), accelerated tropical deforestation (Grainger, 1983), and degradation of mid-latitude grasslands and forests all point to a net degradation of vegetation from natural and human factors. Thus, it is important that we examine human interaction with vegetation change, both to understand the causative role of human activity (debate still rages over the relative contributions of natural and social forces in desertification--Verstraete, 1987) and to improve resource management policy in the face of future changes.

A lack or surplus of precipitation (i.e., drought or flooding) has also been a crucial element of environmental change in the United States (Wilhite, et al., 1987). The "Dust Bowl" of the 1930s is an example of how interacting natural and anthropogenic stresses can create or worsen socioeconomic problems.

Policy-makers occasionally recognize the need for information on the impacts of global change, for example in the National Climate Program Act of 1978 (U.S. House of Representatives, 1977). However, short-term pressures work against incorporating the likelihood of global change into policy-making (Kissinger, 1959; Meyer-Abich, 1980). A key reason is the uncertainty of such change coupled with the facts that (i) costs of preventing or mitigating adverse impacts typically come immediately while benefits come later, and (ii) costs of preventing impacts might fall on one group while benefits might accrue to another.

Several years may pass before either undeniable evidence or credible predictions of change will point unambiguously to needed policy actions. During this time some options may no longer be practicable. Based on what we know now there is justification for developing policy approaches that do not assume a constant environment. These approaches should help us develop more robust socioeconomic systems, better able to respond to both natural and anthropogenic changes.

As global studies create better understanding of the character and degree of past changes and yield more credible forecasts of future changes, it will be necessary to communicate these in a way useful to decision makers. This step is neglected often in research, or assumed to flow automatically from the progress of science; but actually we know little about how to communicate information on slow, uncertain, cumulative environmental changes. Therefore, there is a need to study what kind information is needed and how it should be used.

6.3.3. OBJECTIVES

We propose to answer three questions:

1. How sensitive are social institutions to environmental change? (That is, if change occurs, where are disruptions likely to occur? Will such disruptions be serious enough to justify costly preventive measures?)
2. How do policymakers perceive global change and its impacts, and what information on global change do they need? (Specifically; How does perception of vegetation change, especially forest change, affect forest use and management? And how does perception of changing water availability affect the use and management of water resources?)
3. How can this information be communicated usefully to managers and policymakers?

Note that this allows for a two-way flow of information: a manager could ask a new question. Scientists can learn what possible changes would be most important to policymakers and can communicate the uncertainties in measurements and models. Also, "information" includes policy and impact analyses as well as geophysical data describing global change.

6.3.4. APPROACH

Our overall goal is to increase the fruitful use in policymaking of information concerning global change. We want to facilitate (or invent) the processes whereby geophysical facts become policy facts, i.e. become relevant in policy making. This does not necessarily imply prediction; it could involve accurate description of the present or more credible communication of risks and uncertainties. Discovery of the Antarctic "ozone hole" is an example of the former, while a better explanation of the uncertainties of greenhouse warming is an example of the latter. Nor does this necessarily imply a change in basic policy processes. It means in most cases that new methods of presenting and communicating information must be developed.

Because of the inability of current models to predict global change or its socioeconomic impacts, and because there are many ongoing efforts to improve such models, the Center will approach human-environment interaction in two ways, one broad and one more focused:

(i) A broad effort will be made to develop and define links between human impacts on the one hand and our research on biogeochemical cycles and environmental dynamics on the other. We will also study how policy decisions represent anthropogenic inputs into the global change processes. For example, pollution control policies can affect emissions of exides of nitrogen which, in turn, affect the nitrogen cycle.

(ii) To understand how information on specific manifestations of global change can be used in policy-making, we will focus on two areas particularly sensitive to climate and especially important to regional economic development: water policy and vegetation change. By focussing on two policy areas we will be able to explore specific new ways of communicating information and specific new policy options and alternatives. Where necessary, we will use historical data (e.g., on past droughts) to create credible scenarios (not predictions) for policy analysis thus avoiding the weaknesses of current models.

A specific technique will be the use of environmental impact indicators. Because they have significance and convey information to both the science and policy communities, such indicators become a common metric linking the two.

We will take every appropriate opportunity to involve actual policymakers in our work through workshops and policy exercises that integrate research and outreach programs. Our work will inform and support, but not supplant, governmental and private-sector decision-making.

Finally, we will explicitly solicit feedback from policymakers to keep our research aimed at the right questions without letting short term concerns twist priorities as has happened elsewhere [Brown and Byerly, 1981].

6.3.5. PROPOSED RESEARCH

6.3.5.1. Part 1. Linking policy and natural science research.

(a) Environmental Impact Indicators. One key to effective environmental planning and management is to identify environmental impact indicators that are easily measured, contain a maximum of information, and are inherently understandable or meaningful (Holling, 1978). We propose to develop a set of guidelines for indicator identification, selection, and subsequent use in policy making. The development of such guidelines will relate to specific research activities of the Center. For example, it is well known that El Nino events are associated with weather in many parts of the world and have effects on

such disparate items as wheat harvests in Australia, forest damage by fires in Indonesia, and corn and soybean yields in the Mid-West of the U.S. (Glantz, et al, eds., 1987), each of which could be a primary impact indicator.

The Center's program, integrating environmental histories and perception analysis, provides a unique opportunity to improve the selection of the most useful environmental indicators for global change studies. In any environmental research, a wide range of impact indicators present themselves (from the leaf-area index to sediment yield). The challenge is to collapse the initial roster of possible impact indicators into a small set of the most "useful."

A first stage is to review: (i) a range of variables that are potential indicators; (ii) their practicality and cost; (iii) their information content; and (iv) the ease with which they interface particular models used in both natural science and human-impact research communities.

In a second stage we will use selected indicators to demonstrate how they link the human impact and natural science systems. We will attempt to choose variables that relate to both systems in known ways. For example, corn yield represents moisture and temperature as well as economic value, quantities that can be used in models.

The third stage will emphasize how such indicators may be employed in policy development, thus completing the link between science and policy. Here it will be necessary to recognize that various indicators have their own characteristic time scales, as do policy processes.

These three stages will be applied to both the sspecific cases mentioned below.

(b) Policy and Global Change. The Center will study connections between policy and global change, making these connections more obvious to both the scientific and policy communities. This effort will consist of monitoring, research, synthesis, and outreach.

We will *monitor*

Center research and pertinent, related research outside. In particular, we will follow work to improve models for calculating impacts of global change, so that Center results can provide input to such work.

Research will have three objectives: (i) To understand how global change information does or could find its way into policy. (ii) To widen the range of response options considered by policy makers. (iii) To invent new processes for injecting physical and socioeconomic information into the policy process.

Synthesis will tie together the results of the Center's programs and relate them to other work, recognizing that much research, though conducted narrowly, often has wide relevance. Therefore a continuous effort is needed to maintain and establish linkages.

Outreach efforts will bring our results to the attention of policy makers through conferences, workshops, testimony, etc. Such interactions will provide useful information on how global change information is perceived and used by target communities.

An important task will be to re-examine the basis for a particular policy when research seems to indicate that the basis is inadequate or wrong or that the policy is counterproductive.

6.3.5.2. Part 2. Specific Case: Water Policy and Global Change

Policy cannot be studied only in the abstract: specific cases must be examined. If we want to interact repeatedly with working officials, we must bring to the table policy information useful to them. Therefore we propose to study certain aspects of water policy in some detail. Our proposed work begins with a project which will develop one or more regional scenarios of changed water availability based on historical data and likely climate changes. We will look at two other cases in which there could be severe impacts of changed water availability: urban water systems and legally-governed water systems.

a. Water policy impacts due to changes in extreme events. It has been empirically demonstrated (Mearns, et al., 1984) that small changes in mean climate conditions can translate into large changes in the frequency, intensity and distribution of extreme events. Furthermore, natural hazards research has demonstrated that extremes, rather than mean conditions, tend to drive human perception and response, and also that human response to hazards is rarely efficient in a normative sense (e.g., people continue to build in flood plains, earthquake zones, and hurricane-prone areas).

We propose to analyze the role of extreme hydrological events in water resources management and policy in three ways:

i. Empirical analysis of variability of climate and related runoff changes in the U.S. over the last 50 years; use of historical data to develop credible future scenarios for analysis (as described by Karl and Riebsame, 1984);

ii. Case studies of the impacts of extreme hydrological events on water management systems; and

iii. A policy exercise (repeated as new information develops) in which selected resource managers and policymakers are asked to project impacts and to suggest alternative responses to scenarios developed in (i) above. For example, a major, multi- year drought in the western U.S. (analogous to the dust bowl of the 1930's), or a continuation of high precipitation and lake levels in the Great Lakes could serve as the focus of the exercise.

b. Impacts on Urban Water Systems and Policy). We propose to study the ability of urban systems to deal with two extremes of climate: drought and floods. Typically, urban water supply managers are extremely risk-averse regarding the possibility of shortage. This often results in very high levels of investment in water storage and treatment capacity, as well as the acquisition of excess water rights. These costs to the community can be very large, and decreasing water supply could drive the costs into a highly non-linear region. The issue is whether or not traditional policies are rational in view of the likely range of long-term climate variation.

Climate change might increase or decrease urban flood risk. The issue is how cities can rationally design their flood management programs (including zoning, flood storage, structural and non-structural measures, warning systems, etc.) given existing uncertainty about future climate changes.

In investigating these issues, we will work with a sample of cities to provide feedback into the Center from responsible water managers.

c. Interaction of Climate Change and Water Law Regimes. Existing legal regimes for allocating water are based on expected runoff, i.e., they assume constant climate. Although they allow for some variability, such regimes could be severely impacted by long-term change of water supply or demand.

Using scenarios developed above, we will identify issues that will arise from changes in water supply. Focussing initially on the Colorado River basin and the seven affected states, we will identify water users most likely to be affected and key variables. The compacts under which Colorado river water is allocated are already strained because of poor original assumptions about runoff. The compacts represent a point of rigidity which may make adaptation difficult. As specific issues are identified we will convene workshops of relevant officials to identify alternatives and options which could provide the needed flexibility and robustness in our water law regimes.

6.3.5.3. Part 3. Specific Case: The Human Ecology of Vegetation Change

Vegetation integrates climate, soils, topography and social systems. It is a key element of studies of environmental change proposed by the Center.

Human ecology of vegetation change bears directly on our biogeochemical cycle research since forests represent an important source of fixed nitrogen and the human ecology proposal suggests work in a biome comparable to at least one of those treated in the biogeochemical cycling work. El Nino events studied by the tropical atmosphere group play a great role in the history of forest growth. The Southern Andean component of this proposal is closely to our studies of Holocene climatic variation in the same area.

We need to understand how people perceive vegetation change in order to understand how human activity contributes to change and how managers respond. We propose an integrated analysis that begins with improved histories of vegetation change in selected case studies and assesses people's understanding of and response to the documented change.

a. Documenting Vegetation Change. Investigators involved in this sub-proposal collectively have a great deal of experience in a wide variety of methods for documenting vegetation change. These methods include repeat photography, fire-scar dating, forest age structure analysis, folk history analysis, sediment record analysis, air photograph and remote sensing analysis. Almost all of these methods may be used, regardless of species, in different locations to give a complete picture of forest cover extent over time periods on the order of a few centuries. Some of the methods such as repeat photography and folk history analysis may be used again in the perception studies.

In many cases the documentation of forest cover includes information on the geographic distribution of other types of vegetation. For example when forests are removed by cutting, burning, or other reasons they are often replaced by grasslands. Consequently, although this case study focuses on forests, it implicitly includes other types of vegetation.

Two of the three investigators are also involved with the work on "Records of Global Change". Through such techniques as tree-ring analysis, the historic vegetation change record may be linked with the longer record in the latter sub-proposal.

b. Analyzing Perception of Vegetation Change. The perception analysis will focus on local and regional forest users and managers, applying environmental perception techniques developed by Whyte (1977) for the Man and the Biosphere program. We will document people's perception of the causes, rate, quality, and direction of change, as well as their understanding of past changes. These perceptions can then be compared to the actual record and to current understanding of cause and process of forest change.

We will also establish the range of responses (prescriptions) that managers consider in responding to change and the costs and benefits they attach to their responses.

The challenge here is to apply perception analysis to cases of slow, subtle change as well as to cases of more drastic change. The differences between perceived change (measured by interviews, documentary analysis, and projective techniques) and actual change will provide our first indication of how accurately people perceive environmental trends. Studies of how they rate changes on various scales (quality, cause, importance, threat, etc.) will allow definition of the structure of their environmental images. Surveys of their preferred responses to change will yield insight into the range of adjustments they hold to be feasible.

Two selected areas will be studied for both the documentation of the record of vegetation change and the perception of it by managers and users. By selecting study areas in different parts of the world we will elucidate which techniques in human perception studies are cross-cultural and which are not, and the reasons for this. Clearly, such findings will have major implications for some parts of government policy relating to global change. The study areas are in the Colorado Rockies of the U.S., and the Central and Southern Andes of S. America. These areas are chosen in part because of our record of climate studies focus on a transect running through North America and South America, and because our work on biogeochemical cycles will study similar sites.

c. Area of Study: Colorado Rockies. This area provides many examples of the interaction of anthropogenic and natural disturbances and of manager perception and responses to these changes. Among other disturbances characteristic of the these forests is the effect of insect epidemics. It is generally assumed that forest managers accept conventional wisdom about the influence of fire suppression on frequency and severity of insect outbreaks. But we lack assessments of their perceptions of these influences and their ability to control them. We also lack comprehensive historical data on both fire regimes and insect-caused disturbances. Thus fire and forest pest management policies are being formulated without either historical knowledge of these disturbances or an understanding of long-term consequences of management practices on forest structure and composition.

d. Area of Study: Central and Southern Andes. The Central Andes of Peru and Ecuador provide a good contrast to the Southern Andes (south of 40 degrees latitude) in terms of a high population in the former area related to environmental degradation and deforestation compared to more lightly settled regions in the latter area. In the Central Andes the main research question to be investigated is : to what extent is the deforestation the consequence of post 1945 rapid population growth as opposed to much earlier human activities. This question is clearly the key also to the perception of vegetation change. In the case of the remote Southern Andes, although the vegetation is perceived as either pristine or modified only by European settler influence, aboriginal influence may well have had a major impact.

6.3.6. Institutional Resources

Analysis of the human ecology of vegetation changes requires an interdisciplinary approach, and offers an excellent opportunity to integrate physical and social science and to focus them on a problem important to society. The University of Colorado, through its interdisciplinary institutes (INSTAAR and CIRES) and the Department of Geography, with its strengths in biogeography, natural resources management, and environmental perception studies, affords the opportunity to create a special focus on the social aspects of global change as manifest invegetation changes.

A core group of researchers associated with the Department of Geography will focus their attention on the human ecology of vegetation change: David Greenland has studied climate- vegetation relationships in the central Rocky Mountains (see Greenland, 1985)--he will develop indicators of environmental change that can be applied in several settings: William Riebsame has studied how resource managers perceive and respond to climate change at several scales (see Riebsame, 1985)--he will coordinate the perception components of the proposed case studies; Thomas Veblen has investigated forest dynamics and management policy implications in Peru; and Vera Markgraf has conducted research on climate and vegetation history in Colorado and Argentina;-- they will conduct the central Rocky Mountain and South American case studies. Other faculty who will be involved in the component of the Center as advisors include Payson Sheets, anthropologist who has studied people's interaction with the environment in the regions addressed in this proposal. The Central Andean case study will be made in association with the university's ongoing Rio Abiseo project operated by the Anthropology Department.

6.3.7. PROCUCTS/OUTREACH

The combination of activities in each case study will produce information directly valuable to resources managers. For example, in the central Rocky Mountains, managers need to know more about the differences between the historical record of forest change (including the effect of fire supression) and their own perceptions. To continue the forest example, our assessment of the percieved range of adjustments to foraest change will point to gaps in the managers response rosters—gaps that should be filled if future

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7. EDUCATIONAL FEATURES

The University of Colorado has strengths in a number of areas emphasized in the proposed Center for Global Change. These range over biological, chemical, geological, societal and other disciplines relevant to Earth System Science. These activities are currently housed in the Departments of Environmental, Population, and Organismic Biology (EPOB), Geology, Geography, Astrophysical, Planetary, and Atmospheric Sciences (APAS), Chemistry, Electrical and Computer Engineering (ECE), Aerospace Engineering, and in the Law School. Relevant courses, offered in these programs, are listed in the University of Colorado Course Catalog.

7.1. Curricula currently offered

Perhaps the largest academic component of the center is represented by environmental biology studies in EPOB. This program is comprehensive in its coverage of the biosphere and its role in the environment -- both on the macroscale and on the microscale. Coursework covers the gammot of ecological issues, beginning from fundamental principles of ecology and passing onto active research topics such as fresh water ecosystems, limnology, microbial ecology, plant ecology, population biology, biometry, and advanced listings in microbiology and ecology. In cooperation with this extensive program is additional coursework taught in conjunction with the Geography and Geology Departments, such as forest geography, biogeography, and evolution of continental ecosystems.

Climate and environmental studies is another area of widespread activity. Although more descriptive than the degree of quantitative involvement represented elsewhere, educational opportunities in this broad area cover many important subjects. Coursework in physical climatology, synoptic and dynamic climatology, theories of climate change, arctic and alpine environments, and seminars on special topics in climatology are offered by the Geography department. Courses in fundamental elements of atmospheric motion, such as principles of fluid mechanics, waves and instability, geophysical and astrophysical fluid dyanamics, and the dynamics and photochemistry of the upper atmosphere are offered as part of the APAS curriculum.[1] Radiative processes in planetary atmospheres is also part of the APAS curriculum.

In addition to these graduate offerings, are a number of undergraduate listings on environmental topics. Introductory courses in the earth's atmosphere and oceans are cosponsored by APAS and Geography. Sequences on environmental systems, such as vegitation and soils, and on global change are offered by the Geography and Geology departments, respectivley. There are also single selections on oceanography offered in Geology and in Aerospace Engineering.

Researchers in the department of chemistry are involved in reaction rate studies relevant to ozone and coursework exists on ......, important in studies of the nitrogen cycle which will figure actively in the center's investigations of how the environment interacts with the surface, e.g., through vegitation and marine systems. These courses complement instruction in geomorphology and surface hydrology, offered in the Geography department. There is also interest in air pollution studies, focusing on urban source regions. In addition to anthropogenic influences on urban environments, these investiga-

1. Owing to the heterogeneous composition of APAS (atmospheric science being the component of relevance here), these courses serve interests which are wideranging, from fluid motions of the earth's interior to stellar envioronments and the distribution of galaxies. Although the intent is to develop fundamentals common to all of these disciplines, the emphasis and certainly applications developed in these courses will vary according to the interests of the instructor.

tions could provide an important means of monitoring the dispersion of both man-made and natural constituents by atmospheric motions. Observing radiative emmissions of different chemical species from space has already proven extremely useful in stratospheric studies for diagnosing how atmospheric circulations transport quantities, such as angular momentum, water vapor, and ozone, from regions where they are produced to other ares on the globe. More.................

Complementary to these curricula on scientific fundamentals are a number of technological/applications courses which will support the design operation, and analysis of environmental monitoring systems. Classes in remote sensing, chiefly ground-based (?), and in radar are offered in ECE. Techniques in ecology and biometry are taught in EPOB. A survey course in earth system science technological issues is offered in Aerospace Engineering. A number of courses on observational techniques, including statistics for earth science, cartography and interpretation of aerial photography, remote sensing of the earth's surface, Geographic information systems, and data processing, are offered in the geography department.

On the side of societal impact and response, is coursework in conservation of natural resourses, water resources and management, the interaction of population and environment, and environmental policy are taught in the geography department. A comprehensive curriculum on natural resources exists in the School of Law, including enviornmental law, mining law, water resource management, and wildlife management.

7.2. Required curricula

While a fairly rich spectrum of coursework, relevant to global change, is currently offered, there exist some important weaknesses in the academic coverage. Perhaps most visible is the rather lean development of key issues on environmental dynamics. There exists no structured program in climate dynamics and supporting areas such as tropospheric dispersion, dynamics of the tropical atmosphere, equatorial ocean dyanamics, atmosphere-ocean interactions, and mixed layer processes. Along these lines, atmospheric convection is noticeably absent.

Radiative processes are developed at the fundamental level in APAS. However, as far as the many important considerations to the terrestrial environment are concerned, e.g., CO_2 and the greenhouse effect, the role of atmospheric particulates, aerosols, and clouds in the earth's energy budget, the application is tenuous.

As the interaction of the atmosphere with the earth's surface, e.g., through the biosphere, hydrology, and ocean surface, will play a key role in the center, the need for instruction in planetary boundary layer and related fluxes is great. Currently, there exists only modest coverage of this topic in the course on geophysical and astrophysical fluid dynamics in APAS, due to other demands. A valuable complement to this area would be the development of surface exchange processes, e.g., between vegitation and microbial systems and the atmosphere, and also a strengthening of transport considerations relevant to the earth's environment.

Lastly, the role of satellite monitoring in the proposed center is a great one. While there exists emphasis on the design and operation of such platforms, and on studying surface processes, there is a real need to establish supporting coursework on the analysis of the fluid environment by remote sensing, which departs significantly in nature and complexity from other focuses of satellite monitoring covered.

Not all of these needs reflect genuine voids in campus expertise. Some of the vacant areas are due to thin instructional staffing and demands other than those supporting environmental issues. Some of this shortfall may be ascribed to curriculum redundancies assiciated with the dispersed character of the supporting courses. However, this feature may be endemic to interdisciplinary programs such as this one.

7.3. Attracting students and minorities

As with any good academic program, the best instrument for drawing quality graduate students into environmental reseach activies,such as global change, is the success of the program itself. The better qualified candidates will familiarize themselves with the various graduate opportunities available and the reputations of such programs. In this direction, it will be essential that the 'interdisciplinary' aspect of the center become a reality. This will require a working interaction between various components of the center, leading eventually to jointly authored publications. Only in this manner can genuine progress be made on the pressing issues relevant to earth system science.

More immediate progress can be had along these avenues by effectively advertising the varied opportunities that exist at the University of Colorado in conjunction with neighboring research organizations such as NCAR and NOAA. Scholarships and other financial support instruments could be used to bolster the number of minority students enrolled in the program. One measure of the success of these devices in drawing students would be the change in enrollment in environmental disciplines before and after the various activities were unified under the umbrella of the center.

NATIONAL SCIENCE FOUNDATION

Proposed Budget

Institution: The Regents of the University of Colorado Boulder, Colorado 80309

Title: Center for the Study of Global Change

Desired Starting Date: January 1, 1989

Center Director: Robert E. Sievers

Duration: Five Years

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTALS
A. SALARIES & WAGES						
Center Director: Robert E. Sievers						
50%, 9 MO AY	41,864.00	44,794.48	47,930.09	51,285.20	54,875.16	240,748.94
100%, 1 MO SUM	9,653.00	10,328.71	11,051.72	11,825.34	12,653.11	55,511.88
Associate Director: Mark Meier						
35%, 9 MO AY	27,654.00	29,589.78	31,661.06	33,877.34	36,248.75	159,030.94
100%, 2 MO SUM	18,220.00	19,495.40	20,860.08	22,320.28	23,882.70	104,778.46
Assistant Director: To be named						
100%, 12 MO	50,000.00	53,500.00	57,245.00	61,252.15	65,539.80	287,536.95
OTHER FACULTY AND SENIOR INVESTIGATORS:						
John Andrews						
5%, 9 MO AY	3,047.00	3,260.29	3,488.51	3,732.71	3,994.00	17,522.50
100%, .5 MO SUM	3,412.00	3,650.84	3,906.40	4,179.85	4,472.44	19,621.52
Richard Armstrong						
50%, 12 MO	18,150.00	19,420.50	20,779.94	22,234.53	23,790.95	104,375.91
James Avery						
10% AY	4,845.00	5,184.15	5,547.04	5,935.33	6,350.81	27,862.33
100%, 1 MO SUM	5,669.00	6,065.83	6,490.44	6,944.77	7,430.90	32,600.94
Susan Avery						
15% AY	8,458.00	9,050.06	9,683.56	10,361.41	11,086.71	48,639.75
100%, 1 MO SUM	6,598.00	7,059.86	7,554.05	8,082.83	8,648.63	37,943.38
Ben Balsley						
25%, 12 MO	20,625.00	22,068.75	23,613.56	25,266.51	27,035.17	118,608.99
Robert Barkley						
50%, 12 MO	29,346.00	31,400.22	33,598.24	35,950.11	38,466.62	168,761.19
Roger Barry						
10%, 9 MO AY	6,722.00	7,192.54	7,696.02	8,234.74	8,811.17	38,656.47
100%, 1 MO SUM	7,750.00	8,292.50	8,872.98	9,494.08	10,158.67	44,568.23

	YEAR 1	\R 2	YEAR 3	YEAR 4	YEAR 5	TO
5%, 9 MO AY	4,606.00	4,928.42	5,273.41	5,642.55	6,037.53	26,487.90
100%, .5 MO SUM	5,310.00	5,681.70	6,079.42	6,504.98	6,960.33	30,536.42
Peter Birkeland						
5%, 9 MO AY	2,440.00	2,610.80	2,793.56	2,989.10	3,198.34	14,031.80
100%, .5 MO SUM	2,600.00	2,782.00	2,976.74	3,185.11	3,408.07	14,951.92
John Birks						
10%, 9 MO AY	5,772.00	6,176.04	6,608.36	7,070.95	7,565.91	33,193.27
100%, 1 MO SUM	6,656.00	7,121.92	7,620.45	8,153.89	8,724.66	38,276.92
Maurice Blackmon						
NOAA Collaborator	0.00	0.00	0.00	0.00	0.00	0.00
Ronald Brunner						
7%, 9 MO AY	0.00	4,000.00	4,280.00	4,579.60	4,900.17	17,759.77
Radford Byerly						
50%, 12 MO	36,915.00	39,499.05	42,263.98	45,222.46	48,388.03	212,288.53
Robert Chase						
15%, 9 MO AY	9,478.00	10,141.46	10,851.36	11,610.96	12,423.72	54,505.50
100%, 1 MO SUM	7,394.00	7,911.58	8,465.39	9,057.97	9,692.03	42,520.96
David Crumpacker						
15%, 9 MO AY	8,303.00	8,884.21	9,506.10	10,171.53	10,883.54	47,748.39
100%, 2 MO SUM	12,764.00	13,657.48	14,613.50	15,636.45	16,731.00	73,402.43
J. DeLuisi						
NOAA Collaborator		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
Ray Fall						
5%, 9 MO AY	2,394.00	2,561.58	2,740.89	2,932.75	3,138.05	13,767.27
100%, 1 MO SUM	5,521.00	5,907.47	6,320.99	6,763.46	7,236.90	31,749.83
Fred Fehsenfeld						
NOAA Collaborator	0.00	0.00	0.00	0.00	0.00	0.00
Alexander Goetz						
5%, 9 MO AY	3,959.00	4,236.13	4,532.66	4,849.95	5,189.44	22,767.18
100%, 1 MO SUM	9,130.00	9,769.10	10,452.94	11,184.64	11,967.57	52,504.25
David Greenland						
15%, 9 MO AY	6,705.00	7,174.35	7,676.55	8,213.91	8,788.89	38,558.71
100%, 2 MO SUM	10,310.00	11,031.70	11,803.92	12,630.19	13,514.31	59,290.12
Robert Hamm						
20%, 9 MO AY	8,829.00	9,447.03	0.00	0.00	0.00	18,276.03
100%, 1 MO SUM	4,072.00	4,357.04	0.00	0.00	0.00	8,429.04
Howard Hanson						
25%, 12 MO	13,200.00	14,124.00	15,112.68	16,170.57	17,302.51	75,909.75

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTAL
Charles Howe						
5%, 9 MO AY	3,413.00	3,651.91	0.00	0.00	0.00	7,064.91
100%, 1 MO SUM	7,871.00	8,421.97	0.00	0.00	0.00	16,292.97
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
Siri-Jodha Khalsa						
10%, 12 MO	4,197.00	0.00	0.00	0.00	0.00	4,197.00
25%, 12 MO		11,227.00	12,012.89	12,853.79	13,753.56	49,847.24
Sr Res Assoc.						
50%, 12 MO	17,132.00	18,331.24	19,614.43	20,987.44	22,456.56	98,521.66
William Lewis						
30%, 9 MO AY	19,551.00	20,919.57	22,383.94	23,950.82	25,627.37	112,432.70
100%, 2 MO SUM	15,028.00	16,079.96	17,205.56	18,409.95	19,698.64	86,422.11
Lawrence MacDonnell						
25%, 12 MO	12,130.00	12,979.10	13,887.64	14,859.77	15,899.96	69,756.46
Vera Markgraf						
25%, 12 MO	12,417.00	13,286.19	14,216.22	15,211.36	16,276.15	71,406.93
Alfred McLaren						
25%, 12 MO	12,584.00	13,464.88	14,407.42	15,415.94	16,495.06	72,367.30
Gifford Miller						
5%, 9 MO AY	2,410.00	2,578.70	2,759.21	2,952.35	3,159.02	13,859.28
Russell Monson						
5%, 9 MO AY	1,801.00	1,927.07	2,061.96	2,206.30	2,360.74	10,357.08
100%, 1 MO SUM	3,988.00	4,267.16	4,565.86	4,885.47	5,227.45	22,933.95
James Peterson						
NOAA Collaborator		0.00	0.00	0.00	0.00	0.00
Tad Pfeffer						
100%, beg. 7/1/90	0.00	18,000.00	38,520.00	41,216.40	44,101.55	141,837.95
William Riebsame						
10%, 9 MO AY	4,108.00	4,395.56	4,703.25	5,032.48	5,384.75	23,624.04
100%, 1 MO SUM	4,808.00	5,144.56	5,504.68	5,890.01	6,302.31	27,649.55
James Saunders						
50%, 12 MO	17,174.00	18,376.18	19,662.51	21,038.89	22,511.61	98,763.19
Steven Schmidt						
10%, 9 MO AY	2,959.00	3,166.13	3,387.76	3,624.90	3,878.65	17,016.44
100%, 2 MO SUM	6,551.00	7,009.57	7,500.24	8,025.26	8,587.02	37,673.09
Russell Schnell						
50%, 2 MO	6,232.00	6,668.24	7,135.02	7,634.47	8,168.88	35,838.61

	YEAR 1	Y[illegible] 2	YEAR 3	YEAR 4	YEAR 5	TOTA[illegible]
Payson Sheets						
5% AY	2,355.00	2,519.85	2,696.24	2,884.98	3,086.92	13,542.99
100%, 1 MO SUM	5,810.00	6,216.70	6,651.87	7,117.50	7,615.72	33,411.79
Susan Short						
15%, 12 MO	6,750.00	7,222.50	7,728.08	8,269.04	8,847.87	38,817.49
Herman Sievering						
100%, 1 MO SUM	5,827.00	6,234.89	6,671.33	7,138.33	7,638.01	33,509.56
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
A. Tuck						
NOAA Collaborator	0.00	0.00	0.00	0.00	0.00	0.00
Thomas Veblen						
15%, 9 MO AY	6,316.00	6,758.12	7,231.19	7,737.37	8,278.99	36,321.67
100%, 2 MO SUM	9,578.00	10,248.46	10,965.85	11,733.46	12,554.80	55,080.58
Carol Wessman						
100%, 12 MO	32,703.00	34,992.21	37,441.66	40,062.58	42,866.96	188,066.42
James White						
15%, 9 MO AY	5,859.00	6,269.13	6,707.97	7,177.53	7,679.95	33,693.58
100%, 1 MO SUM	4,325.00	4,627.75	4,951.69	5,298.31	5,669.19	24,871.95
Eric Williams						
50%, 12 MO	17,792.00	19,037.44	20,370.06	21,795.97	23,321.68	102,317.15
Hydrologist-new faculty hire						
5%, 9 MO AY	1,397.00	1,494.79	1,599.43	1,711.39	1,831.18	8,033.78
100%, 1 MO SUM	3,269.00	3,497.83	3,742.68	4,004.67	4,284.99	18,799.17
Plant ecologist-new faculty hire						
5%, 9 MO AY	1,397.00	1,494.79	1,599.43	1,711.39	1,831.18	8,033.78
100%, 1 MO SUM	3,269.00	3,497.83	3,742.68	4,004.67	4,284.99	18,799.17
Environ. Chemist-new faculty hire	4,666					
Visiting Scholars						
15 person-months (2-6)	60,000.00	64,200.00	68,694.00	73,502.58	78,647.76	345,044.34
SUBTOTAL SENIOR PERSONNEL	757,000	833,267.07	883,166.36	944,988.00	1,011,137.16	4,424,456.60
Postdoctoral Research Associates						
(24) 100%, 12 MO	905,000	807,454.10	863,975.89	924,454.20	989,165.99	4,339,680.18
Professional Research Assistants						
(21) 100%, 12 MO	468,700	234,330.00	250,733.10	268,284.42	287,064.33	1,259,411.84
Graduate Research Assistants						
(47), 50%, 12 MO	536,000	372,092.50	398,138.98	426,008.70	455,829.31	1,999,819.49

	YEAR 1	ᴧR 2	YEAR 3	YEAR 4	YEAR 5	TO⁻
Undergraduate Student Aides (10) Hourly Basis ($7/hr.)	25.000	15,964.40	17,081.91	18,277.64	19,557.08	85,801.03
SUPPORT STAFF:						
Administrative Assistant 100%, 12 MO	30,000.00	32,100.00	34,347.00	36,751.29	39,323.88	172,522.17
Senior Secretary: Rosella Chavez 100%, 12 MO	26,000.00	27,820.00	29,767.40	31,851.12	34,080.70	149,519.21
Word Processor Operator 100%, 12 MO	16,500.00	17,655.00	18,890.85	20,213.21	21,628.13	94,887.19
Diatom Technician: K. Williams 25%, 12 MO	6,600.00	7,062.00	7,556.34	8,085.28	8,651.25	37,954.88
Sedimentology Technician 15%, 12 MO	6,000.00	6,420.00	6,869.40	7,350.26	7,864.78	34,504.43
Data Management Systems Coordinator 50%, 12 MO	18,000.00	19,260.00	20,608.20	22,050.77	23,594.33	103,513.30
Computer Programmer Analyst 50%, 12 MO	15,000.00	16,050.00	17,173.50	18,375.65	19,661.94	86,261.09
Image Analysis Technician 50%, 12 MO	15,500.00	16,585.00	17,745.95	18,988.17	20,317.34	89,136.45
SUBTOTAL SUPPORT STAFF	133,600.00	142,952.00	152,958.64	163,665.74	175,122.35	768,298.73
TOTAL SALARIES & WAGES	2,825,000	2,406,060.07	2,566,054.87	2,745,678.71	2,937,876.22	12,877,467.87
B. FRINGE BENEFITS						
Senior Personnel/Staff (17%)	151,000	343,060.54	365,641.78	391,236.70	418,623.27	1,669,096.95
First Year Researchers (5%)	69000	0.00	0.00	0.00	0.00	48,681.50
Students (1%)	5.600					
Tuition (15NR, 32 R)	185.000	128,760.50	141,636.55	155,800.21	171,380.23	714,632.48
TOTAL FRINGE BENEFITS	410,600	471,980.68	507,449.15	547,219.68	590,199.07	2,433,268.94
C. PERMANENT EQUIPMENT						
	618,796.00	544,000.00	105,000.00	70,000.00	50,000.00	1,387,796.00
TOTAL PERMANENT EQUIPMENT	618,796.00	544,000.00	105,000.00	70,000.00	50,000.00	1,387,796.00

D. TRAVEL

1) Domestic:

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTAL
Scientific conferences	70,000.00	74,900.00	80,143.00	85,753.01	91,755.72	402,551.73
Field work	35,000.00	55,000.00	58,850.00	62,969.50	67,377.37	276,196.87
Researcher relocation	4,250.00	4,547.50	4,865.83	5,206.43	5,570.88	24,440.64
New faculty recruitment	7,500	0.00	0.00	0.00	0.00	5,000.00
Visiting scholars	3,000.00	3,210.00	3,434.70	3,675.13	3,932.39	17,252.22
Workshops	10,000.00	30,000.00	32,100.00	34,347.00	36,751.29	143,198.29
2) Foreign:						
Scientific conferences	15,000.00	5,350.00	5,724.50	6,125.22	6,553.98	28,753.70
Field work	58,600.00	85,000.00	66,000.00	76,500.00	62,250.00	348,350.00
Workshops (Policy Exercise)	0.00	0.00	8,000.00	8,000.00	0.00	16,000.00
TOTAL TRAVEL	263,350	258,007.50	259,118.03	282,576.29	274,191.63	1,261,743.44
E. OTHER DIRECT COSTS						
1) Materials & Supplies:						
Piura Upgrade--						
Fuel	10,000.00	20,000.00	21,000.00	22,000.00	23,000.00	96,000.00
Spare parts	15,000.00	15,000.00	15,000.00	15,000.00	15,000.00	75,000.00
Office & computer-related	18,000.00	19,260.00	20,608.20	22,050.77	23,594.33	103,513.30
Data acquisition	7,500.00	8,025.00	8,586.75	9,187.82	9,830.97	43,130.54
Software (incl. Ingress DEMS)	11,580.00	12,500.00	2,500.00	0.00	0.00	26,580.00
Laboratory & field	128,500.00	137,495.00	147,119.65	157,418.03	168,437.29	738,969.96
Subtotal Materials & SUpplies	190,580.00	212,280.00	214,814.60	225,656.62	239,862.59	1,083,193.81
2) Publication costs	13,000.00	18,000.00	19,260.00	20,608.20	22,050.77	92,918.97
3) Computer costs: time & maint.	48,000.00	51,360.00	54,955.20	58,802.06	62,918.21	276,035.47
4) Subcontracts:						
University of Piura	11,000.00	17,100.00	18,310.00	19,640.00	21,100.00	87,150.00
Piura Wind Profile Installation	75,000.00	0.00	0.00	0.00	0.00	75,000.00
5) Other:						
Equipment maintenance	20,000.00	30,000.00	32,100.00	34,347.00	36,751.29	153,198.29

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTALS
H. TOTAL DIRECT & INDIRECT COSTS	5,386,000.00					
I. CONTRIBUTIONS						
1) NOAA CONTRIBUTIONS	(1,000,000.00)					
2) Colorado Advanced Technology Institute (CATTI)	(500,000.00)					
3) University of Colorado at Boulder (UCB)	(586,000.00)					
TOTAL CONTRIBUTIONS	(2,086,000.00)					
J. TOTAL REQUESTED FROM NSF	3,300,000.00					

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	TOTALS
Consultant costs	5,000.00	5,350.00	5,724.50	6,125.22	6,553.98	28,753.70
Shipping	4,000.00	15,000.00	8,000.00	8,500.00	14,000.00	49,500.00
Helicopter charter	0.00	15,000.00	20,000.00	15,000.00	20,000.00	70,000.00
Image processing	10,000.00	10,700.00	11,449.00	12,250.43	13,107.96	57,507.39
Communication & duplication	12,000.00	12,840.00	13,738.80	14,700.52	15,729.55	69,008.87
Image analysis workststion time @ $20/hr.	5,000.00	5,350.00	5,724.50	6,125.22	6,553.98	28,753.70
C-14 dates (AMS & conventional)	15,000.00	15,000.00	10,000.00	5,000.00	5,000.00	50,000.00
TOTAL OTHER DIRECT COSTS	4=8 580	620,260.00	628,891.20	652,411.88	703,490.92	3,204,214.00
TOTAL DIRECT COSTS	4,467,000					
INDIRECT COSTS 42.5% of MTDC	919,000					