CIRES has aligned its research along scientific themes (rather than organizational structures) to foster a more interdisciplinary approach. We are addressing questions of scientific and societal relevance to present useful results in a meaningful context. This approach enables rapid adaptation to a dynamic world as needs evolve. There are currently four scientific foci, the advanced tools that support them, and the underlying philosophy that integrates them.

Climate System Variability

1. Overview

Climate variability affects virtually all natural systems and human activities. Areas of direct climate impact include agriculture, water quantity and quality, ecosystems, air quality, and human health. Understanding and potentially predicting climate changes is therefore critical to the public, and also to decision-makers within government and industry for resource management and hazard mitigation.

Climate variations may have natural or human-induced causes. Clarifying the relative importance of these two causes is an outstanding research and societal issue. Also, "large-scale" and "long-term" climate variations may be linked to variations in local weather quantities such as temperature, precipitation, cloud cover and storminess, as well as in atmospheric carbon dioxide, ozone, and water vapor. Understanding these links across scales is another major issue.

A systematic approach to these problems involves 1) detecting and describing climate variations; 2) diagnosing and attributing their causes; and 3) prediction, which can ultimately only be probabilistic given the chaotic nature of the system. Predictions of the likelihood of extreme events and abrupt climate changes are especially important because of their potentially major societal and ecosystem impacts. To address these fundamental problems, six sub-topics, which are in established areas of CIRES expertise, are proposed for future research in climate variability. CIRES will continue to conduct observational, diagnostic, modeling, and prediction research in these areas.

2. Research Activities

a. Detection of Climate Modes, Trends, and Variability

Newly developed century-long observational data sets, reconstructions of past climate from paleoclimatic proxy records, and the ability to make multi-century runs with improved general circulation models (GCMs) will make it possible to approach climate system variability issues more rigorously. The goal is a better understanding of the structure and range of natural climate variability, to help, among others, in distinguishing it from anthropogenic climate change. This goal is particularly important because at the lowest frequencies the power spectra of the major modes of climate variability such as ENSO, the NAO, and the Arctic and Antarctic "oscillations" are difficult to distinguish from noise. The development of paleoclimate reconstructions and their combination with newly extended instrumental records will aid in this effort.

b. Mechanisms and Forcings of Climate Variability

Although progress in this area over the last two decades has clarified some questions, it has also raised others. For example, to what degree is all predictable natural climate variability from seasonal to decadal scales related to ENSO? What are the basic generation mechanisms of the NAO and the Arctic and Antarctic oscillations? What are the regional and global impacts of the variability in the tropical Atlantic and Indian oceans? To what extent do human-induced changes, such as in atmospheric composition and aerosols, or in ground cover and land use, affect climate variability? To what extent have observed climate changes been influenced by volcanic and solar forcings, and how do these compare in magnitude with anthropogenic forcings? What is the precise nature of climate forcing by tropospheric aerosols? How can we use our understanding of these forcings to detect climate changes and attribute the causes of those changes? CIRES scientists are in an excellent position to address these issues in collaboration with their NOAA colleagues.

Projections of future climate change can of course only be as good as the models that are used to make them. Many dynamical and physical processes are not well represented in climate models. Investigations of these processes, with a view toward model development, will therefore remain an important goal. Here the importance of interactions across scales again needs to be stressed. For example, most global coupled models used in global warming research do not adequately represent ENSO, which is known to affect global temperatures. The initiation of ENSO events is affected by intraseasonal Madden-Julian Oscillation (MJO) events in the equatorial western Pacific. The MJO itself is known to be influenced by synoptic cold surges along the east Asian coast and the south China sea, which are themselves affected by local air-sea interactions, and so on. Similar links can be drawn across scales starting with, say, global cloud cover or the global monsoons. The implication is that at least the general statistics of some critical regional processes, if not their detailed dynamics, must be represented in global climate models if one is to trust their predictions. Documenting, diagnosing, and modeling regional processes and their variability from intraseasonal to sub-centennial scales are clearly central to this effort.

Further, because predictability is determined by the signal-to-noise ratio, accurate estimates of the noise are just as important as those of the signal. Underestimating the noise will overestimate the predictability. What is 'signal' and 'noise' depends upon the problem at hand. In anthropogenic global warming predictions, all natural variability, including ENSO, is 'noise'. In predictions of ENSO-induced seasonal anomalies, the MJO and extratropical weather variations are 'noise'. The dynamics and statistics of the noise need to be thoroughly understood in both types of problems to correctly distinguish it from the signal.

c. Climate and Cryosphere Interactions

The cryosphere is an integral but relatively poorly observed component of the global climate system, with possibly important feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, surface hydrology, and the atmospheric and oceanic circulation. These interactions are not well understood at present and not well represented in climate models. Uncertainties in the surface energy balance (including those in the surface albedo and its dependence on surface type) as well as in surface hydrology are especially critical. Because of this, it is not yet clear to what extent the cryosphere is an important driver of global climate variability. It is however, already clear that it is a sensitive indicator of change in the climate system.

Some important emerging questions are: Do the pronounced changes in the Arctic ice extent and thickness observed over the past several decades reflect natural variability or human influences? Do they represent a significant regime shift? How much of the global sea level rise over the last 100 years can be explained in terms of reductions of land ice volume, especially glacier recession? How reliable are the current estimates of 15-20%, based on a poorly distributed network of observed glaciers representing only about a third of all glaciers?

d. Prediction of Climate Variability

Success in the mid 1980s in predicting several aspects of tropical Pacific SST (sea-surface temperature) evolution associated with the ENSO phenomenon helped launch the TOGA program and its successors programs GOALS (Global Ocean-Atmosphere-Land System) and CLIVAR (Climate Variability and Predictability program). These programs have led to a continuous improvement in the predictions of ENSO-related seasonal climate fluctuations around the globe. They have also generated a new set of questions, such as: to what extent can one go beyond ENSO in search of predictable climate signals? The NAO and the polar oscillations may be of comparable amplitude to ENSO, but are they predictable to the same extent? To what extent does the longer memory of the deep ocean, and/or changes of sea ice, contribute to atmospheric predictability on decadal and longer scales?

The small signal-to-noise ratio of most climate variations on sub-centennial scales raises another set of questions concerning their inherent predictability. A particularly important question is: how large is a GCM's advantage in predicting such variations over simpler statistical models and semi-empirical stochastic models? Put another way, are fully coupled ocean-atmosphere-cryosphere-land surface models likely to lead to significant further improvements in climate prediction? What is the best way to utilize probabilistic predictions? Again, CIRES scientists are well placed to address these issues, especially in collaboration with their colleagues in NOAA/CDC, GFDL (Geophysical Fluid Dynamics Laboratory), NCEP (National Centers for Environmental Prediction) and elsewhere.

e. Development of Extreme Events and Rapid Climate Change

A growing appreciation of the intrinsically probabilistic nature of climate prediction has also led to questions such as: To what extent are extreme anomalies and events predictable, or are they merely "the luck of the draw"? If the latter, to what extent can one say that their likelihood is enhanced or diminished in a particular climate regime? Are current GCMs adequate to address this? What is the likelihood of abrupt climate change, for example, the collapse of the thermohaline circulation, and what would be the global and regional manifestations of such a change? How can one best use the available paleoclimate record to detect past extreme events and estimate their frequency?

f. Atmospheric Ozone

Important emerging questions in this area include: To what extent is the stratospheric ozone layer beginning a rehabilitation, and how can predictions of future changes be improved? What processes are leading to the observed ozone depletion in the northern hemisphere, especially over the Arctic? To what extent are the changes in the stratospheric ozone layer affecting the stratospheric thermal and wind structure, and hence wave propagation characteristics which may in turn influence tropospheric structure and climate? More generally, what are the quantitative relationships among ozone depletion, radiative forcing and climate change? CIRES scientists are well placed to address these questions, especially in collaboration with NOAA/AL and NOAA/CMDL scientists.

3. Research Linkages

Many strong collaborations exist between researchers on campus and in the Climate Diagnostics Center. CDC is the one NOAA group that also exists as a formal University center, and common areas of interest are being pursued by CDC and CU's Program in Atmospheric and Oceanic Sciences (PAOS). The new Water in the Interior West assessment jointly led by CIRES and CDC has established collaborations with the Geography and Economics departments, the National Snow and Ice Data Center (NSIDC), the Institute for Arctic and Alpine Research (INSTAAR), the Institute for Behavioral Sciences (IBS), and the Natural Resources Law Center (NRLC). Other collaborations exist with the International Research Institute (IRI) for Climate Prediction, the Scripps Institution for Oceanography, and other federal agencies including the Bureau of Reclamation. Further connections exist with the National Centers for Environmental Prediction (NCEP) through the Coupled Model and Reanalysis projects and with the Geophysical Fluid Dynamics Laboratory (GFDL) through the University Consortium project.

4. Plans

CIRES scientists and their NOAA colleagues already have 5-year research goals with many of the above issues in mind, and also specific plans to achieve those goals. These are listed briefly below. Constraints of space precludes discussing them at much greater length than done here. It should perhaps be mentioned that most of these projects represent extensions of ongoing funded research, and as such have already undergone some form of peer review.

a. Detection of Climate Modes, Trends, and Variability

- Develop a serially complete long-term precipitation and temperature dataset for the United states from a network of 10,000 daily reporting stations. Construct spatial correlation patterns of global mean trends and variability within the instrumental record for 1901-1997.
- Develop a monitoring capability of the hydrologic cycle of the Arctic landmass. Use products from EOS-era satellites, NWP models and other datasets in conjunction with an atmosphere-land surface water budgeting scheme to compile time series of gridded water-budget fields. Use "baseline" water budgeting schemes in conjunction with atmospheric reanalyses and pre-EOS satellite data to extend these series into the pre-EOS era.
- Continue monitoring stratospheric ozone. Develop or upgrade existing surface and satellite atmospheric constituent retrieval algorithms. Perform diagnostic analyses to improve the existing world Umkehr dataset and reevaluate climate trends and variability.
- Continue monitoring key parameters of the Arctic system. Complete analysis of snowmelt variability. Quantify trends, identify factors that force variations, and quantify the temperature-albedo feedback for diminished snow cover using radiometric measurements from Barrow.
- Continue mapping and analysis of Northern Hemisphere snow cover trends and expand this to global

coverage. Develop a specific algorithm to assess contribution of snowmelt to Arctic Basin river drainage. Focus initially on developing an optimal algorithm for deriving global snow water equivalent.

- Investigate the origin of natural decadal to centennial scale atmospheric variations through atmospheric GCM simulations with prescribed observed global and tropical sea surface temperatures. Make connections to seasonal to interannual variability.
- Construct a multi-linear model of natural low-frequency atmospheric variability from global observations for 1969-1997. Use this to provide multi-colored noise models of natural decadal variability that are superior to simple red noise models.
- Expand the database of cryospheric and paleoclimatic records and reconstructions, and improve their availability to the research community, decision makers and the general public. Begin by developing and implementing new multi-proxy, relational database tools to manage and distribute the data.
- Develop new reconstructions of past climate and environmental conditions that can be combined with instrumental records to fully understand climate variability at seasonal to decadal time scales. Begin with new reconstructions at seasonal to decadal resolution over recent centuries.
- Quantify the magnitude and effect of climate forcing agents on past climate through comparisons of GCM results and observations. Make paleoclimate GCM results and corresponding observational data sets generally available.

b. Mechanisms and Forcings of Climate Variability

- Advance understanding of tropical SST evolution using observed data and output from coupled models. Analyze model output using empirical techniques to reconcile model simulations with observations. Continue investigation of physical processes acting as noise. Investigate impact of MJO-induced SSTs on ENSO evolution. Investigate the role of water vapor and cloud feedbacks in determining the east Pacific cold tongue.
- Investigate the sensitivity of the global atmospheric response to details of the tropical SST forcing through a large set of GCM integrations with prescribed SST anomalies in localized "patches" in the tropical ocean basins.
- Investigate the nonlinearity of the global response to ENSO, especially over the remote north Atlantic.
- Study tropical-extratropical interaction through ocean currents and waves, as well as through the "atmospheric bridge".
- Investigate the role of ENSO in regulating climate through altered poleward heat transports. Seek further support for the "heat pump" view of ENSO in which surface radiative warming forces ENSO, which then ejects heat poleward
- Investigate processes which affect extratropical SSTs and the extent to which those SSTs, and anomalies of sea-ice and snow cover influence the atmosphere. Investigate both the direct effect and the indirect effect through altered storm tracks.
- Investigate the role of stochastic forcing on the large-scale atmospheric evolution. Provide numerical modelers with rigorous methods of stochastic modeling and methods to evaluate their importance. Use analytical expressions, developing them as necessary, to assess the viability of implementing stochastic parameterizations in GCMs.
- Investigate the mechanisms of drought over the Indonesian maritime continent and its influence on the global weather and climate. Use local long-term records, gridded reanalysis products, and GCM simulations for this purpose.
- Improve understanding of tropical intraseasonal variability and its representation in global climate models. Identify mechanisms through which tropical intraseasonal variations may affect wintertime as well as summertime extratropical weather and climate.
- Improve representation of tropical convection in climate models. Use wind profiler observations to examine the frequency and behavior of equatorial waves. Analyze multiple field campaign data sets, such as from TOGA/COARE, to assess the relation between tropical convection and large-scale circulation. Conduct a detailed examination of the horizontal and vertical structure of tropical waves coupled to convection.
- Investigate the dominant balances in the atmospheric angular momentum budget from intraseasonal to interannual scales. Investigate the role of orographic gravity-wave drag stresses. Seek further support for the important result that inclusion of gravity-wave drag in many global models improves the simulation of

the extratropical zonal mean jets but may upset the balance of global angular momentum.

- Identify the chemical and physical properties of tropospheric aerosol through both field and laboratory measurements. Recognizing that there is almost no such thing as a "pure" one-component aerosol, focus on the physical properties of internally mixed organic/sulfate aerosols. Also measure ice nucleation on mixed aerosol particles. Cirrus clouds and contrails present major uncertainly in climate models and their nucleation mechanism is unknown.
- Elucidate the interplay between radiation, clouds, chemistry, and climate. Determine through laboratory experiments the chemical characteristics of fine particles that promote their serving as ice nuclei. Examine the data taken near Florida in 2000 with the NOAA P-3 aircraft to evaluate the vertical profile of the NO_2 produced by high electrical activity. Conduct laboratory evaluations of how chemical reactions on the surfaces of fine soot particles can alter the surrounding atmospheric abundance of reactive chemical species.
- Investigate complexity in the climate system through a hierarchy of models, with emphasis on the role of the hydrological cycle in the possible self-regulation of climate. Focus initially on fully coupled, zero-dimensional models which include radiation, oceans, land, dynamic vegetation growth and decay, the water and carbon cycles, and possibly ice. Consider questions such as: (a) under what parametric conditions do such models exhibit self-regulation under self-induced oscillations and chaos? (b) what key features of the earth's climate do they exhibit? (c) how can complicated dynamical models be simplified within a stochastic-dynamic framework?

c. Climate and Cryosphere Interactions

- Improve the description of high-latitude climate processes and climate change. The Global Land Ice Measurement from Space (GLIMS) aims to map a significant fraction of the ca.100,000 ice bodies not yet in the World Glacier Inventory. CIRES/NSIDC will maintain an archive of relevant glacier data. The Russian glacier maps in the World Atlas of Snow and Ice Resources will be used to provide a GIS data base enabling comparative change studies between the 1960-70s and 2000-2003 high-resolution space imagery.
- Determine to what degree the primary modes of climate variability such as the AO, PDO, ENSO affect the Arctic climate, sea ice extent and concentration, and annual cycle of snow cover etc. Perform correlative analyses of mode indices and observed changes to assess teleconnections.
- Investigate the effect of variations in seasonal snow cover on biogeochemical cycles, e.g., CO_2 and methane uptake/release as a function of season length; also the effect on tundra growth indices.
- Improve polar climate models by developing better parameterizations of cloud-radiative-dynamic interactions. Account for sea-ice and snow cover variability and validate using real observations from Barrow.
- Improve GCM parameterizations of Arctic surface energy fluxes. Create a unified community SHEBA dataset for validation. Use the dataset to improve parameterizations of turbulent heat fluxes in stable conditions. Use a two-way nested mesoscale model to evaluate methodologies for best representing the SHEBA turbulent heat fluxes on GCM scales.
- Advance understanding of mixing processes in the Arctic PBL through analysis of SHEBA sodar and sonic anemometer data.
- Investigate ice shelf breakup in the Antarctic through a model based on the effect of melt ponds on crevasse propagation within a shelf. Surface melting hastens shelf disintegration by seeping into cracks and mechanically breaking up the ice. The mechanism is radically different from iceberg calving and basal melting.
- The importance of a better understanding of the role of the global cryosphere in climate has been recognized by the establishment of a World Climate Research Programme project "Climate and Cryosphere (CliC)" in March 2000. NOAA is leading a multi-agency effort to establish a Study of Arctic Environmental Change (SEARCH) which it is expected will make a major U.S. contribution to CliC. CIRES scientists are active participants in planning these international and national endeavors.

d. Prediction of Climate Variability

- Diagnose the seasonal predictive skill of climate forecast models in use at NCEP, GFDL, NCAR, ECMWF and IRI. Compare the GCM forecast skill with that of a simple multilinear statistical model derived from 30 years of NCEP reanalysis data.
- Determine the predictability of anomalous storm activity, blocking frequency, wet and dry spells etc during ENSO events. Generate large sets of GCM integrations with prescribed El Niño and La Niña conditions in the tropical Pacific for this purpose.
- Investigate the predictability of the extratropical circulation on intraseasonal, seasonal, interannual and decadal scales through a linear inverse model of atmospheric variability constructed from global observations for 1969-1997. Use this to quantify the role of tropical heating on extratropical predictability at different time scales.
- Investigate the effect of stochastic forcing on climate predictability, with an emphasis on ensemble prediction. Determine the circumstances under which the noise affects not only the spread but also the mean of a forecast ensemble. Investigate the extent to which implementation of stochastic parameterizations affects a GCM's simulated climate.

e. Development of Extreme Events and Rapid Climate Change

- Investigate the effect of ENSO on the probability distributions of remote atmospheric variables though observations and large sets of GCM integrations. Emphasize the changes of extreme risks. Diagnose the changes of 'noise', i.e. the changes of variability on synoptic, intraseasonal, and seasonal scales using simpler dynamical models.
- Investigate rainfall variability in south America, with a focus on extreme precipitation events and streamflow.

f. Atmospheric Ozone

- Characterize tropospheric ozone and its radiative role in past or future climate changes. Plan and develop an FY 2002 airborne and ground-based field experiment to examine the transport of chemically and radiatively active atmospheric species from East Asia to North America This study will lay the baseline for understanding how growing Asian emissions, as well as natural processes such as lightning, could influence the chemical and radiative characteristics across the Pacific.
- Expand observational and diagnostic information on the abundance and patterns of tropospheric ozone and its role in radiative forcing using airborne measurements and 3-D chemical/transport modeling.
- Establish model-based representations of the distributions of tropospheric ozone in key global regions (e.g., North Atlantic, Asian outflow, and Indonesian and North American fires) and estimate the radiative forcing from such ozone changes and variations.
- Perform statistical analyses of extended data sets for trends and predictions of changes in trends, such as the turn-around of ozone depletion. Datasets include trace gases, temperature and some satellite observations.
- Improve understanding of stratospheric ozone depletion and the radiative properties of the atmosphere. Characterize the chemical composition of the upper troposphere and lower stratosphere, particularly at low latitudes, including the molecular speciation of the organic and inorganic contents of individual atmospheric particles. Analyze data from the winter 2000 field mission of Arctic ozone loss, the SAGE III Ozone Loss and Validation Experiment. Analyze field observations of stratosphere/troposphere exchange at low latitudes.

Regional Processes

1. Overview

Many of the research endeavors within CIRES and NOAA have a regional focus because they address a particular confluence of geography, demographics, weather and climatic regimes, and scientific challenge. This confluence of factors has produced a range of research within CIRES and NOAA that is not only rich in its diversity but provides an essential connection between science and its constituents. These constituents include human populations ranging from those coastal megalopolises to those of the indigenous people on the margin of the Arctic Ocean, all of who must coexist with sensitive aquatic and terrestrial ecosystems in a highly variable and evolving climate. Indeed, the impact of short-term climate variability and extremes is often regionally focused, influencing very specific populations, economies, and ecosystems.

Increasingly, the research community is being called upon to develop the scientific understanding necessary to deliver improved environmental prediction and better tools with which to manage the impact of extremes in weather and climate coupled with changing land use. The challenge in this endeavor lies in the fact that such prediction must cover many scales of forcing and response. In this context, "regional scale" might range from the scale of influence of the Arctic Oscillation on the Arctic and sub-Arctic ice cover and related ecosystems down to the response of local watersheds to seasonal-to-decadal cycles of drought and flooding. Similarly, chemical constituents added to the atmosphere may influence society from urban scales to hemispheric scales such as the transport of Saharan dust to South America or Asian aerosols to the North American Continent. Further, very small-scale processes such as permafrost physics can influence large scales and long periods through changes in carbon sequestration. Such issues cross many scientific disciplines and will require an integrated science approach based on improved observations, diagnosis, and modeling of regions subject to accumulating natural and anthropogenic stresses.

These regional science applications within CIRES, by their very nature, resist categorizing in rigid bins but can be loosely organized with the following foci:

- Region-Specific Impacts of Climate Variability and Extreme Events
- Atmospheric Chemical Forecasting
- Regional Air Quality
- Intercontinental Transport and Chemical Transformation
- Hydrological Cycles in Weather and Climate
- High Latitude Processes
- Surface Exchange Processes

2. Research Activities

a. Region-Specific Impacts of Climate Variability and Extreme Events

Goal: Across North America and around the globe, the impact of climate variability is clearly regionally specific, often focused within natural boundaries associated with topography, watersheds, and/or other geographical features (e.g. ocean-land, ice-land boundaries etc). The goal of this element is to couple enhanced observations and research within regions characterized by a strong climate variability signal with analysis of past data and improved modeling. A special emphasis will be on determining factors influencing the occurrence of extreme events.

Issues and Questions: Only a limited observing capability exists for the study of regional processes. Even this capability may be compromised by the failure to provide adequate resources to maintain long-term records and to observe critical physical and chemical processes of regional importance. The understanding of such processes and the assurance of their inclusion in global climate models are crucial for the reliability of the models. Because of a dearth of observations, processes in oceanic regions including the Arctic are especially poorly understood. Interregional dynamical features such as the Arctic and Southern Oscillations link regional climate changes to changes over North America. In addition, global climate models do not provide the specificity necessary to predict the regional impact of climate variability and trends. However, new observing capabilities have emerged in terms of satellite, airborne, and ground-based remote sensing as well as in-situ observing methods that now provide new opportunities for diagnosing processes on regional scales and stimulating improved models. The study of regional scale chemical and physical processes needs to include scientific investigation of air-sea interaction and the coastal zones. Many issues of environmental concern are located at our nation's coastlines (for example, hurricanes and coastal development, West Coast air pollution, East Coast flooding, loss of key wetlands, etc). The oceans play an important role in modulating global and regional climate. In addition, the near coastal zones of the oceans are integral to the modulation of weather and climate for the coastal landmasses and other habitable areas. These coastal regimes are complex in structure, due to the physical, chemical, and biological interaction between the air, sea and land. An improved understanding of the coastal zone processes that modulate our weather will provide input for the prediction of severe events such as hurricanes and land-falling winter storms.

b. Atmospheric Chemical Forecasting

Goal: Improved forecasts of the chemical composition of the atmosphere are relevant to public health and safety issues. The goal of this topic is to undertake research that contributes to the development of air quality prediction and forecasting capabilities. The research under this topic will seek to identify the natural and anthropogenic emissions that influence the formation of ozone and fine particles in urban, rural regions and coastal areas of the United States and determine the chemical and meteorological processes that control their transformation and redistribution. This information must be integrated with an enhanced understanding of the interrelationships between climate and air quality. The research under this topic will underlie national, regional, and local efforts to evaluate and improve air quality.

Issues and Questions: The development of air quality prediction and forecasting capabilities that have broad applicability across the United States will require an integration of efforts. These efforts must provide quantification of emissions, understanding and better parameterization of chemical and meteorological processes, and improved data assimilation in numerical models. In particular, efforts will be made to identify the natural and anthropogenic emissions that influence the formation of ozone and fine particles in urban, rural regions and coastal areas of the United States. Increased understanding of processes and sources will be used to improve model modules and emission inventories and the data from field studies will be use to help evaluate the models use to forecast air-quality.

c. Regional Air Quality

Goal: The goal of this topic is to improve the understanding of the chemical and meteorological features that determines air-quality in various regions of the United States.

Issues and Questions: Improved scientific information relevant to public health and safety issues on a regional basis is needed to better manage air-quality in the United States. The information will be used to enhance understanding of the interrelationships of climate and meteorology with regional air-quality. A focus of the regional research during the next five years will be the Western United States. The scientific study of the air-quality problems in the Western United States provides opportunity and a challenge. The Western United States has several features that define its interest for regional studies. Many air-quality problems in the Western United States are year-round as opposed to the focus on summertime pollution that most concerns other parts of the nation. The West is one of the most rapidly growing parts of the country and hence susceptible to growing stresses on air-quality. The West contains the bulk of the publicly managed land in the country. These lands cover much of the region and their management rest in the public and hence governmental domain. The goal of this element is to understand the chemical and meteorological features that determine air-quality in the Western United States. This effort will provide improved scientific information relevant to public health and safety issues in the Western United States; enhanced understanding of the interrelationships of Western climate and meteorology with Western air-quality. In this element, an effort will be made to craft new initiatives that build on the "Water in the West" theme and the results of past and ongoing studies in the western U.S. in which NOAA and CIRES staff have participated.

d. Intercontinental Transport and Chemical Transformation

Goal: The aim of this research is to elucidate the processes that determine the intercontinental transport of photochemical pollution and control the chemical transformation that occurs during this transport.

Issues and Questions: Previous studies have documented that photochemical pollution can be transported into the remote atmosphere. However, no attempts have been made to systematically consider the complexities of chemical transformations over intercontinental scales or to quantify, beyond reporting isolated events, the amount of these short-lived compounds that are transported over these distances. The goal of this effort will be to elucidate the processes involved in the intercontinental transport of photochemical pollution and improve the understanding of the larger-scale influences on regional air quality and the relationship between climate variability and long-range transport. In this effort, CIRES in cooperation with NOAA will undertake to develop capabilities to better quantify the transport of pollution into and from North America. Emissions from North America can impact

European air quality. In addition, transported pollutants become part of the U. S. "background" that defines a limit for air quality management. The research will initially focus on the long-lived pollutants, CO, ozone and fine particles.

e. Surface/Atmosphere Exchange

Goal: The goal of this research is to improve the understanding of the role that surface-atmosphere exchange plays in shaping regional climate and air-quality.

Issues and Questions: Accurately characterizing the exchange of heat, momentum, moisture, gases, and aerosols at the surface of the Earth provides one of the major challenges for the diagnoses and prediction at regional scales. From the perspective of air-quality, on a regional scale the emissions of VOCs from biogenic sources (forest) are known to influence the chemical formation of regional pollution. However, a great deal of study is required to better understand the compounds that are emitted, the sources and extent of those sources and, even, their impact on the environment. Likewise, the deposition of material from the atmosphere can have a profound influence on the biosphere. Damage to ecosystems by acid deposition and ozone is well documented. However, better understanding of the processes that deliver harmful material from the atmosphere to the ecosystems is lacking and useable estimates of the amount and extent of the deposition presently not available.

Turning to the physical processes, oceans cover some 70% of the globe and maintain much of the memory of past climate that is carried into the future. They constitute one of the major data voids of the Earth yet are the major supplier of moisture that eventually flows through terrestrial and aquatic ecosystems back to the ocean. Over land, the exchange is complicated by spatially and temporally varying land use, often in topographically complex regions. In addition, seasonal to decadal changes in snow and ice cover and soil moisture further compromise our ability to observe and predict future climate. Thus, major efforts are underway within CIRES and NOAA to better characterize these exchanges over land, ice, and water. A major step in this effort is the upcoming series of ocean cruises as part of the Climate and Global Change Program's Pan American Climate Studies (PACS) as part of the Eastern Pacific Investigation of Climate (EPIC) studies. Further, efforts coupling models and measurements of surface fluxes of heat, momentum and radiation are underway using data sets collected in the Arctic and as part of air-quality field studies carried out in Tennessee, Texas, and California. The research on this theme also investigates the processes that shape the structure and behavior of the top of the atmospheric boundary layer. These processes control transport from the boundary layer where local effects are determined to the free troposphere where a more region-wide transport could occur.

f. Hydrological Cycles in Weather and Climate

Goal: To better observe, model, and predict the consequences of climate change and variability on hydrological variables on time scales ranging from those of flash floods to those of the Pacific Decadal Oscillation and on multiple spatial scales.

Issues and Questions: Water plays a critical role in our weather and climate system connecting oceanic processes to day-to-day changes in the weather. Understanding the water cycle and its controls will lead to better prediction of floods and droughts and affects a multitude of users from emergency managers to farmers. In addition, the importance of predicting its behavior crosses many disciplinary boundaries. For example, water is a critical feature in the prediction of air quality affecting many chemical processes, the growth of hydroscopic particles, and vertical exchange processes that affect dilution in the boundary layer. Its residence in the ground provides a memory of past weather, and soil moisture tracks a number of biogeochemical cycles. In the west, water is often a scarce resource that must support urban needs as well as agricultural and aquatic ecosystems.

Emerging research indicates that the current generation of mesoscale atmospheric models, when nested down to fine spatial scales (e.g., 1 km2) are reasonably successful at forecasting spatial variations in near-surface fields. The land surface schemes (LSS) of these models include physically based characterizations of exchanges of energy and mass between the land surface and atmosphere, soil moisture and ground water storage, and surface runoff. Coupled atmospheric-LSS models have the potential to resolve some of the scale issues involved with distributing precipitation and energy over drainage basins and would provide a more physically-based representation of basin scale hydrologic processes.

g. High Latitude Regional Processes

Goal: To carry out interdisciplinary studies of high latitude regions of the Earth where atmosphere, water, ice, and land meet and are expected to allow complex responses and feedbacks to climate variability and change on local scales.

Issues and Questions: The inhospitable nature of the high latitudes of the Earth has led to great challenges in the study of polar and sub-polar climate. Technological advances have begun to redress the sparseness of polar data leading to a new focus on processes in these regions. However, the identification of persistent regimes in polar atmospheric circulation and their effects on regional polar climate has given new impetus to research in this area. For example, warming in the Arctic regions initiates strong positive feedback between the seasonal changes in Arctic sea ice cover and hemispheric weather, warming of the permafrost regions may release large stores of carbon and methane, and changes in the Arctic hydrological cycle may influence the stability of the Arctic Ocean and sea ice cover. Because of the unique differences between north and south Polar Regions, we also have the opportunity to compare and contrast the behavior of these heat sinks and examine their role in the general circulation. For example, a more persistent northern polar vortex will play a critical role over northern continental landmasses whereas in the Southern Hemisphere, the effect may be felt more strongly as a modulation of the atmospheric forcing of the ocean circulation. Further, communities inhabit the far northern regions whose traditional lifestyles render them vulnerable to environmental change. Again, there are new opportunities to address the observation and diagnoses of these changes and impact on local ecosystems and their teleconnection to mid-latitude weather and climate.

Specific questions of interest include: How do the various atmospheric, cryospheric, land, and oceanic processes interact to produce the current Arctic climate? How are these components changing in order to produce the observed changes in the Arctic? Are these changes a natural or anthropogenic-induced variability? How do anthropogenic effects affect the process interactions? Can current models (GCM or regional) produce the correct process interactions? Can the correct process interactions be represented in climate models? How do climatic changes in the Arctic region affect the global climate?

3. Research Linkages

Each of these activities relates strongly to the NOAA mission; each is an activity that CIRES has scientific capability to provide significant new understanding. In support of atmospheric chemical forecasting, CIRES can help to characterize the essential atmospheric processes that underlie forecasts. We can help to develop the real-time analytical techniques for observing the essential variables. Scientists from CIRES can be involved in NOAA-led regional studies aimed at developing and testing forecast models. For air-quality in the West, we would invest in understanding the atmospheric processes that shape the air-quality in the region where we work and live. This research would allow CIRES to contribute information that will be required to effectively manage the increasing complex air-quality problems of the region. The intercontinental transport and chemical transformation of photochemical pollution currently is attracting considerable interest. There are increasing indications that chemical pollutants, even compounds with reasonably short lifetimes, can be detected at great distances from their sources. The interest in the problem is further heightened by questions regarding how long-range transport may change with climate variability. CIRES' scientists have the capability to measure the important chemical and meteorological parameters. We are familiarity with and have studied the transport processes in the Pacific. We have access to and are involved with NOAA's aircraft and surface monitoring stations, which are represent the infrastructure needed to undertake this type of research.

In support of hydrological cycles in weather and climate, CIRES can make a major contribution toward understanding the water cycle and its controls. This will lead to better prediction of floods and droughts and affects a multitude of users from emergency managers to farmers. The inhospitable nature of the Polar Regions has led to great challenges in the study of polar climate. Technological advances have addressed the sparseness of polar data leading to a new focus on processes in these regions. However, the identification of persistent regimes in polar atmospheric circulation and their effects on regional polar climate has given new impetus to research in this area. CIRES can provide scientific expertise on Polar Regions while NOAA can provide the infrastructure necessary for successful monitoring and process studies.

In addition to CIRES expertise, strong scientific support for this research would come from the Chemistry Department of the University and from the Aeronomy Laboratory, the Environmental Technology Laboratory and the Forecast Systems Laboratory of OAR/NOAA. The research would provide support for proposed NOAA related initiatives in chemical forecasting. The research will draw on the expertise in the Center for Limnology and the Climate Diagnostics Center. Strong scientific support for this research would come from the Geography

Department and EPO Biology of the University. The research will provide support to extend CIRES research in Water in the West. The research will draw on the expertise in the Program in Atmospheric and Ocean Science of CIRES. This will augment the NOAA Climate and Global Change program by supporting a new activity in International Transport and Chemical Transformation.

4. Plans

a. Region-Specific Impacts of Climate Variability and Extreme Events

- Analysis and modeling of land-falling winter storms on the west coast and their variability during the past El Niño/La Niña cycle.
- Initiate new studies of coastal weather with an emphasis on integrated observing systems as well as outreach to the user community.
- Using observational methods, statistical analyses, and numerical modeling approaches, examine mechanisms responsible for extreme events using specific events and case studies of opportunity.
- Determine the effect of climate variability on air quality in diverse regions of the U.S. during the past several years, including cases of extremes in air pollution concentrations and events influenced by sub-seasonal to inter-seasonal variability.

b. Atmospheric Chemical Forecasting

- Conduct laboratory and field experiments to understand the role of nighttime chemistry in the chemistry of the lower atmosphere.
- Analyze field data to determine the chemical composition of individual fine particles, with the aim of furthering our understanding of the relation between chemical composition and effects on human health.
- Investigate how atmospheric chemistry influences the growth and/or the chemical composition of aerosols.
- Investigate how the chemical processing and removal of compounds of anthropogenic origin can influence the regional budgets of ozone and fine particles as a function of region and season.
- Investigate the chemical processes that control the formation or destruction of chemical pollutants in the atmosphere and provide laboratory characterization of the chemical oxidation reactions.
- Incorporate this information to produce reliable forecast tools and forecast model evaluations.
- Characterize the meteorological and climatological variance of air quality to provide a better assessment of emission-related trends and thereby a better accounting to the public of the effectiveness of emission reductions.
- Study the impact of meteorological and climate variability on regional air-quality.
- Quantify the impact of global warming on air quality to help assess the potential negation of the gains from emission reductions.

c. Regional Air Quality: Western Issues

- Analyze data from regional air-quality studies, with a focus on understanding the air quality effects of atmospheric chemical and meteorological processes and the influence of manmade emissions sources.
- Analyze data from regional air-quality studies, with a focus on understanding the structure and behavior of the top of the atmospheric boundary layer.
- Analyze data from regional air-quality studies, with a focus on understanding surface/atmosphere interactions including exchange of energy, water vapor, and trace gases at the surface.
- Carry out a field studies in selected regions to determine the influence of regional anthropogenic pollution versus long-range transport on air-quality in the United States.

d. Intercontinental Transport and Chemical Transformation

- Analysis of data from the North Atlantic Regional Experiments (NARE) to quantify the transport of ozone and ozone precursors from North America to the remote troposphere over the North Atlantic.

- Carry out a field studies on the West Coast of the United States to determine the influence of long-range transport versus local sources (shipping, aircraft emissions and recirculation of North American continental pollution) on air quality in the Western United States.
- Estimate the influence of biomass burning that occurs in mid- and high-latitudes of the Northern Hemisphere (> 30º N) on regional air quality and climate.
- Carry out laboratory studies to elucidate the physical and chemical characteristics of fine particles.
- Investigate long-term CO measurement data to search for inter-annual variability consistent with seasonal variations and magnitude of high-latitude fires.
- Determine the chemical composition of gaseous and fine-particles emitted by these fires and the chemical evolution of those emissions once the particle enters the atmosphere.
- Determine the influence of these aerosols on hemispheric climate forcing and variability with particular emphasis on the their impact in the North Polar Region.

e. Surface/Atmosphere Exchange

- Carry out a series of ocean cruises studying air-sea interaction as part of the Climate and Global Change Program's Pan American Climate Studies (PACS) as part of the Eastern Pacific Investigation of Climate (EPIC) studies including measurement of CO_2 fluxes.
- Using data from the Surface Heat and Energy Budget Studies of the Arctic (SHEBA) to develop improved parameterizations and models of the transfer of heat, momentum and moisture over the Arctic Ocean for a full seasonal cycle.
- Continue studies of atmosphere ocean exchange under high wind speed conditions.
- Analyze data obtained in field studies to better understand the processes that control exchange between the boundary layer and the free troposphere.
- Analyze the results from airborne measurements that were made over the southeastern United States of the concentration of compounds (isoprene, acetone and methanol) that may be emitted from natural and/or biogenic sources.
- Compare these results with model simulation of those compounds to test our understanding of the distribution of emissions from those sources.
- Produce more reliable estimates of the emissions from natural sources that combine in a synergistic way with manmade compounds responsible for the formation of regional pollution.
- Based on identification of the major emissions of a new class of biogenic VOCs (e.g. pentenols during autumn leaf senescence and freeze-thaw), develop fast response detection schemes for these VOCs that can be used to determine fluxes of these compounds.
- Use these techniques to measure the fluxes of the compounds from major biogenic sources.
- Use this information to assist in the development of improved natural emission algorithms for the U.S.
- Carry out studies of biosphere/atmosphere exchange in the Rocky Mountains to better understand its influence on regional air-quality and the impact on the mountain ecosystems.

f. Hydrological Cycles in Weather and Climate

- Improve the overall skill and portability of hydrologic models used in stream-flow forecasting. These are ultimately limited by their conceptual as opposed to physically based nature.
- Determine how remote-sensing data can be used to improve seasonal stream-flow predictions? In particular, integration of satellite-derived snow cover into hydrologic forecast models is an attractive avenue for improving predictions of seasonal runoff. However, the spatial and temporal resolutions and type of remote sensing data used as well as data assimilation decisions will affect the quality of results. These issues need to be fully explored.
- Improve understanding of local, regional and remote effects of snow cover on western U.S. climate. This will require a combination of data analysis and numerical model experiments. Key elements are to quantify links between the onset and strength on the summer monsoon and the lagged effect of snow cover, and

effects of regional snow-cover anomalies over Eurasia on the downstream atmospheric circulation.

g. High Latitude Processes

- Establish the impacts of snow cover, soil moisture, and air temperature on the ground thermal regime, assess seasonal freeze/thaw cycles of soils using ground-based data analysis, remote sensing, and modeling, establish the characteristics of seasonal snow melt and investigate the role of high latitude lakes in the northern high latitude climatic system.
- Improve methods for estimating surface albedo from satellites over seasonally snow-covered regions will provide much needed observations. NCEP-NCAR Reanalysis data allow us to map patterns of temperature and atmospheric circulation. Regional scale atmospheric models, coupled to physically based land surface schemes will help assess the magnitude and variability of albedo-temperature feedbacks over snow-covered regions.
- Continue current work of mapping and analysis of Northern Hemisphere snow cover trends and expand this to global coverage. Develop a specific algorithm to assess contribution of snowmelt to Arctic Basin river drainage.
- Determine whether statistical and dynamical methods can provide accurate fields of Arctic precipitation. Precipitation is a key Arctic variable. The Arctic precipitation measurement network has always been sparse. Unfortunately, at the same time that environmental changes are being observed in northern high latitudes, the measurement network is being degraded through the closure of stations and a trend toward automation. This points to the need for greater reliance on methods such as circulation downscaling and the use numerical weather prediction models to provide fields of precipitation.
- Examine the dynamics of seasonally frozen soil, permafrost active layer thickness and snowmelt? Permafrost, active layer depth, seasonally frozen soil and snow melt impact strongly on the high-latitude hydrologic cycle and terrestrial ecosystems. However, their dynamics are not well understood. Obtaining a better understanding will require a blending of models and remote sensing.
- Determine the radiative feedbacks of polar clouds on the surface energy balance of the ice sheets under conditions of changing surface albedo? Over bright snow/ice surfaces, clouds may have either a cooling or a warming effect, depending on the surface albedo and the optical thickness of the cloud. The brighter the surface, the thicker the cloud must be to have a cooling effect. Understanding cloud radiative feedbacks is a key issue in understanding polar climate and climate change.
- To study methods of temperature and current changes in a strongly range dependent Fram Strait environment using modern acoustic methods of remote sensing temperature and current variation in Polar region. Water mass and heat exchanges through the Fram Strait are essential boundary conditions for large-scale ocean circulation models and global climate models.
- Continue current work of mapping and analysis of Northern Hemisphere snow cover trends and expand this to global coverage. Develop a specific algorithm to assess contribution of snowmelt to Arctic Basin river drainage. Year one will focus on developing an optimal algorithm for deriving global snow water equivalent.
- Continue work on testing of algorithms to map the seasonal freeze/thaw cycle in soils. Year one will focus on comparing current algorithms with in situ measurements.
- Study the role of transitory vertical exchange processes in the boundary layer over the Arctic pack ice in transporting aerosols. Determine the impact of these processes on the climatic relevance of aerosols. Deduce links between quasi-permanent boundary-layer features and the transitory exchange processes.

Planetary Metabolism

1. Overview

The sustainability of the biosphere during the current period of rapid changes in the earth system is an issue of prime importance for the environmental sciences. The physical and chemical features of the earth are intimately tied to organisms and the activities required for their sustenance. The health of the biosphere can usefully be considered using the concept of "planetary metabolism", which refers to the complex web of biochemical and ecological processes that occur within the biosphere, and the interaction of these processes with the lithosphere, atmosphere and hydrosphere. Both natural and anthropogenic disturbances drive the structure and dynamics of natural systems, and a thorough understanding of these complex processes is essential for efforts to protect the biosphere from adverse effects due to pollution, destruction of natural landscapes, and alteration of climate. The overriding goals of the CIRES effort in planetary metabolism are:

1. to increase our knowledge of the fundamental processes that drive the biosphere;
2. to use experimental tools to accurately measure indicators of change;
3. to enhance the sophistication of prognostic models capable of forecasting the response of ecosystems and the global biosphere to future environmental changes;
4. to carry out research that will develop science and technology to help us restore and protect the health of the biosphere.

2. Research Activities

a. Biogeochemical Cycling

The primary pools and fluxes that compose the major biogeochemical cycles must be quantified and located within a geographically explicit context. This is accomplished through a combination of studies involving global circulation modeling, the identification and location of primary sources and sinks for the major biogeochemical fluxes, and landscape-level analysis of the distribution of various ecosystems using satellite imagery.

Global networks of trace gas and stable isotope analysis, in combination with global circulation models, are currently being used to discern the global distribution of photosynthetic and respiratory sources and sinks. Through an 'inverse modeling' approach CIRES scientists have been able to partition components of the global carbon cycle into oceanic and terrestrial components, and identify more explicit latitudinal and longitudinal coordinate bands for particularly strong source and sink activity. This approach has been widely recognized by scientists, federal agencies and legislative representatives, and has become a crucial component of the interagency U.S. Global Change Research Program.

Studies of landscape-level patterns in terrestrial ecosystems have been done with an emphasis on the use of remote sensing by satellite imagery. Remotely-sensed data is used to interpret the state and flux of biogeochemical cycles, particularly those associated with nitrogen and carbon. These efforts have included detailed studies of semi-arid savanna ecosystems in the American Southwest, semi-arid southern Africa, and tropical Africa. This experimental approach is particularly useful in coupling patterns of land-use change to perturbations in local and regional biogeochemical cycling and net primary productivity. The research has produced specific discoveries in (1) the linkage of specific spectral bands in remotely-sensed data to the nitrogen status of ecosystems, and the linkage of nitrogen status to rates of net primary productivity, and (2) the development of specific algorithms which can be used to invert spectral reflectance data in a way that is informative of the structure and leaf-area index of terrestrial canopies.

b. Biosphere-Atmosphere Interactions

A number of CIRES scientists investigate biosphere/atmosphere interactions. These interactions are studied at the biochemical level, with a search for the enzymes and pathways responsible for the emission or uptake of reactive and/or climatically-active trace gases. This topic requires investigations of the properties of organic aerosols containing biogenic organic compounds, by direct measurement of elemental fluxes using tower and aircraft sampling, and through ecosystem and global-level modeling of trace-gas exchanges between various biomes and the atmosphere. Examples of specific studies include:

- The isolation and characterization of enzymes involved in the production of isoprene and methylbutenol, two reactive hydrocarbon compounds produced by various plants. These hydrocarbons are involved in the oxidative photochemistry of the lower troposphere, particularly with regard to the formation of tropospheric ozone, a potent radiatively-active gas and a powerful oxidative pollutant.
- The investigation of the reactivity of organic molecules in organic aerosols. The organic material in these aerosols is derived from organic material at the surface of bodies of water, and undergoes chemical reactions in the atmosphere that alter the nature of the organic material and possibly the properties of the

aerosol particles, as well.

- Research using two tower flux systems in the Colorado subalpine forest, with the specific aims to (1) quantify carbon fluxes between the forest and the atmosphere, (2) understand the primary ecological controls over the rate and seasonal pattern of carbon sequestration, and (3) elucidate the manner by which volatile organic emissions from the forest interact with pollutants that are carried from the nearby Denver metropolitan corridor and deposited to the forest. The tower flux site is part of the Department of Energy-funded Ameriflux network, a national network of flux towers accommodating studies of ecosystem-level carbon sequestration and aimed at providing the validation needed by regional and global carbon balance models.
- Studies of regional carbon fluxes using tall towers in Wisconsin and North Carolina, and aircraft sampling across the Midwestern U.S. These studies are intended to validate larger-scale prognostic studies using global and regional transport models in inverse mode to identify terrestrial photosynthetic sources and respiratory sinks.
- Studies on the ecological controls over methane emission from tropical wetland ecosystems. This work shows that methane emissions from tropical wetlands, which have been treated as a major global source, have probably been overestimated. If so, the new methane sources must be postulated and explored.
- Construction of ecosystem and global-scale models of volatile organic compound emission and nitrogen oxide assimilation. These models are being developed from mechanistic principles embedded in the biochemical and physiological processes of plants and microorganisms.

c. Response of Natural Systems to Perturbations

The response of natural systems to perturbations is studied at scales ranging from the microbial to the global. Four major areas of research are proposed for the next cooperative agreement period.

- The evolution of a novel metabolic pathway for degradation of a toxic and xenobiotic pesticide, pentachlorophenol, in a soil bacterium. This work contributes to our knowledge of the ability of microorganisms to adapt to and degrade novel compounds in the environment. Since pentachlorophenol was introduced only about 70 years ago, it appears that this pathway has been assembled in a very short period of time and does not function as well as most metabolic pathways that have evolved over millions of years. This research has shown that enzymes needed to catalyze newly needed reactions can be recruited from completely unrelated pathways - an enzyme that removes chlorine from an intermediate in the pentachlorophenol degradation pathway appears to have been recruited from an enzyme that isomerizes a double bond during degradation of either tyrosine or benzoate.
- Studies of regional and global land-use perturbations and their influence on biogeochemical cycles.
- Studies of the factors controlling the deposition of oxidants, primarily ozone and nitrogen oxides, to forest ecosystems in the Front Range of Rocky Mountains. This investigation determines how such deposition affects primary productivity and ecosystem water use, and their relevance to regional hydrological needs.
- Studies of the perturbations in the nitrogen cycle of watersheds caused by increases in atmospheric deposition of nitrogen from anthropogenic sources. Of particular interest for this research is the role of organic nitrogen as a source of nitrogen for microbes in watersheds that are not anthropogenically enriched in nitrogen, and changes in the processing of organic nitrogen in response to varying degrees of enrichment with inorganic nitrogen from the atmosphere.

d. Transport and Fate of Chemicals in the Biosphere

The primary and secondary influences of pollution are studied through analysis of the transport and fate of various chemicals. These studies include biophysical investigations of primary transport mechanisms in soil, air and water, as well as biochemical and genetic studies of the degradation and transformation of reactive compounds. Four active projects that will be continued include:

- Investigation of the fate of nitrogen oxide compounds emitted from temperate agricultural soils and tropical soils. Some fraction of these compounds escapes to the atmosphere and some fraction is assimilated by the overlying plant canopy. The focus of this work is on the quantification of these fractions and the investigation of biochemical and ecological controls over the emission and uptake processes.
- Studies of the uptake of atmospheric aerosols by various biological surfaces, including the waxy, cuticular

external surface of leaves and the moist, mucosal internal surface of the human respiratory system. This research will contribute to our fundamental understanding of how vegetated surfaces on the earth interact with the atmosphere through heterogeneous processes and provide the basis for certain medical applications that require the absorption of medicines into the respiratory system.

- The development of a new approach for estimating yields of nitrogen from continents to oceans under pre-industrial (background) conditions. This information can be used as a benchmark against which human perturbations of the nitrogen cycle can be judged.
- Work on the biodegradation of pentachlorophenol which helps elucidate the biochemical and physiological adaptations required for degradation of recalcitrant and toxic chlorinated aromatic compounds.

3. Research Linkages

Many of the research components in the Planetary Metabolism area are interdisciplinary, requiring the interaction of biologists, chemists, and atmospheric scientists. Nearly every project described above reflects this fundamental interaction. CIRES research teams include faculty and scientists from the Departments of Chemistry and Biochemistry; Environmental, Population, and Organismic Biology; Molecular, Cellular and Developmental Biology; and Electrical Engineering as well as from the NOAA Aeronomy Laboratory and Climate Monitoring and Diagnostic Laboratory. The research in this theme is fundamental to our understanding of the complex interactions of the physical and chemical environment with biological systems. The theme relates to NOAA's current program in the Health of the Atmosphere as well as emerging NOAA initiatives in ecosystems and air quality.

4. Plans

Long-term plans to further develop the areas represented by Planetary Metabolism within CIRES are focused on enhancing interdisciplinary collaborations and applying investigations to identified needs in the national science agenda. Much of the previous work will continue during the first years of the next cooperative agreement period. However, within the first year of the five-year agreement, the following initiatives will receive priority for development.

a. Biogeochemical Cycling

- Development of molecular approaches to studying microbial ecology and controls over biogeochemical cycling. This initiative has great potential to integrate CIRES with the discipline of molecular biology, which has not previously been particularly strong. Many new molecular approaches to studying environmental issues are emerging, and development of this initiative will poise CIRES to take advantage of these developments within the first few years of the new agreement.
- Development of approaches to studying aerosols and their relevance to biosphere-atmosphere exchange. An understanding of heterogeneous processes remains one of the big hindrances to understanding the physical and chemical properties of various types of aerosols that are important in terms of air quality and climate (vis-à-vis the effects of aerosols on the radiative balance of the earth). Several CIRES scientists have interests in aerosols and heterogeneous chemistry. Internal funds have been allocated as 'seed money' to fund research in this area. It is poised for rapid development within the first year of the five-year agreement.
- Development of a biological component of the Water in the West Initiative. Big breakthroughs are expected in linking nitrogen deposition due to rapid urban and suburban development in the western U.S. to the processing of organic nitrogen in aquatic ecosystems and, ultimately, to the health of food webs in these ecosystems. This issue has profound implications to the maintenance of limiting hydrological resources in the arid west and to the health of fisheries and recreational industries in the region. This area should develop rapidly within the first year of the new agreement.

b. Biosphere-atmosphere interactions

New research initiatives in the field of biosphere-atmosphere interactions include (1) the application of new techniques to elucidate the role of microorganisms in biogeochemical cycling and to characterize atmospheric trace gas concentrations and distribution patterns, (2) the development of new models to predict the effects of future climate change on carbon sequestration dynamics, and (3) the role of terrestrial ecosystems in affecting photochemical dynamics in the atmosphere.

- Use functional genomics to elucidate the metabolic capabilities of Pseudomonas Putida, an organism with great potential for biodegradation of organic pollutants.
- Develop new techniques that allow detection of single molecules in the gas phase that will allow identification of specific bacteria responsible for the production of compounds such as NH3, NO, N2O, NO2, H2S, and other environmentally important volatile compounds.
- Assess the magnitude and distribution of biogenic sources and sinks for the ecosystem-atmosphere exchange of carbon dioxide.
- Develop aircraft sampling protocols to discern broad regional dynamics in the atmospheric carbon dioxide concentration, and through the use inverse modeling techniques and the measurement of stable isotopic dynamics, achieve validation of surface source and sink distribution.
- Develop measurements of landscape-scale fluxes of CO2 to and from a wide-range of ecosystems using kites, balloons, powered parachutes, and light aircraft. Many of these techniques show promise for the characterization of atmospheric gradients in trace gas species above complex terrain and across broad footprints. Access to such techniques will be imperative to expanding studies of surface-atmosphere exchange to include areas not previously amenable to study.
- Initiate studies to develop two-dimensional surface flux models for forested ecosystems in the western U.S. These models will deal explicitly with the complex geometrical properties of coniferous ecosystems, including the complexities of radiative photon transfer within the canopy. Radiative transfer models will be coupled with advective and turbulent transport schemes, and with biochemical and biophysical models of photosynthesis and transpiration, respectively. The models will accommodate the effects of tropospheric ozone deposition to the forest.
- Develop new approaches to making measurements of atmospheric concentrations of volatile organic compounds and ammonia from natural and biogenic sources in order to improve our understanding of the role natural emissions play in regional air quality. An emerging paradigm is that biological processes can profoundly affect the rate and magnitude of photochemistry in the lower atmosphere, primarily by controlling the emission and deposition of reactive precursors. New approaches to detection of the reactive compounds involved in important photochemical reactions include the combination of mass-spectrometry and gas-chromatography in novel configurations and the incorporation of enzymatic processes as a means of detecting trace amounts of reactive compounds.
- Initiate a new line of research on sub-cellular controls over the production of isoprene and methylbutenol, two of the most reactive biogenic hydrocarbons emitted from forest tree species. This research focuses on the fact that, to date, an intact chloroplast system is not available for studying the sub-cellular flow of carbon to the production of these compounds.
- Estimate the flux of ozone and aerosol precursors from natural and/or biogenic sources in order to provide scientific input to pending decisions regarding potential modifications of air quality standards in the U.S. This research fills a sorely needed initiative to better integrate the scientific process and scientific data into the policy-making process. This represents a principal area of future research development in the Planetary Metabolism group and reflects the commitment of the group as a whole to the overarching goal of producing "science in the service of society".

c. Response of Natural Systems to Perturbations

During fiscal year 2000-2001, CIRES has committed to a new faculty search in the field of molecular microbial ecology, with a special emphasis on the use of molecular tools to study the composition of microbial communities underlying biogeochemical cycling and the community-level interactions that underlie dynamics in biogeochemical processes. The emergence of molecular phylogenetic methods to identify microorganisms has created novel opportunities to understand how microbial communities are organized, how they respond to natural perturbations (such as climate variability) or anthropogenic perturbations (such as pollutant deposition), and how their metabolism contributes to biogeochemical cycles. The hiring of this type of scientist, and the incorporation of this person into CIRES, will immediately provide new interdisciplinary opportunities.

Within the community of existing CIRES researchers, several new initiatives are planned.

- Develop new methods of spectral analysis to deconvolute remotely-sensed reflectance patterns and provide a deeper understanding of the effects of climate variation, physical changes, and chemical changes on grassland/shrub land and montane forest ecosystems.
- Understand the resilience of the grassland/shrub land and montane forest ecosystems to perturbations such as climate change and the regional effects of land-use changes. This investigation is focused on the effects of rapid suburbanization in the western U.S., including the indirect effects of development such as alterations in water use patterns and mesoscale effects on weather dynamics.
- Develop novel approaches to using stable isotope information to assess aquatic biogeochemistry and new techniques with greater sensitivity to detect the origins, transport, and fate of anthropogenic nitrogen in aquatic ecosystems in the western U.S., and the effects of such transport on aquatic food webs. The same approaches are also being applied to tropical floodplains, some of the most climatically-sensitive ecosystems on the earth.

d. Transport and fate of chemicals in the biosphere

- Initiate studies of the importance of organic nitrogen in the aquatic nitrogen cycle, particularly with regard to aquatic ecosystems within the influence of urban and suburban activities and the nitrogen oxides that they produce. There is great potential for increased nitrogen loads due to human development to impact the natural dynamics in the aquatic nitrogen cycle.
- Develop a new method for reconstructing the baseline export of total nitrogen and nitrogen fractions from terrestrial environments to rivers, and thence to oceans. This provides the opportunity to expand information on regional nitrogen emission and deposition to the global scale, and to ultimately connect the terrestrial and marine nitrogen cycles.

Geodynamics

1. Overview

At its most basic level, the goal of geodynamics is to better understand the process of convection within the Earth's mantle, and of how that convection affects the surface of our planet. The mantle, which extends from the top of the Earth's liquid core at a spherical radius of about 3500 km up to the Earth's surface at a radius of about 6400 km, behaves as a solid at the time scales over which we live, but convects as though it were fluid over geological time scales. The convective motion, which is on the order of a few cm per year, causes oceans to open and close, continental plates to drift across the earth's surface, and the Earth's crust to buckle and deform creating mountain ranges and other structural features. The convective displacements are the underlying source of earthquakes and volcanic activity. In fact, in an indirect but very real sense this convective process even plays a fundamental role in determining the Earth's climate, through its impact on surface topography. As the topography changes, for example, so may the climate.

Most of the fundamental issues concerning the convection are still not well understood. Among the major outstanding questions are: What dynamical processes and structural parameters determine the style and vigor of the convection? How well known are the values of the important structural parameters (e.g. mantle viscosity, plate thicknesses), as estimated using independent geophysical observations? How are the motions of surface plates related to flow in the deep mantle, and what can be learned about convection and tectonic processes by measuring that motion? How is the Earth layered, and what are the tectonic implications of that layering? What is the origin of various near-surface geological and geochemical features (e.g. mountain ranges, magma bodies), and what do those features tell us about mantle dynamics? Can we improve our understanding of the earthquake process: how is it related to tectonic forces? what determines earthquake magnitudes and recurrence times? how does the slip along a fault evolve with time during an earthquake?

All of these questions are being addressed to at least some degree by CIRES scientists, through a combination of field campaigns, data analysis, laboratory measurements, and dynamical modeling. GPS, absolute gravity, and other geodetic measurement techniques are being employed in the field and from space to detect tectonic motion at all scales; from the large-scale motion of plates relative to one another, to the regional deformation within individual plates and near plate boundaries, to the local motion associated with slip on individual faults. Seismic observations are being used to map out the Earth's internal structure in different regions of the globe, at depths ranging from the near-surface down to the mid-mantle and below. In the lab, the techniques of isotope geochemistry are being applied to rocks collected in the field to study the process of continental evolution. And the properties of rocks at high pressures and temperatures are being studied to better understand the relationship between the things of direct interest to geodynamics (e.g. composition, temperature, density, stress levels), and the wave velocities that a seismologist actually measures. Dynamical models are being employed to address a number of geodynamics problems, from determining the effects of the Earth's viscosity profile and other rheological properties on various types of tectonic motion, to modeling the mountain building process, to trying to understand the fundamental, non-linear behavior of earthquakes and earthquake cycles.

In addition, there are numerous cases within CIRES where research programs initiated to address issues in geodynamics have spawned vigorous activity on problems related to the Earth's outer fluid envelope and represented in the other CIRES themes described in this proposal. Some of these latter activities are described in Section III..

2. Research Activities

Geodynamics research within CIRES can be loosely and somewhat arbitrarily separated into projects that look at the Earth's outermost layers (the outer surface, crust, and lithosphere) and those that probe deeper into the mantle and fluid core. In this section, we describe representative CIRES projects for both regions.

a. Mantle/Core Studies.

Seismology. CIRES scientists are combining earthquake seismology with other geophysical methods, to learn more about mantle structure. The mantle is thought to be the driving engine of most plate tectonic activity, but it is hidden from view beneath the Earth's crust, which ranges in thickness from 10 km beneath oceans to 70 km beneath some high mountain ranges. Thus, to learn about the mantle we must use techniques that can remotely image the subsurface. Seismology, the study of wave propagation in the Earth, provides a powerful tool for performing that imaging. The energy sources for seismic exploration include "active" sources, such as explosions, and "passive" sources, such as earthquakes. By studying the mantle we can prospect for subducted slabs, look for sources of mantle upwelling such as at mid-ocean ridges and hotspots, and study the deep structure of mountains.

For example, CIRES scientists have been constructing high resolution seismic images of deep mantle discontinuities using dense deployments of state-of-the-art seismic instruments available through the Program for Array Studies of the Continental Lithosphere (PASSCAL), one of the programs of the Incorporated Research Institutions for Seismology Consortium. The sharpness and depth of these discontinuities are important for constraining models of composition and temperature in the Earth. We have developed new techniques of using data from these dense seismic arrays that allow us to determine the lateral variation in these discontinuities with unprecedented resolution. Our results have implications for the role of the deep mantle in mid-ocean ridges, hotspots and mantle plumes, subduction zones, and mountain ranges.

Laboratory experiments. CIRES scientists have been conducting equation of state measurements on mantle minerals in the laboratory. We have developed techniques for measuring the relation between stress and strain that use ultrasonic measurements in the GHz range, where ultrasonic wavelengths are near optical wavelengths. We have adapted this technique for use with a diamond anvil cell, which allows us to obtain results at the extraordinarily high pressures representative of the Earth's deep interior. Our data become part of a larger data pool required to gain a better understanding of the Earth's inner workings. Since the Earth's deep interior is not readily accessible to sampling, interpretations of geophysical measurements tend to rely heavily on these laboratory data.

Modeling. CIRES scientists are engaged in various modeling efforts aimed at understanding deep Earth processes and variables. For example, we are attempting to better understand the mantle dynamics of mountain belts, and of how surface elevations can be affected by convective instability, such as might exist beneath Tibet. We are combining modeling efforts with geodetic and geological observations to learn more about the post-glacial-rebound process (the viscous response of the Earth to the deglaciation following the last ice age) and thereby to better constrain the Earth's viscosity profile. We have been modeling the possible effects of mantle phase transformations and of mantle dissipative processes on different types of tectonic and seismic processes, and have studied the effects of the core on the Earth's rotation.

b. Surface/Crustal/Lithospheric Studies.

Geodesy. CIRES has been conducting geodetic measurement programs in China, Tibet, Nepal, India, Mexico, Ethiopia, Venezuela, New Zealand, and the eastern Caribbean, mostly aimed at resolving the details of plate motions. We are particularly interested in the velocity fields across plate boundaries because these hold clues about the generation and distribution of future earthquakes. We use GPS and absolute-gravity measurements to determine strain and vertical motions, occasionally supplemented by leveling, tiltmeters, and strainmeters. For example we monitor volcano inflation and slow earthquakes along the Mexican coastline with 1 km fluid tiltmeters.

We have, for example, completed a geodetic study on the rotation and translation of the Indian Plate relative to Eurasia. Using GPS, we have been able to clarify the renewal times of great earthquakes and the approximate northern and southern bounds of Himalayan ruptures. From historical triangulation data we have been able to constrain the rupture zones of some of the largest events of the past 200 years and thereby identify regions overdue for future great earthquakes that threaten the large local population of more than 100 million people.

Modeling. Much of the geodetic work is complemented by efforts aimed at understanding the dynamic processes responsible for the observed phenomena. For example, CIRES scientists have used the cumulative observational evidence to suggest that the Tibetan Plateau, which was built by gradual north-south shortening and thickening of Asian crust, underwent a rapid increase in elevation beginning about 8 million years. North-south compression of the Indian Ocean floor began at about the same time. A simple explanation is that Tibet rose abruptly in response to mantle flow beneath the plateau, which had the effect of replacing relatively cold, near-surface rocks, with hotter, less dense material from deeper in the mantle. The greater elevations lead to increased compressive stresses on the plateau's flanks, which caused the compression of the Indian Ocean sea floor. This study has lead directly to an investigation of the origins of the Asian monsoon in geologic time, as discussed in Section III below.

Seismology. CIRES has been conducting seismic field studies of continental lithospheric structure and evolution. We have been involved with several PASSCAL portable broadband seismic experiments in the western United States, including a high resolution crustal seismic imaging experiment at the Coso geothermal area in California, and the Continental Dynamics of the Rocky Mountains project which focuses on the southern Rocky Mountains (Wyoming, Colorado, New Mexico). Data from these experiments are being used to construct detailed images of crust and mantle structure beneath the target areas.

Earthquakes. CIRES has been developing new computational methods of addressing fundamental questions related to earthquakes. For example, non-linear models are being developed to simulate the earthquake process to better understand the origin of the spatial and temporal scales of representative events. And the methods of principal component analysis are being used to identify patterns in earthquake activity.

Laboratory experiments. Studies of nonlinear dynamic properties of earth materials are being done at CIRES. For example, we have shown that the complex structure of rocks (grains, cracks, small fluid saturation) can cause an extremely strong and sophisticated non-linear (hysteretic) response to vibrations, which is important for non-destructive testing and oil surveillance, as well as for bottom sediment studies in seas.

Geomorphology. CIRES scientists are engaged in geomorphological studies aimed at understanding the origin of specific topographic features. For example, CIRES personnel have mapped Lake Ontario and are investigating a known shallow, Charity Shoal, which displays a geomorphology highly suggestive of a meteor impact. Follow-up studies will test this hypothesis with more sophisticated geophysical measurements in addition to looking at the bathymetry. As another example, a large part of the seafloor topography in the Gulf of Mexico is dominated by salt tectonics, revealed in the dome and crater topography and the Sigsbee Escarpment. CIRES investigators have mapped the Gulf of Mexico and produced a GIS-compatible data set of the bathymetry.

3. Research Linkages

There are a significant number of CIRES research projects focused on climate change and other topics related to the atmosphere, the oceans, and the hydrological cycle, that have spun off of activities in geodynamics, often in ways that were totally unanticipated. Some of these projects involve the interaction of the solid earth with the oceans and atmospheres. Others involve the application of measurement technology normally used primarily to address problems in geodynamics. Here, we describe examples of both these types of interdisciplinary projects.

Tectonics and climate change. The geologic record contains examples of geologically-abrupt climate change, where the magnitude of the change is huge compared with what many anticipate for the next 50-100 years. Understanding what can cause such changes contributes to the understanding of climate and its variability.

CIRES scientists have identified two examples of extreme climate change with origins that can be ultimately traced to tectonic activity.

For example, we have argued that the closing of the Indonesian Seaway 3-5 million years ago, caused by the northward migration of New Guinea, lead to the aridification of East Africa (when and where humans evolved), and may have provided the switch that initiated the cooling leading to the ice ages. In its present position, New Guinea blocks the passage of warm Southern Pacific water into the Indian Ocean, resulting in a colder Indian Ocean and a warm pool of water in the western equatorial Pacific. This warm pool would presumably have been much less pronounced prior to 3-5 million years ago. It is the presence of the warm pool that creates the conditions necessary for El Niño/Southern Oscillation events. It is conceivable that the oceanic circulation pattern prior to 3-5 million years ago, when New Guinea was a few hundred km south of its present position, may have resulted in warmer higher latitudes, because heat transport from the tropics may have been more effective than it is now - where solar energy is wasted heating cold water in the eastern Pacific.

As another example, studies of fossilized micro-organisms in the Indian Ocean imply that the monsoon may have begun or at least strengthened about 8 million years ago, roughly the same time as the increase in the uplift rate of the Tibetan plateau described in Section II. The implication is that the uplift may have played a role in initiating the monsoon cycle. The change in elevation of Tibet at that time could not have been large, only 1000-2000 m, compared to the 5000-m elevations that exist at present. The implication is that a relatively small change in the elevation distribution of Eurasia may have caused a large change in regional climate. Understanding such a change, both with better geologic documentation and a better understanding of how such a change in elevation could affect regional circulation, could provide a key to understanding and eventually predicting monsoons.

Studies of the connection between climate and the solid Earth also run in the opposite direction, towards estimating the influence of past climates on the solid Earth. For example, CIRES investigators are mapping the lake floors of the Great Lakes and describing the geomorphology carved by glacial advances of the Pleistocene, a case where past climates have had a remarkable influence on the solid Earth.

Groundwater contamination. CIRES is exploring methods of using seismic measuring techniques to remotely detect the infiltration of contaminants into groundwater and to monitor the success of remediation. We are studying the change in the attenuation of strain waves as they traverse a region that is either being infiltrated by contaminants or from which contaminants are being removed. We have performed many supporting laboratory studies on simple systems, including flow studies and attenuation in single cracks. At present we are studying contamination in small (2.5cm diameter) sedimentary rocks and are planning an intermediate experiment at the meter scale before we test in the field.

Greenland ice sheet. Since 1995-96, CIRES scientists have been using GPS and absolute gravimeters to monitor crustal uplift and changes in gravity at two bedrock sites along the margin of the Greenland ice sheet. These observational techniques are normally used to study solid Earth processes, and, indeed, part of the original motivation was to infer information about the Earth's viscosity profile. The results have shown an unexpectedly large rate of crustal subsidence along the southwestern ice sheet margin. Efforts to model this subsidence have lead to the conclusion that the ice sheet in that region may have advanced by about 50 km during the last 3000-4000 years.

GRACE. NASA, in partnership with the German Space Agency DLR, will launch the dedicated Gravity Recovery and Climate Experiment satellite near the end of 2001. This five-year mission will map out the Earth's gravity field to unprecedented accuracies at monthly intervals. The temporal variations in gravity inferred from these data will allow people to study a wide range of processes, from different Earth science disciplines, that involve redistribution of mass within the Earth and at or near its surface. It will be possible, for example, to produce monthly estimates of changes in continental water storage anywhere in the world, averaged over scales of a few hundred km and greater, to accuracies of better than 1 cm water thickness. Changes in the distribution of snow and ice on the polar ice sheets will be determined to this same level of accuracy. Monthly estimates of changes in sea floor pressure over scales of a few hundred km and greater will be determined to a few tenths of a mb or better, everywhere over the globe. The effects of the solid Earth's viscoelastic response to the removal of the enormous late Pleistocene ice sheets can be determined.

CIRES is taking a leading role in exploring the possible applications of this novel technique, developing methods for converting the GRACE gravity fields into useful measurements of mass redistribution, and looking at ways of combining GRACE measurements with measurements from other techniques (i.e. radar and laser altimetric observations of the oceans and ice sheets, respectively; GPS crustal motion measurements) to optimize the scientific return. In addition, issues that have surfaced in preparing for GRACE have lead us further afield, to study such diverse problems as assessing the typical accuracies of global, analyzed atmospheric pressure fields, and estimating the relative importance of short-period (i.e. sub-monthly) barotropic disturbances versus longer-period baroclinic disturbances in the ocean.

4. Plans

Virtually all of the activities described in the preceding sections will continue during the next few years. In addition, several new observational programs will be initiated or significantly expanded. Some of these new observational programs are described in this section.

GPS Geodesy. New GPS observing projects are being planned for Bhutan, Pakistan, Algeria and Bangladesh. The Bhutan study is designed to examine the predicted reduction in the rate of Himalayan collision in the region, which not only has important consequences for increasing the renewal time between great earthquakes, but also changes the rate of uplift compared to surface erosion. The Pakistan study is aimed at the western and NW boundaries of the Himalayan plate that hitherto have not been examined geodetically. We are interested here in intraplate earthquakes that have occurred in the Indus delta, and in the Chaman transform boundary whose rate and earthquake hazard potential is similar to parts of the southern San Andreas fault. Of particular interest are clues about the evolution and sustenance of the elevation of Tibet. In Bangladesh, we plan to use GPS receivers to monitor subsidence of the Ganges Delta now aggravated by the starvation of sediments. We hope to install a GPS meteorological monitoring program from Southern Tibet to the Bay of Bengal with the ultimate goal of quantifying the driving mechanism of the monsoon. The Algerian study is designed to investigate the initiation of subduction. The European/African plate boundary is one of the few places where we can catch a surface collision process in the act of initiating subduction. We plan to collaborate with local scientists in the installation of GPS arrays across the north Algerian seismic belts to examine the unique deformation fields that will ultimately lead to the descent of part of the Earth's crust into the mantle.

Seismology. Upcoming work includes a seismic array experiment in the Marlborough Fault Zone of the south island of New Zealand, with the goal of better understanding what faults do at depth, and a broadband seismic experiment in Nepal and Tibet. The Nepal/Tibet project, in particular, will fit nicely with CIRES GPS and modeling work done in the Himalayas. The GPS work maps the pattern of present-day surface deformation. The data from the seismic experiment will allow us to determine how this deformation is accommodated at depth.

GRACE. GRACE will be launched near the end of 2001, at which time our GRACE studies will switch from the design of analysis techniques on hypothetical data, to the analysis and interpretation of actual incoming satellite measurements.

Advanced Observing and Modeling Systems

1. Overview

Models play a vital role in the study of the earth system. They represent our understanding of natural processes, prompt specific questions, suggest further measurements, and permit forecasting of future conditions. Mathematical models have the added advantage of quantifying interactive processes, as we are describing the inputs, forcing conditions, and internal parameter that control the behavior of these systems.

Accurate observations of the state of the earth system are equally critical. Observations provide information on the spatial and temporal variability of geophysical parameters, which can be used to improve understanding of fundamental processes, to provide input and updated data to mathematical models, and to validate mathematical or conceptual models of simple or complex processes. To effectively move forward in characterizing and predicting the state of the earth system on all scales, strong research efforts aimed at improving models and observational techniques, and at enhancing the coupling between models and measurements must be important elements.

We are faced with two challenges: not being able to study the full complexity of the systems, and not possessing a full enough understanding to know what is essential to include in earth system models. Models will always be limited by the knowledge of those who build them, and by how well we know the inputs. Models have become increasing complex and hopefully a more realistic representation of the physical world. The trend is towards coupling models of different regions, atmosphere-ocean, magnetosphere-ionosphere, for instance.

Data assimilation is a method to produce a four dimensional representation of the state of a physical system. It is derived from; (1) a heterogeneous array of in situ and remote sensing measurements which sample imperfectly and irregularly in space and time, (2) known physics of the system, and (3) prior information (including prior analyses). From a theoretical point of view, data assimilation can be viewed as the quantitative analysis of information using the principles of estimation theory. Data assimilation techniques, coupled with satellite remote sensing and other observations have a high potential of improving our understanding of the Sun-Earth system, including the variables needed for improved climate simulations, and the operational models of the space environment.

No model, simple or complex, exists that can faithfully mimic the real world; rather, models represent an idealization of reality. All models must therefore be validated. To validate models is not an easy task, but one of the most challenging endeavors given the advances of observing systems and techniques currently available or presently developed.

Models, in general, are also unable to physically represent all processes and parameters that are important in modeled systems. Many processes must be parameterized. Observations, often analyzed during closure experiments, provide the understanding and data necessary to develop and assess model parameterizations.

Observations are important on all measurement scales. Space-based systems have the unique advantage of obtaining global spatial coverage, particularly over vast expanses of the oceans, polar regions, sparsely populated land, and space. For example, hyperspectral imaging is a standard method for remote observation of the Earth to acquire all the information that is available from solar scattered photons or self-emission from the surface. The technique is to acquire images in hundreds of registered spectral bands such that each pixel represents a spectral vector that is sampled at sufficient resolution to acquire all the electronic transition and molecular vibration information available for solids and liquids. While this technique appears to acquire an overwhelming amount of data, computer horsepower is now becoming sufficient to apply sophisticated algorithms to extract compositional information for a component that consists of as little as 5% of the area of a pixel. A whole variety of environmentally important surface constituents can be identified by these techniques.

But satellite measurements alone are not sufficient; their vertical resolution is often not adequate, requiring in-situ and surface-based remote measurements for calibration and validation. In-situ observations are required for the measurements of parameters that cannot be estimated from space platforms (e.g., ground water, subsurface ocean parameters). Surface or aircraft-based observations of critical parameters, e.g., near-surface atmospheric vertical structure wind and water vapor profiles, cloud properties, can provide both validation as well as high resolution, more accurate measurements at key locations to augment and complement space-based observations.

An important application combining advanced in situ and remote observing systems and state of the art models is the understanding and prediction of regional-scale processes. Combining high resolution observations, advanced data assimilation techniques, and mesoscale atmospheric and chemical models will enable improved forecasting of events that endanger health and property such as flash floods, severe pollution events, damaging windstorms, and the impact of solar storms on power grids, satellites, navigation, communication, and human safety. The methodology is used to understand the processes important for climatic change and improve their model representation.

The analysis and understanding of complex nonlinear earth systems is considerably enhanced by recent developments in information technology leading to the rise of sophisticated numerical simulation technologies, e.g., mantle convection simulations, simulation of earthquake dynamics, or methods to study the changing earth's surface using synthetic aperture radar interferometry.

The applications for advanced observing and modeling techniques are manifold; they do cover the entire space and time domain, such as: biology and biogeochemistry of ecosystems, composition and chemistry of the atmosphere, paleoenvironment and paleoclimate, human dimensions and climate change, the global water cycle, and the carbon cycle - just to name a few key programs from the U.S. global change research program (FY2000). All of the above initiatives and projects make use of advances in observing and modeling techniques.

Several research initiatives and ongoing projects in CIRES are currently using advanced observing and modeling techniques. It is our aim to make use of this synergism and to promote cross-discipline discussions and collaborations in this field.

2. Research Activities

Research goals associated with Advanced Measurements and Modeling encompass a wide variety of technical disciplines and reach across a broad spectrum of science applications:

a. Atmospheric Chemistry

Goals: Our inability to properly characterize the state of the atmosphere, in terms of its chemical composition and physical characteristics, limits the advancement of scientific understanding. The goal of this element is the development of essential new measurement techniques and instrumentation for advancing our understanding of important chemical processes. Research will focus on improving observations of important chemical species, aerosols and their precursors, with emphasis on remote measurements, miniaturized instruments for deployment on kites or small aircraft, fast response observations, and high sensitivity. Specifically, fast response methods will be developed to enable high resolution observations of the temporal and spatial variability of aerosols and fine particles. New absorption techniques for characterizing the column density of chemically active and/or radiatively important compounds that influence regional air quality and climate, especially from airborne platforms, will also be pursued.

Issues and Questions: CIRES has identified regional air quality and atmospheric chemical forecasting as major research areas that will be addressed over the next 5 years. To develop the understanding of the important physical and chemical processes that affect air quality, major observational campaigns are planned. This research element will aim to ensure that the measurement capability exists to obtain observations of the important chemical parameters with the necessary accuracy and resolution. Because typically measurements must be made over large, inhomogeneous regions, a significant emphasis will be on instruments suitable for aircraft deployment or that provide remote observations.

b. Atmosphere and Ocean Physical Parameters

Goals: Advances in techniques for observing physical characteristics of the atmosphere and ocean promise to greatly enhance understanding and prediction of weather and climate processes. The goal of this element is investigate the use of new remote sensing methods to observe atmospheric winds and water vapor, cloud microphysical and radiative properties, and ocean surface characteristics. An important focus of this element will be the development of techniques and instrumentation suitable for mounting on ships, aircraft, remotely piloted vehicles, and kites and balloons. Another area of concentration will be the investigating the benefits of combining measurements from different sensors and numerical models to produce estimates of parameters not well measured with any single technique.

Issues and Questions: Development of new measurement and modeling techniques requires advances in theoretical understanding, new technology, and data analysis methods to significantly extend current capabilities. The impact of advances in each of these areas will be addressed within this research element. Theoretical studies will aim to improve understanding of emission and scattering of electromagnetic waves from the sea surface, and the relationship between these parameters and atmosphere/ocean properties such as wind speed, wave spectrum, stability, and effects of large scale sea surface perturbations. New technology in optics will be utilized to develop of stand-alone lidar instruments for continuous monitoring of atmospheric humidity, ozone and other gases. Advanced analysis techniques will be applied to measurements from wind profiling, precipitation, and cloud radars, wind lidars, and combinations of sensors to stimulate advances in estimation of important parameters such as small-scale turbulence, vertical fluxes of heat and momentum, supercooled water, and cloud microphysical and radiative properties. Results of these research efforts will potentially lead to new instruments that can be used to provide better observations for weather, climate and air quality research.

c. Cryosphere

Goals: High latitude regions of the earth are predicted to provide early signatures of global warming. Observation of the properties of the cryosphere, such as snow cover and albedo, energy balance, and ice sheet characteristics enable assessment of changes in polar regions and provide input and parameterizations for models of important processes. The goal of this element is to improve measurements and models of important cryospheric parameters. A main focus will be assessment of data from a new generation of satellite sensors and its impact on measurements of snow cover, snow albedo, ice sheet mapping, and energy balance modeling. Modeling efforts will be conducted in parallel with observational research to parameterize snow structure, model surface energy balance based on atmospheric and cryospheric interactions, and to investigate ocean-ice-atmosphere and land-atmosphere processes. at high latitudes.

Issues and Questions: Recent and planned launches of innovative new satellite-based sensors, including the Multiangle Imaging Spectroradiometer (MISR), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Hyperion imaging spectroradiometer, and the Geosciences Laser Altimeter System (GLAS) will provide new information from which to derive earth system properties. A question to be addressed in this research element is the extent to which observations from these sensors improve measurements of cryospheric properties, including snow cover and snow albedo. Although the sensors will provide multiangle measurements of reflected radiation, images with higher spectral resolution, and observations of surface altimetry and aerosol and cloud cover, the extent to which this additional information improves snow cover and snow altimetry measurements remains a topic of interest. Other issues associated with modeling are also being addressed within this research element. In particular, validation of an arctic region climate system model and its applicability to the study of high latitude process remains an important component of this research element. Additional model research focuses on the use and performance of a physical snow system model to parameterize the important characteristics of snow that affect its remote sensing from aircraft and space, and the extent to which a model can be used to predict ground temperature beneath snow cover.

d. Data Centers and Data Management

Goal: Manage in-situ and remotely sensed data to extend time series, validate measurements, and enable the Earth system scientist to make use of combinations of measurements and derived products from multiple sources.

Issues and Questions: Good data management is essential to ensuring the preservation of important in-situ and satellite observations and continuing long data time series. This is crucial for the validation and parameterization of models, data assimilation efforts, and the understanding of regional-scale processes. CIRES is connected with several groups involved in data management that include NSIDC, CDC, NGDC and CSES (CIRES Center for the Study of Earth from Space). They facilitate advanced observing and modeling and cross-discipline discussions in the field of Earth science. During 2000-2004, data from the MODIS, GLAS, and AMSR instruments of the NASA Earth Observing System (EOS) will receive high priority.

e. Ecosystem and Environmental Modeling

Goal: Develop new and effective methods to characterize and model managed ecosystems, prioritize management needs, and prescribe appropriate actions.

Issues and Questions: Increasingly, natural systems are becoming significantly controlled if not dominated by human action. The term "managed ecosystems" thus refers to potentially all ecosystems, in recognition of the fact of, or need for, human intervention. From this perspective, human activity is important in two respects: unplanned human influence, and planned human management. Management is ambitiously expected to mitigate undesired human influence; and even more ambitiously to deal with undesired natural changes. To make progress toward these goals, new and effective methods are needed to characterize and model managed systems, to prioritize management needs, and to learn appropriate actions. Much of this work centers on the proper development and use of information from assessment, monitoring, and research; but it also demands adaptive information that we may use to evaluate prior actions and to adjust to evolving needs. Traditional approaches to mapping ecological variables, for example, tend to emphasize mechanistic approaches; that is tracking "objects" and their movement or changes. However, we are now challenged to incorporate more complex views, where the definition of objects (ecosystems) that we characterize must also be understood as changing and evolving, both in response to natural change and human influence/management. This places greater importance on dynamic, repeatable, automated methods of characterizing ecosystem variables and relationships within ecological maps and databases.

f. Remote Sensing of Terrestrial Properties

Goals: Remote sensing of terrestrial properties from satellite and aircraft remote sensors offers the opportunity to identify a wide variety of important surface constituents and to study a wide range of processes that involve redistribution of mass within the earth and at or near its surface. A goal of the research under this element is to investigate the use of hyperspectral imaging as a standard technique for remote observation of the earth. This includes the development of better compensation for the intervening atmosphere. Another goal to be pursued is the application of data from the gravity mapping satellite GRACE, scheduled for launch in 2001, to estimate parameters that can be identified through redistribution of mass within the earth. As part of this research, plans are to develop methods for converting gravity fields into useful measurements of mass redistribution, and investigating combination of GRACE measurements with other observations such as GPS measurements of crustal motion and GLAS observations of surface height.

Issues and Questions: Application of hyperspectral imaging techniques involves acquisition of images in hundreds of registered spectral bands such that each pixel represents a spectral vector that is sampled at sufficient resolution to acquire all the electronic transition and molecular vibration information available for solids and liquids. While this technique appears to acquire an overwhelming amount of data, computer horsepower is now becoming sufficient to apply sophisticated algorithms to extract compositional information for a component that consists of as little as 5% of the area of a pixel. The opportunity to work with the first spaceborne hyperspectral data available in the civilian community will enable verification of atmospheric correction models necessary for processing hyperspectral data. These models developed at CIRES make it possible to remove the effects of spectral path radiance and two-way spectral transmission with models that acquire input from the image data themselves. The application of GRACE observations of gravity fields for estimation of mass redistribution within the earth promises to provide information on a variety of important geophysical parameters, including monthly estimates of continental water storage, changes in the distribution of snow and ice on polar ice sheets, and changes in the sea floor pressure to a few tenths of a mb or better. Development and assessment of techniques to estimate mass redistribution from gravity fields is an important aspect of this research effort.

g. Non-linear Systems

Goals: In general, complex, nonlinear fault systems exhibit a wealth of emergent, dynamical phenomena over a large range of spatial and temporal scales, including space-time clustering of events, self-organization and scaling. Examples of the latter include the Gutenberg-Richter magnitude-frequency relation, the Kolmogorov four-fifths law for turbulence, the power-law spectrum of earths' temperature history as revealed in ice core data, and so forth. Many other examples can be found in other sub-disciplines. The analysis and understanding of complex nonlinear earth systems is considerably enhanced by recent developments in information technology leading to the rise of sophisticated numerical simulation technologies. The primary goal of this research element is to develop nonlinear Earth system models and simulations to address fundamental questions that can be understood by no other means. An important aspect of this research is cataloging and understanding the nature and configurations of space-time patterns of earth system phenomena, and examining whether these are scale-dependent or scale-invariant in space and time. This includes identification of certain characteristic patterns that may indicate smaller events precursory to more disastrous, great events such as destructive earthquakes, hurricanes, ENSO's, ozone hole, extinction events, and asteroid impacts. Other goals of this element are aimed at developing and testing potential forecast algorithms, based primarily upon the use of space-time patterns in the earth systems of interest, and understanding the physical conditions that allow space-time coarse-graining of sub-grid scale processes in simulations. A key aspect of testing model predictions will be development of the theoretical framework to integrate diverse data and extrapolate existing data in space and time so that the predictions can be tested with new observations (Model-Based Inference).

Issues and Questions: With natural hazards in particular, the development of forecast or prediction methodologies has been complicated by the fact that large events responsible for the greatest damage can repeat infrequently at irregular intervals of hundreds to thousands of years, a limited historical record that frustrates phenomenological studies. For these problems, it is increasingly being recognized that the analysis of realistic numerical simulations can help to bridge the gap between the space and time scales of human experience, and those of the phenomena themselves. With such simulation capabilities, "model based inference" is then possible in which seemingly diverse data sets taken at different scales can be interrelated, reconciled, leading to predictions that can be extrapolated to motivate and guide further observational studies. The impact of this new simulation technology on earth system science will be to allow hypothesis testing and data integration on a scale not heretofore possible. Here, it is important to consider the issue of multi-scale physics. Past earth systems research has often focused on problems that display only a limited range of spatial and temporal scales. In most earth systems, however multi-scale processes are at work, similar to those observed in many other areas of physics. Examples of these complex nonlinear systems that exhibit qualitatively and quantitatively similar multi-scale features include neural networks with learning and cognition, superconductors and charge density wave systems that exhibit magnetic de-pinning transitions, liquid crystals undergoing smectic or nematic transitions, and ferromagnets and thin films in which magnetized domains evolve.

Large-scale computing approaches have had a significant and lasting impact in many areas of science where the underlying phenomena span significant ranges in spatial and temporal scales. Therefore it is highly likely that a computational approach to complex nonlinear earth systems problems will produce a similarly successful outcome, provided that the major focus of the work is understanding the origins and implications of the fundamentally multi-scale phenomena that are observed in these many seemingly disparate systems.

h. Space Weather

Goals: Physical models of each region of the space environment (upper atmosphere, magnetosphere, solar-interplanetary) are mature, and provide a realistic characterization of the individual systems. One goal of this element is to investigate the coupling between the various regions of the space environment, such as solar wind-magnetosphere, magnetosphere-ionosphere, and lower atmosphere-upper atmosphere. A second goal will be to develop Kalman filter and adjoint modeling data assimilation techniques, in order to parallel recent advances in tropospheric weather forecasting for optimal combination of models and data in strongly forced systems. This activity will include investigation of the infrastructure to ingest data from new satellite constellations such as COSMIC (Taiwan and US) and NASA's Living with a Star (LWS) mission.

Issues and Questions: Space Weather Forecasting involves not only predicting solar events, but also following the propagation of disturbances through the interplanetary medium, to determine their impact on the near-Earth environment. The objective is to combine understanding of the physical system with observations from the Sun to the Earth. Advances in meteorological weather forecasting have come from improvements in physical models, vast increases in the availability of satellite and ground-based data, and the optimal combination of the two. The challenge for space weather is to parallel the data assimilation advances for tropospheric weather forecasting, and transition new physical models to operational use through the Space Environment Center's (SEC) Rapid Prototyping Center (RPC).

3. Research Linkages

Each of the research elements outlined above has strong linkages to the NOAA mission as well as to recognized national and international science issues. Observations and modeling associated with atmospheric chemical and physical parameters will contribute directly to the NOAA research objective of understanding and predicting regional air quality. Some of the instrumentation developed will be mounted on the NOAA WP-3 aircraft to measure horizontal and vertical structure of important constituents. Other sensors will be surface, ship or kite-mounted to provide a time series of observations to observe, for example, diurnal variability or vertical transport of aerosols and atmospheric constituents.

Observations of the atmosphere, ocean and cryosphere will also contribute to important climate and weather activities within NOAA. The focus on automated or continuously-operating remote sensors for observing profiles of aerosols, water vapor, cloud parameters and precipitation will lead to measurement capabilities that support, e.g., the quantitative precipitation forecasting objective of the US Weather Research Program, the effort to detect aircraft icing conditions to improve aircraft safety, and the research effort to monitor and predict changes in polar climate on decadal to centennial time scales.

In addition to these two primary areas, the CIRES research described under this theme will support NOAA efforts in space environment forecasting, geophysical data archiving and analysis, satellite data retrieval, and environmental modeling. The research will draw on the skills of CIRES and NOAA scientists from the Atmospheric and Climate Dynamics Division, Environmental Chemistry and Biology Division, and Cryosphere and Polar Processes division. NOAA laboratories heavily involved will include the Aeronomy Laboratory and the Environmental Technology Laboratory, as well as the Climate Monitoring and Diagnostics Laboratory and the Space Environment Laboratory.

4. Plans

a. Atmospheric Chemistry

- Develop fast-response methods to measure the atmospheric concentration of aerosols, fine particles and their precursors.
- Develop methods to determine the column density of chemically active and/or radiatively important compounds in the atmosphere.
- Develop new methods, including miniaturized instruments, to profile important chemical parameters from land surface, ship, aircraft, balloons, and kites.
- Develop methods to measure transport of water vapor and other atmospheric constituents such as ammonia and aerosol particles.
- Develop an instrument that can detect single gas-phase molecules

b. Atmosphere and Ocean Physical Parameters

- Develop new methods, including miniaturized instruments, to profile important atmospheric parameters from land surface, ship, aircraft, balloons, and kites.
- Develop methods to measure transport of water vapor and other atmospheric constituents such as ammonia and aerosol particles.
- Develop combined remote sensing techniques for measurement of cloud microphysical and radiative properties, boundary layer measurements, supercooled water.
- Develop the theoretical basis to improve understanding of sea surface scattering mechanisms.
- Apply radar and radiometer remote sensing techniques to measure ocean surface properties, including wind speeds, currents, wave spectra, and modulation of waves by large scale perturbations.
- Improve interpretation of radar images of the ocean surface.

c. Data Centers and Data Management

- Engage the scientific community in decisions concerning data deposition and management through advisory groups, workshops, and contacts at meetings.
- Ingest and verify the content and quality of data and derived products.
- Acquire and develop necessary documentation. Preserve and maintain products and documentation.
- Reprocess and generate new derived products in conjunction with the scientific community.
- Continue to improve open access to the data.

d. Cryosphere

- Assess how the new generation of satellite-based sensors improves measurements of snow albedo.
- Map snow albedo and characterize its temporal and spatial variability.
- Apply photoclinometry and data cumulation to ice sheet mapping.
- Characterize Holocene history of the west Antarctic ice stream system.
- Develop an enhanced global snow cover product by combining visible spectrum data with passive microwave data.
- Develop a physical snow structure model to efficiently parameterize the most important elements of snow structure that affect the remote sensing of snow.
- Develop an automated climate monitoring system on the Greenland ice sheet.
- Assimilate remotely sensed data for energy balance modeling of the Greenland ice sheet.
- Continue development of an Arctic region climate system model for studies of ocean-ice-atmosphere and land-atmosphere interactions in the high latitudes.
- Use geodetic measurements of crustal motion to put constraints on both the present day mass imbalance and the late Holocene deglaciation of the Greenland ice sheet.

e. Ecosystem and Environmental Modeling

- Develop new and effective methods to characterize and model managed ecosystems, prioritize management needs, and prescribe appropriate actions.
- Convene a forum of international scientists to examine and revise the agenda for research in environmental problem solving using environmental models informed by spatial-temporal analysis techniques.

f. Remote Sensing of Terrestrial Properties

- Make hyperspectral imaging a standard method for acquiring all the information available from solar scattered photons or self-emission from the surface in earth remote sensing.
- Investigate conversion of GRACE gravity fields into useful measurements of mass distribution to investigate geophysical scientific issues.

g. Non-linear Systems

- Develop non-linear earth system models to address fundamental geophysical questions.
- Develop and test potential forecast algorithms based on space-time patterns in the earth systems of interest.
- Develop the theoretical framework to integrate diverse data and extrapolate existing data in space and time to test model predications with new observations.

h. Space Weather

- Investigate and understand the importance of coupling between the geophysical regions.
- Develop data assimilation techniques in the space environment.

Integrating Activities

CIRES engages in a wide range of integrating activities in research, education, and outreach that encompass each of the Institute's Research Themes and contribute to the overall mission of the Institute, NOAA, and the University of Colorado. The five categories below (which themselves overlap in important respects), K-14 Interdisciplinary Education and Outreach, Graduate and Post-Graduate Education, Scientific Assessments, Interdisciplinary Research, and Science and Technology Policy Research, represent CIRES long-standing commitment to work across conventional disciplinary boundaries and traditional institutional lines. The Institute's Integrating Activities result in the production of rigorous, cutting-edge science and technology, the sharing of such knowledge and techniques with students from kindergarten to post-graduate levels, and to developing the significance of scientific and technological discovery for a wide range of decision makers in public, private, and non-governmental settings. CIRES Integrating Activities are an important contributor to the success of the Institute.

K-14 Interdisciplinary Education and Outreach

CIRES strongly supports and encourages education outreach. Programs exist for K-14 school districts, teachers and students, undergraduates at CU and elsewhere, and other community groups. Our goal is to support exemplary science education at all levels; encourage curiosity and understanding about our environment, and to bring our research to bear as a resource in service of societal needs, including education. CIRES has established a K-14 Outreach Program that combines rigorous science with innovative teaching practices. Ongoing projects include classroom and prospective teacher professional development, volunteer opportunities for scientists, education components for research projects, district systemic reform, research mentors for high school students and undergraduates, classroom presentations and more. Other projects include a digital resource for geoscience education project evaluation and developing new knowledge of how research scientists may best be engaged and supported in outreach activities. At the undergraduate level, CIRES faculty and researchers work within academic departments and programs to offer education and research opportunities. CIRES strongly supports and contributes to interdisciplinary research and education in environmental and Earth science across campus.

Graduate and Post-Graduate Education

CIRES has a long-standing commitment to disciplinary and interdisciplinary graduate education. CIRES sponsors graduate students in many departments on the University of Colorado Campus, including Atmospheric and Oceanic Sciences, Chemistry, Biology, Physics, Geography, Geology, Geophysics, Engineering, Political Science, Economics, and Environmental Studies. CIRES also conducts a Visiting Fellows program that allows recent doctoral graduates from many disciplines to continue their education in a research position that may foster interdisciplinary training and exposure to scientific assessments and policy research. CIRES has established a particularly close relationship with the University of Colorado's new Graduate program in Environmental Studies, with CIRES faculty and scientists taking leading roles in the development and teaching of the program's core curriculum as well as through support of graduate fellowships and assistantships.

Scientific Assessments

CIRES researchers collaborate across traditional disciplinary, institutional and programmatic boundaries in support of interdisciplinary assessments with significance for both research and policy. For example, a team of CIRES researchers and their partners seek to understand, support and enhance the local decision-making process on the North Slope of Alaska in the face of climate variability on seasonal to decadal timescales, both natural and anthropogenically induced. The primary goal is to help stakeholders clarify and secure their common interest by exchanging information and knowledge concerning climate and environmental variability. Another team of CIRES researchers and collaborators is focused on the decision-making processes of the individuals, groups, and organizations in the Interior West that have responsibility for managing, using, treating, and protecting water resources. By understanding decision-making processes, the stresses, and the constraints of this community, researchers seek to assess vulnerability to climate variability and develop hydro-climate products that help achieve more informed decisions. Such scientific assessments bring together CIRES expertise across a range of fields, including policy research and technology transfer, in collaboration with experts and end users who partner from outside the Institute.

Interdisciplinary Research

Within each of CIRES Research Themes are commitments to rigorous, interdisciplinary research. For example, climate variability affects virtually all natural systems and human activities. Areas of direct climate impact include agriculture, water quantity and quality, ecosystems, air quality, and human health. Understanding climate variability and its impacts on environment and society requires a commitment to work across conventional disciplinary boundaries. Similarly, many of the research endeavors within CIRES and NOAA have a regional focus because they address a particular confluence of geography, demographics, weather and climatic regimes, and scientific challenge. A regional focus is necessarily interdisciplinary because such issues cross many scientific disciplines and require an integrated science approach based on improved observations, diagnosis, and modeling of regions subject to accumulating natural and anthropogenic stresses. A third example is the health of the biosphere, which can usefully be considered using the concept of "planetary metabolism," referring to the complex web of biochemical and ecological processes that occur within the biosphere, and the interaction of these processes with the lithosphere, atmosphere and hydrosphere. Both natural and anthropogenic disturbances drive the structure and dynamics of natural systems, and a thorough understanding of these complex processes is essential for efforts to protect the biosphere from adverse effects due to pollution, destruction of natural landscapes, and alteration of climate. Such understanding depends upon successful integration of disciplinary and interdisciplinary research. Interdisciplinary research can be found throughout the Institute and its Centers, which supports attainment of the goals of each of CIRES primary Research Themes.

Science and Technology Policy Research

The recent decade has seen growing interest among scientists in investigating research problems that require the input of more than just a single traditional discipline. At the same time, decision makers in both public and private settings have asked the science and technology communities to provide knowledge that is more directly usable in their decision-making. Science and technology policy research provides a mechanism to reconcile these two closely related - but not identical - trends. By linking integrative science with the needs of decision makers, science and technology policy research can serve a valuable role in helping the research community better focus its efforts on issues of importance to society, and in helping decision makers to effectively incorporate scientific and technological advances into their decision processes. CIRES supports a unique set of efforts at the interface of science and decision making. These efforts focus on rigorous research on themes such as science in support of policy development, policy development in support of science, technology policy, and technology assessment. Science and technology policy research draws on a rich tapestry of expertise and collaboration - such as found in the physical, biological, earth, and social sciences, as well as law, journalism, health sciences and the humanities - to further integrate disciplinary and interdisciplinary research supported through CIRES Research themes, scientific assessments, education and outreach with growing demands for science and technology to better serve decision making needs in the public, private and non-governmental sectors.

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