WISE
Washington Internships for Students of Engineering

GLOBAL CLIMATE CHANGE:
U.S. Pathways for Research, Observation, and Modeling

By

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WISE

The Washington Internships for Students of Engineering is a ten week program for outstanding engineering students who have completed their junior year and display evidence of leadership skills and interest in public policy. The students spend the summer in Washington, DC learning how engineers contribute to public policy decisions on complex technological matters. Through frequent meetings and discussions with government officials and other policy makers, students examine a variety of public policy issues. Each student completes a paper that analyzes specific engineering public policy issues of concern to the sponsoring society. For information about the WISE program, contact WISE, Attn: Anne Hickox, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

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EXECUTIVE SUMMARY

Global climate change is a political hot topic, even though the extent and severity of its possible effects remain uncertain. Decision makers cannot write responsible policy until scientists and engineers sufficiently answer the questions: Is climate changing? To what extent? What actions can be taken to mitigate it? How well do they work? Would it be possible to adapt to climate change? What will be the physical and socioeconomic consequences of preventative action? What will be the consequences of inaction?

Answering these questions will require concerted efforts in climate research, observation and modeling. The body responsible for coordinating these activities is the U.S. Global Change Research Program. The USGCRP has nine member agencies that participate in seven categories of research with the intent to reduce the uncertainty associated with global change. The USGCRP provides the only existing infrastructure for communication and cooperation between research groups in the United States, and it should make efforts to continually improve in this role.

The future of climate observation in the United States will be the implementation of earth observing satellite systems. Observation currently suffers from incomplete global coverage and poor resolution, both of which could be improved by satellites. However, remote sensing by satellites is not likely to entirely replace surface-based observation, and the United States must continue to sustain and improve surface-based activities. There are many climate variables that are hard to measure or are not measured at all, and many variables are recorded with significant inaccuracy. The observing community must address these issues because climate research and modeling can only be as good as the data that is put into them. The storage of climate data would benefit greatly from increased efforts at centralization and uniformity. Increased cooperation in data sharing between nations is especially important, and will require diplomacy on the part of the United States.

The advancement of climate change research is necessary to distinguish between natural and anthropogenic variability in climate. Research will also help to identify areas of climate observation that need improvement, as well as to improve climate modeling. Key research imperatives include understanding the composition and chemistry of the atmosphere, understanding the global carbon and water cycles, understanding the human dimensions of global change, studying the paleoclimate, understanding the biology and biogeochemistry of ecosystems, and interpreting changes in climate over a range of timescales. The United States must commit to remaining at the forefront of this research.

Climate modeling has advanced rapidly within the last decade, but can still make considerable improvements. The biggest disadvantage facing the modeling community is a lack of adequate computing resources. The types of computer systems necessary for high-grade modeling are very expensive and have restricted availability, while their alternatives sacrifice resolution for speed. The lack of software and trained personnel with which to run these systems also poses a considerable problem. Improvements in model resolution and speed will allow for better climate prediction, while models that can demonstrate the regional and socioeconomic effects of climate change will be especially useful in educating policy makers.

The United States must make a commitment to supporting and improving climate research, observation, and modeling, as well as strengthening the coordination of the USGCRP. Scientists and engineers must commit to reducing the uncertainty associated with climate change so that policy makers can judiciously direct the U.S. response to it. Finally, it is crucial to remember that science can only illuminate the possible consequences of potential courses of action; it is up to policy makers to decide which course is best.

INTRODUCTION

"Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise."[1] This strongly worded statement was made by the National Academy of Sciences in its June 2001 report to the White House. The report was requested to help inform the Bush Administration's ongoing review of U.S. climate change policy; a political hot topic for nearly the last decade. Policy makers are concerned because there have been many frightening scenarios proposed as results of the increasing global temperatures that the National Academies report affirmed. Melting ice caps, thawing permafrost, disappearing islands, retreating shorelines, dying coral reefs, decreasing biodiversity, scarcity of arable land, severe droughts and flooding, increased incidences of crop damage, pests, disease, and famine; all have been predicted as results of global warming. These nightmarish scenarios promote concern for the fate of humanity, which is heightened by our ignorance as to whether such changes could be reversed.

But then there are critics.

Some people believe climate is not changing at all. While global surface temperatures have risen within the last century, satellites and weather balloons have shown no change in upper atmosphere temperatures. Some people argue that it will take centuries for climate to change appreciably, and even then, it may actually benefit humanity. There are projections of a longer growing season, more rapid plant growth, more arable land, and essentially a state of agricultural abundance.[2] Others believe that the earth's climate may actually be cooling.[3] Is it worth the severe economic impacts that may result if measures are taken to prevent the earth from this questionable warming? Many people argue it isn't.

The problem is one of scientific uncertainty. There is enough wiggle room among climate predictions and hypotheses that nearly any view can be reasonably justified. The earth's climate is an extraordinarily complex system, and it is not fully understood by any means. While it makes sense to take preliminary actions against drastic effects that science is moderately sure of, there is also great justification for further research into the workings of climate so that mitigating actions can be made more effective---if they are necessary at all.

Many pieces of proposed legislation in the 107th Congress address the issue of climate change. The Clean Power Plant Act of 2001 (H.R. 1335) warns of "global climate change that may fundamentally and irreversibly alter human, animal, and plant life,"[4] and proposes to increase power plant efficiencies as a means for slowing the increase of atmospheric greenhouse gas concentrations. Other bills, including The International Carbon Conservation Act (S. 769), the Carbon Sequestration Investment Tax Credit Act (S. 765), and the Carbon Conservation Incentive Act (S. 785), propose to stimulate land use changes that will remove carbon dioxide from the atmosphere and sequester it in terrestrial systems. Of course no one in the political world would advocate the potential disastrous effects of global warming. However, the scientific uncertainty that remains makes it easy for policy makers to disagree on what action to take in response to it.

Before constructive legislation can be written, several questions must be answered to a reasonable degree of certainty. To what extent is climate change occurring? What are the actions that could be taken to suspend it? How well do they work? Would it be possible to adapt to it? What will the physical consequences be if action is not taken to prevent climate change? What will be the socioeconomic consequences of preventive actions? What will be the socioeconomic consequences of inaction?

Without knowledge of the answers to these questions, it is difficult to define the problem that policy makers should address. It is up to scientists and engineers to solve the problem of uncertainty in global climate change predictions, so that politicians can solve the problem of what to do about those predictions.

SCIENTIFIC BACKGROUND

Definitions

"Climate" is the average state of the atmosphere and the underlying land or water, on time scales of seasons and longer.[5] In other words, it is the average weather in a particular region over a prolonged period of time. "Climate change" is an overall alteration of average climate conditions, while "climate variability" entails any fluctuation about this average.[6] "Climate variables" are things that can be measured and used to describe climate; e.g. temperature, precipitation, wind, humidity, cloudiness, soil moisture, sea surface temperature, and the concentration and thickness of sea-ice.[7] The "global climate system" consists of the earth's atmosphere, oceans, land surface, stratosphere, and cryosphere (i.e., land-based and marine snow and ice), along with the sun and the interactions between these different components.[8]

"Albedo" is the reflectivity of the earth's surface, which depends on the different reflectivities of oceans, ice, soil, and vegetation; albedo influences the amount of solar radiation the earth absorbs.[9] An alteration of the earth's albedo can be caused by changes in land use, and can result in global climate change. "Land use" is man's practice of managing the terrestrial biosphere, whether as farmland, paved urban centers, or undisturbed forests, deserts and plains. "Land use change" refers to activities that significantly alter the landscape---usually deforestation. Land use directly influences the amount of solar radiation the earth absorbs, while land use change can indirectly influence it by altering levels of atmospheric radiation-absorbing gases.

Gases that absorb infrared radiation in the wavelengths at which the earth radiates energy to space are called "greenhouse gases"[10], because they act like the panels of a greenhouse to trap heat inside the atmosphere. These "GHGs" include methane, ozone, nitrous oxide, halocarbons, and most importantly, water vapor and carbon dioxide,.[11] The trapping of heat by greenhouse gases is referred to as the "greenhouse effect".

Aerosols are microscopic airborne particles or droplets that appear in the troposphere and can reflect solar radiation, which leads to a cooling tendency in the climate system.[12] "In addition, changes in aerosol concentrations can alter cloud amount and cloud reflectivity."[13] Anthropogenic aerosols can be produced by fossil fuel and biomass burning. Black carbon soot is an aerosol which can actually warm the climate system, because it absorbs solar radiation.[14] While greenhouse gases and aerosols have competing effects on climate, they do not sufficiently cancel each other out. Aerosols have a much shorter atmospheric life span than do such GHGs as carbon dioxide, therefore greenhouse warming is much more prevalent than aerosol-induced cooling.

Explanation of Climate Change

The earth's climate system is controlled by a simple energy balance. If the atmosphere absorbs more energy than it radiates, the system attempts to restore equilibrium by moving toward a state of increased temperature. This energy imbalance is referred to as "radiative forcing," while processes leading to the imbalance are called "external forcing" effects. Forcing that causes temperature to increase is considered "positive", while forcing that cause temperature to decrease is "negative". Climate variations can be caused by three things: "natural external" forcing, "anthropogenic (human-caused) external" forcing, and factors internal to the climate system.[15] These include many complicated and delicately interrelated phenomena.

An example of an internal climate factor is the El Niño/Southern Oscillation (ENSO) phenomenon, which arises from interactions between the ocean and atmosphere in the tropical Pacific Ocean. "ENSO operates in a quasi-cyclic manner on a time scale of 2-8 years, and has clear regional consequences over a wide area, including an increased incidence of extreme weather events."[16] Some scientists have proposed that ENSO may be influenced by human activities, thus blurring the lines between "natural internal" and "anthropogenic external" factors.

There are two prevalent examples of "natural external" forcing factors: changes in solar output, and explosive volcanic eruptions.[17] Both alter the amount of radiation absorbed by the earth's atmosphere, either by changing the amount of radiation that reaches the earth, or by changing the ability of the atmosphere to absorb it.

An important example of anthropogenic external forcing is the "enhanced greenhouse effect". This occurs when a human-generated increase in greenhouse gases amplifies the naturally occurring greenhouse effect, thereby causing the earth's temperature to rise above natural equilibrium levels. This is the "global warming" that policy makers are concerned about. It is important to recognize that "the basic physics of an increasing greenhouse effect is well known, but feedbacks in the climate system involving water in its three phases depend on a variety of poorly understood small-scale processes."[18] Therefore, just because scientists know that the greenhouse effect exists and can be influenced by humans, it is not direct proof that our emissions today will cause a particular amount of warming 100 years from now.

Climatic responses to forcing effects are called "feedback" mechanisms, or "feedbacks". An example of feedback would be a global-warming-induced melting of ice caps that would serve to decrease the earth's albedo. The melting of ice caps would be considered a "positive" feedback because it is a result of warming, and it would cause even more warming. An example of a "negative" feedback would be one that is a result of warming, but in effect causes cooling. Many feedback mechanisms can result from a single forcing effect, and they may either compound or contradict one another. These mechanisms either amplify or modify the effects of the imposed forcing, allowing for various degrees of climate sensitivity.

It is important to understand that global climate change entails more than just warming; it is the combination of climate activities that result from a temperature-elevating radiative imbalance. The United Nations Framework Convention on Climate Change (UNFCCC) defined "adverse effects of climate change" to mean "changes in the physical environment or biota resulting from climate change which have significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or on the operation of socio-economic systems or on human health and welfare."[19] These are the effects that policy makers would like to prevent.

COORDINATION OF CLIMATE CHANGE ACTIVITIES

The USGCRP

Climate change research, observation, and modeling efforts in the U.S. are coordinated by the U.S. Global Change Research Program (USGCRP). The USGCRP is given a budget to fund all major U.S. climate change research (with the exception of that conducted by the Department of Defense), and it appropriates that money to a number of groups:

1. The National Oceanic and Atmospheric Administration (NOAA), under the Department of Commerce
2. The Department of Energy (DOE)
3. The U.S. Geological Survey (USGS), under the Department of the Interior
4. The Environmental Protection Agency (EPA)
5. The National Institutes of Health (NIH), under the Department of Health and Human Services
6. The National Aeronautical and Space Administration (NASA)
7. The National Science Foundation (NSF)
8. The Smithsonian Institution (SI)
9. The U.S. Department of Agriculture (USDA)

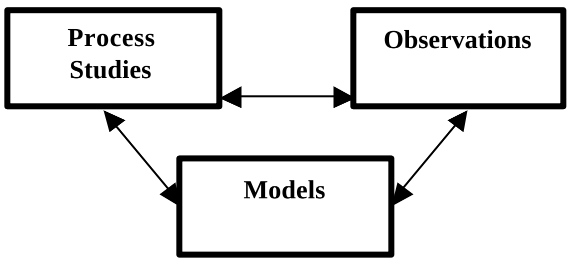
USGCRP-funded research is categorized into seven major program elements, with multiple agencies participating in each one. The total USGCRP budget for Fiscal Year 2001 was over 1.7 billion dollars.[20] (See table)

	NOAA	DOE	USGS	EPA	NIH	NASA	NSF	SI	USDA
Understanding the Climate System	✓	✓				✓	✓	✓	
Understanding the Composition & Chemistry of the Atmosphere	✓	✓				✓	✓	✓	✓
Global Water Cycle	✓	✓				✓	✓		✓
Global Carbon Cycle	✓	✓	✓			✓	✓	✓	✓
Understanding Changes in Ecosystems		✓	✓	✓		✓	✓	✓	✓
Understanding the Human Dimensions of Global Change	✓	✓		✓	✓		✓	✓	
Paleoclimate: The History of the Earth System	✓		✓				✓	✓	
FY 2001 Budget (millions)	**$95.0**	**$119.3**	**$21.4**	**$22.7**	**$48.0**	**$1149.2**	**$187.5**	**$7.0**	**$84.6**

One of the most important roles of the USGCRP is to oversee the U.S. National Assessment of the Potential Consequences of Climate Variability and Change. The National Assessment was mandated by the "Global Change Research Act of 1990" which states that the Federal government "shall prepare and submit to the President and the Congress an assessment" which, among other things, "analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity;" and "analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."[21]

The National Assessment Synthesis Team's overview report "Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change" was released in June 2000, and offers scenarios of climate change based on two different climate models. The purpose of the National Assessment report is to help policy makers "identify vulnerabilities and plan for contingencies."[22] It is the United States' primary defense against the potential impacts of global warming.

The scientific efforts necessary to fulfill the ongoing needs of the National Assessment are conducted primarily by the agencies under the umbrella of the USGCRP. These efforts can be separated into three interrelated categories: research, observation, and modeling. (See diagram)



Each agency may specialize in only a few areas, so coordination between groups is essential. It is the role of the USGCRP to organize the transfer of information and sharing of resources necessary for progress to be made in the huge and complicated pursuit of understanding the earth's climate. Researchers who are attempting to understand different climate systems cannot do so without having the data that such groups as NASA and NOAA can provide. Groups who do climate modeling could do nothing without the researchers who reveal the mechanisms by which climate change occurs. Policy makers are reluctant to act on the issue of climate change without knowing the possible effects that modelers can project. The USGCRP has the enormous job of managing an intricate web that spans many disciplines, and includes many thousands of people and many millions of dollars.

CLIMATE OBSERVATION

Observation---The State of the Art

- The average global temperature rose about 0.6 degrees Celsius in the twentieth century, and precipitation increased nationally by 5 to 10%.[23]

- The 1990's was the warmest decade within the last thousand years.
- 1998 was the warmest year in the instrumental record since 1861.[24]
- The atmospheric concentration of carbon dioxide has risen about 30% since the late 1800s, and is now higher than it has been at any time in the last 400,000 years.[25]

These statistics are known from direct measurement as well as proxy climate records. Proxy records include ice cores, lake sediments, corals, tree rings, glaciers and ice sheets[26], as well as fossilized plant and marine life.[27] The "instrumental record" consists of a slew of direct measurements of different climate variables. "Widespread direct measurements of surface temperature began around the middle of the 19th century. Nearly global observations of other surface "weather" variables, such as precipitation and winds, have been made for about a hundred years. Sea level measurements have been made for over 100 years in some places, but the network of tide gauges with long records provides only limited global coverage. Upper air observations have been made systematically only since the late 1940s. There are also long records of surface oceanic observations made from ships since the mid-19th century and by dedicated buoys since about the late 1970s. Sub-surface oceanic temperature measurements with near global coverage are now available from the late 1940s. Since the late 1970s, other data from earth-observation satellites have been used to provide a wide range of global observations of various components of the climate system. In addition, a growing set of palaeoclimatic data, e.g., from trees, corals, sediments, and ice, are giving information about the Earth's climate of centuries and millennia before the present."[28]

Because detailed observations of many variables have been made for as few as three decades, it is difficult to make conclusions about climate change based on them. Climate varies naturally over periods of decades and centuries, so a change observed since 1940 or 1970 does not necessarily prove unnatural climate variation. Because of this, great efforts are being made to institute global observation systems that will provide a complete, detailed climate record for decades to come.

Climate observations can be divided into two categories: surface-based and remote. Surface based measurements record properties of terrestrial, ocean, and surface air systems. Terrestrial measurements are taken by automated or manual sensors and gauges, and cover the spectrum of properties relating to soil, rivers, snow, vegetation, and land-based ecosystems in general; two of the most important groups in terrestrial observation are the U.S. Geological Survey (USGS) and the U.S. Department of Agriculture (USDA). Ocean and atmospheric observations are the domain of National Oceanic and Atmospheric Administration (NOAA), which uses a variety of methods, including drifting and moored buoys and volunteer observing-ships to measure a suite of climatic properties relating to air and water systems. While surface-based measurements are important, there is little new technology that can be applied to them. Because of this, valuable surface monitoring is merely being preserved, while efforts to improve climate observation are almost entirely directed at remote sensing by satellites.[29]

Remote observation of the earth's climate system is achieved by satellites carrying such technologies as radiometry, spectroscopy, radar, and optical remote sensing.[30] While observational satellites have orbited the earth since the late 1970s, the early systems recorded only a handful climate variables. The future of remote climate observation will be a series of new and upcoming satellites that will combine to form NASA's Earth Observing System (EOS). EOS will make it possible to measure many new variables, and significantly increase their resolution (the number of data points measured per unit area). EOS-Terra, the flagship of the series, was launched in December 1999. Terra will observe clouds, aerosols, trace gases, land surface, ocean properties, and the earth's radiation budget.[31]

Another EOS satellite, the Active Cavity Radiometer Irradiance Monitor (ACRIMSAT), was launched in December 1999 to record total solar irradiance. The lofty goal of ACRIMSAT as stated by the USGCRP is to "elucidate solar-terrestrial connections and the effect of solar variations on the atmosphere and weather, and distinguish between natural variability caused by solar forcing and that induced by anthropogenic greenhouse gases."[32]

NASA's Landsat-7 was launched in April 1999, and began high-quality data distribution in August 1999. The Landsat-7 system includes a 15 meter resolution panchromatic band for imaging which contributes directly to the monitoring of land cover and land-use changes.[33]

The QuikSCAT spacecraft, launched in June 1999, joined the Tropical Rainfall Measuring Mission (TRMM) and the Ocean Topography Experiment/Poseidon (TOPEX/Poseidon) to form a suite of space-based observational assets to track phenomena such as El Niño/La Niña events. "QuikSCAT measures sea-surface wind speed and direction at a spatial resolution of 25 km over at least 90 percent of the ice-free global oceans every two days."[34] Other valuable space assets include the Sea-viewing Wide Field-of-view Sensor

(SeaWiFS) which measures ocean productivity, the Upper Atmospheric Research Satellite (UARS) which takes measurements of stratospheric trace chemicals, the Total Ozone Mapping System (TOMS) which records the Antarctic ozone hole, and the Earth Radiation Budget Experiment (ERBE) which takes measurements of incoming solar radiation and outgoing radiation from the earth.

U.S. climate observation efforts are also aided by satellites belonging to other nations; for example, Canada's RADARSAT is used to track the motion of sea-ice, and to perform Antarctic mapping. Other valuable satellite systems include the Advanced Earth Observing Satellite platforms from Japan, and the current ERS-1, ERS-2, and the future ENVISAT polar platforms from Europe.[35]

New uses for satellite remote sensing within just the last two years include: measuring global rainfall over the tropics, producing near-daily ocean color maps, documenting the waxing and waning of El Niño, resuming global measurement of winds at ocean surfaces, assessing global forest cover, measuring concentrations of ozone and ozone-depleting substances, determining thinning and thickening rates for the Greenland ice sheet, providing the first detailed radar mosaic of Antarctica, and providing daily observations of the polar regions from space. These observations have helped improve short-term weather prediction and quantification of the availability of fresh water, helped uncover the role of oceans in removing carbon dioxide from the atmosphere, facilitated improved seasonal climate forecasts, and improved short-term, global weather prediction and tracking of major hurricanes and tropical storms.[36]

Observation---Weaknesses

Even with all the progress that has been made in climate observation, there are still many weaknesses. The basic properties required of a climate monitoring system as enumerated in the National Research Council's (NRC) report "Capacity of U.S. Climate Modeling to Support Climate Assessment Activities" were:[37]

- Changes to an observing network should be assessed in terms of the effects on climatic time series.
- Any replacement instruments should be overlapped with the old ones for an appropriate period of time.

- Data which documents the observational instruments and procedures should be kept and archived along with the observed data.
- Data quality and homogenity should be assessed as part of routine operating procedures.
- The data should be used in environmental assessments of various types so that it will be constantly examined.
- Historically important time series within the observing system should be maintained and protected.
- Data poor or otherwise unknown or sensitive regions should receive special priority.
- The entire system should be designed with climate and weather requirements in mind.
- Commitment to old systems and a transition plan from research to operations needs to be a part of the system.
- Every effort should be made to facilitate access and use of the data by national and international users.

According to the NRC, "a climate observing system is inadequate when it either fails to measure climatically important quantities or when the measured quantities do not satisfy the 10 properties above. By this standard there is not an adequate climate observing system."[38]

Many important properties are being measured inadequately, or not at all, by climate observing systems. For example, time-series measurements for forcing agents with short atmospheric residence times (e.g. aerosols) have been taken for only a short time, and are incomplete because they are hard to measure and are spatially heterogeneous.[39] Other examples of variables that need improved observation include subsurface ocean temperature and salinity, land soil moisture, and the concentrations of specific atmospheric species such as the hydroxyl radical.[40] It is very important that the U.S. make efforts to measure all necessary climate variables in order to satisfy the research necessary for the National Assessment, among other needs.

Even with variables that have been observed extensively, there is still much inaccuracy in measurements. For example, precipitation measurements in some locations during mid-winter months are only 25% accurate.[41] Climate research and modeling can be only as good as the data that is used for them, so it is critical that observations be as reliable as possible.

One of the most important improvements that can be made to climate observing systems is to increase their resolution. The USGCRP is currently shooting for a 3^0 to 5^0 grid for satellite and surface measurements,[42] but ideally the grid would be even finer. Also, many observation networks do not have full coverage of the area they intend to monitor. Upper ocean buoy network coverage is as low as 25-30%.[43] The goal of climate observation is to obtain a complete and detailed record of the earth's climate system; full coverage and fine resolution are essential to meet this goal.

Another facet of climate observation is data storage. The National Climatic Data Center (NCDC) and the World Data Center for Meteorology (WDC) are currently at the forefront of data cataloging, storage, and dissemination. The NCDC is the largest data center of its kind in the world, and is responsible for archiving over 99 percent of all NOAA data. It stores information in various forms including paper, microfiche, magnetic tapes, and satellite images.[44] It is very important that data be saved in a uniform fashion to facilitate sharing between groups. For example, it is difficult to build a computer model if the data required for it was measured by someone else and is saved only on microfiche. It would require an unreasonable number of man-hours to convert that data to an acceptable computerized form, thus it would probably not get used in the model. In the future it will become increasingly important for different groups to coordinate their methods of data recording so that compatibility in data sharing will not be compromised.

The NCDC has done a good job of centralizing climate data storage in the U.S., however, efforts must be made for it and similar groups in other countries to better share their data with one another. For example, according to a report by the National Academy of Science, "The World Meteorological Organization's Global Runoff Data Center in Koblenz, Germany, holds information on nearly 3000 [river and stream] discharge monitoring stations. However, in accordance with the wishes of the donor nations, access to this information is restricted and no transfer of the complete global dataset or substantial portions of it are possible."[45] Because it would be impossible for U.S. researchers to measure all the data they need in locations all over the world, cooperation between nations is necessary in building a global dataset. This is a role for policy makers: diplomacy is needed to facilitate the partnership of different nations in meeting their common goal of solving the climate change puzzle.

CLIMATE RESEARCH

Research Imperatives

The USGCRP divides climate research into seven categories:

1. understanding the climate system
2. understanding the composition and chemistry of the atmosphere
3. understanding the global water cycle
4. understanding the global carbon cycle
5. understanding changes in ecosystems
6. understanding human dimensions of global change
7. studying the paleoclimate (the history of the earth's climate system)

These are all broad areas, each containing many sub-fields of study, and each having its own level of sophistication. The USGCRP is responsible for funding this research because it is not a profitable field for private industries to pursue. While competition among research groups can be beneficial in some cases, there is no money to be made in climate research and no companies competing to be at the forefront of it; therefore it is a field that must be sustained by government funding.

Climate research is necessary because observation alone cannot determine how much of an observed climate change is attributable to human activities, and how much to natural variability. Research contributes to the climate observation process by identifying variables that are being measured inadequately or not at all. Research into the mechanisms by which change occurs is also necessary to aid modelers in predicting future climate scenarios.

Climate research entails the attempt to understand the workings of all systems that influence the earth's climate. It is a huge field with many questions left to answer, and if the U.S. is determined to understand the workings of the earth's climate and predict its future behavior, then it must make every effort to support and improve basic scientific research. Research imperatives for the coming decade that were identified by the National Academy of Science[46] include:

Biology and Biogeochemistry of Ecosystems

- **Land surface and climate:** Understand the relationships between land surface processes and climate change.
- **Biogeochemistry:** Understand the changing global biogeochemical cycles of carbon and nitrogen.
- **Multiple stresses:** Understand the behavior of ecosystems under multiple stresses.
- **Biodiversity:** Understand the relationship between biodiversity and ecosystem function.

Changes in Climate on Seasonal to Interannual Timescales

- **ENSO:** Maintain and improve the capability to make El Niño/Southern Oscillation System (ENSO) predictions.
- **Global monsoon:** Define global seasonal-to-interannual variability, especially the global monsoon systems, and understand the extent to which it is predictable.
- **Land surface exchanges:** Understand the roles of land surface energy and water exchanges, and their correct representation in models for seasonal-to-interannual prediction.

Changes in Climate on Decade-to-Century Timescales

- **Natural climate patterns:** Improve knowledge of decadal-to-century-scale natural climate patterns, including their distribution in time/space, optimal characterization, mechanistic controls, feedbacks, sensitivities, and their relationship to anthropogenic climate change.
- **Paleorecord:** Extend the climate record back through archeological records for time series long enough to achieve a better understanding of the nature and range of natural variability over decadal-to-century timescales.
- **Long-term observational system:** Implement and maintain a long-term observing system for a definitive observational foundation on which to evaluate decadal-to-century-scale variability.

- **Climate system components:** Address those issues whose resolution will most efficiently and significantly advance our understanding of decadal-to-century-scale climate variability for specific components of the climate system.
- **Anthropogenic perturbations:** Improve understanding of the long-term climate response to the anthropogenic addition of radiatively active atmospheric constituents, and devise methods of detecting anthropogenic phenomena against the background of natural decadal-to-century-scale climate variability

Changes in the Chemistry of the Atmosphere

- **Stratospheric ozone and ultraviolet (UV) radiation:** Define and predict secular trends in the intensity of UV exposure to the earth. Document the concentrations and distributions of stratospheric ozone and the key chemical species that control its destruction. Elucidate the coupling between chemistry, dynamics, and radiation in the stratosphere and upper troposphere.
- **Greenhouse gases:** Determine the fluxes of GHGs into and out of the earth's systems and the mechanisms responsible for exchange within those systems. Expand global detection techniques to elucidate the processes that control the abundance and variability of atmospheric CO_2, CH_4, N_2O, ozone, and water vapor.
- **Photochemical oxidants:** Develop the observational and computational tools that are necessary to effectively manage ozone pollution, and elucidate the processes that control ozone precursor species, tropospheric ozone, and the oxidizing capacity of the atmosphere.
- **Atmospheric aerosols and UV/visible radiation:** Document the chemical and physical properties of atmospheric aerosols, and elucidate the processes that determine their size, concentration, and chemical characteristics.
- **Toxics and nutrients:** Document the rates of exchange of toxics and nutrients between the atmosphere and ecosystems, and elucidate the extent to which the atmosphere-biosphere relationship is influenced by toxic/nutrient concentrations.

Paleoclimate

- Document how the global climate and the earth's environment have changed in the past and determine the factors that caused these changes. Explore how this knowledge can be applied to understand future climate and environmental change.
- Document how the activities of humans have affected the global environment and climate and determine how these effects can be differentiated from natural variability.
- Define the natural limits of the global environment and determine how changes in the boundary conditions (e.g., greenhouse gases, ocean circulation, ice extent) for this natural environment are manifested.
- Document the important forcing factors (e.g., greenhouse gases, solar variability, ocean circulation, volcanic aerosols) that control climate change on societal timescales (season to century).

Human Dimensions of Global Environmental Change

- **Understanding the social determinants of environmentally significant consumption:** Understand natural resource usage patterns as a function of economic growth and development, which is a key variable driving trends in the human impact on atmospheric composition, land use, and biogeochemcial cycles.
- **Understanding the sources and processes of technological change:** Look into the determinants of rates of adoption and innovation of technologies that could either mitigate or contribute to global climate change.
- **Making climate change assessments and predicitions regionally relevant:** Project the consequences of climate change on a regional scale, develop indicators for vulnerability, improve warning systems, and tie social and economic factors to the projected impacts of climate change.
- **Assessing social and environmental surprises:** Explore the historical record of surprises and identify the human activities that alter their likelihood.
- **Understanding institutions for managing global change:** Clarify the conditions favoring success or failure of resource management and policy instruments for altering the trajectories of anthropogenic global change.

- **Understanding land use/land cover dynamics and human migration:** Link social and economic driving forces to land cover dynamics, and model the effects of land use changes on ecosystems and biogeochemical cycles.
- **Improving methods for decision making about global change:** Develop a way to represent non-market values of environmental resources, and improve ways of representing scientific analyses and uncertainty to decision-makers.
- **Improving the integration of human dimensions research with other global change research:** Human dimensions research relates to all fields of scientific global change research, and requires extensive coordination.
- **Improving geographic links to existing social, economic, and health data:** Collection of human dimensions data requires stable international support, and centralized, uniform storage.

These research imperatives suggest the huge scope of the area that is left to cover by climate change research. It is necessary that the U.S. support further research so that policy-makers can be given the information they need to address the problem of climate change. Further research will help answer the questions:

- Is climate changing?
- To what extent?
- What can be done about it?
- What will be the consequences of our actions or inaction?

The U.S. must be committed to answering these questions.

CLIMATE MODELING

Modeling---The State of the Art

Global climate models, or "GCMs", are mathematical representations of the major climate systems whose interactions govern climate variability. A single forcing effect may be represented by a very large series of equations that must be solved by a computer; multiple forcings add increased complexity. For the most advanced models, components of the climate system may be linked, or coupled, using algorithms describing the connections between these systems.[47] Models are heavily dependent on the researchers who observe the global climate and discover the workings of its mechanisms because a model can only be as good as the equations and data points used to create it.

There are many different players in the modeling game. The Department of Energy's contribution to modeling efforts consists of its Climate Change Prediction Program (CCPP)---a series of projects scattered throughout different national labs and research centers. The National Center for Atmospheric Research (NCAR) currently has two models: the Parallel Climate Model, and the Community Climate System Model (CCSM) which is a widely used model in its third generation. The Lawrence Livermore National Laboratory in California has developed the Program for Climate Model Diagnosis and Intercomparison (PCMDI), while the Los Alamos National Laboratory in New Mexico has a program for Climate, Ocean and Sea Ice Modeling (COSIM)[48].

NASA's modeling efforts are conducted by the Goddard Institute for Space Studies (GISS). GISS activities are primarily aimed at the development of three-dimensional GCMs and atmosphere-ocean models. Research efforts also include the development of two-dimensional energy balance models (EBMs) and one-dimensional radiative-convective models (RCMs). GCM developmental research at GISS is collaborative with the International Satellite Cloud Climatology Project, and the Lamont-Doherty Earth Observatory at Columbia University.[49]

NOAA is also active in climate modeling, with most of their efforts coordinated by the Geophysical Fluid Dynamics Laboratory (GFDL). The GFDL carries out many small-scale projects at once, but they also have larger models, some of which were consulted for the USGCRP's National Assessment.[50]

It is important to note that many university-based and independent research groups are also active in small-to-moderate-scale modeling. While none of these groups receive much attention on their own, they would have the potential to become a significant player in the modeling game if they were to coordinate their efforts into a unified endeavor.

Modeling---Computers

A critical aspect of climate modeling is availability of computing resources. Within coming years, there are four categories of high-end computer systems that will become prevalent in the international climate modeling field:

1. Systems comprised of clusters of nodes (collections of processors grouped together so that they share access to a common memory unit[51]). These systems are built from mass-produced or "commodity" processor and memory chips running in parallel, and using variants of the Unix operating system; their networks are custom built.[52]
2. Systems comprised of loosely integrated clusters of PCs running in parallel on the Linux operating system. These are based completely on mass-produced parts and are considerably cheaper than custom built networks, however they tend to be software-poor and unreliable. It is important to note that mass-produced "commodity processors" are at least ten times slower than custom-designed "vector processors", and require larger networks that effectively hinder the speed of their memory chips.[53]
3. Systems based on innovative new architecture produced by TERA, a small U.S. company, using specially designed processors that support fine-grain parallelism. This is extremely promising technology, but is still expensive and hard to obtain. The San Diego Supercomputer Center owns an 8-processor TERA, one of the premier machines in the U.S.[54]
4. Tightly integrated "vector parallel processor" (VPP) systems with high-performance processors, memory, and custom-designed networks. These are manufactured in Japan, and are not sold in the U.S. due to political pressures. VPP systems may eventually become available from the U.S. company, Cray Research Inc.[55]

A system comprised of processors working in parallel (items 1 and 2) is referred to as a "massively parallel processor" (MPP). When asked about the relative merits of MPP versus VPP systems, modeling groups tended to prefer VPP architectures for several reasons. MPP systems are more difficult to program and require more personnel with better expertise. Data assimilation and processing are more difficult on MPPs, and they also pose significant scalability problems. VPPs are generally considered to be easier to use and more reliable.[56] Out of the four types of systems, it is believed that VPP and TERA-built systems will be the most capable of supporting future high-end modeling efforts.

Among modeling groups, the upgrades most needed include additional processors, nodes, and disk space, as well as network bandwidth to more rapidly acquire data sets from remote sources. Increased collaboration with larger-size modeling centers could benefit small groups with limited resources; it is estimated that half of the large modeling groups in the U.S. share their computational time with the wider community.[57]

The expense and availability of computing power poses one of the most significant challenges to climate modeling today. While many of the world's largest super computers are currently used for global climate models, they are still inadequate to process models containing too many forcing or feedback mechanisms. In Winter 1998, the National Center for Atmospheric Research (NCAR) was asked to create a model to be used in the USGCRP's National Assessment. The "Climate of the 20th Century" model required the equivalent of three months of run-time on a Cray C-90 supercomputer (running 24 hours a day, seven days a week), but the USGCRP did not give NCAR that much time. The National Assessment had to be carried out using models from Canada and the United Kingdom instead.[58]

Run-time is a considerable hurdle in climate modeling. Many models must be run for thousands of simulated years in order to reach equilibrium conditions, and then they must run for hundreds more simulated years to sample the range of time-scales present in climate variability. Completing such long runs in an acceptable amount of wall-clock time places limits on the spatial resolution that can be used.[59] A high resolution model would have points spaced about 300 kilometers apart, which may have to be reduced to 800 km to accommodate high run-times. Low resolution limits researchers' ability to estimate model uncertainty, which in turn decreases model quality. For models to be effective at predicting climate behavior, high resolution and faster run-times are necessary.

The problem of computing is that the fastest, most powerful computers that are most capable of being applied to modeling are in the possession of many scattered groups. The U.S. does not have a modeling center comparable to the United Kingdom's Hadley Centre, or the Canadian Centre for Climate Modeling and Analysis (the facilities responsible for producing the two models used in the National Assessment)[60]. There is little coordination between modeling groups in the U.S., creating an ineffective use of computers, as well as the trained personnel required to run them. Climate modeling would be vastly improved by better cooperation of groups in sharing data, research, and computer resources. As with climate research and observation, the organization and implementation of a modeling infrastructure is a role for the USGCRP.

Modeling---Regional and Socioeconomic Impacts

Two significant challenges in modeling are the treatment of climate on regional scales and the modeling of the socioeconomic effects of climate change. Regional models are needed to provide policy makers with an idea of how global warming will affect their particular constituencies. Also, regional modeling could help to refine mitigation or adaptation strategies, thereby making them much more effective.

The socioeconomic effects of climate change cannot be ignored. To say that "global temperatures will rise five degrees in the next century" does not provide a complete description of the effects of climate change. However, to say that "rising temperatures will decrease agricultural productivity in some areas, increase disease in others, and in turn create general social and economic stress" better illustrates the potential seriousness of the problem. The economic effects of climate change (as well as of climate change mitigation efforts) may well be more serious an issue to the U.S. than climate change itself.

This is a role for improved modeling. Research into the regional and human impacts of climate change (as mentioned in a previous section) will be necessary, as well as the gathering of regional climate data and significant economic data. Once again, increased access to computing resources and the personnel needed to run them will also be critical. Models will be a useful descriptive tool for providing policy makers with the knowledge they need to shape the human response to climate change. Improved models will be able to predict the consequences of mitigation, or adaptation to climate change. While they cannot tell decision makers what the best possible course of action will be, models will illustrate possible alternatives so that politicians can choose wisely between them.

CONCLUSION

Global climate change research must be continued and improved in order to provide necessary answers to policy makers. It is a field that will continue to require support from the federal government because there is no economic incentive for companies to participate in it. There are still many questions regarding the mechanisms of climate change, and it will require the interplay of observation, research and modeling to answer them. Scientific efforts to understand the role that humans play in climate change are also quite necessary. The U.S. must be committed to remain at the forefront of this research.

Climate observation is still insufficient to satisfy current research and modeling efforts. There are important variables that are not being measured. Many variables are measured with insufficient frequency, range, or accuracy. The goal of observation should be to produce a comprehensive record of all climate variables over an extended period of time, with high resolution over the earth's surface. Climate observation is an increasingly complex and involved pursuit, and will be best achieved by large groups with the capacity for global coverage, such as NASA and NOAA. The U.S. should also make every effort to partner with the United Nations as well as other countries in achieving total, high resolution climate observation for years to come.

A crucial part of climate observation is data storage. Data should be centrally stored for ease of dissemination, and must be uniform for compatibility between its producers and users. This is a role for the National Climatic Data Center in particular, because it has an existing infrastructure for data storage.

Climate modeling can be significantly improved. Models with higher resolution, that contain more forcing and feedback mechanisms, and that are more capable of approximating reality will be attainable with improved computer resources. Modeling groups must be given access to the necessary high-end computing facilities, as well as the personnel and software that are required to use them. To do this, the U.S. will need centralization and coordination of its modeling efforts; the implementation of a modeling infrastructure is a role for the USGCRP.

Every effort should be made to increase compatibility between research, observation, and modeling. Cooperation is essential to achieve active sharing of resources, and the U.S. must stress the responsibility of the USGCRP in aligning its participating agencies into a powerful force for climate change study. The USGCRP is the closest thing to a solid climate research infrastructure that exists in the U.S., and it must be supported as such.

POLICY RECOMMENDATIONS

The climate change issue is two-sided. If severe mitigation efforts are taken, there may be painful economic consequences. On the other hand, if no mitigation or adaptation efforts are made, then global warming could disastrously affect many aspects of human life. Responsible policy will depend on scientists and engineers to provide the technical information necessary to weigh the risks against the benefits.

Climate research should be made an issue of utmost importance, and no effort should be spared to supplement and improve it. The U.S. government must continue to assume its role as a dominant player in the study of climate change. It is a field that is not profitable for private groups, and is too great to be handled sufficiently in universities and small research groups. However it is a field that must be pursued all the same, and the U.S. should continue to utilize powerful agencies like NASA, NOAA, and the DOE to do it. The organizational efforts of the USGCRP will be crucial, and should be continually strengthened.

In the future, it will become increasingly useful to partner with other nations in climate change treaty-making, but the U.S. must not compromise its research efforts by leaving many questions to be answered by outside parties. As always, U.S. economic interests must be protected, and because climate change mitigation could heavily influence the national (and global) economies, we must base policy decisions on our own models and research. Cooperation between countries on some research will be helpful, but again, the U.S. must remain a dominant voice.

Scientific uncertainty is still too great for policy makers to know the extent to which climate change mitigation efforts may be necessary, however it may be wise to begin mitigation on a small scale. The adoption of such activities will go a long way in alleviating the public anxiety over climate change, while biding time until scientists can be more certain of the seriousness of the problem. At this stage mitigation activities should not be allowed to inflict deleterious economic effects, since that outcome may be worse than the scenario they were intended to prevent. Policy makers should also be aware that in the future it may be prudent to favor adaptation over mitigation, although they should depend on science to provide the facts necessary to perform a cost-benefit analysis.

It is important to recognize that scientific consensus on climate change will not necessarily point to policy recommendations. Scientists will someday be able to say with high confidence that anthropogenic global warming is or is not occurring to such-and-such extent, and that it will have such-and-such physical, economic and social effects. However, scientists can do no more than propose the scenarios that are most likely to result from expected human activities; it is up to policy makers to decide which scenario will best serve the public good, and make laws to ensure that scenario will be achieved. Climate change research and policy are two separate subjects, but the policy depends extensively on the research. As Carl Sagan put it "Science by itself cannot advocate courses of human action, but it can certainly illuminate the possible consequences of alternative courses of action."[61] The U.S. must recognize this relationship, and support research as a means to achieve sound public policy decisions.

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