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Climate and Water Resources: A Challenge to Integrated Science/Social Policy Formulation

The local broadcast meteorologist comes on the air and reports that he missed the "three degree guarantee" for the first time in a week. He is not perfect but more often than not this forecast is accurate. Rain, snow, ice, tornado, and hurricane forecasts are better today than ever before, but they still have high degrees of uncertainty reflecting the complex and sensitive physical phenomena that drive their generation.

The physical and chemical processes involved in weather systems are fairly well understood, but more accurate measurements of chemical reactions rates and atmospheric particulate concentrations and size distributions are needed. The computational power and algorithms to allow weather models to be solved have advanced strikingly over the past generation. However, the ability to accurately calibrate and incorporate into forecast models the needed physical quantities such as pressure, temperature, and humidity at spatial and time scales needed for accurate predictions is lacking. Weather prediction has advanced much over the past generation, but it is still wrought with challenges.

The Old Farmer's Almanac predicts a wetter than normal spring for central North Carolina. Generally, long term forecasts are reliable, but it is accepted that they will be incorrect for some years. These longer term forecasts move from the realm of weather prediction to climate prediction. Climate is the "average weather" over a period of time ranging from months to thousands of years with the classical period defined as 30 years.

Over historical time spans there are a number of static variables that determine climate, including latitude, altitude, proportion of land to water, and proximity to oceans and mountains. Other climate determinants are more dynamic such as the wind-driven and thermohaline circulation of the ocean that leads to a 5 °C warming of the northern Atlantic Ocean compared to other ocean basins. The density and type of vegetation coverage affects solar heat absorption, water retention, and rainfall on a regional level. Alterations in the quantity of atmospheric greenhouse gases determine the amount of solar energy retained by the planet, leading to global warming or global cooling (Ledley et al., 1999).

The Earth has undergone periodic climate shifts in the past two millions years, including four major ice ages. These consisted of glacial periods where conditions were colder than normal, separated by interglacial periods. Interglacials have been reoccurring at intervals of roughly 100,000 years. About 125,000 years ago the land ice on Earth reached a minimum amount. In the intervening period glaciers advanced until the ice cover reached its maximum about 20,000 years ago. The accumulation of snow and ice during a glacial period reflects more of the Sun's energy into space and maintains a lower atmospheric temperature. The ice sheets started to shrink rapidly around 15,000 years ago leading to the current interglacial period. These pronounced climatic swings are believed to be driven by relatively small variations in the Earth's orbit that affect the average intensity of incident solar radiation.

Increases in greenhouse gases, such as by volcanic activity, also can increase the global temperature. The following observation illustrates this phenomenon. The total energy output of the sun was somewhat lower about 440 million years ago than now, but the mean Earth temperature was much higher. This paradox is explained by the fact that the greenhouse effect was much stronger at that time. This greenhouse effect was most likely associated with elevated levels of carbon dioxide with concentrations about ten times greater than current values.

Thus, the study of the Earth System to understand climate change involves observing and predicting global environmental changes by studying cross interactions among land, atmosphere, oceans, biosphere, societies, technologies, and economies. These interrelationships are very complex and dynamic, and the data needed to understand them is often difficult to obtain. The traditional academic "silo" structures are not well suited to the integrated study of the Earth System, the ways that it is changing, and the implications for global and regional sustainability. This type of study is so challenging that no individual academic department or university is capable of developing and offering the enormous depth and breadth of knowledge needed to make optimal decisions. A *holistic approach is needed that brings faculty and students from different disciplines together.*

Interdisciplinary Research Center Model for Studying Climate Change

The National Oceanic and Atmospheric Administration (NOAA) recently funded an Interdisciplinary Scientific Environmental Technology Cooperative Science Center (ISETCSC, http://noaaiset.org) at NCA&T. The ISETCSC serves as a test-bed for innovative approaches to approaching Earth System issues. The Center, which is led by North Carolina Agricultural & Technical State University (NCAT), partners seven universities to study climate change, five underrepresented student serving institutions (NCAT, City University of New York, Fisk University, California State University-Fresno, and the University of Alaska Southeast), and two large research universities (North Carolina State University and the University of Minnesota). African American, Hispanic, and Native Alaskan students are involved in the Center. The ISETCSC involves thirty-one scientists and engineers representing nine academic departments.

Disciplines represented include meteorology, physics, chemistry, mathematics, electrical engineering, civil engineering, and chemical engineering. Scientists from

NOAA's Earth System Research Laboratory in Boulder, CO (http://www.esrl.noaa.gov) partner through a cooperative agreement with the university faculty in the training of students. Scientists at NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov) in Asheville, NC are also involved with Center activities.

Center research is focused on three interrelated thrust areas: I - Sensor Science and Sensor Technology Development (developing remote sensing tools and measurement of climate related chemical data), II - Analysis of Observing Systems (mathematical modeling using climate related data), and III - Information Technology Applications (methods for handling, managing, compressing and storing complicated, large data sets). Group I conducts research with the aim of developing sensing strategies, sensor technologies, and sensor packages that fill some of the existing data gaps in observation systems. Thrust area II explores (i) the impact of climate change on precipitation and hydrological variables including severe storms such as hurricanes, and (ii) the role of aerosols in affecting cloud properties and the resulting impacts on climate. Group III analyzes, correlates, and interprets large volumes of data from extensive networks of heterogeneous sensors that present a challenge for state-of-the-art data fusion. Also, traditional data-mining techniques are challenged by the complex, dynamic relationships to be discovered in large volumes of climate data (including image data). Some of the activity in thrust III is tied to a NOAA long-range plan for enhancing the accessibility of weather and climate data and models to the general public

The ISETCSC has a comprehensive educational strategy that includes informal education outreach, K-12 teacher summer workshops and curriculum development, community college 2+2 programs, undergraduate general education (UNST 224: Weather and Climate Studies), and online courses. The formation of the Center at NCAT led to the establishment of a B.S. degree program in atmospheric sciences and meteorology and a concentration in atmospheric sciences in the interdisciplinary Energy and Environmental Systems Ph.D. program.

The Challenge

There is a world-wide consensus among the scientific community that the average surface and subsurface ocean temperature of the globe has increased since 1000 and continues to increase.

There is also a consensus that the changes observed over the last decades are most likely due to human activities even though natural climate variability cannot be ruled out. As our understanding of causes of climate change evolves, researchers, policy makers, the press, and the public must be informed because these developments affect our understanding of the seriousness and complexity of this issue and the optimum response to it.

Long-lived greenhouse gases that are increasing primarily as a direct result of human activity include carbon dioxide, methane, nitrous oxide and halocarbons. It is estimated that their relative contribution to the change in radiative forcing (greenhouse effect) is as follows: carbon dioxide 55%, methane 15%, nitrous oxide 6 %, and halocarbons 24%. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), the global increase in carbon dioxide concentration is due primarily to fossil fuel use and changes in land use. The increases of methane and nitrous oxide are primarily due to agriculture. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 to 384 parts per million (ppm) in 2008. This exceeds the natural range of concentrations over the last 650,000 years as determined by isotope ratios from ice cores. The global atmospheric concentration of methane increased from a preindustrial value of about 715 to 1780 ppb in 2008. The global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 to 322 ppb in 2008. Halocarbons are manufactured for the use in refrigeration units and as foaming agents and solvents.

Two classes of carbonaceous aerosols (sulfate and carbon-bearing compounds associated with particles) affect radiative balances and, therefore, influence climate. Other potentially important climate factors include volcanic aerosols, anthropogenic land use, and solar variability. The societal challenge is to determine the appropriate level of resources to devote to climate research, climate change mitigation efforts, and climate change response technology development.

Convergence of Local, National, and Global Impacts

North Carolina is a good model of the complexity of climate change issues and how local, national, and global scale phenomenon overlap. Potential physical impacts on North Carolina include:

- An increase in sea level due to climate change would significantly influence the North Carolina Coastal region leading to flooding, erosion and increased salinity.
- The impacts of hurricanes on North Carolina's piedmont and mountains are generally less severe when compared to those on the coastal plain. However, stronger hurricanes will be able to reach the piedmont and mountains. Large amounts of precipitation may cause flooding and, in the mountains, landslides.
- The global temperature increase does not directly transfer to increased temperature in North Carolina due to the state's complicated geography and influences from atmospheric motion and processes in other regions.
- Other effects of rising temperatures are heat waves during the summer months. This will have significant impact on agriculture, health, and air quality.

To allow a state like North Carolina to make wise decisions as to how to respond to climate change, more research is needed to improve local, national, and global weather and climate models, computing facilities, and observations, so that effects of climate change on the weather in North Carolina and its distinct geographical areas can be identified and more precisely predicted. Considering the global nature of the problem, North Carolina's first focus should be investigating and making plans to mitigate and manage the local effects (possibly catastrophic) of global warming on its population and environment. This work should be coordinated with efforts in the rest of the U.S. and world to establish centers to explore the science of global warming and to increase the public's awareness and consciousness of the environmental problems involved.

Sea Level Rise

Climate change is expected to trigger a rise in the sea level by increasing the volume of water in the ocean's basins. This happens through thermal expansion of ocean water and melting of polar ice and mountain glaciers. In the past 150 years, sea level has risen at a rate of 18 cm per century (Neumann et al., 2000). An increase in sea level due to climate change could significantly influence the world's coastal zone, adversely affecting the ecologically and economically important coastal systems where the majority of the human population lives. Major physical impacts of sea level rise include: (1) Erosion of beaches and shores; (2) Permanent inundation of wetlands; (3) Increased flooding and erosion of marshes, wetlands; (4) Increased flooding and storm damage in low-lying coastal areas; and (5) Increased salinity in estuaries, marshes, coastal rivers. This rise in sea level will obviously affect the coastal regions in a number of ways including the possibility of stronger destructive hurricanes. To mitigate the negative effects of catastrophic flooding, city building codes for communities along the coast should be examined critically and revised to mitigate the effects of flooding and wind damage.

Erosion

Global warming may also affect erosion. Erosion is an intrinsic natural process that can be enhanced by human activities. Poor land use (extensive deforestation, overgrazing, unmanaged construction activity on roads and buildings) can accelerate erosion. Excessive erosion causes problems such as increasing sediments in water and loss of topsoil. The rate of erosion depends on climatic factors (precipitation, temperature, wind speed, and storm frequency), geologic factors (soil and rock type, porosity, and permeability; and slope of the land), biological factors (vegetation type, faunal composition), and land use (cropping pattern, tillage). The impact of erosion varies among the geographical regions (mountain, piedmont, or coastal region) in North Carolina. Hurricane activity and extreme increases in rainfall caused by global warming could increase erosion over the mountains and the coastal regions.

Droughts and Heat Waves

The divergent findings of previous research on droughts highlight the importance of further research to better understand such Earth System phenomenon. Dai (2004) reported that the amount of land affected by droughts has more than doubled over the last 30 years. The key factor appears to be the rise in global temperatures and not decreases in precipitation. Somewhat different findings on global changes in droughts have been reported by Sheffield and Wood (2008). These authors concluded that drought duration, intensity, and severity are, for the most part, decreasing.

Herweijer et al. (2007) analyzed data on droughts in North America in modern times. The authors argue that cool "La Nina-like" conditions in the tropical Pacific are correlated with North American drought. Similar conclusions are drawn in Cook et al. (2007). Andreadis et al. (2006) present similar conclusions regarding drought dynamics in the US: "Droughts have, for the most part, become shorter, less frequent, and cover a smaller portion of the country over the last century." Mixed conclusions are drawn about the dynamics of global drought. Researchers agree, however, that the overall climate in the U.S. is becoming wetter. It is unclear if this trend is related to global warming.

Forests and Forest Fires

Investigations of forest fire activity in the U.S. indicate that warmer temperatures tend to increase the duration and intensity of the wildfire season in the western U.S. Large wildfire activity increased suddenly and markedly in the mid-1980s, with increased large-wildfire frequency, duration, and season. These increases in fire activity are strongly associated with increased spring and summer temperatures and an earlier spring snow-melt.

Balshi et al. (2008) investigated areas burned by wildfire in boreal North America and found that wildfire activity responds to factors correlated with changes in climate. In mountainous areas, global warming results in an upward shift of the biota (Brown, 2001). Kirilenko and Sedjo (2007) investigated the impact of climate change on forests due to effects of (1) temperature, precipitation, and CO_2 concentration change, and (2) fires, insects, pathogens, and extreme events. The authors indicate a rise in temperature may cause a pole-ward shift of vegetation of 500 km or more for boreal zones. Although Kirilenko and Sedjo (2007) argue that increasing concentrations of atmospheric CO_2 may also increase plant productivity through the "carbon fertilization effect" other forest ecologists argue that the "effects will likely differ in direction and magnitude among forest ecosystems" (Gower, 2003). Kirilenko and Sedjo (2007) conclude that the second group of factors (2) will have negative effects on forest growth dynamics. They concluded that it is difficult to predict which effect will dominate on a global scale at this time. As stated earlier, the uncertainties in the model predictions and of methods used in analysis requires more research to predict trends in forest fire activity and their effects on forests.

Expansion of Human Pathogens

Global warming's impact on climate change has already included the expansion of subtropical and tropical pathogens into new habitats (Foley et al., 2005). This occurs through changes in terrestrial and aquatic ecosystems. The vectors of many tropical diseases such as yellow fever, malaria, and dengue fever are cold-blooded organisms, such as insects. Increasing temperatures allow insect vectors greater geographic range, activity, and population densities. There is also evidence that warm-blooded vectors of disease such as rodent populations are increasing due to global warming. Increased transmission of Hantavirus in the Southwestern United States is an example (Epstein, 1995). The parasites themselves are also favorably impacted by warmer temperature. Malaria (*Plasmodium falciparum*) has an incubation period of 14 days at 25° C, but this decreases to 10 days at 32° C (Giles, 1993). This would increase the number of generations this species would undergo in its host, thus likely improving its ability to evolve new mechanisms to evade host defenses.

Aquatic ecosystems also impact disease transmission. Mosquitoes require aquatic environments to complete their larval stage. Warming temperatures, along with changing patterns of rainfall would create new mosquito habitats, in turn increasing transmission of malaria, yellow fever, and dengue fever (Foley et al., 2005). Warming marine temperatures are allowing new variants of cholera (*Vibrio cholera*) to evolve, as well as increasing the frequency of food poisoning resulting from toxic algal blooms (Giles, 1993; Epstein, 1995; EPA, 1997; Foley et al., 2005).

Insurance Industry Impact

The insurance industry is directly affected by the risks of major natural disasters. The number of these disasters has tripled since the 1960s; insured losses have increased fifteen fold in real terms (adjusted for inflation). Recent studies suggest that both internationally and in the US, insurance losses have greatly increased (American Association of Insurance Services). In the Mid-Atlantic region, each 1% increase in annual precipitation could enlarge catastrophe loss by as much as 2.8% (Choi and Fisher, 2003).

Weather related risks for households and property in North Carolina are already increasing due an increase in severe weather events such as hurricanes and heavy precipitation. North Carolina lawmakers are currently examining whether the insurance industry is prepared financially to handle a category 5 hurricane and the resulting billions of dollars in claims. A state-sponsored program for affordable coastal insurance currently exists; however, the insurance industry is worried that the program does not have enough money to pay for claims for storm and flood damages from a 100 year storm. Insurance premiums for coastal residents will increase, as does the risk that flood insurance will become unaffordable for some North Carolina residents. Financial institutions, including the world's two largest insurance companies, Munich Re and Swiss Re, warned in a 2002 study that "the increasing frequency of severe climatic events, coupled with social trends could cost almost US$ 150 billion each year in the next decade."

General Economic Impact

The global economic impact of climate change is currently a subject of a great debate among economists and other social scientists. One point of view, represented by Stern's (2006) report suggests that climate change will cause the greatest and widest-ranging market failure ever seen.

The report concludes that one percent of global GDP must be invested in research to mitigate the effects of climate change; a failure to do so could risk a recession worth up to twenty percent of global GDP. On another hand, Mendelsohn (2004) argues that the impact is likely to differ by region. Countries in the polar-regions would benefit from warming, and countries in mid-latitudes would benefit at first and then be harmed. The countries in tropical regions would be harmed immediately by global warming.

The major economic impacts of global warming have been listed by the Center for Integrated Environmental Research (CIER) at the University of Maryland (2008). These economic impacts are especially severe for the coast. Sea level rise will have a negative effect on tourism, real estate, and fishing industries and could endanger water supplies there (CIER, 2008). Any increase in severe weather will hurt agriculture and forestry.

Human Displacement

Perhaps the most worrisome problems associated with rising temperatures and sea levels are from large-scale migrations of people -- both inside nations and across existing national borders. Poor and underdeveloped areas are likely to have fewer resources and less ability to deal with climate change in even its very modest and early manifestations. Poorer communities also tend to lack the insurance, savings or, access to credit needed to recover from disasters (Peterson, 2002).

Importance of Interdisciplinary Research Centers for Studying Climate Change

Decision makers who influence choices related to climate change issues face huge challenges in making optimum decisions. Sample actions they might choose include:

- Improve research and education on global warming and climate change by increasing the number of and funding for holistic interdisciplinary programs involving the physical, life, and social sciences.
- Facilitate the agricultural sector's contributions to the emerging carbon markets and the growing biofuels industry.
- Develop a plan to reduce carbon footprint through conservation, waste minimization, and improved energy efficiency.
- Increase the use of nuclear energy.
- Develop comprehensive plans for protection of coastal regions.

However, decisions to invest in such actions are wrought with a high degree of uncertainty and often times may generate a conflict between short-term benefits and long-term benefits that are difficult to quantify. Interdisciplinary climate change research centers, such as NOAA ISETCSC, need to contribute to the development of innovative approaches to managing the integrated science/social policy issues associated with climate change.

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