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IMPROVING THE CAPACITY OF U.S. CLIMATE MODELING FOR DECISION-MAKERS AND END-USERS

HEARING

BEFORE THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION UNITED STATES SENATE

ONE HUNDRED TENTH CONGRESS

SECOND SESSION

MAY 8, 2008

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SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

ONE HUNDRED TENTH CONGRESS

SECOND SESSION

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IMPROVING THE CAPACITY OF U.S. CLIMATE MODELING FOR DECISION-MAKERS AND END-USERS

THURSDAY, MAY 8, 2008

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Committee met, pursuant to notice, at 2:41 p.m., in room SR–253, Russell Senate Office Building, Hon. John F. Kerry, presiding.

OPENING STATEMENT OF HON. JOHN F. KERRY, U.S. SENATOR FROM MASSACHUSETTS

Senator KERRY. We will officially begin. I will not call you to order because I have never seen such a quiet, almost somnambulant crew. Are you all right? This whole audience is quiet.

Welcome. We are really, really happy to have you here today and I apologize for the delay. We just have a little bit too much going on right now.

This is really an essential component of our Nation's effort to try to understand climate change, and as you know, we are going to be having a very important debate here in a matter of weeks on this subject in the form of our cap and trade legislation. A lot of issues are being raised and are continually being raised with respect to our ability to be able to understand future climate impacts and what our response ought to be to those impacts. A lot of that will enter into the debate. No question.

We are in good company, in a sense, today. There may not be as many of us as there are in London, but in England today 150 of the world's top climate modelers are meeting, focusing on exactly the same set of issues that we are talking about here today.

As our panel well knows, but just for the public's understanding and the record, we want to emphasize that climate modeling has been a subject of this Committee's inquiry for over 20 years now. Al Gore and I held the first hearings back in 1987, and then in 1988 Jim Hanson made the first comments with respect to climate change being upon us. Subsequently we have had many different hearings and meetings to try to better understand how we can define to people what we are looking at and what to expect. For the public, it is obviously very important in terms of policy.

These models are the basis for the predictions of future temperature increases, sea level rise, storm surge, and the other impacts of global climate change. To date, the U.S. Government has played a key role in developing several of the world's best and most accurate models which serve as the basis for much of the information in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

However, we are now beginning to understand the limitations of these models. They currently cannot provide us with predictions on a regional or local level, and they cannot provide us information that is essential for states, communities, and resource managers as they adapt to the localized impacts of climate change. The models also tend to provide information over a long horizon, a long period of time, rather than on a decadal scale that would be more useful to some of these end-users.

In addition, the models are currently not capable of identifying potential thresholds or tipping points which could also result in abrupt climate change impacts.

One of the key issues that we are going to explore today is the issue of computing capacity. There are a number of different limitations. To run the models at the desired resolution, we need supercomputers a thousand times more powerful than we have today. While the United States has some of the most powerful supercomputing facilities in the world, we do not have a structure or strategy in place to coordinate the hardware, software, networking, and data storage functions required to produce the type of information that we need.

As we consider this multitude of overlapping functions, our efforts have to be driven by the ultimate needs of the end-users of this information, and I hope that Bruce Carlisle is going to keep us focused on that today. Bruce is the Assistant Director of the Massachusetts Office of Coastal Zone Management. He has been one of the leaders in creating a new state program called StormSmart Coasts, and this excellent program provides Massachusetts' cities and towns with the information and tools that they need to protect themselves from coastal storm damage and prepare for the impacts of climate change and rising sea levels. This first-of-a-kind program will serve as a model for the country, and I am proud of the work that has taken place in my home State.

I would like to briefly also introduce the other witnesses and then recognize our Ranking Member of the Committee, Senator Stevens, and then welcome your testimony.

Dr. Sandy MacDonald, Director of the Earth System Research Laboratory at the National Oceanic and Atmospheric Administration; Dr. James Hack, Director of the National Center for Computational Sciences at the Oak Ridge National Laboratory; Dr. Daniel A. Reed, Scalable and Multicore Computing Strategist at Microsoft; Dr. Edward Sarachik, Co-Director of the Center for Science in the Earth System at the University of Washington; and Dr. John Walsh, Chief Scientist at the International Arctic Research Center, University of Alaska Fairbanks.

Gentlemen, we are deeply appreciative for your taking time, some of you to travel considerable distance, and all of you to bring your expertise to the Committee today. We appreciate it very, very much.

Senator Stevens?

STATEMENT OF HON. TED STEVENS, U.S. SENATOR FROM ALASKA

Senator STEVENS. Thank you very much, Mr. Chairman. Sorry to be a little bit late. I thought we were going to have a vote, but it was canceled.

Senator KERRY. So did I actually. I went over there and that is why I was late. I thought I was going to vote early and get back, but I wound up being late.

Senator STEVENS. I think everyone knows that Alaskans depend upon timely, accurate climate information for decisionmaking on a range of issues. The same with the rest of the country, home construction, transportation. But we particularly need it for fisheries and resource management. And I do support research and development of climate models that provide this information to Federal and State agencies, as well as local people who depend on it every day.

I remain concerned, however, that the recent climate models with site-specific data may not be accurate enough for the planning on the State and community levels. It is essential that we have not only the best model capabilities, but also comprehensive climate data to use in those model simulations. Our Nation should make it a priority to improve both climate modeling and access to the necessary supercomputing infrastructure.

I welcome the witnesses here today, as the Chairman has, including Dr. John Walsh who has traveled all the way from the International Arctic Research Center in Fairbanks to be here. I look forward to your testimony, John. Nice to have you here.

I thank you very much for holding the hearing, Mr. Chairman.

Senator KERRY. Thank you very much, Senator Stevens.

So if we could begin with you, Dr. MacDonald, and we will just run right down the line. And if I could ask everybody—each of your testimonies will be placed in writing in the record in full, and if you could summarize in approximately 5 minutes, that way we can have a little more time to engage in a discussion between the panelists and ourselves. Thank you. Dr. MacDonald?

STATEMENT OF DR. ALEXANDER (SANDY) MACDONALD, DEPUTY ASSISTANT ADMINISTRATOR FOR LABORATORIES AND COOPERATIVE INSTITUTES, OFFICE OF OCEANIC AND ATMOSPHERIC RESEARCH, NOAA, U.S. DEPARTMENT OF COMMERCE

Dr. MACDONALD. Good afternoon, Senator Kerry and Vice Chairman Stevens. I am Dr. Alexander MacDonald. My friends call me Sandy. My job is Deputy Assistant Administrator for NOAA Research. And I thank you for inviting me to discuss the key role that NOAA has played in improving understanding and prediction of climate through the use of models.

Advancement of the scientific community's knowledge and understanding of the way our planet's climate system works comes from three steps. One of them is that we improve our observations. Second, we improve our understanding, and third, computer modeling. It is like a three-legged stool—observations, theory, and modeling—that together provide the foundation for our understanding of the way the climate system has changed in the past and how it may change in the future.

NOAA proudly notes that the world's first global climate model was created by our scientists at the Geophysical Fluid Dynamics Laboratory, or GFDL. This climate model has been identified in the popular literature as one of the milestones of scientific computing, along with advances like the invention of the hand-held calculator and the Internet.

A climate model really allows us to create a virtual earth in the computer. They divide the Earth into three-dimensional boxes, millions of boxes, that cover the entire Earth—called grid cells. At each of these grid cells, many calculations are performed over and over in order to simulate the processes that are important to climate. The size of the grid cells determines the resolution of the model. The smaller boxes give scientists information that is more refined.

On this poster, what we see is the current resolution and generation of model, and we are looking at precipitation. So it just kind of shows a big general area of precipitation. In reality, we know that in the western United States the mountains all get a lot of precipitation and the valleys do not get so much. And of course, there is a great deal along the coast. In our new model resolution that we would like to run—we see that detail in the precipitation. So this is what we are after, is getting the regional detail correct.

Computer models of the Earth's climate have been central to NOAA's pursuit of its goal to understand climate variability and change and to enhance society's ability to plan and respond. These models have done so well that they have become central to our integrated assessments, such as the 2007 Intergovernmental Panel on Climate Change that is used to inform industrial and government climate and energy analysis. We know that these models are important. They helped us understand that the Dust Bowl of the 1930s was due to ocean temperatures. They helped us to understand the El Niño/La Niña cycle and we are currently learning how the Atlantic Ocean circulation works. It is crucial to our science.

There is an increasing need for the types of information that climate models provide. We have land managers in the western states that are dealing with prolonged periods of drought and requesting long-term regional temperature and precipitation data. The thing that we are after is getting that local scale so that we can help our decisionmakers in transportation, energy availability and for emergency preparedness. This is not just government. This is the public and industry also.

However, today's models are limited in providing the level of climate information by two things. First, there are significant gaps in our understanding of how the climate system works, and second, we are limited by computing. We do not have the computing that we need to do some of these very regional kinds of things. The best of today's climate models really give us information on large geographic scale such as continental scale. These limitations can be addressed to a significant extent by increased access to large supercomputers.

Our vision of a greatly improved climate prediction during the next 5 to 10 years would require approximately 100 times as much computing power over what is currently available.

Climate models are crucial to providing reliable information on climate variability and change. More accurate projections of future climate will contribute to improved preparation at the Federal, State, and local levels and by the public and by industry.

I look forward to working with the Committee.

[The prepared statement of Dr. MacDonald follows:]

Prepared Statement of Dr. Alexander (Sandy) MacDonald, Deputy Assistant Administrator for Laboratories and Cooperative Institutes, Office of Oceanic and Atmospheric Research, NOAA, U.S. Department of Commerce

Introduction

Good afternoon, Mr. Chairman and Members of the Committee. I am Alexander MacDonald, Deputy Assistant Administrator for Laboratories and Cooperative Institutes in the Office of Oceanic and Atmospheric Research at the National Oceanic and Atmospheric Administration (NOAA) in the Department of Commerce. Thank you for inviting me to discuss climate modeling and NOAA's key role in improving the understanding and prediction of global climate and how it is changing.

NOAA's mission is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs. In support of the mission, NOAA researchers develop and use mathematical models and computer simulations to both improve our understanding and prediction of natural climate variability, as well as to identify and predict climate change. Climate models help create an informed society that uses a comprehensive understanding of the role of the oceans, coasts, and atmosphere in the global ecosystem to make the best social and economic decisions. The ongoing pursuit of these objectives—of increasing our knowledge of the complex global climate system and communicating the relevant information to stakeholders—is summarized in NOAA's climate goal "to understand and describe climate variability and change so as to enhance society's ability to plan and respond."

Today, I will be discussing the societal demands for climate change information, how climate models are used to meet these demands, and how the Nation benefits by improving climate models.

Societal Demands for Climate Change Information

Climate variability and change can have a profound influence on society. Recent evidence of global climate change includes multi-year droughts, warmer global surface temperatures, accelerating sea level rise, decreasing Arctic sea ice, retreating glaciers, the acidification of our oceans, and shifts in ecosystems.

Federal, regional, state, and local decision-makers need credible climate information at increasingly finer geographic scales to adapt to and mitigate climate variability and change on time scales from seasons to centuries. Land managers in western states dealing with drought have requested long-term regional temperature and precipitation data, along with easily accessible and understandable tools for decision-support. Resource managers from numerous Federal agencies have requested site-specific information to help plan for and manage the effects of climate change. Regions and municipalities have requested local information about climate change to improve long-term decision-making on transportation, energy availability, and for emergency preparedness.

A broad scope of industries face operational challenges due to climate variability and change, including: utilities; integrated oil and gas; mining and metals; insurance; pharmaceuticals; building and construction; and real estate. Our understanding of how climate change impacts U.S. fisheries and the health of the world's ocean ecosystems will aid in effective long-term fleet planning and enhance the security of the Nation's food supply.

More accurate predictions of future climate will contribute to improved preparation for and response to phenomena such as drought, hurricane activity, coastal inundation associated with storms and sea level rise, heat waves, poor air quality, and forest fires. The Nation's scientific community can provide this key information with comprehensive, state-of-the-art climate models (with related computational and data storage capabilities), that continue to advance the understanding of climate change and its potential consequences at local to global scales.

Using Climate Models to Meet Societal Demands

Climate Modeling to Inform Society

Many advancements in the scientific community's knowledge and understanding of the way our planet's climate system works come about via a synthesis of improved observations, advancements in theory, and computer modeling. Like a sturdy three-legged stool, observations, theory, and modeling together provide the foundation for our understanding of the way the climate system has changed in the past, and how it may change in the future.

Why are climate models so important for providing reliable information on climate change? Science generally proceeds from observations to theory, then to experiments to verify the theory's predictions against the observations, and finally further refinement or even refutation of the theory. In order to perform experiments, we need to replicate the system being studied. This poses a problem for the study of the Earth's climate, for there is only one Earth! The use of a computer model of the Earth—a "virtual Earth"—allows us to perform "climate experiments." Other fields in which it is expensive or dangerous to perform real experiments make similar use of computer simulation. Car design is a good example—most designs are tested for aerodynamic efficiency and crash testing on a computer, before a design ever makes it to the shop floor. The design of nuclear weapons is another excellent example; given the ban on tests of these weapons, the United States is devoting significant resources to develop the ability to model nuclear detonations.

Climate science and computer modeling of the Earth's climate have advanced greatly since the world's first coupled atmosphere-ocean global climate model was created in the late 1960s. At NOAA we proudly note that the world's first such climate model was created by scientists at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The esteemed journal *Nature* identified this first climate model as one of the "Milestones of Scientific Computing"—along with advances like the invention of the handheld calculator, the Internet, and CT scanners.

Over the last four decades, climate models have improved as both scientific brainpower and high performance computing have been devoted to this work. During that time, climate modeling has gone from being of interest primarily to a fairly small segment of the scientific and academic community to being of great interest to a broad section of society—here in the United States and around the world. More than fifteen climate modeling centers now exist, including those run by NOAA partners at the National Science Foundation's National Center for Atmospheric Research (with additional support from the Department of Energy), and the National Aeronautics and Space Administration. NOAA has remained at the forefront of climate modeling through this transition. This is evident in NOAA/GFDL having produced not one, but two of the premier global climate models that played an integral role in last year's influential report issued by the Intergovernmental Panel on Climate Change (IPCC), for which the IPCC shared the 2007 Nobel Peace Prize.

The best of today's climate models are most reliable on relatively large geographic scales (*i.e.,* for regions comparable in size to a third of the contiguous 48 states, or larger), with increasing uncertainty associated with climate projections on smaller scales. Those climate model results are being used now for an increasing range of applications. Projected changes in surface temperature and precipitation patterns, storm tracks, ocean currents, and Arctic sea ice are only a few of the aspects of climate being examined intensively by experts in the academic, government, and private sector communities. The customer base for high-quality climate model results is rapidly increasing. At NOAA we actively support these efforts by making large amounts of our climate model output freely available. Consistent with the U.S. Climate Change Science Program's (CCSP) strategic plan, anyone can go to NOAA websites and download data files that document many of our climate model results. In this way, the output of NOAA's climate models becomes input into climate impact studies and assessments.

However, the demand for scientifically credible projections (based on variable greenhouse gas scenarios) of future climate change goes beyond what currently can be offered. Today's models are limited in two primary aspects: (a) there remain significant gaps in our understanding of how the climate system works, and (b) models are constrained by available computing. This latter limitation means that while these models are at their best in simulating climate features at scales of several hundred miles and larger, there is increasing uncertainty in their simulation of smaller scale climatic features. In addition, some of the processes operating in the climate system on small geographic scales are missing, and yet these processes may be important for large-scale climate. Both of these limitations can be addressed to a significant extent through the use of very large supercomputers. As an additional benefit, access to advanced supercomputers makes it easier for NOAA to attract and retain the world's best climate scientists, to run models that resolve phenomena at the scale of a single state or even city.

What is a Climate Model?

Climate models divide the three-dimensional global ocean and atmosphere into millions of boxes referred to as grid cells. At each of those grid cells many calculations are performed over and over again in order to simulate the time evolution of processes important to the climate. The number and size of a climate model's grid cells are largely determined by the amount of computer resources available; more, smaller boxes results in more calculations which require more computing power. Higher geographic resolution (more, smaller boxes) are desirable for climate models for much the same reason people prefer the picture quality of a high definition TV as compared to a grainy YouTube video: higher resolution provides a more detailed representation of the features in which we are interested, which benefits both scientific researchers and stakeholders. As a point of reference, in NOAA's recent climate models atmospheric grid points were of a size such that one box's surface area covers about twice the land surface area of the Commonwealth of Massachusetts. That means Maine is covered by two boxes, North Dakota and Washington State by about 4 each, and Texas by 13. Since it takes several grid boxes to properly define or resolve a pattern, we can say that today's global climate models are limited in their ability to fully resolve features on spatial scales much less than the size of the 48 contiguous states.

We test our understanding of climate, as expressed in a computer model, by comparing how well that model does against observations of past climate. For instance, we might initialize our model of the Earth's climate with its known state in, say, 1750—the "preindustrial" climate, then apply the history of all the known external forces on the climate—solar variability, volcanoes, industrial emissions, land use changes—and see how well we do in predicting the known history of the 20th century climate. Our successes and failures help us refine our theories and our understanding. It is possible to "tune" a model to perform well against a given metric of skill—say the global mean surface temperature but we use a wide range of metrics (*e.g.,* temperature, rainfall patterns, number of storms, wintertime snow cover, etc.)—and the only way to do well against a diverse and comprehensive set of metrics is to represent the physical climate system with fidelity.

Models of the Earth system have many components and feedback loops. Today's models include interactions among many components, including the ocean, atmosphere, sea ice, vegetation, ecosystems, and reactions between natural and industrial chemicals in the atmosphere. With increasing complexity, new challenges appear. For example, a key research area in the current generation of climate models is to capture the effect of aerosols, which include industrial pollutants, soot, dust, and sea spray on climate. Aerosols block sunlight directly, but they also impact the formation of clouds, a key player in the climate system. Progress in this key topic is delayed because our ability to represent such computationally expensive climate processes in our models has outpaced the available computing resources on which to run them.

Current Modeling Capabilities and Achievements

Computer models of the Earth's climate have been central to NOAA's pursuit of its goal to "understand climate variability and change and enhance society's ability to plan and respond." These models have done so well over time that they have now become central to the integrated assessments that are used to inform industrial and governmental climate and energy policy. The leading international assessments such the IPCC, and focused products from the CCSP, both synthesize results from computer models to answer key questions asked by policymakers.

At the time of the first IPCC report in 1991, NOAA/GFDL's model was one of the few models capable of producing reasonably realistic simulations of the Earth's climate. Since then, several centers around the world have developed climate models, and the assessment reports are now based on "model intercomparison projects," where coordinated computations are independently run by different centers around the world. It is a testimony to NOAA/GFDL models' pre-eminence in the field that in 2007, at the time of the IPCC Fourth Assessment Report, they are still seen as being at the very apex of climate modeling, on the basis of independent evaluations of their performance against a wide range of metrics of skill.

Specific achievements of NOAA's current climate models are manifold. NOAA climate modeling has helped demonstrate that the U.S. Dust Bowl in the 1930s and the drought in the African Sahel of the 1980s were both caused in part by changes in the temperatures of the oceans. Our current understanding of El Niño and of how El Niño affects the U.S. climate is based in large part on NOAA research with climate models. NOAA climate modeling first pointed to the importance of the circulation of the Atlantic Ocean as a potential source for abrupt climate change. Further, NOAA models have clarified the competition between warming due to increasing concentrations of long-lived greenhouse gases and cooling due to short-lived atmospheric particles generated by human activity.

NOAA models have also been major contributors to the most recent Ozone Assessments conducted by the World Meteorological Organization (WMO), evaluating the response of the Antarctic ozone hole to the reductions in the emissions of chlorofluorocarbons that followed the Montreal Protocol and projecting the future evolution of the ozone shield. NOAA has also developed climate models with higher geographic resolution that are currently being used to develop climate change projections over North America, as part of the North American Regional Climate Change and Assessment Program.

The computer models themselves represent an important NOAA product. NOAA/GFDL's Modular Ocean Model (MOM) is the world's most widely used numerical model for simulating ocean circulation at the global scale and for understanding and predicting ocean climate phenomena. Significant recent advances include the ability to directly predict sea-level changes as well as improved representations of the complex features of the ocean's heat and chemical distributions. Over 400 scientists around the world are now using MOM to perform oceanographic, weather, and climate studies. It is used for operational weather forecasting at NOAA's National Weather Service.

Benefits from Improving Climate Models

NOAA's state-of-the-art climate models were used extensively in the latest IPCC assessment, the most recent WMO ozone assessment, and the ongoing North American Regional Climate Change Assessment Program. But despite recognition from independent experts as being among the highest quality climate models in the world, the models are not able to meet the growing suite of societal demands for climate change predictions. Current models are limited by some remaining gaps in our understanding of how the climate system works, and in computer resources. The lack of adequate computer power prevents us from making optimal use of existing knowledge by extending our simulations to smaller geographic scales and including a more complete set of climate processes.

An example of a gap in understanding that is holding back progress in climate modeling is our lack of understanding of the Greenland and Antarctic ice sheets, a major source of uncertainty in predicting the future sea level. Recent observations have highlighted the potential for rapid changes in the ice sheets and the inadequacies of current theories of ice sheet dynamics. Coordinated progress will be needed in ice sheet observations, a buildup of the human capacity in this research field, and experimentation incorporating new models of the ice sheets into our climate models. Another key gap is our inadequate understanding of the factors that control the Earth's cloud cover and how it might change as the Earth warms. This gap is a key source of uncertainty in predicting the magnitude of the warming resulting from a given change in atmospheric carbon dioxide.

Improving understanding on such central questions is fundamental to progress, and we are confident that our climate models will improve as they begin to explicitly resolve smaller geographic scales. The scales that our models resolve are determined by the available computer resources. With currently available computer resources, our models are most reliable at simulating climatic features with geographic scales of several hundred miles and larger, with increasing uncertainty in the simulation of smaller scale phenomena. The following are some of the benefits related to the inclusion of smaller scale processes in models:

1. Projections of temperature and precipitation on smaller scales than those currently resolved adequately by climate models to aid decision-makers and planners at the regional and local levels. For example, trends in many local water resources are affected by small-scale topographic features and land-use patterns that are not represented in current climate models.
2. Many of the greatest effects of climate change may come about through changes in extreme events, such as hurricanes, heat waves, droughts, and floods. The climate models used in the recent IPCC assessment do not provide adequate simulations of hurricanes, for example. Other extreme events, such as droughts and floods, are strongly influenced by small-scale processes that are not well resolved in these models.
3. It is likely that small-scale ocean currents and other ocean processes may play a crucial role in the future behavior and stability of the Antarctic and Greenland ice sheet, with large potential influences on sea level rise.

4. The response of ecosystems to climate change, including the cycling of carbon through the system, is highly uncertain in current models. This is strongly influenced by limited computational resources, preventing the inclusion of important small-scale processes, such as intense ocean upwelling near the coasts, which are crucial to the global cycling of carbon.

5. Improved predictive capability to support integrated national air quality policy and regional emission management strategies for air quality and climate. The prediction of climate change impacts on air quality could be better assessed by including smaller scale processes into models.

Pathways to Climate Model Improvements

The next generation of climate models that explicitly include smaller-scale processes has been developed in NOAA. Prototypes of these models have been tested, but computer resources in NOAA are inadequate to use these models for the comprehensive simulations of climate change that are necessary to provide stakeholders with robust predictions of climate change. We cite here two examples of next generation models that have been developed but are too computationally expensive to run extensively given current resources:

1. A new climate model has been developed that resolves important ocean features on scales as small as 20 miles (*Figure 1*). For comparison, models used in the most recent IPCC assessment resolve ocean features on scales of 200–300 miles. The inclusion of the small-scale ocean features may produce large improvements in understanding how ocean circulation responds to global warming, with major climatic impacts. This includes how much carbon dioxide the ocean will absorb (or outgas) in the future, the response of marine ecosystems to global warming, how El Niño will respond to global warming, and the potential for abrupt climate change due to changes in the circulation of the Atlantic Ocean.

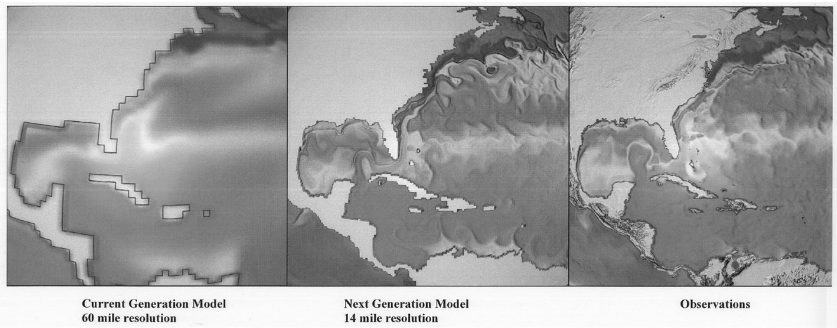


Figure 1. A new climate model has been developed that resolves crucially important ocean features on scales as small as 20 miles. Application of this model for comprehensive climate change predictions would deliver much more credible predictions of the ocean's response to global warming, including the effect on marine ecosystems, carbon uptake, and ocean acidification.

Application of this model for comprehensive climate change predictions would deliver much more credible predictions of the ocean's response to global warming, including the effect on marine ecosystems, carbon uptake, and ocean acidification. This would also greatly improve the prediction of decadal scale changes in the ocean that may strongly influence hurricanes and droughts, as well as predictions of Arctic climate change and sea ice. However, NOAA does not currently possess the computational capability to use this model. Applying this model for the next IPCC assessment report would require approximately 10 times NOAA's current computing resource, which is comparable to the largest machines in the United States. NOAA does not now have access to these systems.

2. A global atmospheric model is being developed that resolves processes on a geographic scale of about 10 miles. A regional version of this model faithfully simulates Atlantic hurricane activity (*Figure 2*). The global version will simulate important high impact climate phenomena and small-scale variations of rainfall around the world. Use of such a model for comprehensive predictions of climate change would increase our confidence in the prediction of how hurricanes will change in the future. This model would also be a great improvement in our ability to predict regional climate change over the United States, including such features as future changes in western U.S. snowpack with associated

water resource implications (*Figure 3*). The output from this model would be of substantial value across a wide suite of applications, from water resource and infrastructure development to agricultural planning.

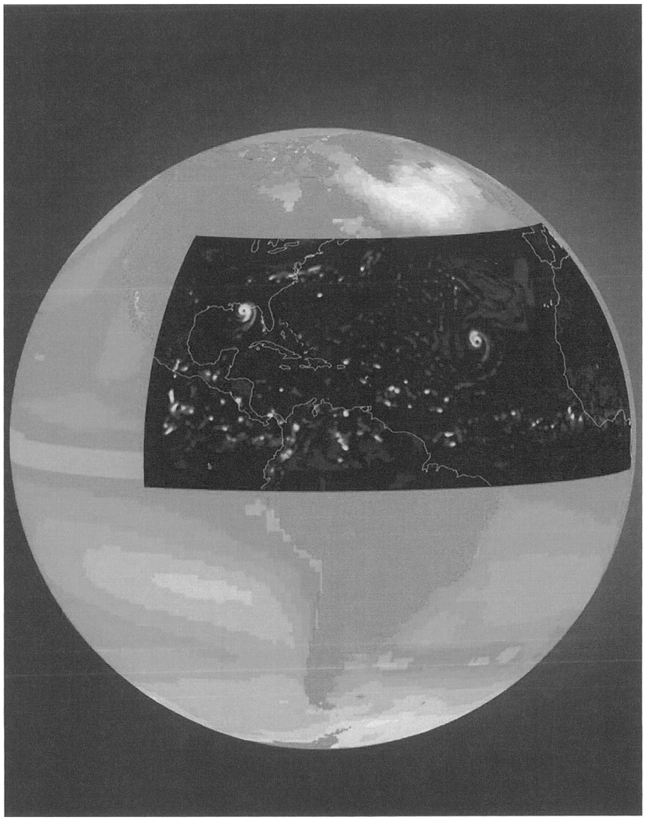
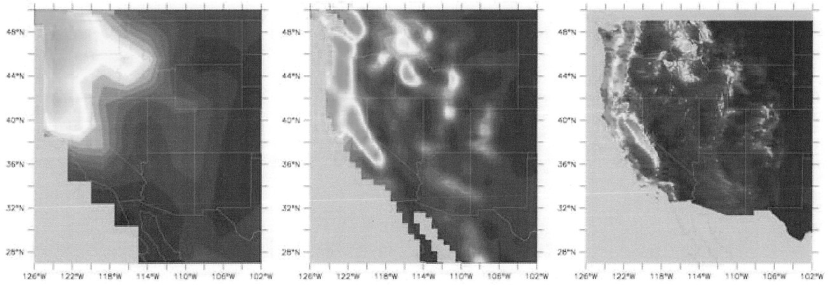


Figure 2. A regional version of a global model with 10 mile resolution can faithfully simulate Atlantic hurricane activity. The global version will simulate important high impact climate phenomena and small-scale variations of rainfall around the world.



Current Generation Model
120 mile resolution

NARCCAP Model
30 mile resolution

Observations

Figure 3. A prototype model with a resolution of 30 miles was used to support the North American Regional Climate Change Assessment Program (NARCCAP) and simulates substantially more of the features in the precipitation field in the western U.S. than do current models. A global model with 10 mile resolution is expected to improve the capture of the amount, timing, location, and type of precipitation in order to better predict water resource issues arising in the western U.S., a key concern that has been identified by NOAA customers.

> The use of this model in comprehensive climate change predictions would provide climate change predictions on geographic scales of ten to twenty miles. However, it would require approximately 50 times NOAA's current computing capability to apply this model to the next IPCC assessment report. Although this level of computing corresponds to roughly half of the Nation's entire research high performance computing capacity, a limited set of climate integrations with this model could be used to advance our understanding of how climate change affects high-impact phenomena.

These fine resolution oceanic and atmospheric climate model components will advance our understanding of and ability to predict climate. But our ambition is to combine them into a fine resolution coupled climate prediction system that is commensurate with the requests of policymakers and stakeholders at the regional and local levels. In the next 5–10 years, NOAA will work toward advancing the fidelity and utility of our climate models and combining the advantages of finer resolution in both the oceans and the atmosphere while fully capturing their complex interactions. Fulfilling such a vision would require approximately 100 times as much computing power as is currently available.

Conclusion

We now have a deeper understanding of the climate system and the delivery of climate information to the Nation as a direct result of NOAA scientists and their collaborators using high performance computing for numerical simulation. Climate models have demonstrably improved our ability to simulate the Earth's climate. However, the demand for scientifically credible projections of future climate change goes beyond what currently can be offered. Scientific advancements and the generation of new climate information products that arise from better climate models are intimately tied to the state-of-the-art computers that are devoted to running them. NOAA is poised to run advanced climate models that resolve regional scale features in the atmosphere and ocean, incorporate the effects of chemistry and aerosols on climate, and provide long lead-time predictions of high-impact climate phenomena such as drought and hurricane activity.

Thank you again for inviting me to discuss climate modeling and NOAA's key role in improving the understanding and prediction of global climate. Robust climate models help NOAA to provide reliable information on climate change. Many advancements in the scientific community's knowledge and understanding of the way our planet's climate system works have come about via a synthesis of improved observations, advancements in theory, and computer modeling. I look forward to working with the Committee on any further information you may require for your deliberations on this topic.

Senator KERRY. Thank you, Doctor.

Dr. Hack?

STATEMENT OF JAMES J. HACK, PH.D., DIRECTOR, NATIONAL CENTER FOR COMPUTATIONAL SCIENCES, OAK RIDGE NATIONAL LABORATORY

Dr. HACK. Thank you, Senator Kerry, and Vice Chairman Stevens, for the opportunity to speak with you today on ways to improve the capacity of U.S. climate modeling. My name is James J. Hack and I serve as Director of the National Center for Computational Sciences, which is located at Oak Ridge National Laboratory, and provides the most powerful computing resources in the world for open scientific research. One of the prominent NCCS research focus areas is the exploration of the Earth's climate system and climate change.

There are many scientific and technical challenges related to monitoring, understanding, predicting, and adapting to climate change. Observations of the climate system are the foundation for our improved understanding of climate change and for building the computer models that are used to project the evolution of the climate system. Computational research associated with the modeling and prediction of Earth's climate includes developing methods for simulating complex multiphase flow over a wide range of scales with high fidelity, with high efficiency on the most powerful supercomputer systems available, and in a software environment that needs to continually incorporate new knowledge and new theoretical concepts into the models.

State-of-the-art climate models embody our best understanding of the many complex processes that are central to the climate system. The goal of such modeling efforts is to accurately represent the collective behavior of these processes as an interactive system. The models are continually developed, tested, and evaluated against observations. They are the best available tools for exploring how the climate system works and how it is likely to evolve.

Despite their imperfections, climate models are remarkably capable of reproducing the climate of the past, which builds confidence in their projections of future climate. They are also remarkably consistent in their projections of continued warming of the climate system for the remainder of this century, which was more completely discussed in the Fourth Assessment Report of the U.N. Intergovernmental Panel on Climate Change. The release of the IPCC report signaled that the detection and attribution of climate change at global scales has essentially been resolved.

So the community is now faced with a new set of urgent problems relating climate change to human health, water resources, food supplies, and changing risks to manage the natural ecosystems. Central to these problems is the demand for much more regional detail about climate change on time scales of resource and infrastructure planning. In order to address these issues, along with important questions on mitigation and adaptation strategies, the climate community needs to develop and undertake a new coordinated research program that is balanced and integrated among observation, theory, and computation.

Meeting these future challenges will require advances in every aspect of the models' theoretical, observational, and computational foundation. Many of society's questions will require the development of a new generation of more comprehensive climate models, frequently referred to as Earth System Models, that predict the coupled chemical, biogeochemical, and physical evolution of the climate system. Addressing the science issues will require new observations and new methods of analysis, new theoretical understanding, and new features and models of the earth system that include the interactions between human and natural systems. These models will play an important role in synthesizing a broad range of observations and projecting the future responses of human society and the natural world to the evolving climate regimes.

The models will also need to be exercised at unprecedented high resolution. The needed increases in complexity and resolution will require transformational changes in computational capability. A flexible leadership-class computational science infrastructure will continue to be essential to making these advances possible.

So in conclusion, there is no single pacing item to the advancement of climate change science, but a collection of interrelated science and technology challenges. Many of the issues discussed in this testimony speak to the need for a balanced investment in computational infrastructure, climate science and modeling, climate observations, computer science, and applied mathematics. In the short and long term, computational capability remains a significant bottleneck and should remain a high priority investment.

But as the science and complexity of climate simulation continues to grow, so will new technical and scientific challenges. Proactive investments in climate modeling science, software, algorithms, data management, and other pacing items will ensure that scientific progress can keep pace with the rapidly evolving computational environment. Strategic programmatic management of such a broad multidisciplinary activity will also likely prove to be the most effective way to ensure that any new investments have the desired impact on accelerating progress.

This is an exciting opportunity for the Nation to lead the world in developing a better understanding of the consequences of climate change. Thank you again for the opportunity to address the Committee, and I look forward to answering any questions.

[The prepared statement of Dr. Hack follows:]

PREPARED STATEMENT OF JAMES J. HACK, PH.D., DIRECTOR, NATIONAL CENTER FOR COMPUTATIONAL SCIENCES, OAK RIDGE NATIONAL LABORATORY

I thank Chairman Inouye, Vice Chairman Stevens, and the other Members of the Committee for the opportunity to speak with you today on ways to improve the capacity of U.S. climate modeling for decision-makers and other end-users. My testimony draws on over two decades of developing global models of the climate system at the National Center for Atmospheric Research. My name is James J. Hack and I currently serve as director of the National Center for Computational Sciences (NCCS) at the Oak Ridge National Laboratory (ORNL). The ORNL NCCS provides the most powerful computing resources in the world for open scientific research. It is one of the world's premier computational science research environments supporting advances in our understanding of the physical world and using that knowledge to address our most pressing national and international concerns. My role as NCCS Director provides a unique perspective on how the application of leadership-class computing technology in a computational science partnership with scientific investigators can radically accelerate basic progress for a variety of extremely demanding scientific domains. Examples of NCCS research focus areas are the simulation of complex biomolecular systems with applications to pharmaceuticals as well as more efficient biofuel generation, simulations that investigate the fundamental properties of materials, such as high temperature superconductors, and simulations exploring the processes that maintain and regulate Earth's global climate system.

There are many scientific and technical challenges related to monitoring, understanding, predicting and adapting to climate change, especially on local and regional scales. Observations of the entire Earth, for instance, are the foundation for improved understanding of climate change and for computer models that accurately predict weather and climate. A newly emerging issue is the development of optimal methods for assimilating this broad range of physical, chemical, and biogeochemical observations into models of the Earth system in order to more completely describe the current state of the system. This is but one example of how the synthesis of models and observations is critical both for understanding the present climate and for simulating its evolution over the next several decades. Computational research associated with the modeling and prediction of Earth's climate system includes developing methods for simulating complex multiphase fluid motions over a wide range of scales with high fidelity and with high computational efficiency, as well as by the need to continually incorporate new theoretical and observational knowledge into global models. The rapid evolution of computer architectures creates its own challenge to fielding stable computational environments that support Earth system science.

State-of-the-art climate models, such as those developed by NSF, NOAA, DOE Office of Science, and NASA programs embody our best understanding of the physical and biogeochemical processes that are central to the climate system. The goal of such modeling efforts is to accurately represent the collective behavior of these climate processes as an interactive system. These models are continually developed, tested, and evaluated against observations. Although they are the best available tools for exploring how the climate system works, they are not perfect. Uncertainties arise from shortcomings in our scientific understanding of the climate system, and in identifying the best mathematical approaches for representing those processes we do understand in numerical models.

Despite these imperfections, climate models are still able to reproduce the climate of the past, which gives considerable confidence in their ability to simulate changes in future climate. For instance, climate modelers are able to test the role of various forcings in producing observed changes in climate over the past century. Such simulations have now reliably shown that global surface warming of recent decades is a response to the increased concentrations of greenhouse gases in the atmosphere. They are also remarkably consistent in their projections of continued warming of the climate system for the remainder of this century, as discussed in the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC). The release of the IPCC AR4 report, along with release of a series of Climate Change Science Program (CCSP) reports, signal that the detection and attribution of climate change at global scales has essentially been resolved. The global community is now faced with a new set of urgent problems relating climate change to human health, water resources, food supplies, changing risks of forests to fires and insect disease, and threats to managed and natural ecosystems. Central to these problems is the demand for much more regional detail on climate change on the time scales of resource and infrastructure planning. In order to address these issues, the community needs to develop and undertake a coordinated research program balanced and integrated among observation, theory and computation. Meeting future challenges in climate change science will require qualitatively different levels of scientific understanding, modeling capabilities, and computational infrastructure than are currently available to the climate science community. Many of society's questions will require the development of a new generation of more comprehensive climate models, frequently referred to as Earth System Models (ESMs) that predict the coupled chemical, biogeochemical, and physical evolution of the climate system. These models will also need to be exercised at unprecedented high resolution. The needed increases in complexity and resolution will require transformational changes in computational capability.

Over the last 30 years, modeling capabilities have advanced considerably in their treatment of complexity, and the ability to treat ever finer scales of motion. Modern atmospheric models represent the observed equator to pole energy transport much more realistically than did earlier model generations. They also do a much better job of representing many detailed features of the observed mean climate state. These improvements have meant that global climate models are now routinely run with fully-interacting atmosphere, ocean, land surface, and sea ice components. These more realistic and complex models can now not only simulate observed changes over the past century in global mean climate, but also climate variability and change on continental scales. This includes the attribution of many of the observed large-scale changes in indicators of climate extremes consistent with a warming climate, such as the annual number of frost days, warm and cold days, and warm and cold nights. Models that contributed simulation results to the IPCC AR4 also generally agree that regions like the subtropics will dry, including the U.S. Southwest, while polar latitudes will receive more precipitation related to large changes and shifts in the extratropical storm tracks.

On finer spatial scales, however, state-of-the-art climate models don't always agree on projected climate change impacts, either on decadal or longer time scales. It is also not clear that they can accurately project changes in extreme events, or can reliably simulate changes in low-frequency climate variability or the likelihood of abrupt change. Near-term investments in the climate science enterprise could lead to a significant quantitative improvement in the scientific community's ability to address these difficult but societally relevant questions, leading to improved guidance to policymakers and stakeholders charged with developing strategies for adapting to climate change.

One immediate scientific challenge and opportunity is the incorporation of chemical and biogeochemical processes in climate models. The science surrounding the chemical and biogeochemical coupling of climate has become central to answering climate change questions, particularly those associated with the global carbon cycle. Addressing the science issues will require new observations and methods of analysis, new theoretical understanding, and new models of the Earth system that include the interactions between human and natural systems. These models will play pivotal roles in interpreting the paleoclimate records, in synthesizing and integrating observational measurements to study the current carbon cycle, and in projecting the future responses of human society and the natural world to evolving climate regimes.

Another example of a pressing scientific challenge is the rate of sea level rise and the impact of that rise on coastal communities. Recent observations indicate ice sheets can dissipate on much more rapid timescales than from melting alone due to dynamical processes in large outlet glaciers and ice streams within the ice sheet. Faster disintegration of the ice sheets will contribute to faster sea level rise and will pose a greater risk of abrupt changes in the climate system. Abrupt climate change can also result from thresholds and nonlinearities in the response of climate to slower time scale forcing of the climate system. Examples include rapid changes in ocean circulation, large scale vegetation mortality and succession, release of methane frozen in ocean and permafrost, and megadroughts. The climate community will need to use models to identify thresholds of forcing in the climate system and explore the likelihood and impacts of such scenarios. The community's efforts to advance climate modeling and its application to science and technology options for mitigation and adaptation will require advances in essentially every aspect of the models' theoretical, observational, and computational foundation. Quantifying uncertainties in predictions will require a new level of integration between modeling and observational science. New mathematical methods and algorithmic techniques will also be required to address the fundamental challenges of multi-scale coupling of physical, dynamical, chemical and biogeochemical processes. A flexible leadership-class computing infrastructure has been and will continue to be a key factor in making these advances possible.

As mentioned earlier, today's climate models are in strong agreement that global and continental-scale temperatures will continue to rise as a result of human activities. However, it is also important to improve our understanding of the likely changes in regional climate over the next few decades. Climate forecasts on decadal time scales are governed primarily by the history of the ocean circulation and the current atmospheric forcing. Therefore, climate forecasts on these time scales will require retrospective analyses of the global oceans to be able to accurately initialize the forecasts. The ocean is responsible for much of the inertia or near-term "memory" in the climate system. The development of ocean data assimilation techniques, largely an applied mathematics and algorithmic challenge, will be necessary to provide an initial ocean state for decadal prediction and represents a pacing item for seasonal, inter-annual, and decadal prediction. While assimilation has been extensively developed and used in the weather community, the climate community will need to evaluate which assimilation methodology is best suited for climate simulation and the creation of realistic initial states for climate change scenarios. Optimal interpolation and simple methods have so far been adequate for the ocean due to sparseness of data, particularly for salinity and for ocean properties at depths below 1000m. With the influx of new ocean data sets, advanced techniques will need to be examined. Recent progress in deploying large numbers of floats and the launch of new satellites that together will measure salinity profiles will greatly improve our ability to effectively constrain ocean models with assimilation. For example, assimilation of data from ARGO floats with a fully coupled climate model has shown great promise in determining the state of the climate system, although the assimilation process is extremely computationally demanding.

Accurate projections of changes in the frequency of climate extremes at relatively high geographic and temporal resolution will be essential for the development of robust adaptation strategies. However, current climate models have been designed primarily to predict patterns of change at a coarser level. Much more research is required to understand how increasing model resolution and employing increasingly sophisticated parameterized treatments of non-resolvable processes may affect the ability of models to more accurately simulate changes in local extremes. In particular, the relationships between extreme statistics and synoptic-scale low-frequency variability are not understood.

A better understanding of low-frequency variability is critical for the detection of climate-change signals. For Earth system modeling, it is important to characterize the natural modes of coupled variability in the carbon cycle, terrestrial ecosystems, and dynamic vegetation. It is also important to develop a better understanding of external forcing mechanisms, such as the role of solar variability in the broader context of the Sun-Earth system. Current understanding of these complex systems is limited by the length of the observational record. The wide dynamic range in the relevant space and time scales further complicates the coupling issues. New mathematical methods designed for multiscale systems hold promise for this class of problems, and these methods should be explored for efficient implementation in next generation models.

As suggested earlier, a large number of significant impacts could follow from abrupt changes in the climate system. These occur when the gradual increases in climate forcing trigger an abrupt transition of the coupled system to a new state. Potential examples of abrupt change include dynamic dissolution of the ice sheets and bifurcations of the ocean circulation system. Characterization of abrupt climate change requires a new paradigm for climate change modeling, one in which the models are integrated over the full range of uncertainties in forcing and parameterized physics. Exploration of this phase space will require implicit formulations of the coupled system designed for fast equilibration combined with new mathematical techniques and a *sustained* petascale computing capability.

Multiscale interactions also complicate treatment of the climate system. As with the broader issues of climate variability, process-level understanding of things like the water cycle is limited by the lack of basic observations. While the absence of these data still represents a barrier to progress, near-term enhancements in computational capacity would permit the resolution of fundamental phenomena at the process level. Targeted investments in observational programs can provide much of the necessary data to validate high-resolution process modeling studies of critical topics like aerosol-cloud interactions, central to the climate model sensitivities that lead to discrepancies in projections of future climate on century-long time scales.

Finally, there are significant software and computational hardware infrastructure challenges pacing progress in climate science. Many scientists have found the growing requirements to support the software on high performance computers as a distraction from the central scientific goals of improving climate models and answering fundamental questions about climate feedbacks and variability. This drawback is offset by the new scientific opportunities provided by dramatic increases in computational power. This becomes an issue of scientific productivity. What is needed is a software framework that not only scales from desktop to petascale, but also that supports multi-scale model development and process integration. As a closer connection with observational data and process studies is required to advance the science of regional climate prediction, the software must also become more closely integrated and supported across scales. A flexible and powerful software development environment will increasingly be required to support data assimilation and other data intensive frameworks. The limitations of existing software environments have emerged as key bottlenecks to progress where near-term investment would have important scientific payoffs.

There are real opportunities to invest in climate change science to improve the utility of global models for decisionmakers and the broader end-user community. High impact opportunities for investment include computational facilities, theoretical efforts associated with model development, targeted observational programs and the development of novel computational algorithms. Investments in modeling will accelerate progress on improving the predictive skill of global climate models. The climate community needs to develop a new generation of Earth System Models based upon new and expansive requirements including the ability to more accurately reproduce major modes of natural variability, incorporating functionality for decadal-scale ensemble forecasts at very high spatial resolution, the flexibility to incorporate new data on the physical, chemical, and ecological climate system in the form of process representation (thereby increasing the fidelity of climate simulations), stronger connectivity with user communities for exploring adaptation and mitigation strategies, and the capability for two-way interactions among emissions, impacts, adaptation, and mitigation.

Modeling over a large range of time scales to fully evaluate the couplings between biogeochemical cycles, chemistry, and ecology will present a significant computational challenge. The growth requirement of characteristic applications of climate change prediction models already more than doubles every year. High-resolution ocean circulation studies and cloud system resolving atmospheric simulations are already pushing the limits of petaFLOP systems that utilize many tens of thousands of processors. As regional climate prediction on decadal to century time scales becomes more important, the required computational power will approach the exaFLOP scale (one quintillion floating point operations per second) that will utilize 100K–1M processors. This will require a continued focus on fielding state-of-the-art leadership class computing facilities so that computational capability does not become a more critical pacing factor. Ancillary investments in software, networking, data storage, collaborative tool, and visualization technologies are necessary for balance. For example, climate science is both distributed and collaborative. As interest in climate science continues to grow and its scope broadens to encompass issues of ecosystem and economic impacts, and the evaluation of mitigation and adaptation strategies, the number of participants will also increase. The overall productivity of researchers and the quality of the research output can likely be improved significantly by the use of advanced collaboration technologies that distribute applications and data across the network. It is easy to project that climate research demands on networks will grow yet further as data volumes increase. With a growing number of participants in the climate science enterprise, and a growing diversity and volume of climate data, the need for new data and network resource management strategies and technologies will emerge. Modern visualization capabilities can also play an important role in the discovery of new scientific results and in the communication of the science to a broader community of stakeholders. For an area like climate modeling this is particularly important because of the societal relevance of our results to policymakers and those concerned about the consequences of climate change.

New observational programs and data assimilation systems represent opportunities to improve our understanding of a variety of physical, chemical, biogeochemical, and ecological processes, reducing key uncertainties in modeling assumptions. Meteorological and oceanic analyses have become important tools for studying the mean state and variability of the current physical climate. These analyses are constructed using a model that is adjusted by incorporating observations during its numerical integration. These analyses have proved particularly useful for understanding the relationship between observations and the underlying dynamics of the climate system. It would be especially valuable to have a comparable analysis of biogeochemical and chemical cycles that could relate local and global biogeochemical processes to more completely describe the state of the global system. However, there are no existing analyses that encompass the physical, chemical, and biogeochemical processes in the climate system. Development of these analyses will require significant investment in assimilation systems for chemical and biogeochemical observations from *in situ* and satellite platforms. Much more advanced models will be required to understand the fidelity of the analysis system, which will further push the sophistication of global modeling activities.

Investments in computational algorithms will increase scientific productivity using leadership-class computers for climate change simulation studies and improved simulation accuracy. There is a broad class of mathematical and numerical algorithms that are ready to be explored for application to the climate problem. For example, there are strong arguments for exploiting higher-resolution variable gridding configurations for the atmospheric component of a climate model. The computational demands of uniform ultra-high resolution configuration of a global atmospheric model would outstrip existing computational capability. An intermediate practical approach to dealing with resolution issues is to use a multi-resolution approach, such as nested refinement. These approaches will allow scientists to improve understanding of the multi-scale interactions in the climate system, to identify those of greatest importance, and to document their effects on climate. Ultimately, such research will help determine the best methods of including these multi-scale interactions in climate models, and it will help differentiate between those processes that can be better or newly parameterized versus those that cannot. Such techniques are already being explored by several research groups including the National Center for Atmospheric Research. With a nested or adaptive resolution approach the computational capability required could be reduced by an order of magnitude or more, and could make the goal of computing with such ultra-high resolution models more feasible. A final example of algorithm opportunities is the need to better characterize the uncertainty in simulation results. Ensembles and basic statistics are currently used to assess uncertainty due to natural internal variability intrinsic to the climate system. More formal methods for verification, validation and uncertainty quantification are needed from the computer science, mathematics and statistical science communities. A particular challenge is the sparse nature of observational data necessary to validate models.

The Nation's climate modeling enterprise is likely to be increasingly driven by the need to obtain scientific results for a large and diverse group of users, including government officials, in a timely fashion. In such an environment, the development of innovative models, algorithms, and software must be managed as a project, as opposed to an open-ended research program. Some aspects of such an approach are well-understood, such as the need for planning, schedule visibility, and milestones. A more difficult problem is the potential dependence of success on delivering high-risk products in models, algorithms, and software on a particular schedule. Many of these products, such as new approximation methods, or new programming models, represent non-incremental departures from the current methods used in production climate models, but may be necessary to achieve National goals. Risk management in such a setting requires careful planning and a close and continuing collaboration between the climate, facilities, applied mathematics, and computer science communities. In addition to the research management needs, there will also be a need to ensure that end-users are sufficiently involved in the prioritization of research efforts, and that the resources and institutions exist to transfer the large volumes of information into the decisionmaking processes of various private and governmental users.

In conclusion, there is no single pacing item to the advancement of climate change science, but a collection of interrelated science and technology challenges. Many of the issues discussed in this testimony speak to the need for a balanced investment portfolio in computational infrastructure, climate science, computer science, and applied mathematics. In the short and long term, computational capability remains a significant bottleneck and should remain a high priority investment. But as the science and complexity of climate simulation grows, so will new technical and scientific challenges. Immediate proactive investments in climate science, software, algorithms, data management, and other pacing items are needed for accelerated progress that can keep pace with the rapidly evolving computational environment. The management of these investments is also critical to success. Strategic management of such a broad multidisciplinary activity will likely prove to be the most effective way to ensure that new investments have the desired impact on accelerating progress.

THE CLIMATE PREDICTION PROJECT

Global Climate Information for Regional Adaptation and Decision-Making in the 21st Century

Challenge

The world recognizes that the threat of global climate change is one of the most important problems facing humanity. To cope with the consequences of climate change, the peoples, governments, and economies of the world must develop mitigation and adaptation strategies, which will require investments of trillions of dollars. The development of science-based adaptation and mitigation strategies will only be possible through a revolution in regional climate predictions.

The Summit

The World Modeling Summit for Climate Prediction was organized to develop a strategy to revolutionize prediction of the climate through the 21st century to help address the threat of global climate change.

Summit Declaration

1. Improved prediction of the changes in the statistics of regional climate, especially of extreme events and high-impact weather, are required to assess the impacts of climate change and variations, and to develop adaptive strategies to ameliorate their effects on water resources, food security, energy, transport, coastal integrity, environment and health.
2. Our current inadequacy in the provision of robust estimates of the risk to society, particularly from possible catastrophic changes in regional climate, is strongly influenced by limitations in computer power and the size of the scientific workforce.
3. Climate prediction is among the most computationally demanding problems in science. It is both necessary and possible to revolutionize climate prediction: *necessary* because of the grand challenge posed by the changing climate, and *possible* building on the past accomplishments of prediction of weather and climate. However, the scientific expertise and the computing capability is not available in any single nation, and a comprehensive international effort is essential. Investing today in climate science will lead to significantly reduced costs of coping with climate change tomorrow.
4. A *Climate Prediction Project* coordinated by WCRP, in collaboration with WWRP and the IGBP and involving the national weather and climate centers should be initiated to provide global climate information for regional adaptation and decision-making in the 21st century.
5. As a part of the Climate Prediction Project, and in addition to enhancing the capacity of the world's existing national climate research centers, a *World Climate Research Facility* (WCRF) for climate prediction should be established that will enable the national centers to accelerate progress in improving operational climate prediction at decadal to multi- decadal lead times, enhancing understanding of the climate system, building global capacity, developing a trained scientific workforce, and engaging the global user community. The WCRF will argue for sustained, long-term, global observations that are needed to initialize, constrain and verify the models. An important component of the WCRF will be an archive of observations and model data with appropriate user interface and knowledge-discovery tools for diagnostic tests.
6. The central component of the WCRF will be one or more *dedicated high-end computing facilities* that will enable the revolution in climate prediction by supporting the model resolution and complexity required for the most advanced and re-

liable representations of the climate system that technology and our scientific understanding of the problem can deliver. This computing capability, with systems at least 10,000 times more powerful than the currently available computers, is vital for regional climate predictions to underpin mitigation policies and local and regional adaptation needs with robust estimates of risk. The computing capability will help advance our understanding of the processes responsible for climate variability and predictability, and provide a quantum leap in the exploration of the limits in our ability to reliably predict climate with a level of detail and complexity that is not possible at the national centers. It will also make it possible to bring to bear the latest and most innovative computer technology on the climate change problem, and provide a common modeling framework through an international computing laboratory and make it possible to conduct specialized experiments to advise decision-making in adaptation, mitigation. This project will permit scientists to strive toward kilometer-scale modeling of the global climate system, which will particularly benefit the simulation and prediction of tropical climate, helping many of the world's developing countries that are especially vulnerable to climate change.

7. The WCRF will make it possible for the first time to deliver climate predictions with a reliable estimate of their uncertainty. To estimate the quality of a climate prediction requires an assessment of how accurately we know the current phase of natural climate variability, on which anthropogenic climate change is superimposed. But also the WCRF will enable the climate research community to assess how model uncertainties limit the skill of climate predictions. All elements of estimating the uncertainty in climate predictions pose an extreme burden on computing resources but also on the availability of observational data.

8. The methodology of initializing weather and short-term climate prediction models with observations must be seamlessly extended to predictions of decadal variations and climate change. The understanding and representation of physical and biogeochemical processes and feedbacks must be improved to make reliable centennial projections.

9. It may be possible that the WCRF will be funded in different ways, *e.g.,* through public-private partnerships with corporate and foundation resources and through governmental treaties and agreements.

The Climate Prediction Project has the potential to help humanity cope with the consequences of climate change.

The lasting legacy of the Project will be to help the citizens of the world in the 21st century.

Senator KERRY. Thanks very much, Dr. Hack.

Dr. Reed?

STATEMENT OF DR. DANIEL A. REED, CHAIR, BOARD OF DIRECTORS, COMPUTING RESEARCH ASSOCIATION (CRA)

Dr. REED. Good afternoon, Mr. Chairman, and Mr. Vice Chairman. I am Daniel Reed, Chair of the Board of Directors of the Computing Research Association and a high performance computing researcher.

Today I would like to make four points regarding the status and future of high performance computing for climate change modeling.

It is clear we now face life and death questions, the potential effects of human activities and natural processes on our climate and their regional impacts. I believe high performance computing and computational science are among our best options to gain that understanding. HPC systems now bring detailed computational climate models to life. However, a recent Department of Energy study estimated that climate modeling could effectively use an exascale HPC system effectively. That is a computer 1,000 times faster than today's most powerful systems, and one nearly a billion times faster than today's PC's.

Why are these climate models so complex? First, one must simulate many years to validate the models against observational data. Second, to understand possible environmental changes, one must model sensitivity to many conditions, including carbon dioxide emissions. Third, to understand the interplay of biogeochemical processes with public policies, one must evaluate model ensembles. And finally, one must study detailed regional effects such as hurricanes and storm surge, not just global ones. And I would add parenthetically that when I was at North Carolina, I spent a great deal of time working on precisely those issues, looking at the regional effects of storm surge and hurricanes.

This leads to my second point, HPC availability for climate studies. In the 1980s, the importance of computing to science and the dearth of HPC facilities for research stimulated creation of the National Science Foundation and the Department of Energy's Office of Science Supercomputing Centers. They now provide much of the U.S. scientific HPC resources, including for climate change. Without question, our HPC infrastructure is enormously greater than 20 years ago, but so too are our expectations and our needs. Equally tellingly, most HPC resources are shared across many scientific disciplines, and only a portion of them support climate change studies.

This brings me to my third point, high performance computing technology trends. Until the mid-1980s, high performance computing was defined by custom designed vector processors, those designed by the legendary Seymour Cray. The ubiquitous PC changed that, creating a new high performance computing model, one based on large clusters of PCs. By analogy, this was a shift from a single bulldozer to 1,000 shovels. However, our 20-year free ride of increasing microprocessor performance, which is to say bigger shovels, has ended, and a second transition, multiple processors per chip, lots of small shovels, is underway. This multicore revolution will be even more disruptive, profoundly affecting the computing industry and, more pointedly, climate researchers. Simply put, we are now suffering the delayed consequences of limited Federal research investment in this domain.

Moreover, the scientific data deluge from new instruments threatens to overwhelm our research institutions and the ability of climate researchers to integrate data with multidisciplinary models.

This leads to my last point, climate high performance computing research and development and procurement models. We must explore new HPC hardware designs that better support scientific and national defense applications, recognizing that the design cost for these systems are rarely repaid by commercial sales. Thus, we must rethink our models for high performance computing research and development and procurement. Simply put, a million rowboats is no substitute for an aircraft carrier.

We also need new programming models that simplify application development for multicore processors. Today climate modeling teams spend inordinate amounts of time tailoring software to HPC systems, time better spent on climate research. Climate analysis also requires diverse investments, as Dr. Hack mentioned. HPC facilities must be balanced with investments in software, storage, algorithms, and tools.

In 2005, I chaired the President's IT Advisory Committee Report on Computational Science and in 2007 co-chaired the President's

Council of Advisors on Science and Technology, PCAST, review of computing research. Both of those reports recommended an interagency strategic road map for research computing and high performance computing infrastructure.

In summary, our challenges are to sustain both the research and the deployment of HPC systems needed to ensure our planet's health.

Thank you very much for your time and attention. I look forward to questions.

[The prepared statement of Dr. Reed follows:]

PREPARED STATEMENT OF DANIEL A. REED, CHAIR, BOARD OF DIRECTORS, COMPUTING RESEARCH ASSOCIATION (CRA)

Good afternoon, Mr. Chairman and Members of the Committee. Thank you for granting me this opportunity to comment on current U.S. computational capabilities and the research and infrastructure needs to support climate modeling. I am Daniel Reed, Chair of the Board of Directors for the Computing Research Association (CRA). I am a researcher in high-performance computing; a member of the President's Council of Advisors on Science and Technology (PCAST); the former Director of the National Center for Supercomputing Applications (NCSA), one of NSF's high-performance computing centers; and Director of Scalable and Multicore Computing Strategy at Microsoft.

I would like to make five points today regarding the status and future of high-performance computing (HPC) for climate change modeling, beginning with the relationship between HPC and climate change models.

1. High-end Computational Science: Enabling Climate Change Studies

We know the Earth's climate has changed during the planet's history, due to the complex interplay of the oceans, land masses and atmosphere, the solar flux and the biosphere. Recently, the U.S. Climate Change Science Program and the Intergovernmental Panel on Climate Change (IPCC)[1] concluded that climate change will accelerate rapidly during the 21st century unless there are dramatic reductions in greenhouse emissions. *We now face true life and death questions—the potential effects of human activities and natural processes on our planet's ecosystem. I believe HPC tools and technologies provide one of our best options for gaining that understanding.*

In 2005, I was privileged to chair the computational science subcommittee of the President's Information Technology Advisory Committee (PITAC), which examined the competitive position of the U.S. in computing-enabled science. In our report, *Computational Science: Ensuring America's Competitiveness,*[2] we noted that

> *Computational science is now indispensable to the solution of complex problems in every sector, from traditional science and engineering domains to such key areas as national security, homeland security, and public health. Advances in computing and connectivity make it possible to develop computational models and capture and analyze unprecedented amounts of experimental and observational data to address problems previously deemed intractable or beyond imagination.*

Computational science now constitutes the third pillar of the scientific enterprise, a peer alongside theory and physical experimentation. This is especially important in a field such as climate change studies, where the models are complex—multidisciplinary and multivariate—and one cannot conduct parametric experiments at planetary scale.

Why then, is HPC especially critical to climate change studies? First, one must simulate hundreds to thousands of Earth years to validate models and to assess long-term consequences. This is practical only if one can simulate a year of climate in at most a few hours of elapsed time. Each of these simulations must be of sufficient fidelity (*i.e.,* temporal and spatial resolution) to capture salient features. Today, for example, most climate models that are run for several hundred to several

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[1] R. Alley *et al, Climate Change 2007: The Physical Science Basis,* IPCC, Working Group 1 for the Fourth Assessment, WMO.

[2] *Computational Science: Ensuring America's Competitiveness* President's Information Technology Advisory Committee (PITAC), June 2005, *http://www.nitrd.gov/pitac/reports/20050609_computational/computational.pdf.*

thousand simulated years do not explicitly resolve important regional features like hurricanes. These are large-scale, capability computing problems (*i.e.,* ones requiring the most powerful computing systems).

Second, to understand the effects of environmental changes and to validate climate models, one must conduct parameter studies (e.g., to assess sensitivity to different conditions such as the rate of CO_2 emissions or changes in the planet's albedo). Each of these studies involves hundreds to thousands of individual simulations. This is only practical if each simulation in the ensemble takes a modest amount of time. These are large-scale, capacity computing problems (*i.e.,* ones requiring ongoing access to multiple, large-scale computing systems).

Third, understanding the sensitivity of physical and biogeochemical processes to social, behavioral and economic policies requires evaluation of statistical ensembles and many model variants. These are hypothesis-driven computational scenarios that are only possible after the physical and biogeochemical processes are understood, requiring additional capacity and capability computing.

This is a daunting problem—developing, validating and evaluating multidisciplinary climate models in time to provide the necessary answers to critical questions:

- *How many simulation scenarios are necessary (minimally and optimally).*
- *What model elements are needed for each scenario?*
- *What temporal and spatial resolution, along with physical models, is affordable?*
- *What are the errors and uncertainties in model predictions?*
- *When must research end and production simulation begin to produce policy guidance?*

Underlying these questions is the need for powerful computers to model climate change at regional and fine scales, and to support the sophisticated and computationally expensive algorithms needed to represent the complexities of both natural and human effects. *We must also manage the tsunami of observational data now being captured via a new generation of environmental sensors, integrating high-resolution Earth system models with assimilated satellite and other data, supported by large data archives and intelligent data mining and management systems.*

Finally, we must develop the multiphysics algorithms and models needed to represent the complex interactions of biological, geophysical, chemical and human activities. New scientific and mathematical advances will also be required to quantify model uncertainty for such complex systems. This fusion of sensor data with complex models is large-scale computational science in its clearest and most compelling form. Equally importantly, those HPC systems must be available for researcher use.

2. High-Performance Computing Resource Availability

In the early 1980s, HPC facilities were accessible only by a handful of U.S. researchers. Most access required both a national security clearance and partnership with one of the U.S. weapons laboratories or international travel—for access to computing research facilities outside the U.S. *The rising importance of computing to science and the dearth of HPC facilities for open scientific research stimulated creation of the National Science Foundation (NSF) supercomputing centers and similar facility investments by the Department of Energy's (DOE) Office of Science.* Although other agencies also support HPC facilities, NSF and DOE now provide the overwhelming fraction of the unclassified resources for computational science, including climate change.

This NSF program and its descendents, the Partnerships for Advanced Computational Infrastructure (PACI) and the TeraGrid, continue to support academic researchers via consulting, HPC systems and archival storage. All of the NSF-supported resources, with the exception of the majority at the National Center for Atmospheric Research (NCAR), are allocated by peer review across all disciplines. The computing facilities at NCAR include peer-reviewed resources allocated for weather and climate research and the Climate Simulation laboratory (CSL) resources dedicated to climate change research. Historically, all NSF computing resources have been substantially over-subscribed, with unmet demand from academic researchers. Recently, however, NSF has funded a series of competitive hardware acquisitions to help address this shortfall, with the largest slated to sustain one petaflop[3] on selected applications.[4]

The DOE Office of Science also maintains a set of unclassified computing facilities, anchored by the National Energy Research Scientific Computing Center (NERSC), two leadership-class computing systems at Oak Ridge and Argonne National Laboratories, and a smaller facility at the Pacific Northwest Research Laboratory. The majority of DOE's NERSC resources are also allocated by peer review, with the requirement that the proposed use be relevant to the DOE Office of Science mission. Finally, the DOE leadership-class facilities target focused projects that could benefit from access to the largest-scale facilities in the country, including the climate change modeling program. Most of these resources are allocated by the INCITE initiative.[5]

Our computational science infrastructure is enormously greater than twenty years ago. However, so are our expectations and needs—science and computing are now synonymous. Equally tellingly, because almost all of our NSF and DOE HPC resources are shared across disciplines, only a modest fraction of these systems is dedicated to climate change studies. Rather, researchers rely on a combination of proposal peer review and programmatic resource allocation to conduct climate change studies on a diverse array of HPC systems.

At present, there is no truly large scale U.S. climate change computing research facility, architected, configured and dedicated to multidisciplinary climate change studies that can deliver timely and accurate predictions. A recent DOE study estimated that climate and environmental modeling could use an exascale system effectively (*i.e.,* one thousand times faster than any extant computer system). Simply put, change modeling is a deep and challenging scientific problem that requires computing infrastructure at the largest scale.

3. Computing Evolution: Lessons and Challenges

In the late 1970s and the 1980s, HPC was defined by vector processors, as exemplified by the eponymously named systems designed by the legendary Seymour Cray. These systems combined high-speed, custom processor design with fast memories and innovative packaging. Researchers and software developers were able to tune selected portions of their codes to the vector hardware, achieving unprecedented performance with modest effort.

With the birth of the PC, a new approach to HPC began to emerge in the 1980s. The increasing performance and low cost of commodity microprocessors—the "Attack of the Killer Micros"—transformed HPC. This new model of massive parallelism partitions computations across large numbers of processors. Via this approach, one can increase peak hardware performance to levels limited only by economics and reliability. However, achieving high performance on complex applications is more problematic and challenging, particularly for multidisciplinary applications. The climate change community expressed great concern about this disruptive technology transition during the 1990s, with concomitant political controversy.

Recognizing this technological shift, the associated challenges and the opportunities, the Defense Advanced Research Projects Agency (DARPA) launched an aggressive research and development program that engaged academia, industry and national laboratories. Other Federal agencies, notably the National Science Foundation (NSF), the Department of Energy's (DOE) Office of Science and the National Aeronautics and Space Administration (NASA), joined in the High-Performance Computing and Communications (HPCC) program.[6]

In the 1990s, research flourished in computer architecture, system software, programming models, algorithms and applications. Computer vendors launched new initiatives, and parallel computing startup companies were born. Planning began for petascale systems, based on integrated hardware, architecture, software and algorithms research. *After a promising start, much of the initiative faded and attention shifted elsewhere.* The most notable exception was DOE's National Nuclear Security Administration (NNSA). Needing to certify the weapons stockpile without testing, NNSA embraced HPC to verify and validate weapon safety and readiness. The com-

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[3] One teraflop is 10^{12} floating point operations/second; one petaflop is one thousand teraflops, or 10^{15} floating point operations/second; one exaflop is one thousand petaflops, or 10^{18} floating point operations/second.

[4] See the NSF Office of Cyberinfrastructure, *http://www.nsf.gov/dir/index.jsp?org=OCI* for details on the NSF acquisition program.

[5] Department of Energy Innovative and Novel Computational Impact on Theory and Experiment (INCITE) initiative, *http://hpc.science.doe.gov/*

[6] The High-Performance Computing and Communications (HPCC) program became the Networking and IT Research and Development (NITRD) program, *http://www.nitrd.gov/about/about_NITRD.html.*

plex physics drove new algorithm and software development and acquisition of some of the world's most power computing systems, all based on massive parallelism and commodity microprocessors.

While the U.S. computing industry largely abandoned purpose-built supercomputers in favor of commodity designs, Japanese vendors, notably Hitachi and Fujitsu, continued to develop and evolve vector supercomputers. In 2002, Japan announced the Earth Simulator—then the world's fastest computer. The Earth Simulator was designed specifically for large-scale climate and weather studies and drew on many years of vector computing research and development.

Although the Japanese plan had long been public, it precipitated considerable concern. The interagency High-End Computing Revitalization Task Force (HECRTF) was chartered to assess the competitive position of the United States. I was privileged to chair the 2003 HECRTF community workshop and edited the associated community report.[7] The Federal agencies produced a complementary report and a proposed action plan. Several agencies launched new programs, of which the largest and most visible were the NSF OCI petascale initiative and the DOE Office of Science's Scientific Discovery through Scientific Computing (SciDAC)[8] and INCITE programs.

Today, the majority of the world's largest HPC systems, dominated by U.S. laboratory and academic holdings, remain based on commodity building blocks and community-developed software. In this high-performance "monoculture," vendor profit margins are small, and competition for sales is intense, with limited vendor opportunity to recover research and development investments in alternative architectures. Equally worrisome, the pool of academic researchers in HPC and computational science is small, and research funding is limited.

Without doubt, the explosive growth of scientific computing based on clusters of commodity microprocessors has reshaped the HPC market. The U.S. remains the undisputed world leader in this space. Petascale systems are being deployed by NSF and DOE for academic and laboratory research, and feasibility assessments of exascale systems[9] are underway. Although this democratization of HPC has had many salutatory effects, including broad access to commodity clusters across laboratories and universities, it is not without its negatives.

Not all aspects of climate change models map efficiently to the cluster programming model of loosely coupled, message-based communication. It is also unclear if we have the resources needed to address the climate change problem at appropriate scale and in a timely manner, particularly given dramatic changes now underway in computing technology.

4. The Brave New World: Multicore and Massive Data

Over the past twenty years, computational science and HPC have exploited the ever-increasing performance of commodity microprocessors. Each new processor generation combined greater transistor density, new architectural techniques and higher chip power to deliver greater single processor performance. This tripartite evolution is now over. Although transistor densities on chip will continue to rise, physics and power constraints make it impractical to increase clock frequencies further. Future chip performance increases will depend on explicit parallelism and architectural innovations. No longer will current software execute faster in the future without change. Parallelism is now required, even at the chip level, to deliver greater performance.

This multicore revolution—the placement of multiple, slower processors on each chip—poses major new challenges for the computing industry. It is just as disruptive as the transition from vector to parallel computing was fifteen years ago. Today's quad-core chips will soon be replaced by chips containing tens, then hundreds and perhaps thousands of cores (processors). *The technical challenges are daunting, and we have no straightforward technical solutions that will hide this complexity from software developers.*[10] This will profoundly affect the software industry and scientific researchers.

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[7] The documents for the High-End Computing Revitalization Task Force (HECRTF), including the community workshop report, can be found at *http://www.nitrd.gov/subcommittee/hec/hecrtf-outreach.*

[8] Department of Energy, Scientific Discovery through Scientific Computing (SciDAC), *http://www.scidac.gov/.*

[9] *Modeling and Simulation at the Exascale for Energy and the Environment,* Summer 2007, *http://www.sc.doe.gov/ascr/ProgramDocuments/TownHall.pdf.*

[10] This realization recently motivated Microsoft and Intel to invest $20M in academic multicore research at the University of Illinois at Urbana-Champaign and the University of California at Berkeley, *http://www.microsoft.com/presspass/press/2008/mar08/03-18UPCRCPR.mspx.*

For multicore chips, new programming models and tools are needed to develop parallel applications, and existing software must be retrofitted. New chip architectures are needed to exploit rising transistor densities, support parallel execution and enable heterogeneous processing. New memory technologies and interconnects are needed to support chips with tens to hundreds of cores. Equally importantly, new algorithms are needed that map efficiently to these new architectures. All of these changes will affect parallel climate models now being developed and executed on clustered commodity systems. *Today, we are suffering some of the delayed consequences of limited research investment in parallel computing—architecture, system software, programming tools, data management and algorithms.*

In addition to dramatic changes in processors and computation, our models of data capture and management are in flux. We can now generate, transmit, and store data at rates and scales unprecedented in human history. Many of our new environmental instruments can routinely produce many tens to hundreds of petabytes of data annually. *The scientific data deluge threatens to overwhelm the capacity of our Federal institutions to manage, preserve and process and of our climate modeling researchers to access and integrate the data with multidisciplinary models.* This data integration is critical to climate model validation.

Although industry is developing massive data centers to host Internet search, social networks and software as a service, our research data infrastructure has not kept pace. Climate researchers need better data management tools, including provenance tracking, translation, mining, fusion, visualization, and analysis. We must not focus exclusively on computing, but on the fusion of sensors and data management with computing hardware and rich climate models.

5. Actions: A Sustainable, Integrated Approach

One can and must draw several important, salutary lessons from the changing nature of computing technology. The U.S. HPC industry is now driven by business and consumer technology economics, with concomitant advantages and disadvantages. Large product volumes and amortized research and development costs lead to rapid innovation and technological change. However, those same consumer economics mean that today's HPC systems are built from commodity hardware and software components, and they are often ill-suited to the numerically and communication intensive nature of climate change models. In consequence, they rarely deliver a large fraction of their advertized peak performance.

Given their unique attributes, the highest capability computing systems have a very limited commercial market. The high non-recurring engineering costs to design HPC systems matched to scientific and government needs are not repaid by sales in the commercial marketplace. Hence, we must rethink our models for research, development, procurement and operation of high-end systems. We must target exploration of new systems that better support the needs of scientific and national defense applications and sustain the Federal investment needed to design, develop and procure those systems. Today's approach is unlikely to provide the necessary resources to address the climate change model problem fully.

New programming models and tools are also needed that simplify application development and maintenance and that target emerging multicore processors. Today, almost all parallel scientific applications are developed using low-level message-passing libraries. Climate modeling teams must have deep knowledge of application software behavior and its interaction with the underlying computing hardware, and they often spend inordinate amounts of time tailoring algorithms and software to hardware and software idiosyncrasies, time more profitably spent on science and engineering research.

Climate change analysis requires large-scale data archives, connections to scientific instruments and collaboration infrastructure to couple distributed scientific groups. *Any investment in HPC facilities must be balanced with appropriate investments in hardware, software, storage, algorithms and collaboration environments.* Simply put, climate change modeling, as with all scientific discovery, requires a judicious match of computer architecture, system software, algorithms and software development tools.

These facts illustrate the importance of a long-term, integrated research and development program that considers the entire computational science ecosystem, something I advocated as chair and co-chair of two recent PITAC and PCAST subcommittees, respectively. *Both the 2005 President's IT Advisory Committee (PITAC) report on computational science and the 2007 President's Council of Advisors on Science and Technology (PCAST) review of the Networking and Information Technology Research and Development (NITRD) program recommended creation of an interagency strategic roadmap for computational science and computing research.* In particular, the 2005 PITAC report found that

> *The continued health of this dynamic computational science "ecosystem" demands long-term planning, participation, and collaboration by Federal R&D agencies and computational scientists in academia and industry. Instead, today's Federal investments remain short-term in scope, with limited strategic planning and a paucity of cooperation across disciplines and agencies.*

The report also recommended creation of a long-term, interagency roadmap to

> *. . . address not only computing system hardware, networking, software, data acquisition and storage, and visualization, but also science, engineering, and humanities algorithms and applications. The roadmap must identify and prioritize the difficult technical problems and establish a timeline and milestones for successfully addressing them.*

In that same spirit, the 2007 PCAST review of the NITRD program, *Leadership Under Challenge: Information Technology R&D in a Competitive World,*[11] which I co-chaired, reiterated the need for a strategic plan and roadmap for high-performance computing and noted that

> *The Federal NIT R&D portfolio is currently imbalanced in favor of low-risk projects; too many are small-scale and short-term efforts. The number of large-scale, multidisciplinary activities with long time horizons is limited and visionary projects are few.*

Based on these studies, I believe we face both great opportunities and great challenges in high-end computing for climate change. Computational science truly is the "third pillar" of the scientific process. The challenges are for us to sustain the research, development and deployment of the high-end computing infrastructure needed to enable discoveries and to ensure the health of our planet.

In conclusion, Mr. Chairman, let me thank you for this Committee's interest in this question and its continue support for scientific innovation. Thank you very much for your time and attention. I would be pleased to answer any questions you might have.

Senator KERRY. Thank you very much, Dr. Reed.

Dr. Sarachik?

STATEMENT OF EDWARD SARACHIK, EMERITUS PROFESSOR OF ATMOSPHERIC SCIENCE, ADJUNCT PROFESSOR OF OCEANOGRAPHY, AND ADJUNCT PROFESSOR OF APPLIED MATHEMATICS AT THE UNIVERSITY OF WASHINGTON AND CO-DIRECTOR, CENTER FOR SCIENCE IN THE EARTH SYSTEM

Dr. SARACHIK. Thank you, Senator Kerry and Senator Stevens. My name is Ed Sarachik. I thought I retired 6 months ago, but I seem to have not. I hold various appointments on the faculty at the University of Washington and I am Co-Director, along with Ed Miles, of the Center for Science in the Earth System at the University of Washington. It is a very interesting center because it goes from climate information to climate impacts, to dealing with stakeholders, and to raising the consciousness of stakeholders, both in the public and private domain.

Basically I can say that although each region of the Pacific Northwest—and there are many climates within the Pacific Northwest—has unique problems. All of them need a skillful prediction of next season's climate—that is precipitation and temperature—and a knowledge of the future variability of climate. It is not just how the mean temperature is going to change. We do not respond to the mean. We respond to variability. You can imagine building for 70 degree temperatures and it would matter if the day is 110

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[11] *Leadership Under Challenge: Information Technology R&D in a Competitive World,* President's Council of Advisors on Science and Technology (PCAST), August 2007, *http://www.ostp.gov/pdf/nitrd_review.pdf.*

and the evening is 30 or if it is going to be 70 degrees all the time. We respond to variability not to the mean.

So the question is can we do these two problems. Can we make skillful predictions a season in advance, and can we figure out what the future variability of climate is going to be as the climate changes?

And here the answer is yes and no. We can make predictions a season in advance. The reason it has been so cold this winter is because it has been a La Niña year, and that was predicted about 6 months ago. But we cannot do the variability correctly. Despite the fact that we are spending a fair amount of money building these models for the IPCC, the IPCC cannot do regional climate. It can only do climate on continental scales. Continental scales are not the scale at which applications are made.

So what do we have to do? The basic reason we cannot do the variability correctly is that the known modes of variability, El Niño, Pacific Decadal Oscillation, and the North Atlantic oscillation, are simply not done correctly and in the right place by these models. In order to get them to do the right thing in the right place by these models, there certainly are modeling issues. As has been mentioned so far, resolution is one of those modeling issues, and for that resolution we need bigger computers, to be sure. But we also need access to these computers. At this moment, none of these big climate models are being run at universities because universities simply do not have the wherewithal to do the running of it. So access to the various places that would have interest in improving the variability of these models is absolutely crucial.

The second leg of the stool, as I believe has been mentioned already, is observations. We do not have a climate observing system. If we do not have a climate observing system, we cannot know what the climate is in all of its specificity around the globe. In particular, we make observations, but these observations are not necessarily connected dynamically.

And there is a certain amount of research that absolutely needs to be done on El Niño southern oscillation, on the Pacific Decadal Oscillation, on the North Atlantic Oscillation, and the effects of CO_2 and various other constituents on the atmosphere.

A lot of these things—modeling observations and research needs to be done in an integrated manner. If we do not have the observations, we cannot really do the modeling. If we do not have the research, we cannot really do the modeling. If we do not have the modeling, we cannot really integrate the observations. These things really do need integration and some method of putting them all together and going ahead in a consistent manner.

There has been a lot of talk about a national climate service. We have a National Weather Service. The National Weather Service takes weather observations, integrates them, and puts out maps twice or four times a day. We have nothing similar for climate, and having a national climate service would go a long way toward solving some of the problems necessary for doing good regional information.

Thank you.

[The prepared statement of Dr. Sarachik follows:]

PREPARED STATEMENT OF EDWARD SARACHIK, EMERITUS PROFESSOR OF ATMOSPHERIC SCIENCE, ADJUNCT PROFESSOR OF OCEANOGRAPHY, AND ADJUNCT PROFESSOR OF APPLIED MATHEMATICS AT THE UNIVERSITY OF WASHINGTON AND CO-DIRECTOR, CENTER FOR SCIENCE IN THE EARTH SYSTEM

My name is Edward Sarachik and I am Emeritus Professor of Atmospheric Science, Adjunct Professor of Oceanography, and Adjunct Professor of Applied Mathematics at the University of Washington. I am also Co-Director of the Center for Science in the Earth System (supported by NOAA) which contains two groups: a Climate Dynamics Group and a Climate Impacts Group. The Climate Dynamics Group studies the physical climate system relevant to the Pacific Northwest and the Climate Impacts Group examines the impacts of climate variability and change on the Pacific Northwest, and produces climate information products and derived predictions (*e.g.,* streamflow forecasts) for a set of local stakeholders. The combined Center studies the general problem of making climate information useful to stakeholders in the Pacific Northwest. The range of our activities and a list of our stakeholders can be seen on our website: *http://cses.washington.edu/*.

I have also chaired two National Research Council committees: one that produced an National Academy Press report *Learning to Predict the Climate Variations Characteristic of El Niño* and the other, *Improving the Effectiveness of U.S. Climate Modeling,* both highly relevant to this hearing. I also chair the advisory group for the International Research Institute for Climate and Society at Columbia University which deals with the same problem as that of this hearing but in an international context.

What do stakeholders want?

They ask questions they would have asked in the absence of climate change: basically, some knowledge about the variability in the near future. Some examples from the Pacific Northwest:

- All stakeholders want to know next season's temperature and rainfall.
- Power companies, city water utilities, and ski area operators want to know whether next winter's snowpack will be thick and long lasting or thin and early melting.
- Fishers want to know if next season's coastal mixed layer will be deep or shallow, warm or cold.
- The tourist industry wants to know if next summer will be clear or cloudy.
- Insurance companies and state flood control agencies want to know if there be an unusual number of storms next winter, and the probability that there will be destructive windstorms.

Then they ask questions about the very long term, say 50 years from now:

- Individuals and developers want to know if they should build near the ocean in the presence of rising sea level. Do they need a sea wall?
- Foresters want to know what species of tree should be planted in what climate regime. In particular, what will be the future range of temperature and precipitation?
- Wineries want to know if it will be too warm for specific grape varieties and whether or not irrigation will be needed.
- Everybody wants to know if it will get too warm for salmon survival.

The progression of climate in a given small region is *not* what we are used to from global warming simulations. For temperature, the global average smoothes the record and the year to year variability is about half a degree F. Local temperature record has a year to year variability about 5 °F. Since the year to year variability in a limited region is of order of the 50 year warming trend, constantly dealing with next year's climate over a long period of time gives practice about dealing with long term climate change since many (but not all) of the climate manifestations are similar.

The problem of producing climate information relevant to decisionmakers' needs then becomes

- Skillfully predicting next year's temperature and precipitation in a limited region.
- Accurately simulating future variability of temperature and precipitation in a limited region.

Can existing climate models do this?

The answer is both yes and no.

Yes. Next years climate can be predicted using current climate conditions, especially in the tropical oceans, as a starting point—this can only be done two or three seasons in advance. There are a number of groups in the world that produce such predictions and there exists a ocean observing system in the tropical Pacific that produce the current climate conditions. Estimates of the predictable part of seasonal temperature variability is about 30 percent for the Pacific Northwest and about 40 percent for the extreme Southeast part of the U.S. so that even if the prediction systems were perfect, only these percentages of future variations can be predicted. This makes predictions of next year's climate intrinsically probabilistic.

No. Existing climate models used for the Intergovernmental Panel on Climate Change (IPCC) process are comprehensive global models and are designed for mitigation, on large space and time scales. The variability known to be important regionally (El Niño, Pacific Decadal Oscillation, North Atlantic Oscillation) in the current crop of models used in the IPCC has been neglected and is done poorly. The IPCC concentrates on global averages and freely admits that the smallest region for which the models are useful is the continental scale, about 3000 mile. On scales smaller than continental scale, the models are not useful and downscaling to smaller space scales by higher resolution models using the large global models as boundary conditions can not be expected to improve the situation. The output of existing models can be corrected to agree with past climate conditions and the correction used for future climates but there is no agreed upon methods for doing this.

What is the best path to producing useful regional climate information?

Ideally we want a comprehensive climate model (similar to the ones currently used for the IPCC process) but which does the known patterns of climate variability (El Niño, Pacific Decadal Oscillation, North American Oscillation, etc.) correctly and which is run globally at high resolution (20 miles rather than the current 100 miles).

This requires:

1. A set of model building institutions well resourced and interacting with the entire public and private research sectors.
2. Far more capable supercomputers. And, equally important, making these supercomputers and advanced models available to the entire research community.

Supercomputing is necessary, but it is not, by itself, sufficient. Also required is:

3. A research program to investigate the nature of climate variability (especially decadal variability) and assure the global climate models are capable of doing variability correctly and in the correct locations.

All research ultimately depends on having good observations—since we do not have a climate observing *system,* all future progress in climate research will depend on implementing one. So also required is:

4. A climate observing system producing regular and systematic climate observations.

Since the output of the climate observing system will never cover every point in the atmosphere, ocean and ice over the entire earth, the models themselves can be used for interpolation, just as current weather models are used to assimilate weather observations into consistent global fields. Therefore the last component required is

5. A monthly analysis of the climate system using the observations produced by the climate observing systems in 4. and the models developed in 1. and 2.

Because this hearing assumes it, it is hardly necessary to add:

6. A distribution network for regional climate and resource information interacting directly with local stakeholders.

At least a major portion of 4, 5, and 6 could be accomplished by the establishment of a National Climate Service.

It may seem strange that starting with models for simulating local climate information we wound up with far more comprehensive requirements, but the ability to produce useful regional climate information to meet stakeholder needs depends on a healthy climate infrastructure. This is precisely the situation in that the ability to produce weather information for public and private use would be impossible without the weather infrastructure contained within the National Weather Service

(NWS) *and* the research that is enabled by the observations and analyses emerging from the NWS. The ability to provide climate information to address end-user needs depends generally on the health of the climate infrastructure and the climate community.

Senator KERRY. Thank you very much, Doctor. Appreciate it.

Mr. Carlisle?

STATEMENT OF BRUCE K. CARLISLE, ASSISTANT DIRECTOR, OFFICE OF COASTAL ZONE MANAGEMENT, EXECUTIVE OFFICE OF ENERGY, AND ENVIRONMENTAL AFFAIRS, COMMONWEALTH OF MASSACHUSETTS

Mr. CARLISLE. Senator Kerry and Senator Stevens, my name is Bruce Carlisle and I am the Assistant Director for the Massachusetts Office of Coastal Zone Management. I want to thank you for the opportunity to offer testimony on the importance of predicting the effects of climate change through a national modeling strategy and ensuring that such a strategy meets the needs of state coastal managers and local officials.

Our presence today is also on behalf of the Coastal States Organization which represents the interests of the Governors from the 35 coastal states, commonwealths, and territories on issues relating to sound management of our coasts, Great Lakes, and oceans.

This testimony will cover climate change issues in the coastal zone, focusing on the priority modeling and information needs of coastal zone managers around the country and highlighting the work being done in Massachusetts to build effective coastal flood plain management strategies from the ground up. Your continuing support for climate change modeling, along with the necessary research, monitoring, and computing infrastructure, is of critical and growing importance to coastal states and communities. One of the points I will emphasize is that while a national strategy for climate change modeling and assessment is necessary, to be truly effective, it must be connected to and coordinated with state, regional, and local partners.

Throughout the Nation, our coastlines and extensive coastal floodplains play a significant role in protecting our homes, personal safety, providing recreational opportunities for all incomes, preserving our natural resources and quality of life, and maintaining our viable economies. Coastal counties host more than half of the Nation's population, support nearly half of the Nation's jobs, and generate more than half of its gross domestic product. With accelerated sea level rise, more frequent intense storms and shifts in precipitation and temperatures, the coastal zone will also feel the brunt of global climate change, and these areas will be subject to increased flooding, shoreline erosion, saltwater intrusion into fresh water aquifers, harmful algal blooms, and the loss of coastal habitats.

For more than 30 years, state coastal managers like those at the Massachusetts Office of Coastal Zone Management have been leaders in integrating coastal hazard response and proactive planning into coastal zone management. As a key sector and end-user, we have identified the following priorities and urge Congress to provide support in addressing these needs.

The first is high resolution data models and diagnostics to generate regional and local sea level rise scenarios. In addition, modification of wind speed and storm surge height models to assimilate changing storm intensity and frequencies and incorporate the unique configurations and characteristics of local embayments. Additionally, more information to better understand the effects of changing sediment transport, erosion, and accretion regimes on habitats and the important ecosystem services they provide. Additional modeling on climate change impacts to local or regional hydrological processes and the rate of saltwater intrusion into coastal aquifers.

In Massachusetts and many other coastal states, coastal land use decisions are being made at the town and municipal level by local officials who are working with shrinking budgets and resources and often lack technical and scientific expertise. Communities are in need of current information and predictions, packaged and delivered through specific tailored guidance on how to put that information to use.

To start to address such needs, the Massachusetts Office of Coastal Zone Management just launched its new StormSmart Coasts program. StormSmart Coasts is designed to give local decision-makers and ultimately businesses and homeowners the information and tools they need to protect themselves from coastal storm damage and flooding and to prepare for sea level rise and climate change. We deliver StormSmart Coasts tools via an extensive website which translates complex technical information into user-friendly guidance and planning frameworks with links to the best information and data from around the Nation. Complicated concepts are reinforced through a series of short fact sheets explaining the tools and providing success stories.

One of the basic building blocks of StormSmart Coasts is hazard identification mapping. The StormSmart Coasts website explains the limitation of current flood maps, which for most communities in Massachusetts are more than 20 years old and do not include the effects of erosion or sea level rise. StormSmart Coasts strongly advises planners to seek and use additional sources of data such as storm surge, shoreline change, and inundation maps to assess their true vulnerability to coastal storm damage.

There are two pending bills that would assist in developing key Federal-state partnerships to support these needs. Massachusetts and the Coastal States Organization appreciate the work of Senator Kerry and strongly support the climate change research and monitoring activities proposed in the Global Change Research Improvement Act of 2007. Under the bill, particular attention will be focused on regional and state vulnerabilities to climate change.

Massachusetts and the Coastal States Organization also support the climate adaptation provisions in America's Climate Security Act of 2007, particularly the specific allocation of 5 percent of the emission allowance account to states which could be used for affected coastal communities to adapt to climate change. These provisions recognize that coastal states and communities are on the front lines of climate change and will need Federal support that is proportionate to this risk.

As you work on a results-oriented national modeling strategy, you must specifically answer the kind of questions asked by all coastal communities looking to implement effective coastal floodplain management. What are the current risks to my community, and how will those risks change in the future?

Thank you again for the opportunity to testify. I would be happy to respond to any questions that you may have.

[The prepared statement of Mr. Carlisle follows:]

PREPARED STATEMENT OF BRUCE K. CARLISLE, ASSISTANT DIRECTOR, OFFICE OF COASTAL ZONE MANAGEMENT, EXECUTIVE OFFICE OF ENERGY, AND ENVIRONMENTAL AFFAIRS, COMMONWEALTH OF MASSACHUSETTS

Mr. Chairman and Members of the Committee, my name is Bruce Carlisle and I am the Assistant Director for the Massachusetts Office of Coastal Zone Management. I want to thank you for the opportunity to offer testimony on the importance of predicting the effects of climate change through a national modeling strategy, and ensuring that such a strategy meets the needs of state coastal managers and local officials, who will be the ultimate decision-makers and end-users of this information. Through my fourteen years of working on coastal policy, planning, and management, I am keenly aware of the coastal climate change information needs in the Commonwealth.

My presence today is also on behalf of the Coastal States Organization (CSO), which since 1970, has represented the interests of the Governors from the 35 coastal States, Commonwealths, and Territories on Federal legislative, administrative, and policy issues relating to sound coastal, Great Lakes, and ocean management. CSO and its members have been actively engaged in this issue, and in November of last year, Dr. Braxton Davis, Chair of the CSO Climate Change Work Group and Director of the Science and Policy Division at South Carolina's Office of Ocean and Coastal Resource Management, gave testimony to your committee on the importance of climate change research to state and local resource managers.

This testimony will cover climate change issues in the coastal zone, focusing on the priority modeling and information needs as conveyed by coastal zone managers around the country and highlighting the work being done in Massachusetts to build effective coastal floodplain management strategies from the ground up. Your continuing support for climate change modeling, along with the necessary research, monitoring, and computing infrastructure, is of critical and growing importance to coastal states and communities. One of the points I will emphasize is that while a national strategy for climate change modeling and assessments is necessary, to be truly effective, it must be connected to and coordinated with state, regional, and local partners.

Background

Throughout the Nation, our coastlines and extensive coastal floodplains play a significant role in protecting our homes and personal safety, providing recreation opportunities for all incomes, preserving our natural resources and quality of life, providing spawning grounds critical to our fishing industry, and maintaining our viable local, regional, and state economies. The coastal zone will also feel the brunt of global climate change. More than half of the Nation's population lives in coastal counties, and key economic sectors are directly linked to the coasts and oceans. Coastal counties host nearly half of the Nation's jobs and generate more than half its gross domestic product. Through the combined effects of climate change—accelerated sea level rise, more frequent and intense storms, and shifts in precipitation and temperatures—these areas will see increased flooding and shoreline erosion, changes in sediment transport, saltwater intrusion into groundwater aquifers and coastal rivers, increased harmful algal blooms, the loss of coastal wetland and coral reef habitats, and changes in population dynamics among marine and coastal species. Unless coastal decision-makers and officials start to plan for and implement effective measures to ensure coastal community resiliency, current and future development and activities—when poorly sited and/or designed—will aggravate these impacts over time.

For more than 30 years, coastal managers—like those at the Massachusetts Office of Coastal Zone Management—have been leaders in integrating coastal hazard response and proactive planning into coastal zone management. We work in close coordination with both Federal agencies and local communities. Our efforts on coastal shoreline and floodplain management are extensive and include such actions as: developing critical information (*e.g.,* high-resolution shoreline change data and coastal high-hazard zone delineation), coordinating the state's Rapid Response Storm Damage Survey Team to help spur recovery efforts, and providing hands-on technical assistance to communities as they review development projects or develop beach management plans.

Think Globally, Act Locally

Large-scale research, observation, and modeling are critical to improving our understanding of, and predictive capabilities for, global climate change. The 2003 National Strategic Plan for the U.S. Climate Change Science Program explains that while research focused on key and emerging climate change science areas is a high priority, directly supporting regional resource management efforts is also a critical component of the national strategy. The plan points to the development of scenarios and comparisons, the implementation and application of models, and the advancement of information supporting adaptation strategies as means of supporting decision-making at all levels. Addressing the limitations of regional- and local-scale analyses of potential climate change impacts and improving the availability of such diagnostics will greatly enhance their effectiveness in regional and local decision-making contexts. As a key "sector" and "end-user," the CSO has identified the following priority information and products to address future impacts of climate change in the coastal zone, and we urge Congress to provide support in addressing these needs:

- *Localized Sea Level Rise Scenarios*—High-resolution coastal topographic and bathymetric elevation data should be coupled with region-specific tide data, sea level rise projections, and other key input parameters to develop basic inundation models for the assessment of lands and resources most vulnerable to accelerated sea level rise. These regional models are an important first step, but coastal states will need more detailed and complex models that incorporate local, embayment-scale changes in coastal geomorphology, hydrological conditions, and human alterations and responses (*e.g.,* seawalls and beach nourishment) to more adequately assess social, environmental, and economic vulnerabilities of climate change. Coastal states and communities would benefit from the development of uniform methods for modeling local-scale shoreline changes associated with varying sea level rise projections.
- *Storm Surge Models*—Existing models that estimate wind speeds and storm surge heights resulting from predicted storm events need to be broadened to incorporate changing storm intensities and frequencies as the result of global climate change. Again, models that incorporate the unique configurations of local embayments or coastline morphologies, water depths, and physical features such as bridges and roads are required to develop accurate storm surge predictions and serve as effective planning tools for decisions being made today about the siting of new development and public infrastructure.
- *Impacts on Coastal Habitats and Ecosystem Services*—The integrity of many coastal habitats, such as estuarine marshes and beaches, are dependent on adequate sources of sediment supply and the accretion of sediments at certain rates. To predict changes to the these habitats and the important ecosystem services they provide—such as flood protection, wildlife habitat, and recreation—more information is needed to better understand erosion and deposition cycles and to improve our ability to predict the effects of accelerated rates of sea level rise on sediment transport, and accretion and erosion. Without sufficient vertical accretion, estuarine marshes, in particular, are extremely vulnerable to being drowned by accelerated sea level rise.
- *Ground Water and Salt Water Intrusion*—Climate change will have significant effects on local hydrologic cycles through altered precipitation, evapotranspiration, and soil moisture patterns. These changes will lead to altered groundwater recharge in watershed areas, which will change the groundwater flow to coastal regions and thus the rate of saltwater intrusion in coastal aquifers. Additional modeling on the climate change impacts to local or regional hydrological processes and coastal water resources is also needed to manage coastal water supplies and estuarine biodiversity.

In Massachusetts and many other coastal states, coastal land use decisions are all too often being made at the town and municipal level by local officials who are working with shrinking budgets and resources, and often lack technical and scientific expertise. Communities are in critical need of current information and predictions, packaged and delivered through specific, tailored guidance on how to put that information to use to make storm resilient communities a reality. Because state coastal programs provide high-quality products, services, and hands-on assistance to these constituents, they are uniquely positioned for the implementation of coastal climate change adaptation strategies.

StormSmart Coasts

Created by the Massachusetts Office of Coastal Zone Management, StormSmart Coasts is designed to give local decision-makers, and ultimately businesses and homeowners, the information and tools they need to protect themselves from coastal storm damage and flooding, and to prepare for sea level rise and climate change. The strategy for initially delivering the StormSmart Coasts tools includes an extensive website (*www.mass.gov/czm/stormsmart*) and a series of regional workshops. The website translates complex technical information into user-friendly guidance and regulatory models with links to the best information and data from around the Nation. Complicated concepts are reinforced through a series of short fact sheets explaining the tools and providing success stories (see attached examples). The next phase of delivery will be to provide targeted technical assistance for StormSmart tool implementation to a select handful of coastal communities, and then take the lessons learned from these efforts and translate and package them for use by other coastal communities within Massachusetts and nationwide.

A Partnership at All Levels

Led by a Coastal Management Fellow provided by the National Oceanic and Atmospheric Administration's (NOAA) Coastal Services Center, the StormSmart Coasts program is very much a team approach. StormSmart Coasts would not have been possible without support and contributions from individuals and groups at all levels. The StormSmart Coasts program was strongly influenced by guidance and advice from an attorney specializing in floodplain and wetlands law, representatives from the national Association of State Floodplain Managers, hazard mitigation staff from our state Department of Conservation and Recreation, Federal Emergency Management Agency (FEMA) personnel, and local officials. Recognizing the value of StormSmart Coasts as a national model, the Coastal Services Center has selected Massachusetts to receive another Coastal Management Fellow starting this summer to implement StormSmart Coast strategies in specific Massachusetts coastal communities.

StormSmart Coasts and the Local Connection

Throughout its development, StormSmart Coasts has benefited from extensive input and review from local officials—the key target audience for the program. By involving local officials at the earliest stages of program development, we have created tools that directly meet their needs, and packaged them in a format that they can easily understand, access, and successfully implement. Empowering local action is critical, because in the end, it is the decisions that are made locally that will determine if we can successfully adapt to climate change and be resilient to natural hazards so as to avoid such tragedies as experienced in the aftermath of Hurricane Katrina.

No Adverse Impact

The StormSmart Coasts program is based around the concept of No Adverse Impact. No Adverse Impact is a set of "do no harm" principles for local communities to follow when planning, designing, or evaluating public and private development activities and storm-damage prevention measures. This approach clarifies that community leaders not only have the legal right to consider the cumulative impacts of their permitting decisions, they have the legal responsibility. No Adverse Impact tools and techniques ensure that private development, public infrastructure, and planning activities do not have direct or indirect negative consequences on the surrounding natural resource areas, private property, or other communities.

Applying Model Outputs to Coastal Land Use Decisions

One of the basic building blocks of StormSmart Coasts is hazard identification and mapping. The StormSmart Coasts website explains the limitation of the current FEMA Flood Insurance Rate Maps, which are engineering estimates of the extent of the floodplain at the time of the mapping. For most communities in Massachusetts, those maps are more than 20 years old and do not include the effects of erosion or sea level rise. StormSmart Coasts strongly advises hazard mitigation planners to seek and use additional sources of data, such as storm surge, shoreline change, and inundation maps, to assess their true vulnerability to coastal storm damage. They need current and specific information, synthesized and adapted to suit their requirements to best plan for and strategically address coastal floodplain management issues, adapt to climate change issues, and reduce impacts for future generations.

The Massachusetts Office of Coastal Zone Management has extensive experience packaging technical information for use by local decision-makers. One example is our shoreline change maps, which measure and estimate the changes in the Massachusetts coastline as a result of natural erosion and accretion, as well as relative sea level rise. These maps and all accompanying data are available on our website (*www.mass.gov/czm/hazards/shoreline_change/shorelinechangeproject.htm*) with a fact sheet explaining how to use the maps. These resources receive thousands of hits per year and are used locally to supplement information provided by outdated flood maps.

The Time to Act Is Now

It is very important to emphasize that this is not a problem only for the future. In an increasing number of communities along the Massachusetts coast, erosion and flooding impacts are increasingly causing damage even during today's minor storms. And with climate change, these impacts will only grow as storms increase in frequency and intensity.

Successful Strategies through Federal-State Partnerships

Through the Coastal Zone Management Act amendment process, provisions should be developed to allow states and territories to develop specific coastal climate change adaptation plans and strategies. States also support increased funding for climate change activities and support legislation that would encourage NOAA and other agencies to assist the states via technical assistance, mapping, modeling, data, and forecasting products, and intergovernmental coordination. Federal activities related to coastal adaptation should be coordinated closely with states by involving coastal zone management programs early in the planning process.

There are several emerging areas where state, Federal, and other partners are actively working on improved coordination and cooperation for more effective coastal and ocean management. One of these is the new Integrated Ocean Observing System (IOOS) initiative. Led by NOAA, the IOOS program seeks to integrate coastal and ocean observing capabilities, in collaboration with Federal and non-Federal partners, to maximize access to data and generation of information products and inform decisionmaking. Massachusetts has been participating in both the Northeast and Mid-Atlantic Regional Coastal Ocean Observing Systems, which are comprised of diverse partners including state and Federal agencies, academic institutions, and coastal and maritime interests. In both of these regions, remote observation technologies (*e.g.,* instruments on buoys and high frequency radar) and the development of prototype products have been prioritized to address the issue area of coastal inundation. When fully operational, real-time observations on meteorological and oceanographic measurements will be integrated into interactive products such as a Gulf of Maine Storm Simulation and Prediction System.

Another example of emerging synchronization is the Northeast Regional Oceans Council (NROC). Consisting of delegates from the six New England states and ex-officio members from Federal agencies, NROC was established in 2005 by resolution of the New England Governor's Association. The primary function of the council is to engage in efforts that require or benefit from regional actions to address issue areas of ocean and coastal ecosystem health, coastal hazards resiliency, ocean energy planning and management, and maritime security. By increasing communication and cooperation among regional interests, the council provides new forums for information exchange and strategic state-Federal collaboration on such actions as regional climate change activities and initiatives.

Finally, the Joint Subcommittee on Ocean Science and Technology created the Interagency Working Group on Ocean and Coastal Mapping in response to recommendations of the U.S. Ocean Action Plan and the 2004 National Research Council report, *A Geospatial Framework for the Coastal Zone: National Needs for Coastal Mapping and Charting*. The Interagency Working Group on Ocean and Coastal Mapping brings together Federal, state, industrial, academic, and nongovernmental organizations to coordinate the best use of mapping resources and to avoid duplication of effort. One of the first tasks for this group is to develop an inventory of ocean and coastal mapping data and activities. At a recent strategic planning workshop in February 2008, highlights of Federal ocean and coastal mapping activities were presented, and representatives from Massachusetts, Florida, and California provided updates of their current data collection and mapping activities, best practices, and challenges. All participants identified coordination, collaboration, and partnerships as keys to successful past and future efforts.

Legislative Opportunities

There are two pending bills that could assist in developing these key Federal-state partnerships. Massachusetts and CSO appreciate the work of Senator Kerry and strongly support the climate change research and monitoring activities proposed in the Global Change Research Improvement Act of 2007 (S. 2307). The proposed legislation would establish a national climate service through NOAA to address weather, climate change, and climate variability affecting public safety, advancing the national interest in understanding, forecasting, responding, adapting to, and mitigating the impacts of both natural and human-induced climate change and climate variability. National level research, infrastructure, and coordinated outreach and communication mechanisms would directly support state and local policymakers by providing comprehensive national research to assist with regional adaptation and mitigation planning. Under the bill, existing Federal climate change research would be coordinated and particular attention would be focused on regional and state vulnerabilities to climate change, allowing communities to utilize national data to help address adaptation and mitigation on a localized level.

Massachusetts and CSO also support the climate adaptation provisions in America's Climate Security Act of 2007 (S. 2191), particularly the specific allocation of 5 percent of the Emission Allowance Account to states, which can be used for specific purposes, one of which is to collect, evaluate, disseminate, and use information necessary for affected coastal communities to adapt to climate change. We are in favor of the expansion of the Adaptation Fund, funded through the emissions cap and trade program, to include coastal adaptation. These provisions recognize that coastal states and communities are on the front lines of climate change and will need Federal support that is proportionate to this risk.

The Future of a Successful Climate Modeling Partnership

As state-level coastal managers, we can develop new tools and package available tools through programs like StormSmart Coasts. While we will always do the best we can with the information we have available, the current scarcity of regional- and local-scale, high-priority data and information is alarming. For example, to improve our understanding of current and future coastal floodplains and high-hazard zones, we need topographical information in finer resolution than the coarse 10- to 20-foot contour intervals available today. Similarly, while there are hydrodynamic models that encompass regional systems (*e.g.,* Gulf of Maine, Massachusetts Bay), these have not been tailored to the region's complex coastline and bathymetry, which includes numerous islands and shoals, and they lack the necessary field measurements for model verification and refinement. Without adequate data or resources, state and local decision-makers cannot accurately map the existing extent of the coastal floodplain, let alone project what that floodplain will look like in the next 30 years. Given the scientific complexity and levels of funding involved, state and local governments cannot possibly hope to fill this data gap alone. We are very pleased to know that the Federal Government is looking to fulfill this role, and we guarantee that if you get us the information we need, we are prepared to use it wisely. Our personal safety, ecosystems, and local and regional economies depend on it.

But data alone cannot solve the problem—this information must get into the hands of the people who can use it to make better choices about development, redevelopment, and storm-damage protection, including municipal officials, business owners, and current and future homeowners in coastal floodplain areas.

Through StormSmart Coasts, we have built the framework and have begun to work with coastal communities to implement results-oriented strategies. But ultimately, the effectiveness of those strategies is limited by the data, models, and diagnostics available—and the information generated through a strategic climate modeling approach that provides such decision-support resources as reliable estimates of sea level rise in the next few decades will be the key to future success. With this critical gap filled, local and state officials will be able to successfully implement real-world strategies to address this very real problem—creating a true partnership that maximizes the best of what all levels of government have to offer.

Conclusion

As you move forward, we strongly encourage you to look at how state programs like StormSmart Coasts serve as successful examples—demonstrating not only how states can fine-tune and package the data and information developed through the Federal climate change programs for the local decision-makers to use in a real-world context—but also how all levels of government can work together successfully. To ensure that you continue to build a results-oriented national climate modeling strategy, we strongly encourage you to work with state coastal managers, as well as local officials, to understand our specific needs. To be effective, such a strategy must specifically answer the kind of questions asked by all coastal communities looking to implement effective coastal floodplain management—what are the current risks to my community and how will those risks change in the future. Please help us put all of the pieces together so we can respond quickly and effectively to future coastal hazards.

Thank you again for the opportunity to testify on the importance of national efforts for climate change modeling. I would be happy to respond to any questions that you may have.

FACT SHEET 1

Introduction to No Adverse Impact (NAI) Land Management in the Coastal Zone

A legally sound way for municipalities to protect people and property

What Is NAI?

No Adverse Impact (NAI) is a forward-thinking, fair, and legally defensible approach to coastal land management. In its broadest sense, it is a set of "do no harm" principles to follow when your community is planning, designing, or evaluating public and private development activities and storm-damage prevention measures.

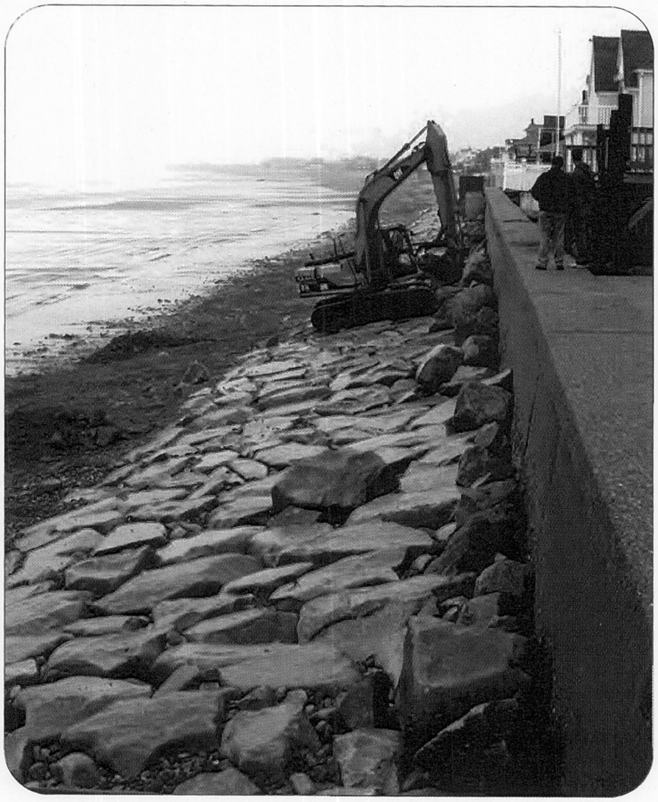


Photo: Massachusetts Office of Coastal Zone Management.

While seawalls and other structures can sometimes provide storm protection, they generally require regular expensive upkeep and often lead to other problems (including beach erosion). Marshfield, Massachusetts.

NAI protects the rights of residents, businesses, and visitors in your community by requiring that public and private projects be designed and completed in such a way that they do not: (1) pose a threat to public safety, (2) increase flood or storm damage to public or private property, and/or (3) strain municipal budgets by raising community expenditures for storm-damage mitigation, stormwater management, emergency services, and disaster recovery efforts.

NAI: Local and Comprehensive

Careful management of coastal floodplains is critical to protect people and property, and to reduce the financial strain on businesses, private property owners, and municipal budgets. While the Commonwealth of Massachusetts has passed regulations to help prevent storm damage, ultimately most of the authority and tremendous responsibility to manage floodplains is entrusted to local governments.

Accurately evaluating the potential effects of proposed activities can be challenging, and requires looking both on and offsite, since damage often isn't confined to the parcel(s) under review. For example, the construction of a home may change stormwater flow and increase erosion (removal of sediment by water or wind) to surrounding properties. Similarly, new parking lots, roads, and buildings may redirect stormwater onto other properties instead of allowing it to be reabsorbed into the ground.

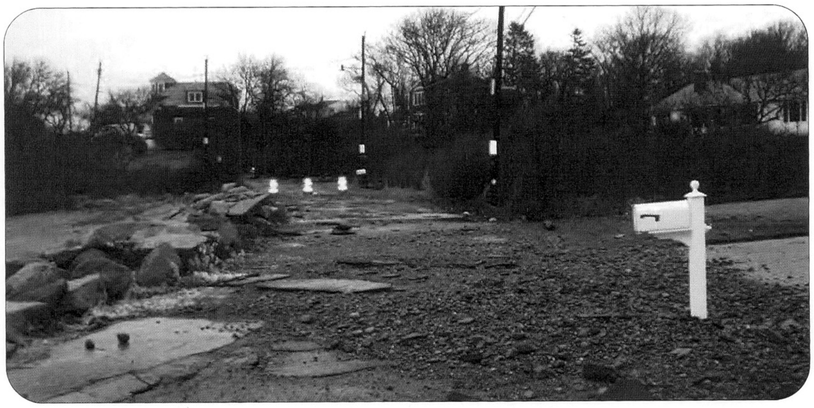


Photo: Massachusetts Office of Coastal Zone Management.

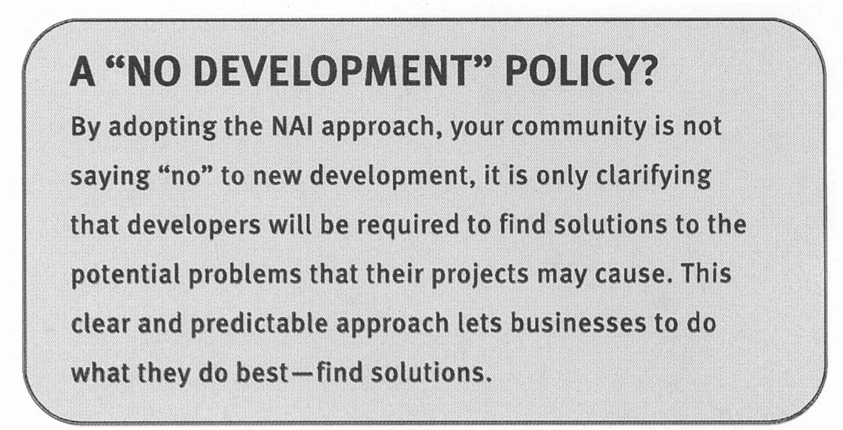
In addition to being costly to repair, roads damaged by storms can become hazards for rescue personnel and others. This road in Rockport, Massachusetts, was destroyed by a 2007 nor'easter.

Since each permit might be considered to set a precedent, it is critical that communities consider the potential cumulative effects of their decisions—a number of seemingly insignificant projects can collectively cause substantial damage. The NAI approach clarifies that community leaders not only have the legal right to consider the cumulative impacts of their permitting decisions, they have the legal responsibility. Increasingly, communities that permit projects that result in flooding or storm damage to other properties end up in land court. (See the StormSmart Coasts Fact Sheet 2, *No Adverse Impact and the Legal Framework of Coastal Management*). Adopting the NAI approach also gives your community the chance to clearly articulate a "do no harm" goal for all future land use.

The NAI Approach

The Association of State Floodplain Managers (ASFPM), a national organization of professional flood hazard specialists from all levels of government, the research community, the insurance industry, and technical fields, identifies three different levels of floodplain management strategies: *Basic, Better,* and *NAI.*

- *Basic:* Approaches typically used to meet minimum Federal or state requirements for managing floodplains and coastal areas to minimize flood losses.
- *Better:* Activities that are more effective than the basic level because they: (1) are tailored to specific situations, (2) provide protection from larger floods, (3) allow for uncertainty in storm magnitude prediction, and (4) serve multiple purposes.
- *NAI:* Tools and techniques that go further than the measures defined as "better" by ensuring that private development, public infrastructure, and planning activities do not have direct or indirect negative consequences on the surrounding natural resource areas, private property, or other communities.



A "NO DEVELOPMENT" POLICY?

By adopting the NAI approach, your community is not saying "no" to new development, it is only clarifying that developers will be required to find solutions to the potential problems that their projects may cause. This clear and predictable approach lets businesses to do what they do best—find solutions.

ASFPM has created seven NAI Building Blocks, which can help communities to maintain and enhance flood protection. These building blocks—hazard identification and mapping; planning; regulations and development standards; mitigation; infrastructure siting and design; emergency services; and public outreach and education—are briefly introduced in the table on the next page. For more information, see ASFPM's *Coastal NAI Handbook* at *www.floods.org,* or the StormSmart Coasts website at *www.mass.gov/czm/stormsmart.*

NAI Building Blocks

NAI Building Block	Basic	Better	NAI
Hazard Identification and Mapping	Use FEMA Flood Insurance Rate Maps for land use decisions.	Gather and use detailed coastal hazard data (*e.g.,* historic erosion rates, actual observed extents of floodwaters) for land use decisions.	Incorporate coastal hazard data (*e.g.,* erosion rates, vulnerability of environmentally sensitive areas, and sea-level rise rates and impacts) into community-wide planning maps and regulations.
Planning	Use land use planning and zoning through a community master plan.	Develop floodplain management plans that include stormwater management and hazard mitigation measures. Promulgate detailed guidance focusing on reducing flood damage.	Design special area management plans to: protect storm damage and flood control functions of natural resources, promote reasonable coastal-dependent economic growth, and improve protection of life and property in hazard-prone areas.
Regulations and Development Standards	Follow Federal Emergency Management Agency National Flood Insurance Program regulations.	Adopt conditions for siting new development. Regulate cumulative, substantial improvements. Revise regulatory tools for addressing erosion along shorelines including: relocation of threatened buildings, building setbacks, beach nourishment and bio-engineering, and stabilization of eroded areas.	Preserve sensitive areas through bylaws and regulations that may: establish maximum densities for development, restrict structures between the shoreline and the setback line, mandate vegetative coastal buffers rather than manmade structures (bulkheads, seawalls, or groins), minimize impervious cover, and preserve stream corridor and wetland buffers. Regulate placement of fill.
Mitigation	Use common practices, such as flood proofing existing structures.	Elevate or relocate buildings. Acquire land. Encourage nonstructural methods for shoreline protection.	Stabilize shorelines with vegetation. Prohibit construction in especially damage-prone areas. Prevent filling of wetlands and other lowlands. Nourish beaches where appropriate. Protect watersheds. Monitor corrective efforts. Regulate construction of shore-protection structures.

NAI Building Blocks—Continued

NAI Building Block	Basic	Better	NAI
Infrastructure Siting and Design	Respond to storm events as they occur. After a storm, rebuild/ repair to previous condition.	Upgrade damaged facilities to more hazard-resistant standards. Inventory hazard risks of all public buildings. Insure buildings for all hazards (as appropriate). Identify, and if possible, relocate or protect "critical facilities."	Prohibit major public infrastructure investments in special flood hazard areas. Ensure that roads, sewer lines, and utility upgrades don't encourage development in hazard-prone areas. Zone to prohibit construction in high-hazard areas. Locate new critical facilities above 500-year flood-plain.
Emergency Services	Create and use generic hazard response plan.	Create and test community-wide hazard plans that involve all local boards and departments.	Create plans to ensure that all people who want or need to be evacuated can be moved to safe shelters, and post-disaster plans that improve community flood resistance through: willing land acquisition, determining which structures are "substantially damaged," and ensuring that appropriate reconstruction meets code requirements. Establish mutual aid agreements with neighboring communities.
Public Outreach and Education	Answer questions and provide information as requested by public.	Periodically inform residents of coastal hazards, vulnerability, and mitigation techniques through public workshops, and in forums after storm recovery.	Create comprehensive education and out-reach programs using expertise of state and Federal agencies (when needed) to encourage community-wide proactive storm preparation. Establish coastal hazard disclosure requirements for property sales.

The Benefits of NAI

While NAI strategies require investment in planning and implementation, they offer real benefits for your community. NAI can . . .

- *Save money:* Less damage means lower post-storm community cleanup costs, fewer demands on public officials' limited time, and reduced strain on public resources.
- *Decrease litigation:* NAI principles have been judicially tested and courts have shown immense deference to regulations that seek to prevent harm (for an example, see the StormSmart Coasts Fact Sheet 3, *A Cape Cod Community Prevents New Residences in Floodplains*). NAI can also help your community avoid potential litigation over ineffectual flood management practices that result in future damage or loss of life. (See Fact Sheet 2, *No Adverse Impact and the Legal Framework of Coastal Management.*)
- *Reduce conflicts with property owners:* NAI doesn't say "no." It says "yes, if . . ." It is a common-sense approach that seeks to protect everyone's property by only allowing projects that eliminate or mitigate their impacts.
- *Reduce risk to people and public and private property:* Better planned and designed development and public infrastructure is less likely to cause and suffer damage. An NAI approach can help protect the beaches that are critical to many communities' economies.
- *Lower flood insurance rates:* The Community Rating System (CRS) is a Federal Emergency Management Agency (FEMA) program that decreases flood insurance rates for communities with effective hazard mitigation strategies. Many NAI strategies qualify for CRS credits. For more information see the CRS Resource Center at *training.fema.gov/EMIWeb/CRS/*.
- *Increase your capacity to bounce back after a storm:* Reduced storm damage means less downtime and less costly clean up for local businesses, which is especially important for small, locally owned businesses that may otherwise struggle to stay solvent during frequent or prolonged closures.
- *Clarify your land use objectives:* By adopting NAI principles, your community can articulate the overarching goals that help bring consistency and predictability to permitting.

- *Preserve quality of life:* With NAI you can help make your community safer while preserving quality of life for your citizens now and in the future. An NAI approach can help ensure that your community resources, including beaches, public parks, and other open spaces, are there to be enjoyed by future generations.

For More Information . . .

- For more on the theory of NAI and its application in coastal areas, see the Association of State Floodplain Managers website (*www.floods.org*), especially their *Coastal NAI Handbook.* Also see the StormSmart Coasts website at *www.mass.gov/czm/stormsmart.*
- For more on the legal issues surrounding coastal management, see the StormSmart Coasts Fact Sheet 2, *No Adverse Impact and the Legal Framework of Coastal Management.*
- For an example of NAI-type regulations at work, see the StormSmart Coasts Fact Sheet 3, *A Cape Cod Community Prevents New Residences in Floodplains.*
- For a more detailed look at the legal theory behind this and similar cases involving land management in hazardous areas, see the Association of State Floodplain Managers' *No Adverse Impact Floodplain Management and the Courts* by attorneys Jon Kusler and Ed Thomas, at *www.floods.org.*

FACT SHEET 2

No Adverse Impact and the Legal Framework of Coastal Management

How communities can protect people and property while minimizing lawsuits

Managing coastal floodplains is a challenging endeavor that sometimes is incorrectly thought to put local government's duty to protect people and property in direct conflict with property rights. Most local officials want to reduce the harm and costs associated with coastal storms, and recognize that unwise development can worsen the situation. Unfortunately, as our society has grown more litigious, it may seem harder for municipal governments to stay out of land court when preventing or conditioning development projects, even when there is good evidence that these projects may create problems for others. However, the No Adverse Impact (NAI) approach to land use management is an appropriate way to protect people, property, and property rights. (To learn more about NAI, see the StormSmart Coasts Fact Sheet 1, *Introduction to No Adverse Impact (NAI) Land Management in the Coastal Zone.*)

While nothing can prevent all legal challenges, following the NAI approach can help to: (1) reduce the number of lawsuits filed against local governments, and (2) greatly increase the chances that local governments will win legal challenges to their floodplain management practices. The legal system has long recognized that when a community acts to prevent harm, it is fulfilling a critical duty. The rights of governments to protect people and property have been well recognized by the legal system since ancient times. Courts from the Commonwealth of Massachusetts to the U.S. Supreme Court have consistently shown great deference to governments acting to prevent loss of life or property, even when protective measures restrict the use of private property. This "prevention of harm" principle is the foundation of the NAI approach. The goal of this fact sheet is to provide local officials with information on how to use the NAI tools to confidently protect people and property in a fair and effective way, while avoiding lawsuits (even those alleging takings).

Two key points:

1. *Communities have the legal power to manage coastal and inland floodplains.*
2. *Courts may (and often do) find that communities have the legal responsibility to do so.*

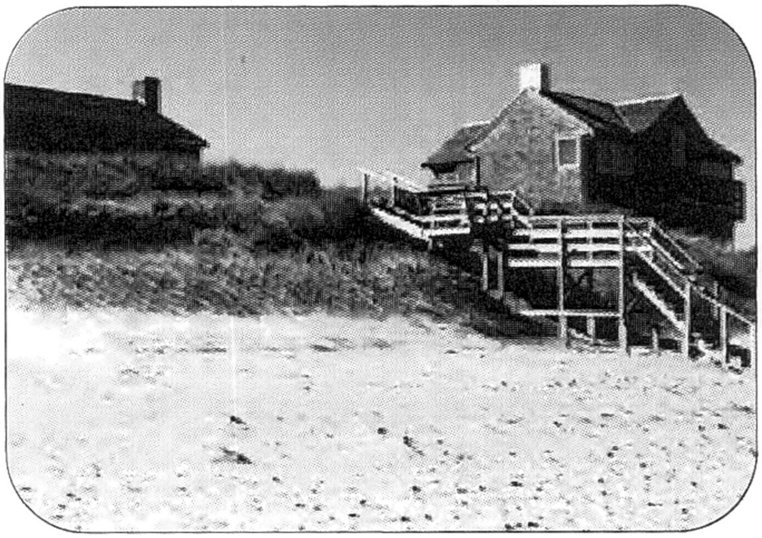


Photo: Massachusetts Office of Coastal Zone Management.

These Sandwich homeowners proactively protected their property by planting beach grass. Vegetating dunes and banks can reduce erosion and slow floodwaters without adversely impacting other properties.

How NAI Can Help Your Community Avoid Lawsuits

The best way to avoid losing in court is to stay out of court. One of the strengths of the NAI approach is that its clear goal (the prevention of harm) fosters and encourages cooperation between landowners and regulators as they work together to try to find solutions to the problems associated with proposed projects. Such collaboration is a great way to stay out of land court.

When avoiding court isn't possible, following the NAI approach can greatly increase the chances that local governments will win in lawsuits arising from their floodplain management practices. The most common and historically problematical challenges that local officials face while trying to regulate use of private property are allegations of "constitutional takings."

Not all the uses an owner may make of his property are legitimate. When regulation prohibits wrongful uses, no compensation is required."—The Cato Institute

Takings background: This fact sheet summarizes a complex body of law under the so-called "Takings Clause" of the Fifth Amendment to the U.S. Constitution. This summary is not intended to be legal advice for any particular situation, and may not be relied upon as such. To determine whether a particular regulation would cause a taking, communities should consult with an attorney. Property owners file takings cases when they believe regulations violate their constitutional property rights. The legal basis for these arguments can be found in the Fifth Amendment of the U.S. Constitution, which prohibits the Government from taking private property for public use without compensation. The interpretation of the courts through the years has clarified that the Fifth Amendment encompasses more than an outright physical appropriation of land. In certain situations, the courts have found that regulations may be so onerous that they effectively make the land useless to the property owner, and that this total deprivation of all beneficial uses is equivalent to physically taking the land. In such a situation, courts may require the governing body that has imposed the regulation to either compensate the landowner or repeal the regulation.

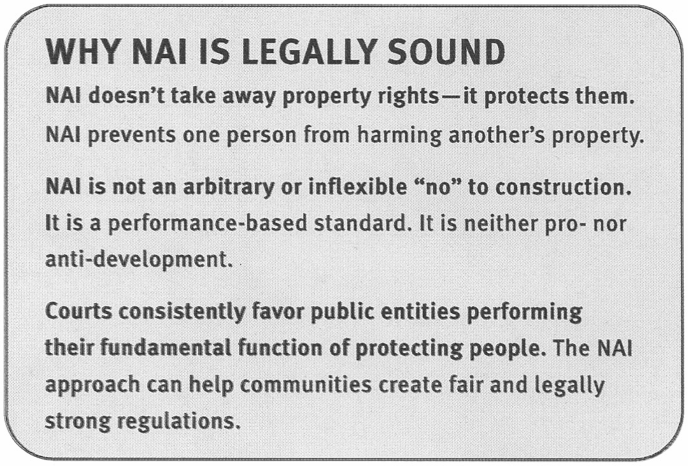
Needless to say, with local budgets strapped and coastal land values skyrocketing, it is rarely economically feasible for local governments to compensate landowners when, for example, prohibiting a house on a solid foundation in an area known to flood, or preventing the construction of a seawall to protect a home on an eroding bluff.

NAI to the Rescue: It is critical that management decisions respect property rights and follow general legal guidelines (see the "Legal Dos and Don'ts of Floodplain Management" text box). The courts have made it very clear that property rights have limits. For example, both Commonwealth of Massachusetts and Federal laws acknowledge that property owners do not have the right to: be a nuisance, violate the property rights of others (for example, by increasing flooding or erosion on other properties), trespass, be negligent, violate reasonable surface water use and riparian laws, or violate the public trust.

The Four Types of Regulatory Takings

The best way to understand how the NAI approach helps to prevent takings challenges is to look specifically at what the courts have decided may constitute a regulatory taking. In 2005, the U.S. Supreme Court ruled on a precedent-setting case (*Lingle* v. *Chevron*), which clearly established regulatory taking guidelines. In their unanimous decision, the Court determined that there are four ways for a regulation to be a taking. *Each way is briefly discussed below, with a non-technical explanation of how they are relevant to an NAI approach.* (For a more detailed legal explanation of these cases, see the latest edition of *No Adverse Impact Floodplain Management and the Courts,* published by the Association of State Floodplain Managers at *www.floods.org.*)

1. A physical intrusion. Governments may not, without compensation, place anything on private property against the wishes of the owner. The case discussed (*Loretto* v. *Teleprompter Manhattan*) involved a New York City requirement that building owners allow the cable company to install a small cable box and cables on all residential buildings. *Because the NAI approach doesn't generally promote structural solutions, this type of regulatory taking is unlikely to apply. However, if a community's NAI plan involves the placement of structures (culverts, for example) on private property, this ruling makes it clear that the community may be required to obtain the permission of the landowner or pay compensation.*



WHY NAI IS LEGALLY SOUND

NAI doesn't take away property rights—it protects them. NAI prevents one person from harming another's property.

NAI is not an arbitrary or inflexible "no" to construction. It is a performance-based standard. It is neither pro- nor anti-development.

Courts consistently favor public entities performing their fundamental function of protecting people. The NAI approach can help communities create fair and legally strong regulations.

2. A total or near-total regulatory taking. If a regulation restricts property rights to such a degree that it eliminates all or essentially all economically viable uses of a piece of property, this may constitute a taking. The case reviewed (*Lucas* v. *South Carolina Coastal Council*) was filed by a landowner who was prohibited from building a home on a barrier beach. *In their opinion, the Court clearly states that regulations aimed at preventing nuisance don't constitute takings. It warns, though, that governing bodies arguing that specific regulations are designed to prevent nuisances will need to demonstrate how they are addressing similarly situated nuisances (i.e., regulations may not be applied arbitrarily).* The NAI approach can help your community to consistently articulate how potentially harmful projects are nuisances. When designing land use regulations, your community should always try to ensure that the owner retains at least some economically beneficial uses. This is both fair and helps establish the legal reasonableness of your regulations. Note that land uses that harm others are not legal or beneficial, and that beneficial uses don't necessarily include building residences or other structures, especially in hazardous areas. Where new regulations, even hazard-based regulations, could sharply decrease the market price of property, consider allowing the transfer of development rights to areas where your community would like growth to occur. To learn about transferable development rights, see *www.mass.gov/envir/smart_growth_toolkit/pages/mod-tdr.html.*

3. A significant, but not near-total regulatory taking. Courts hearing takings arguments should consider three factors that have "particular significance"—(a) the magnitude of the economic impact, (b) how severely the regulation affects "investment-backed expectations," and (c) the character of the government in action. The central case discussed (*Penn Central* v. *City of New York*) concerned a denied expansion of Grand Central Station in New York City. *The historic preservation regulation reviewed in this case seeks to protect neighborhood character—not to prevent physical harm.* These are two very different things in the eyes of the law. The U.S. legal system sometimes requires governments to compensate landowners when property rights are compromised for community improvement, but less frequently when they prevent potential harm. *There is no property right to use or develop land in a way that harms others, even if that use maximizes the particular site's economic potential. There is no constitutional or legal right to a good return on investments.* Unfortunately, some people invest in land with erroneous ideas about what they are legally allowed do with it, and when forbidden to do as they wish, may argue that regulations have devalued their property. The courts have made it clear that while regulations designed to prevent harm may reduce the market value of a piece of property, they do not decrease its true value, and hence NAI-based regulations cannot trigger this aspect of a taking test. A 2005 Massachusetts Supreme Judicial Court decision upheld a coastal town's regulation prohibiting new residences in its coastal floodplain because the town successfully established that this regulation was designed to prevent harm and did not render the land valueless.

LEGAL DOS AND DON'TS OF FLOODPLAIN MANAGEMENT

Do clearly relate regulations to hazard prevention.

Do help landowners to identify economic uses.

Do apply identical principles to government activities.

Don't neglect your duty to manage the floodplain. (A hands-off approach is the surest way to be successfully sued.)

Don't apply regulations inconsistently or arbitrarily.

Don't interfere with landowners' rights to exclude others.

Don't deny all economic uses. Consider the use of transferable development rights in valuable, heavlily regulated areas.

For more information, see the StormSmart Coasts Fact Sheet 3, *A Cape Cod Community Prevents New Residences in Floodplains.*

4. Insufficient relationship between the requirement and the articulated government interest. If a community conditions a permit, the requirements it exacts from the landowner must be related to the goals of the regulation and must be "roughly proportional" to the predicted impacts of the proposed development. In the two cases, *Nollan* v. *the California Coastal Commission* and *Dolan* v. *City of Tigard,* landowners were required to provide a public right of way as a permit condition, even though the proposed developments did not reduce public access. The NAI approach avoids this type of taking by tightly binding regulations to the specific goal of preventing harm.

With these and other decisions, the courts have made it clear that governments may regulate land without compensation if they do so with the intent of preventing harm. *Fairly applied No Adverse Impact regulations make the "takings issue" a non-issue.*

From the property rights perspective, it's worth noting that the Cato Institute, which advocates for limited government, individual liberty, and free markets, agrees that preventing landowners from causing harm to others does not constitute a taking:

> "Owners may not use their property in ways that will injure their neighbors. Here the Court has gotten it right when it has carved out the so-called nuisance exception to the Constitution's compensation requirement. Thus, even in those cases in which regulation removes all value from the property, the owner will not receive compensation if the regulation prohibits an injurious use."—Roger Pilon, Senior Fellow and Director—Cato Institute (to the U.S. House of Representatives, 2/10/95)

"The takings clause was never intended to compensate property owners for property rights they never had."—Massachusetts Supreme Judicial Court

Why You Should Manage Your Floodplains

Protecting people and property is a fundamental duty of all levels of government. One of the most effective ways that local governments protect people and property is through the permitting process. Here, local officials can and should do what they can to reduce the likelihood that the development or use of property will cause harm.

Communities should also be aware that in a growing number of states, courts are favoring plaintiffs that sue local governments for permitting projects that later cause damage to property (for example, permitting the construction of roads that back-up streams and increase flooding in the community). For more information on this trend, see *No Adverse Impact Floodplain Management and the Courts* (available at *www.floods.org*), where the authors found that a community is vastly more likely to be successfully sued for allowing improper development that causes harm than for prohibiting it.

The take-home lesson: As a local official, you have been given the responsibility and the legal rights to manage coastal and inland floodplains. If you do so in a way that expressly seeks to prevent harm, the courts will support you.

For More Information . . .

This is not and cannot be legal advice. To answer specific legal questions please see an attorney licensed in your jurisdiction. To learn more about the general legal framework of NAI-based floodplain management see:

- *No Adverse Impact Floodplain Management and the Courts* for an excellent overview of the case history of NAI at *www.floods.org.* While this document is designed for attorneys, it is useful for anyone working in floodplain management.
- The StormSmart Coasts Fact Sheet 3, *A Cape Cod Community Prevents New Residences in Floodplains,* which examines a community's successfully defended NAI-type bylaw.
- The *Coastal NAI Handbook* at *www.floods.org.*
- The NAI section of the Association of State Floodplain Managers website at *www.floods.org.*
- The Institute for Local Government's one-page publication, *10 Tips for Avoiding Takings Claims,* at *cacities.org/index.jsp?displaytype=11&zone=ilsg&section=land&sub_sec=land_property&tert=&story=20219.*
- The American Planning Association's 1995 *Policy Guide on Takings* at *www.planning.org/policyguides/takings.html.*
- The StormSmart Coasts website at *www.mass.gov/czm/stormsmart.*

FACT SHEET 3

Case Study—A Cape Cod Community Prevents New Residences in Floodplains

Lessons learned from Chatham's legally successful conservancy districts

In a landmark 2005 ruling, the highest court in Massachusetts decisively affirmed the authority of municipalities to regulate or even prevent residential or other high-risk development in flood-prone areas without financial compensation to the property owners, so long as the regulation does not render the land entirely valueless.

The case arose from the town of Chatham's refusal to permit the construction of a new home in a flood zone because the local zoning bylaw prohibited new residential units in the town's mapped floodplains. After multiple appeals by the landowner, the Massachusetts Supreme Judicial Court ruled on July 26, 2005, that the zoning bylaw was based on reasonable public interest, and did not render the lot economically worthless. Therefore, no compensation was due. The decision was not appealed.

The Zoning Bylaw

Chatham's zoning bylaw designates "conservancy districts" encompassing all land in the town's 100-year floodplain as mapped in its most recent town-approved Flood Insurance Rate Maps. The goal of the bylaw is to protect people, property, and resources (see "Chatham Conservancy District Purposes" sidebar). The bylaw clearly delineates three types of activities in designated conservancy districts—permitted uses, special permit uses, and prohibited uses—examples are shown in the table below.

Examples from Chatham's Zoning Bylaw

Permitted uses	Special permit uses	Prohibited uses
Fishing, cultivation, and harvesting of shellfish (including excavation of areas for cultivation and harvesting of marine foods); various horticulture activities Outdoor recreation activities, provided that related structures do not destroy beneficial character of district Floats Maintenance of existing raised roadways Installation of utilities Agriculture Government dredging of navigation channels Construction and maintenance of town landings and public boat launching ramps; nourishment of town beaches Mosquito control by Cape Cod Mosquito Control Project Maintenance of existing channels and marine facilities	Construction of certain structures, including catwalks, piers, ramps, stairs, boat shelters, tennis courts. Construction of structures or buildings used in conjunction with a marina or boatyard. Construction and maintenance of driveways or roadways of minimum legal length and width. Construction and maintenance of private boat launches and beaches. Installation of submerged pipes or cables used for swimming pools or commercial fishing operations.	Filling of land Draining of land Discharging of hazardous substances, treated sewage, or thermal effluent Construction of residential units or use of houseboats or barges as dwellings Building of any structure in V and V1–30 Zones Construction of pipelines to carry crude oil or unprocessed natural gas Actions that destroy natural vegetation, alter existing tidal flow, or otherwise alter the character of the land Destruction of natural growth that prevents erosion or storm damage Draining, damming, or relocating water courses except for aquaculture, agriculture, or flood or mosquito control

"The takings clause was never intended to compensate property owners for property rights they never had."—Massachusetts Supreme Judicial Court

The Case

The lawsuit concerned a 1.8-acre parcel located in Chatham's mapped floodplain (and therefore, in a conservancy district). In 1998, the owner of the lot received an offer of $192,000 for the parcel, contingent upon the ability of the purchaser to obtain the permits necessary to build a home. The proposed home was to be elevated on open piles above the mapped 100-year flood elevation.

Because the lot is located within a conservancy district, the town's Zoning Board (the district permitting authority) denied the building permit application. The owner of the lot responded by filing one suit against the Selectmen and Zoning Board and another against the town's Conservation Commission (the construction would have also violated a local wetlands bylaw), each suit alleging that the bylaws violated the owner's constitutional property rights, and that the town had thereby effectively "taken" her property (for more on constitutional takings, see StormSmart Coasts Fact Sheet 2, *No Adverse Impact and the Legal Framework of Coastal Management*). A Superior Court judge combined the two suits. After a two-day trial, which included testimony on the flood history of the property, the risks and impacts of its potential development, and the difficulty in safely evacuating the area, the Superior Court found insufficient evidence to support the plaintiff's claims that the bylaws had resulted in a regulatory land taking, and upheld the town's decision.

When the plaintiff appealed the decision, the Massachusetts Appeals Court affirmed the Superior Court's decision. While acknowledging that the bylaw did severely constrict the possible uses of the lot, the Appeals Court noted that "a land-use regulation may deprive an owner of a beneficial property use—even the most beneficial such use—without rendering the regulation an unconstitutional taking." The Appeals Court further noted that:

> "As a matter of Massachusetts law, restricting residential development within the path of floodwater, the flood plain, is a direct, logical, and reasonable means of safeguarding persons and property from those hazards occasioned by a flood and advances a substantial state interest, that is, the health, safety, and welfare of the general public as well as that of its individual members."

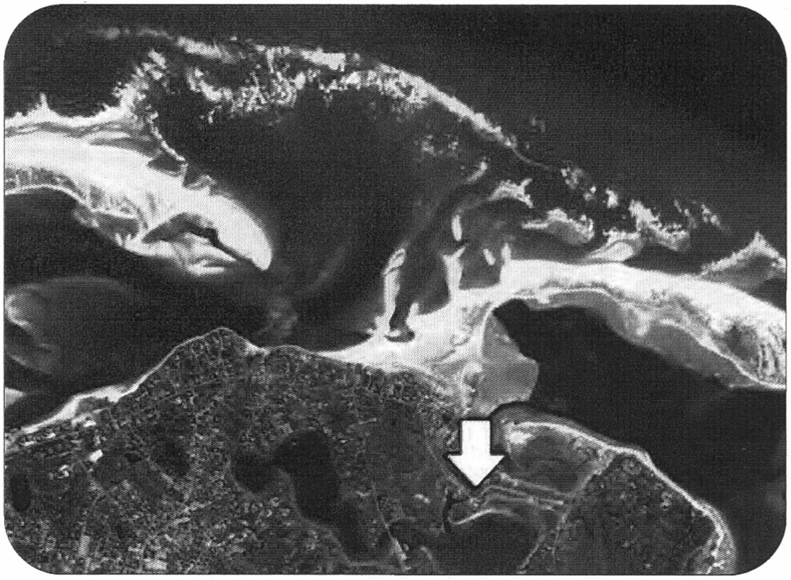


Photo: Google Earth

The arrow indicates the approximate location of the proposed home site. This satellite photograph also shows the breach in the barrier beach from 1987. The breach greatly increased the exposure of the lot and surrounding properties to wave and storm surge.

The plaintiff then appealed to the Massachusetts Supreme Judicial Court, which, after reviewing the case, upheld the lower courts' rulings, citing a recent U.S. Supreme Court decision that had rendered zoning bylaws and ordinances valid under the U.S. Constitution so long as their application bears a "reasonable relation to the State's legitimate purpose" (such as protecting people and property).

The decision also noted that while the regulation may have indeed reduced the market value of the property, the prevention of one potential use for a piece of property did not constitute a total taking. A witness for the plaintiff estimated that with the bylaw, the lot was worth at least $23,000—a substantial reduction but still more than a "token" interest, according to the decision which cited a (2001) case where the U.S. Supreme Court ruled that no compensation was due when a regulation reduced the appraised value of a parcel from $3,150,000 to $200,000.

Finally, the decision noted that there was ample evidence showing that the construction of a home on the lot could have severe adverse impacts on the surrounding community. The plaintiff's expert testified that the proposed house could be picked up off its foundation and floated away by a severe storm, potentially damaging neighboring homes. The defendant offered testimony that efforts to evacuate the home during a flood would pose risks to rescue workers, as well as the home's occupants.

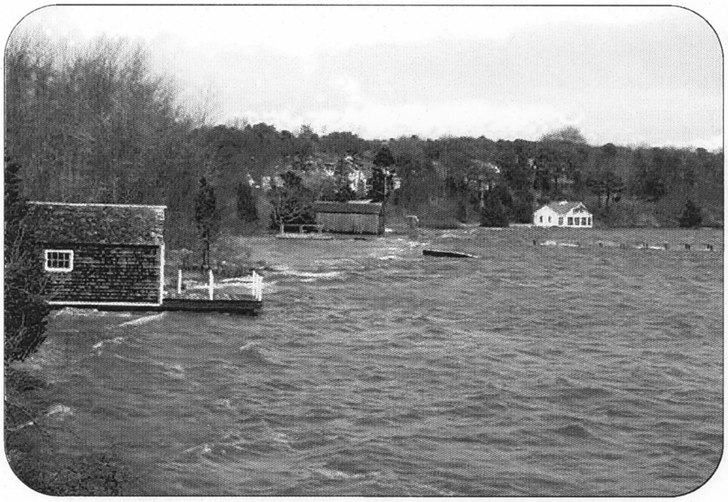
A Nauset Beach home destroyed by a 2007 storm. As was noted in the Massachusetts Supreme Judicial Court's ruling, damaged structures like the one in this photo can create debris that may threaten other structures.

The Massachusetts Supreme Judicial Court concluded that no compensation was due to the property owner, because: "The taking clause was never intended to compensate property owners for property rights they never had."

The decision was not appealed.

Why Chatham Won the Case

1. The zoning bylaw had the clear goals of protecting people and property.
2. While the bylaw prevents construction of new homes, it leaves property owners with many alternative uses. The land retains more than a "token" value.
3. The law was fair, and applied to identifiable, mapped areas (*i.e.,* wasn't "spot zoning," which unfairly prevents one individual property owner from using property in a certain way).
4. The town's emergency management experts testified that evacuation of the areas would put rescue workers at risk.
5. The town was willing to legally defend its position.

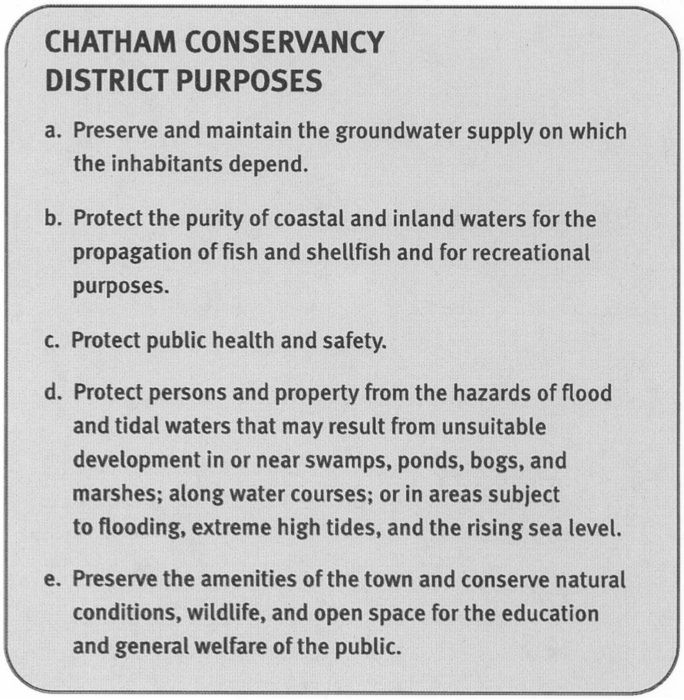


Top: The erosional beach near the proposed home site is prone to flooding and storm damage. Bottom: An area ofChatham in the floodplain where flooding can make evacuation difficult.

For More Information . . .

- For an overview of the legal framework of coastal management in Massachusetts, see the StormSmart Coasts Fact Sheet 2, *No Adverse Impact and the Legal Framework of Coastal Management.*
- For the text of the decision, see *www.socialaw.com/slip.htm?cid=15382.*
- For a copy of the bylaw see *www.chatham-ma.gov/Public__documents/chathamma__CommDev/Zbylaw2005.pdf.*
- For a more detailed look at the legal theory behind this and similar cases involving management of land in hazardous areas, see the Association of State Floodplain Managers' *No Adverse Impact Floodplain Management and the Courts,* by attorneys Jon Kusler and Ed Thomas at *www.floods.org.*
- The Massachusetts StormSmart Coasts webpage: *www.mass.gov/czm/stormsmart.*

As coastal areas of Massachusetts continue to change in response to erosion and storms, the relative risks to properties do too. While the risk to these homes near a new breach is obvious, homes on the mainland that were once protected by the shifting barrier island also face increased exposure. (Photo: Nauset Beach, Chatham.)



CHATHAM CONSERVANCY DISTRICT PURPOSES

a. Preserve and maintain the groundwater supply on which the inhabitants depend.

b. Protect the purity of coastal and inland waters for the propagation of fish and shellfish and for recreational purposes.

c. Protect public health and safety.

d. Protect persons and property from the hazards of flood and tidal waters that may result from unsuitable development in or near swamps, ponds, bogs, and marshes; along water courses; or in areas subject to flooding, extreme high tides, and the rising sea level.

e. Preserve the amenities of the town and conserve natural conditions, wildlife, and open space for the education and general welfare of the public.

Senator KERRY. Thank you very much, Mr. Carlisle.

Dr. Walsh?

STATEMENT OF JOHN E. WALSH, DIRECTOR, COOPERATIVE INSTITUTE FOR ARCTIC RESEARCH, INTERNATIONAL ARCTIC RESEARCH CENTER, UNIVERSITY OF ALASKA

Dr. WALSH. Senator Kerry, Senator Stevens, thank you for the chance to speak today. I am John Walsh from the International Arctic Research Center. I am also Director of NOAA's Cooperative Institute for Arctic Research at the University of Alaska.

In many respects, Alaska is ground zero for recent climate change. We are seeing a dramatic loss of ice, melting glaciers, warming permafrost. Senator Stevens is well aware of the changes that are ongoing in Alaska.

I would like to focus on the gap between what the stakeholders need, what they are requesting of the climate community, and what climate models are actually delivering.

Alaska has a diverse population. It ranges from small indigenous communities that are reliant on subsistence activities to growing urban areas and to an energy sector on which the rest of the U.S. depends. Much of the infrastructure is built on permafrost, and one of the main characteristics of Alaska's climate is its wide seasonal swings. In addition to that, there are tremendous spatial variations. The graphics in the written testimony provide an example of the extreme contrasts spatially in the variables such as temperature.

I will cite one example for what that means for the weather and climate of Alaska relative to modeling. The interior valleys, the Yukon River Valley, the Tanana River Valley, are precipitation shadows in reality. The present climate models with their resolutions of 100 to 200 kilometers present these areas as maximum elevation regions with precipitation greater than the surrounding areas. So we are completely losing the precipitation signal over a large portion of the state because of inadequate resolution. The resolution that we need in order to capture fields such as precipitation is between one and two orders of magnitude finer than what we now have in the latest generation of global models.

A high priority for Alaskans is the tailoring of model output to include the information that is most relevant to the needs of planners and the public, as well as other stakeholders. The variables that are carried in climate models are often not the ones that correspond most to the user needs. In Alaska, some examples of these user needs are information about the firmness of the ground for overland transportation, snow cover characteristics, vegetative dryness during the fire season, and wind chill temperatures in exposed areas.

A recent illustration of the needs and the gap relative to the modeling capabilities is the attempt by Peter Larsen and his colleagues in Anchorage to estimate the economic risks to public infrastructure in Alaska as a result of climate change in the coming decades. The global models on which he based his scenarios have uncertainties in themselves, and they produced a range of a factor of two to three in the estimates of infrastructure costs to be expected from climate change over the next 50 years.

But more importantly are the limitations on the availability of variables beyond temperature and precipitation which were used in the Larsen study. Infrastructure such as buildings and roads will clearly be affected by freeze-thaw cycles, by changes in snow loads, by the temperature extremes, the peak-wind events, and the occurrences of flooding. We are a long way from being able to obtain that type of information in a credible manner from today's climate models, and there has actually been little effort to translate model output into these quantities that the users and the stakeholders need. So the bridging of the models and the user needs is an emerging area of activity. This need is intertwined with this need for higher resolution and for more credible model simulations.

So the people of Alaska are already calling for more detailed and robust information than they are receiving from climate models, and I would argue that the challenge of integrating user needs such as those in Alaska with advances in climate modeling gives us an opportunity to respond to our taxpayers at the regional scale and to serve as a prototype for some globally integrated climate delivery services.

Thank you.

[The prepared statement of Dr. Walsh follows:]

PREPARED STATEMENT OF JOHN E. WALSH, DIRECTOR, COOPERATIVE INSTITUTE FOR ARCTIC RESEARCH, INTERNATIONAL ARCTIC RESEARCH CENTER, UNIVERSITY OF ALASKA

Climate Modeling for Decision-Makers and Stakeholders in Alaska

Alaska's statewide annual average temperature has increased by 3.4 °F since the mid-20th century, and the increase is much greater (6.3 °F) in winter. The higher temperatures of the recent decades have been associated with an earlier snowmelt in spring, a reduction of summer sea ice coverage, a retreat of many glaciers, and a warming of permafrost. These surface changes, as well as their associated climate drivers, have two characteristics that require advances in modeling if projections of change are to meet the needs of decision-makers and planners. First, feedbacks between ice, snow and the atmosphere exert potentially strong leverage on high-latitude climate change, and these feedbacks introduce large uncertainties into simulations by existing climate models. For example, the recent retreat of summer sea ice is occurring at a faster rate than projected by any of the models in the recent Fourth Assessment (2007) of the Intergovernmental Panel on Climate Change (Stroeve *et al.,* 2007). There are also indications that feedbacks may already be occurring between the earlier spring snowmelt and the surface energy budget, resulting in an increase of vegetative greenness (photosynthetic activity) in parts of Alaska (Euskirchen *et al.,* 2007). Second, the surface changes are highly variable over small spatial scales, largely as a result of complex topography and coastal configurations around the region. The figure below illustrates the fine resolution required to capture the spatial variations in Alaskan climate.

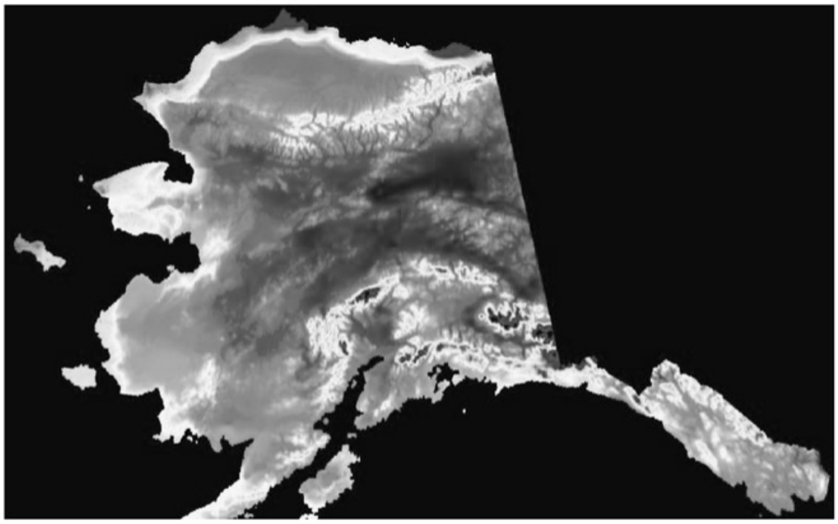


Figure 1. Average July daily high temperatures in Alaska for 1961–1990. Color ranges are 40–45 °F (blue), 45–50 °F (green), 50–55 °F (yellow), 55–65 °F (orange), and 65–75 °F (darker red). Image is from the PRISM database (Daly *et al.,* 2008).

In contrast to the 2 km resolution in figure above, the grid cell dimensions (spatial resolution) of global climate models are typically 100–200 km. Figure 2 below shows the smoothness of projected temperature changes obtained from the global models for Alaska. The mis-match of scales is even greater for precipitation, which is a variable that is of great interest to users of climate information pertaining to water supplies, inland transportation, forestry, and terrestrial ecology.

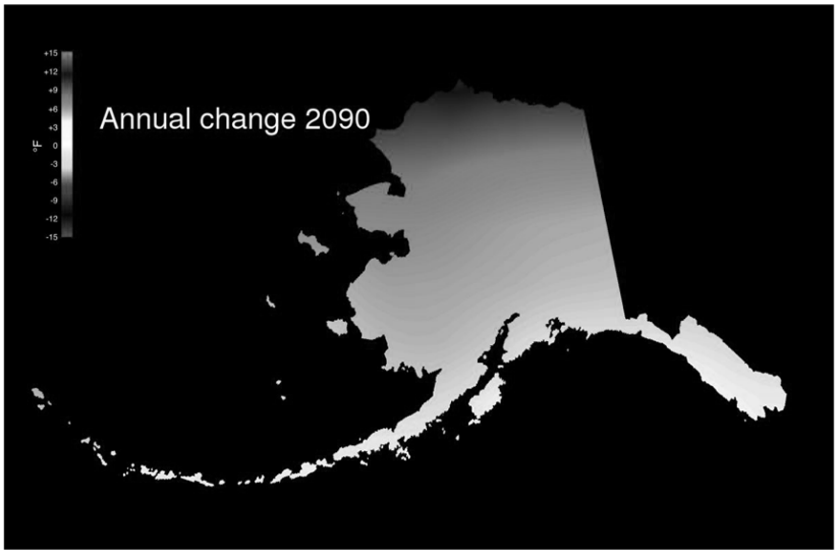


Figure 2. Projected changes of annual mean temperature (°F) over Alaska for the late 21st century (2090), based on the B1 simulations by the models used in the IPCC's (2007) Fourth Assessment. Yellow denotes a warming of 3–5 °F, deep red a warming of 8–10 °F.

How can the utility of climate projections be made more useful to decision-makers and stakeholders in Alaska? Based on the experience of the Alaska Center for Climate Assessment and Prediction (a NOAA Regional Integrated Sciences and Assessment Center), the greatest needs are: (1) downscaling of the coarse-resolution model output, (2) reduction of the uncertainty inherent in the model-derived projections, and (3) tailoring of model output to include variables and information more directly relevant to the needs of planners and stakeholders. In the remainder of this testimony, we address these needs and approaches to meeting these needs.

The mis-match of scales between Figures 1 and 2 can be addressed by two types of downscaling: dynamical and statistical. Dynamical downscaling consists of the nesting of a high-resolution regional model inside a coarser-resolution global model. This approach has been tested in various regions of the world, and its effectiveness is highly dependent on the validity of the input supplied at the lateral boundaries by the global model. For Alaska, the approach is being applied to simulations of the mass balance of glaciers in southeastern Alaska. The nesting of finer grids inside coarse grids achieves 1 km resolution over the glaciers. Applications to other surface features (*e.g.,* permafrost, ecosystem changes) are being developed. The second approach to downscaling is statistical in its nature. In this case, statistical algorithms (*e.g.,* multiple regression equations) are developed to relate model-computed quantities and observational data for which sufficiently long records exist. The predictors can be either pre-selected or screened. This approach, which generally requires *a priori* knowledge of a system's behavior in order to select candidate predictors, has been used successfully in weather prediction, where the term "Model Output Statistics (MOS)" describes the products. The predictor fields can be model counterparts of the desired quantity (*i.e.,* a model's grid-cell temperature can be used as a predictor of temperature at a specific location, *e.g.,* a weather station), or the predictors can include other model variables such as wind, humidity and cloud cover from the target location's grid cell and/or from upstream grid cells. This approach has significant potential to meet user needs for site-specific scenario information, but it has not been applied extensively in Alaska.

The reduction of the uncertainty in climate projections from global models is essential for the validity of applications such as downscaling, whether dynamical or statistical. While global models are improving over time (Reichler and Kim, 2008), a promising area for advancement is the selection of subsets of models that are most credible for the application at hand. In the case of Alaskan climate simulations, several global climate models used in the IPCC Fourth Assessment capture the present climate (including its seasonal cycle) more successfully than other models. Preliminary studies indicate that a composite over a subset of the best 5–7 models (out of the total of 20–25 available models) provides the greatest skill in simulations of Alaska, the Arctic and the Northern Hemisphere. These models tend to project larger changes of temperature and precipitation over Alaska for the remainder of the 21st century. In this respect, selection of models based on quantitative metrics of performance can reduce the uncertainty of future climate projections. Such activity should be a high priority for user services provided by the climate modeling community.

A high priority in climate research is the tailoring of model output to include variables and information most relevant to the needs of planners and stakeholders. The variables carried by climate models are not always the ones that correspond to user needs, which can include (for example) the firmness of the ground for overland transportation; snow cover characteristics; vegetative dryness during fire season, etc. A recent illustration of such needs is the attempt by P. Larsen (Nature Conservancy) to estimate the economic risks to public infrastructure in Alaska as a result of climate change in the coming decades. While global model uncertainties limit the robustness of such estimates, an even greater limitation is the availability of variables beyond temperature and precipitation. Infrastructure such as roads and buildings will clearly be affected by changes in the freeze-thaw cycles, snow loads, temperature extremes, peak-wind events and occurrences of flooding. There has been little effort to translate model output for Alaska into these quantities that are most relevant to infrastructure risks as well as to other concerns of users. The bridging of models and user needs is an emerging area of activity, and it is intertwined with the need for site-specific (downscaled) climate projections and for reduced uncertainty in climate model output.

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Senator KERRY. Thank you very much, Dr. Walsh.

It was very helpful, all of you, and I might add here and there a little baffling and confusing as to how we make layman's sense out of what we need versus what your hopes are and requests are.

I gather, in listening to you, that the principal obstacle that we have got is a human resource pressure. We have this whole issue of high-end computing, adequate access to it, which we just heard about. The appropriateness of software, software standards, protocols, et cetera, and what they are going to be. More observational data, which you have all said we have got to have, and obviously, adequate research funding.

What I am trying to figure out, as I listen to this, and perhaps you can help us understand. Give it to us in relative terms. We have now had several rounds of the IPCC. We are gearing up globally to make certain decisions. Now, obviously, Dr. MacDonald, you would like resolution, and Dr. Walsh you are talking about that in terms of the ability to be able to really predict something for a community.

To what degree are we able now to adequately predict in a way that allows public policymakers to make a smart decision? Is there an element of guesswork in this now? Is there a sufficient level of accuracy that you can make some predictions, and then we need to go further to make the others? Who wants to tackle that? Dr. Sarachik?

Dr. SARACHIK. I think right now we are able to make certain predictions. We are able to say certain things. For example, there was a recent paper by a group out of Scripps talking about, as time goes on, the snowpack will decrease. Those are firm results because they are based on science. As it gets warmer, you have less ice, and therefore you have less available water for irrigation and various other things because the snowpack serves as reservoirs.

On the other hand, we cannot make very fine-scale decisions because we do not have very fine-scale information. And a lot of our people want to do things at the watershed level. Puget Sound, for example, an estuary, is a climate regime in itself that has a lot of very unique problems that simply cannot be dealt with until we can make predictions of variability and actual climate for the coming year on that scale, and we cannot do that right now.

Senator KERRY. And to do that, what will it take?

Dr. SARACHIK. I think it takes a balanced program of—sorry to say this—observations, modeling, and research because I do not think one of them can be allowed to get ahead of the others. They are all necessary and you cannot make progress without doing them all.

Senator KERRY. Who will define the balance?

Dr. SARACHIK. I think you can define the balance by asking the National Academy to define that balance. So far, nobody has really thought about what the progression is going to be, and at the moment everybody is arguing for his own little specialty, but nobody is arguing for everything going together. And that is what is really necessary.

Senator KERRY. The answer to that means you have got to have resources in every sector. That is a resource-based request.

Dr. SARACHIK. I think it is a resource-based request and it is an organizational problem for Government because government is not presently organized to do this very well. There have been continuing complaints about the United States Global Change Research Program, for example, which is not able to focus money on problems because agencies have different needs and requirements. Therefore, you cannot really solve some major problems.

One of the outstanding problems has been decadal variability. We do not have a program on decadal variability despite its being recommended for a very long time. It is absolutely crucial for both understanding ENSO and for understanding global warming.

Senator KERRY. For understanding what first?

Dr. SARACHIK. Global warming and El Niño Southern Oscillation.

Senator KERRY. Can you give us the kind of dollar-to-result connection, or is that completely speculative?

Dr. SARACHIK. We have actually done this in various committees of the National Academy that I have served on, and the answer is if we want the national climate service which will give us the largest scale of information correctly, the observations, modeling on the large scale that will interact with offices on a small scale, it would be on the order of $1 billion a year.

Senator KERRY. $1 billion a year. Where are we now?

Dr. SARACHIK. It is a little hard to say because each agency defines climate in different ways and, therefore, cannot bring resources to bear on problems.

Senator KERRY. With respect to that, anybody else jump in when you want to here. I am not just targeting one person.

Does that mean that we need to pull the effort of all these agencies under one roof? Would that serve the agency interests adequately if we did that?

Dr. SARACHIK. Or within a single agency. I do not know of any weather service which is not a single agency throughout the world. There are hundreds of weather services throughout the world, and they are all separate agencies I would think. A climate service should be either a separate agency or within a single agency in order to be able to accomplish a single goal.

Senator KERRY. Dr. Reed, do you want to weigh in?

Dr. REED. Just to echo that comment. That challenge is mirrored on the side of computing research and infrastructure as well. It is scattered across many agencies. There is a loose confederation of programs, and as I alluded in my testimony, one of the perpetual recommendations of the community is tighter coordination of those activities to focus on the underlying R&D that enables the computational science, of which climate change is one example, but also the procurement process for open scientific research facilities that support problems like this.

Senator KERRY. How far are we, in your judgment, on the current scale of what we are putting in and the current rate of progression in modeling? The modeling, you would all agree, is better today than it was 5 years ago, and that is better than it was 10 years ago. So we are making some progress. We are not making all the progress you would like to make. Is the progress we are making sufficient to responsively address the concerns of people like Mr. Carlisle, Dr. Walsh, and others who are trying to make decisions at a local level? Or is there a correlation here between the amount of money, energy, effort, leadership that ought to go in to accelerating the supercomputing capacity and the other things so that we are getting better real-time results?

Does anybody want to take it? Yes, Dr. MacDonald. You can all have a shot at it.

Dr. MACDONALD. Senator Kerry, our scientists at GFDL feel that we do need a balanced program, but we are at a point where significantly higher resolution models really would give us much better regional information, and they made that point that it was not just that they thought that, that they had been able to test that concept, instead of running at 130 miles, running at like 30- and 40-mile resolution. So they tested that out, and that is where they got this figure that you see.

Senator KERRY. What does it take us to get there?

Dr. MACDONALD. The increase by a factor of four in resolution with better physics takes something like 100 times as much processing as today.

I want to add one more point.

Senator KERRY. What is the limitation on that? Is it just the commitment to the funding or is there a technical limitation?

Dr. MACDONALD. I do not think there is a large technical problem since they have proved that they are able to do it. So I think it is just access to the computing.

And one more point.

Senator KERRY. Do you agree with the figure that Dr. Sarachik gave us, $1 billion a year?

Dr. MACDONALD. I guess to understand that figure, I would have to know what all do we include, whether we include all of our satellite systems and so on. So I cannot comment on it.

But I did want to make an additional point that part of the reason I think we can advance rapidly in climate modeling is that we did the same thing in weather models. When I started my career, they were really poor on precipitation and we got higher and higher resolution. They got better and better. I guess some would argue with that, but we think they are a lot better.

Senator KERRY. I saw another hand. Yes, Dr. Walsh.

Dr. WALSH. I would like to pick up on this analogy to the weather models. I realize weather and climate prediction are certainly different beasts, but I think that there is a lesson we can learn from the weather prediction community that may help us accelerate progress toward meeting the user needs. That is the statistical adjustment of model output. The adjustments are made for specific locations based on algorithms that have been developed using observational data. Now, that type of approach shortcuts to some extent the slow progress in model resolution and in model capabilities.

But there are two requirements there. One is for an integrated observational system that is truly integrated with what the modeling community is doing, and the second is it requires some coordination, some organization in the national-level program, whether it is through multi-agency or not. It is not going to happen piecemeal.

Senator KERRY. Senator Stevens?

Senator STEVENS. Well, thank you very much. I woke up this morning and thought about this problem that just hit Myanmar, whatever we call it now.

Senator KERRY. Burma.

Senator STEVENS. Do you remember, Dr. Walsh, we had a typhoon off of the northern coast of Alaska? We had cyclones, hurricanes. We seem to be unable to predict these things, and I think the total damage that comes from not being able to predict them are fairly obvious to everyone.

Have we used space enough in terms of getting that data for you all to use in your computers? Goldwater used to believe we could get a lot of information by just observing what is going on on the globe as a whole rather than just one spot. Have we ever proceeded on any of this?

Dr. WALSH. The satellite information seems to have been most useful in the weather prediction arena. In the sense that climate includes the statistics of weather over time, I think we may have more of a challenge in incorporating the satellite information into an enhancement of the climate models. I see the payoff more in the weather prediction arena.

Senator STEVENS. Dr. MacDonald, my staff thinks I ought to ask you the question of whether the budget this year will keep NOAA on track in obtaining supercomputing resources for improved climate modeling. Do you have enough money?

Dr. MACDONALD. Senator Stevens, we have been able to get the support that we need, and I think our climate modeling is going quite well. And what we are talking about here is kind of the next big jump up in the 5 to 10 year timeframe.

Senator STEVENS. This is not the place to get into it. I have been worried about the predictions that many people are relying on in terms of some of these, for instance, the IPCC because of what went into their computers. Do we have enough reliable information about the past to really feed the stuff into the computers as we are doing now?

Dr. MACDONALD. I think within NOAA and elsewhere, there are a lot of programs where we do try and look at not only the last 100 years but the last 1,000 years. It is tough work. You are drilling into glaciers and trying to see what it was. And that has taught us a lot about our models. I think if we look objectively, our models have improved greatly from the 1990s and I think it is partly because we were able to look at the past and see what it was. So I am kind of an optimist to think we are making great progress, but the need for understanding climate is so great, that we are really looking for trying to get much better.

Senator KERRY. Can I just extrapolate on that? What is the level of accuracy about the longer-term predictions of consequences of climate change? I think that is part of what Senator Stevens was asking. Has enough data gone in here that is good data to be able to say the sea level rise is accurate, that the vegetation migration is accurate, these expectations that we are now factoring in?

Dr. SARACHIK. I think you can say that on a large enough space scale. The problem is that that is very good for the IPCC, which is interested in mitigation. To simplify, mitigation is global, but adaptation is local. We do not have that sort of information on a local scale.

Senator KERRY. You just do not know where that is going to happen, but you know it is going to happen.

Dr. SARACHIK. It is not clear to me it is going to happen because I think it depends on the health of the climate community. I work in the trenches, or I used to. I have had 10 students getting Ph.D.'s, five of whom are no longer in the field because there were no opportunities for them in the field. This is a field which is simply not providing enough opportunities because there is not enough money. I do not know what it is like for government organizations, but the money is not working its way down to the universities where a lot of this work is done and a lot of people are trained.

Senator STEVENS. Dr. Sarachik, again a question. I am told the NOAA research program has been active for more than a decade. That program in Alaska was started in 2006. What are the challenges in translating scientific research and complex modeling, particularly the data, information that can be used by people, by just ordinary citizens?

Dr. SARACHIK. We deal with that pretty much every day in my center, and they need information that is translated into resource predictions. We, for example, use whatever climate information we can get from the models. We correct the models as best we can. It is not a very well defined procedure. Then we make hydrological predictions for things like stream flow, and from stream flow, we can make energy predictions, because most of our energy is hydropower, and salmon predictions and water availability predictions, irrigation, and agricultural predictions. That is the sort of thing we need to do. It is not being done well enough because the global models are not good enough, and it is not being done in enough places in the United States.

Senator STEVENS. Well, I guess I could not get too specific. And Dr. Walsh might correct me on this if I am wrong, but it is my understanding that few of the computers that are producing information that looks at the Arctic for the future have taken into account the vast amount of Atlantic water that has gone into the Arctic Ocean at a fairly deep level and that that water has been very warm and that the thawing in our area has been from the bottom up, not from the top down, not from warming on top, but from the warm water that is coming from the Atlantic Oscillation and bringing up more warm water than ever before. And theoretically, it may stop at any time. It may reverse and go back to its normal pattern.

How do computers figure that in? The net result of the computers today say ice is going to disappear in our Arctic Ocean by 2020, 2030. Our people dispute that. As I understand it, we believe it is thinning and we are going to lose summer ice, but we are not going to be ice-free as these computers predict. How do we really get any balance in terms of the public information as to the results of something like these computers that are fed one basic group of statistics and other statistics that are not made available to them?

Dr. SARACHIK. I think all of the models currently being done for the IPCC process do include deep water coming up, thermohaline circulation, if you will. The fact that the models do not agree among themselves is an indication that we are a long way from making reasonable predictions.

The policy issue is, how much do you need in order to make decisions? How much do you need to know about the future? And the future is always murky. The more we know about the future, the better those decisions will be.

My attitude toward models is it tells us the range of things that could happen. It does not necessarily tell us what would happen. And that is the best we can do at the moment, but I think we can do better.

Senator STEVENS. I thank you.

John, what coordination now exists between our International Arctic Research Center and those entities that are producing these global climate models that we are hearing so much about? Are they really feeding in some of the information that you have gathered through the International Arctic Research Center now for over 20 years?

Dr. WALSH. Well, I think you touched on a good example with the inflow of Atlantic water into the Arctic Ocean. As Dr. Sarachik mentioned, there is a wide range among models and how they simulate that inflow. What we need is a good observational assessment to pin down which models are doing things right for the right reason. So I think what we are pointing to here is the need for, again, a coordination between the observations and the models. In this case, it is the model assessment side of the modeling enterprise.

Senator STEVENS. I do not want to offend my friend here. But around here if I criticize IPCC, I am criticizing motherhood. And yet, I think that their models are deficient in terms of the information base that has been made available to us in the Arctic. Am I wrong?

Dr. WALSH. There was a polar chapter in the IPCC assessment. But you are right that it contained very little use of the model output and very little critical assessment of the models.

Senator STEVENS. And now we face the problem of having the polar bear declared endangered because its habitat may be affected, and that question of whether the habitat is going to be affected comes from this IPCC model that was deficient to start with, as far as I am concerned.

Now, I do not want to put this on my friend from Alaska. But what do you do about this, Dr. Sarachik? How do we find some way where we can obtain models that the public as a whole can rely on without the hype that comes from something like IPCC? We do not have hype with the Alaska models, but they have been financed, by the way, by the Federal Government for 20 years.

Dr. SARACHIK. We will never have perfect information about the future. There will always be an uncertainty in the policy decisions that need to be made.

What we now know is that there is a possibility of large ice depletion in the Arctic. We do not know how much it is going to be. We have seen one example of complete melting of summer ice in the opening of the Northern Passage. Nobody would have expected that 25 years ago, but some of the models, in fact, have predicted that, but some of them have not.

Senator STEVENS. Would it surprise you to know that we know in history that it has been open before for substantial periods of time?

Dr. SARACHIK. If you go back in the geological record, yes, of course.

Senator STEVENS. I am talking about in recent history, the last 800 years.

Dr. SARACHIK. I do not believe that there is firm evidence that the Northern Passage has been open during that time.

Senator STEVENS. Well, it was open several times, as a matter of fact.

Senator KERRY. Where is that documented?

Dr. SARACHIK. The ability to go across the Arctic Ocean in the summer which would shorten the distance between Asia and Europe considerably and the fact that it was open——

Senator STEVENS. The question is what is open and how long it has to be open in order to be classified as being open. But very clearly, there have been periods of time when people could go from the Atlantic to the Pacific across the top of this continent.

And now it is being predicted that it will be open for a period of time, a substantial period of time. Many people believe that will be year-round. I am told it will not be year-round. It might be open for a period of time in the summertime, but winter ice is not going to be gone. Would you disagree with that?

Dr. SARACHIK. I would plead ignorance because some models say that it will and some models say that it will not.

I think one of the things we should recognize is that a lot of—I know this is on the one hand and on the other hand, but predictions are not made by models. Predictions are made by the emissions that go into the models. So the models simply give you the response to those predictions. If in fact we emit more greenhouse gases, more CO_2, then the climate will be warmer and a lot of these things will happen more. The models simply describe the response to the emissions of the various greenhouse gases.

Senator STEVENS. Mr. Chairman, we mentioned this question of earmarks for the last 4 years. Through earmarks we have kept four vessels taking statistics on the Arctic Ocean for a period of time in the summertime. I do not know how long. We thought that would disappear because of the inability to get the earmark, but thankfully NOAA has agreed now to finance the same concept and keep it going so we get reliable predictions over a period of time of what the actual changes are in the Arctic Ocean. So I look forward to having accurate observational statistics coming at us now in this period ahead of us, and I hope we can do that in places where there are areas of real controversy like what is going to happen in the Arctic because those vessels, being from various nations, are collecting the same type of data throughout the Arctic Ocean, which is not just a little pond. It is an enormous place. If we can get that information and feed it into the computers, we are liable to start getting some accurate predictions, Doctor. So I agree with you. Stuff in and stuff out. So we want to put the right stuff in.

Thank you.

Senator KERRY. Can I say to my friend from Alaska—I just want to pick up on this—I think the key of what Dr. Sarachik just said is you have to look at what the input is to whatever the model is that you are looking at. And he said that if emissions continue to go up, it will get warmer.

Now, on the current track that we are on, emissions are absolutely guaranteed to go up at an alarming rate. Is that correct? Does anybody disagree? Good. And if they go up——

Senator STEVENS. You are talking about CO_2.

Senator KERRY. I am talking about CO_2. I am talking about all greenhouse gases. Greenhouse gases are going to go up. If we reach 600 to 900 parts per million, which the current rate of China's and India's and our own pulverized coal powerplant production levels are, the ice is going to continue to melt. And then the polar bear is going to be threatened.

So it is a question of your input. You and others have to look at the input and make a public policy judgment as a person whether you find it accurate and concerning or not.

I do not disagree. I have always said this, that there is a level of inexactitude in the modeling. We cannot tell you exactly what is going to happen in a lot of different places, but we get a big enough picture, do we not, gentlemen, that gives you pretty good indications of trend lines, which as a matter of public policy indicates you better take notice or not take notice?

I mean, you have seen these transitions in Alaska. We are spending, what is it? $100 million and some to move a village. Your permafrost is melting, is it not?

Senator STEVENS. We would like to have that $100 million, though. We need $100 million.

Senator KERRY. And you, sir, have about as much ability as anybody here in the Senate to make sure it will happen.

[Laughter.]

Senator KERRY. That is why I like sitting by you here in this Committee.

Anyway, the point is made that I think we know we want to try to bring this down to a greater level of exactitude, and the question I am trying to get at is how rapidly can we do that, at what kind of expense. I think it is important that you have said we have to do this with much greater coordination. We have got to coordinate more effectively, and we have got to look in this committee at how you do that. We have to look at the question of whether or not you bring this under one roof. Correct? We need to get the National Academy perhaps involved in how we can best do this is what I am trying to glean out of this.

What else do we need to do as a committee and as a Congress to try to get us on the right track here as fast as we can?

Dr. SARACHIK. I have served on a lot of Academy committees which have talked precisely about this problem, and this has been over a course of the last 15 years I would say.

Senator KERRY. So are the studies already there?

Dr. SARACHIK. A lot of the studies are there, yes. In particular, there was a study called *Pathways* which was done in the late 1990s. I served on that committee. And it described the balanced approach to things, and it also objected to the way that research was currently being carried out in the United States by the USGCRP, the U.S. Global Change Research Program.

I think climate science has made some tremendous advances. We now know that there only seem to be three major phenomena that we have to explain, El Niño, Pacific Decadal Oscillation, and North Atlantic Oscillation. If we can do that, we can get a large amount of the predictable part of climate in the future.

I do not know of any programs in the United States which actually concentrate on that. I have been working on El Niño for 25 years, and at this moment, I do not know where I would apply for money in order to study that problem.

Senator STEVENS. You have come to the right place because I will sure help you if you could find some way to get a program that we could finance that would make some sense.

Dr. SARACHIK. I have made recommendations and the Academy has made recommendations. For example, I worked on a committee about decadal variability. The idea is that the basic problem in predicting El Niño was our inability to understand its decadal variations, and one of the big problems of global warming is the fact that it is being modulated by decadal variability. So we recommended only one thing, a program in decadal variability. When we presented this to the various agencies, they said we cannot do it. So they did not get together and form an initiative, which I would have hoped and expected that they would do.

Senator STEVENS. I am serious, Mr. Chairman. I wish you would really give Congress some recommendations along that line. In spite of the earmarks, I think it is high time we understood both the Atlantic Oscillation and the Pacific El Niño concepts and try to understand why they apparently are not there in the southern hemisphere. At least, I have not seen any sign of them having a reciprocal effect on, I think, the South Pole.

Dr. SARACHIK. Oh, you mean why the——

Senator STEVENS. Why was not the southern hemisphere affected the same way? If you go to the South Pole, you will find the ice has been piling up there for 40 years and not melting at all.

Dr. SARACHIK. —the basic reason for that is that there is a circumpolar current in the South Pole which goes all the way around, which allows water to come up from the deep. That water is extremely cold and will stay cold for a very, very long time.

Senator KERRY. But I understand there was a very significant breach in the ice in the Antarctic just recently.

Senator STEVENS. That was because of the weight of the ice. It fell off.

Dr. SARACHIK. There is melting of the Antarctic continent, but in general, the predictions are that the Arctic will melt far more than the Antarctic basically because cold water will come up in the Antarctic which does not necessarily come up in the Arctic.

Senator STEVENS. Well, why do you not present us your recommendations? Maybe we can find some bipartisan way to get around this problem of no earmarks. I think that is the most significant thing that has come out of this. There really is not enough information to know about these oscillations and what it does to the North American continent.

Dr. SARACHIK. Correct.

Senator STEVENS. And I would like to join in demanding that the money be made available to do so.

Senator KERRY. Would it have just fallen off if it stayed colder? That is OK.

Dr. Hack, a quick question. Is your center over-subscribed?

Dr. HACK. We are fully subscribed.

Senator KERRY. Fully subscribed. And how do you prioritize and allocate the time for the computers?

Dr. HACK. Right now, all of the time at the center is allocated through a program called INCITE. It is a program that is open to all comers.

Senator KERRY. How much is allocated toward climate use?

Dr. MACDONALD. Fourteen percent of the total cycles are allocated to——

Senator KERRY. If I could interrupt, let me just say, before Senator Stevens goes, if you could get the Committee in the next days your specific thoughts about how we address Senator Stevens' concern, we will go to work and see what we can do here and we will leave the record open. Fair enough?

Senator STEVENS. Thank you. I am sorry I have to leave. Thank you very much.

Senator KERRY. I have to leave in about 5 minutes, folks. I have a foreign guest coming in. So I need to get up to that meeting.

Dr. HACK. The center has had a very long history with the climate community back in the IPCC days when the AR4 computations were being done.

Senator KERRY. But it is competing. It is competing with these other interests. Right?

What I am getting at is, do we need a climate-specific supercomputer center?

Dr. HACK. It would be a tremendous asset to the climate community to have something like that I think.

Senator KERRY. What would that cost?

Dr. HACK. If you are talking something on the order of a petascale type of center, we are probably talking between $50 million and $100 million.

Senator KERRY. Where would be the preferred place of siting that other than Massachusetts?

[Laughter.]

Dr. HACK. Well, Oak Ridge would make a nice place.

[Laughter.]

Dr. HACK. But I think the main thing is to see—I think the harder thing is to try and coordinate this as an interagency question so that the agencies are all on board and one could tailor the needs of a center like that to meet all the disparate needs of the different agencies that would be running on the computer system.

I just wanted to follow up on a couple of things that have come up. And that is that I think a lot of the questions, when we are asking about prediction and what is going to happen in the future, really come down to uncertainty in the modeling frameworks. How certain are the forecasts? And there is no one single thing you can put your finger on that is going to tell you why they are uncertain. Certainly resolution plays a very large role, as Dr. MacDonald showed. We have done our own experiments with resolution to illustrate the same sort of thing. You cannot capture, for example, orographic precipitation accurately with a very course model. That is a very simple thing.

For things like ice, say, sea ice in the Arctic, the processes that are embodied in these models, the mathematical representations are approximations, and we improve those approximations through the observations. And as the observations get better, the approximations get better and the models get better and the uncertainties are reduced.

So this is why I think putting one's finger just to say that this one magic pill that will solve all these things—I do not think that is the right way to look at it. I think that all these factors are interrelated. They all rely on one another. Computing is certainly as important as the investments in modeling and the investments in the observational systems to help improve the models.

Senator KERRY. I guess with any of these models at some point you have to be willing to just draw a line and dismiss the imponderables, I assume, like the sunspot argument or dust storms or the Gulf Stream shuts down and all of a sudden that are unpredicted. There is a point, is there not, where you are able to take all of the potential variables that people can conjure up and adequately address them? Or is there just ultimately a level of imponderability here?

Dr. HACK. I think there are gaps in what we understand about the climate system. I think it is encouraging that the models are as good as they are at their ability at least on global scales to reproduce the observed record.

Senator KERRY. And the key is just really to look at what is going into it, is it not? You then decide, hey, what is the probability of this in a sense——

Dr. HACK. As far as we are going to be able to do is to give a sense——

Senator KERRY.—and take the data on that. We know there is going to be X amount of powerplants in China, X amount. We know there is going to be X amount of greenhouse gas. We are getting pretty good, I assume, at correlating the degrees, the Centigrade or Fahrenheit degrees of the warming level according to the greenhouse gases. As for forest migration or CO_2 in the ocean, how do you bring all those together?

Dr. HACK. I am optimistic that these kinds of problems can—the noise, let us say, and the uncertainty can be driven down with——

Senator KERRY. How long will it take us to get there? Because time is ticking on us. We have got some skeptics around still.

Dr. HACK. I think with a focused effort, goals are achievable within the decade.

Senator KERRY. Within the decade.

Dr. HACK. And the other aspect of this is the stakeholder community, the people I have interacted with. For example, a year ago, I was in a meeting with western water judges who were looking at a rule on water rights matters. The message was that they would much rather have data with uncertainty in it than no data at all. And the stakeholder community is a very sophisticated, intelligent community. They know how to use data that is not perfect, and as long as we make an attempt to try and establish what the error bounds are and start to be able to address some of the issues Dr. Sarachik talked about with regard to low frequency variability in the system, the answers that they are getting are going to be tighter and they will be of more use to their planning with regard to infrastructure and resources, resource management.

Mr. CARLISLE. Senator, I would like to echo that point, if I could. A decade is a long time for coastal communities who are faced with siting decisions every single day. So we are willing to accept a certain level of uncertainty. As long as we can frame it and base it back to sound science, we can at least start to have informed conversations. And even a little bit of information helps. So the sea level rise, with all the uncertainties around it—at least we can track that trajectory, and that is important. We can start to build in freeboard.

So one of the things I will make a call for is while the modeling at the global scale and regionals is really important, we still can use things like high resolution topographical and bathymetry data and we can get a lot from that type of information. So these are very, very important, but we can also make progress while we are going through these long-term decadal research improvements to make some progress on the ground.

Dr. HACK. I would like just to make one more statement about——

Senator KERRY. You will have to do it quickly because I have got to wrap it up.

Dr. HACK. That is that the IPCC showed very clearly that the models show predictive skill on subcontinental scales, certainly on continental scales. So the issue of resolution I think does provide an opportunity for a rather substantial improvement in predictive skill in the models if we can explore that part of parameter space. It is just too expensive and this is where the whole computational infrastructure issue comes into play. With dedicated facilities, these models can be configured to at least explore what the predictive skill of the models would be if you were able to run them at resolutions that are more typical of weather prediction models.

Senator KERRY. Well, we will give you the chance in the next few days to get in to us what that best practice is going to be over the course of these next few years, as I will leave the record open. We really welcome that.

Last question, Dr. MacDonald, just quickly. You talked about the three-legged stool, the increased computation measurement, et cetera. Are each of those legs equal today?

Dr. MACDONALD. I think that they are equal, and we are investing in them. We are trying to get the climate sensors onto NPOESS. We are trying to get the really big increases in computing, and we have expeditions up to the Arctic to try to understand what is happening with the ice. So they are equally important.

Senator KERRY. And do we need to make an equal amount of advancement in each of them in order to get this level of predictability we want, or is there one more than the other that we ought to be focused on?

Dr. MACDONALD. No. I think of it as equal. That is why we like using the example of the stool. You cannot have one leg that is a lot longer. It is not a very good stool if it is.

Senator KERRY. So we are back to our balance. Good enough.

Folks, we could spend more time. I unfortunately cannot, not because I do not want to. Is that a vote we have on? Well, that is another reason we cannot.

I am greatly appreciative. It has been very, very interesting certainly, and we will leave the record open for a week to allow any other colleague who wants to submit a question and to get your response back. And we thank you again. I know you have traveled a distance. Enjoy Washington for a day or so. And thank you all very, very much. I appreciate it.

We stand adjourned.

[Whereupon, at 4 p.m., the hearing was adjourned.]

APPENDIX

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN F. KERRY TO BRUCE K. CARLISLE

Question 1. You emphasize the need for a national strategy on climate modeling to be coordinated with state, regional and local partners. How should states and cities inform the development of these models and the products generated based on the models?

Answer. State coastal management programs are primarily using models and products from the Intergovernmental Panel on Climate Change, academia, and the National Oceanic and Atmospheric Administration. As these and other entities look to fine-tune and expand their models or begin working on next generation, they should engage with "end-users" at the regional, state, and local levels to assess their needs and identify opportunities for pilot applications. State governments are a very effective level to start at as many state programs have existing mechanisms for communicating, coordinating, and working directly with counties, cities, and towns. State coastal programs, in particular, have a demonstrated track record of working in close coordination with both Federal agencies and local communities to successfully provide high-quality products, services, and hands-on assistance to constituents in and beyond the coastal zone. The Coastal States Organization (CSO) serves as a central mechanism to coordinate input from and collaboration with state programs. In addition, ICLEI—an international association of local governments—represents another venue for communicating local needs. If modelers and product developers need to distribute and/or translate data into local tools and strategies, CSO can also work with the state programs and ICLEI to increase local awareness and implementation for real world change.

Question 2. What information does the state need to advise cities, towns and citizens about the impacts of climate change and how they can prepare and adapt?

Answer. For coastal communities, municipalities and citizens need to be aware of increased vulnerability to storms and sea-level rise. Therefore, information on the potential magnitude of impacts—including increased flooding, shoreline erosion, saltwater intrusion into fresh water aquifers, invasive species, harmful algal blooms, and the loss of coastal habitats such as beaches and marshes—within the next 20 to 50 years is paramount for states to provide technical assistance to communities for effective climate change adaptation planning and implementation. Within these issue areas, high-resolution topographic and bathymetric elevation data are required, to be coupled with region-specific tide data, sea level rise projections, and other key parameters in order to identify the areas and resources most vulnerable to accelerated sea level rise

Question 3. How should that information be delivered to end-users?

Answer. State coastal programs have the ability to work with the scientific community hand-in-hand to tailor high-quality products, services, and hands-on assistance to best suit the needs of both state and local decision-makers and resource managers. Massachusetts has found that concurrent, targeted outreach and technical assistance is essential to successful implementation. To that end, the Massachusetts Office of Coastal Zone Management has developed the StormSmart Coasts program, which is designed to give local decision-makers, and ultimately businesses and homeowners, information and tools on coastal resiliency through a user-friendly website, fact sheets, workshops, and direct technical assistance. We have received extensive positive feedback from municipalities, acclaim from national organizations, and interest from a multitude of state programs. A national version of StormSmart Coasts could be used to communicate current information on climate modeling.

Question 4. In your written testimony, you discuss the state's role in developing high-resolution shoreline change data and coastal high-hazard zone delineations. Are you capable of projecting that information into the future, given the likely impacts of global climate change?

Answer. Shoreline change data and identified flood- and erosion-hazard areas are extremely critical for coastal managers. However, identification of current and future risk zones is limited by the state of the science as well as our lack of resources to apply current scientific understanding. Erosion rates in Massachusetts and across much of the Nation have been increasing as a result of human alterations, changes in sediment supply, increasing frequency of storms, and sea-level rise, therefore, funding for updates of shoreline change data every five to 10 years is critical. More accurate and up-to-date flood-hazard maps are also critical.

Question 5. What additional information do you need in order to make those projections?

Answer. Additional topographic and bathymetric data are needed by all coastal states. These data are often limited to sparse coverage over oceanfront shorelines and do not extend into bays or estuaries, where impacts will be experienced. Increased resolution of the following models is also essential:

- Sea-level rise—Coastal states will need more detailed and complex models that incorporate local, embayment-scale changes in coastal geomorphology, hydrological conditions, and human alterations and responses (*e.g.,* seawalls and beach nourishment).
- Storm surge—Models that incorporate the unique configurations of local embayments or coastline morphologies, water depths, and physical features such as bridges and roads are required.
- Sediment transport, wetland changes, and river hydrology—More information is needed to better understand erosion and deposition cycles, improve our ability to predict changing sediment transport, accretion and erosion regimes.
- Ground water and salt water—More information is required on climate induced changes to local hydrologic cycles through altered precipitation, evapotranspiration, and soil moisture patterns.

Atmospheric models would provide some input to the above, but they are at scales not directly useful to state coastal managers.

Response to Written Questions Submitted by Hon. Daniel K. Inouye to Dr. Alexander (Sandy) MacDonald

Question. Are regional climate models ready to be run today? If not what needs to be done to get them to the point where they can be used and deliver adequate information?

Answer. Regional climate models with resolutions of 50 kilometer (km) and finer have been developed within NOAA and other U.S. Government agencies, and are ready to be used for regional projections. In the recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (AR4), NOAA and other U.S. Government agencies used a climate model with ocean resolution of 100 km and atmospheric resolution of 200 km. Since then, U.S. Government scientists have developed and validated models with much finer resolution (*e.g.,* 50 km resolution in the atmosphere and 10–25 km resolution in the ocean). Implementing these new, finer resolution models to produce comprehensive climate projections for reports such as the IPCC Fifth Assessment Report (due out in 2013) would require a 100-fold increase in computer capacity, an estimate compatible with that reported in the 2004 *Federal Plan for High-End Computing: Report of the High-End Computing Revitalization Task Force* (*http://www.nitrd.gov/pubs/2004_hecrtf/20040702_hecrtf.pdf*). NOAA is exploring a Memorandum of Agreement (MOA) with DOE to address HPC requirements collaboratively. This MOA would apply to NOAA use of DOE computing for prototyping models for climate research.

Response to Written Questions Submitted by Hon. John Kerry to Dr. Alexander (Sandy) MacDonald

Question 1. In your written testimony, you discuss the smaller-resolution prototype models NOAA has developed. However, you note that NOAA's computer resources are inadequate to run comprehensive simulations of climate change using these models. What level of computing resources do you need? How much does that cost? Should these resources be centralized at NOAA, or is it appropriate to have several computing centers that can run these advanced models?

Answer. The Nation's climate mission requires dedicated support for large scale High Performance Computing (HPC). The Administration's FY 2009 Budget Request for NOAA provides a set of priorities to sustain core mission services and address some of our highest priority program needs. Roughly $19 million of the FY 2009 President's budget request for NOAA is for climate research HPC. Currently, these funds are allocated to the following high-priority activities:

- The development and application of the next generation of climate change and Earth System Models, in preparation for the IPCC Fifth Assessment Report (AR5; due out in 2013), including new atmospheric and global ocean component models.
- Support for climate modeling requirements in developing the Climate Change Science Program Synthesis and Assessment products.
- Computational support for the World Meteorology Organization/United Nations Environment Programme Stratospheric Ozone Assessments.
- Computational support for developing a modeling capability for monitoring and making predictions of Atlantic Meridional Overturning Circulation changes.
- Continued limited integrations of high-resolution atmospheric models to support the North American Climate Change Assessment Program.
- Support for reanalysis and reforecast of 1979–2008 using the coupled Climate Forecast System.

NOAA's global climate models, as well as other U.S. models, are among the best in the world. Currently, the HPC available to the Nation's climate scientists allows global climate models to resolve climate research questions down to the scale of continents. Additional research HPC capacity for climate would be targeted toward using currently available higher resolution models to meet stakeholder demand for regional to local scale climate information. The additional HPC would also be used to produce more comprehensive climate outlooks with advanced models that improve treatments of processes critical to our understanding of climate change, such as aerosols and clouds. These advanced models would also include processes that are missing in today's models, such as ice sheet melting that is crucial to address sea-level rise. Another example of what advanced models would include are complex biogeochemical cycles that can be applied to answer questions about the carbon cycle and interaction of climate and ecosystems, such as the effects of ocean acidification.

In July 2003, the Climate Change Science Program specifically identified two centers, NOAA's Geophysical Fluid Dynamics Laboratory and the National Centers for Atmospheric Research (NCAR), to produce sophisticated simulations, such as those required for assessment by the IPCC. Scientific uncertainty, numerical algorithm variations, non-unique parameterizations of sub-grid size phenomena, and gaps in knowledge make it essential that multiple models be used to explore different approaches to improve understanding of the climate of the global integrated Earth system. At this time, NOAA is exploring partnerships with the Department of Energy and NCAR to identify the most cost-effective solution for facilities to house the Nation's climate computing. Should these activities be successful, leveraging these national partnerships and adopting a phased approach to implementing the required level of computing represents an executable strategy for meeting the Nation's growing climate information needs.

Question 2. In your written testimony, you discuss NOAA's Modular Ocean Model. Are we capable of modeling the oceans with the same level of confidence that we model the atmosphere? Do we need more ocean observations to feed into those models?

Answer. At the global scale, the ocean's role in climate change is governed by well understood scientific principles which are suitably represented by the present class of climate models. The NOAA Geophysical Fluid Dynamics Laboratory's Modular Ocean Model (MOM) is the world's most widely used numerical model for simulating the ocean circulation at the global scale and for understanding and predicting ocean climate phenomena. MOM is used for operational seasonal (including El Niño) forecasting at NOAA's National Weather Service, and was prominently used by several groups in the U.S. and worldwide in the recent IPCC Fourth Assessment Report.

Uncertainty remains, however, when asking questions about regional spatial patterns and precise time scales of the ocean's response to climate change (*e.g.,* how fast and how much will the Massachusetts coastal waters warm and the sea levels rise?). Such regional questions represent a grand challenge to be addressed by the next generation of global climate models.

The geography of the world's ocean basins is extremely complex, with many relatively small scale features (*e.g.,* continental shelves, narrow straits, and marginal seas) playing an important role affecting key features of large scale ocean properties (*e.g.,* heat, salinity, nutrients). In addition, the spatial scales for ocean "weather eddies" is roughly 10 times smaller than the atmospheric weather eddies, thus making it roughly 10 x 10 times (factor of 10 for each of the two horizontal directions) more computationally expensive to represent ocean eddies in a numerical simulation. These two characteristics of the ocean underscore the benefits of model grid resolution finer than 10 km resolution, to address questions of regional climate impacts, including those most pertinent to the U.S. coastal zones.

An ocean model is evaluated by confronting simulations with ocean observations. This evaluation in turn provides feedback to observing system design (*i.e.,* do we need more observations, and if so, where?). The scientific reliability of global ocean climate simulations will match the level of atmospheric simulations through: the development of refined resolution global ocean climate simulations; targeted ocean field studies, observations, long-term monitoring; and theoretical studies, which enable a rigorous assessment of the models based on the real ocean system.

Question 3. In your written testimony, you note that NOAA makes large amounts of your climate model output freely available. Is this information accessible only to advanced researchers, or are end-users able to access and utilize this data? Is the information available in a format that is useful for end-users?

Answer. NOAA is committed to making our climate model output available to the public. With respect to access, the NOAA Operational Model Archive and Distribution System (NOMADS), provides open access to climate model output. NOAA's Geophysical Fluid Dynamics Laboratory modeling center provides climate data on the NOMADS publicly accessible data portal, and works directly with researchers to facilitate use of the data. Because information portals and access systems work best when we also invest in partnerships with decisionmakers, NOAA also works directly with end-users to help them interpret model projections in a manner useful to their needs. There are different types of users of our climate model output: climate researchers; researchers who study the impact of climate change on various sectors (*e.g.,* agriculture, public health, air quality, water resources, migration, international security, travel, trade); and the engaged public (*e.g.,* policymakers, urban planners, state and regional resource managers, or even curious students). Some examples of NOAA working successfully with different users include:

- Department of Energy's Program for Climate Model Diagnosis and Intercomparison. Through this program, NOAA climate model output from simulations of past, present and future climate was used to prepare the IPCC's Fourth Assessment Report on Climate Change.
- NOAA's Earth System Research Laboratory (ESRL), and the Climate Program Office's Regional Integrated Sciences and Assessments (RISA) Program generate regionally downscaled projections of future climate change. Through sustained interaction with stakeholders, ESRL and RISAs also provide regionally tailored analyses that transform the global climate projections into value-added decision-relevant information.
- The National Integrated Drought Information System Drought Portal, an interagency effort coordinated by NOAA, provides valuable information to stakeholders such as: early warning about emerging and anticipated droughts; assimilated and quality controlled data about droughts; model-based drought outlooks and forecasts; information about risk and impact of droughts to different agencies and stakeholders; information about past droughts for comparison and to understand current conditions; and explain how to plan for and manage the impacts of droughts.

NOAA, with its mission to act as a research and information service on environmental issues, is uniquely poised to serve the range of climate data needs, from researchers to end-users.

Question 4. Given likely investment and innovation in computing infrastructure, when would data from the next generation of climate models be available to end-users and researchers?

Answer. NOAA is committed to sharing climate model data with end-users and researchers as rapidly as possible. However, before data can be shared, the data must be verified and validated for scientific credibility by peer review, and packaging and quality assurance tasks must be completed. As in the past, NOAA prioritizes computing infrastructure acquisitions for the following: simulations and analysis to understand and project climate change; archival storage of large volumes of data generated by these simulations; and for networking, to deliver the data to our partners and stakeholders. NOAA modeling centers have long-term experience in acquiring and maintaining a balanced infrastructure with available resources.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN F. KERRY TO EDWARD SARACHIK

Question 1. The National Research Council (NRC) released reports in 1998 and 2001 stating that the United States lagged behind other nations in our ability to model climate change. As chair of the 2001 NRC Panel, do you believe that our capacity has improved since these reports were released? What improvements have been made? What challenges does the U.S. climate modeling community still face?

Answer. Our capacity for the kind of climate modeling that the IPCC does has indeed increased—we now have higher resolution coupled climate-biogeochemistry models. But the kind of models the IPCC does is in support of the Framework Convention on Climate Change, and this involves getting global averages correct in order to avoid dangerous interference with the climate system. On the other hand, the kind of modeling that this hearing was about, namely climate modeling for the use of decisionmakers and end-users, involves getting the *regional scales* right and this has *not* improved. The IPCC itself recognizes that the results of its models are valid on space scales of 3,000 miles (continental scale) and this is not useful for any decisionmaking other than mitigation of greenhouse gases. The failure of our major large scale modeling institutions (we only have two—NCAR and GFDL) to address regional problems is the failure to get climate variability correct—annual cycle, El Niño, Pacific Decadal Oscillation and North Atlantic Oscillation. The failure to get climate variability correct is due to the general inadequacy of our (sub-critical) climate community to address new problems—a combination of lack of sustained observations, absence of the development of a model-based climate analysis (which would serve as the primary material for analysis of climate variability), and general inability of the CCSP to concentrate resources on research problems outside the direct interest of the participating government agencies.

Question 2. In your written testimony, you emphasize that the university research community needs access to the supercomputers themselves, as well as access to the information generated by the models. What is the best way to facilitate that?

Answer. It really wouldn't help to simply make supercomputer time available since the enormity of coupled climate models is generally beyond the capacity of individuals or small groups of individuals to deal with. The NCAR Community Climate Systems Model is an excellent template, one that has the broad community interacting with a core NCAR group—this is the best synergy between model builders at NCAR and model users in the distributed community and is far more than the sum of the parts. Supercomputer time needs to be made available to enable this synergy as well as funding. What the U.S. needs is *many* of these core model building institutions interacting with anyone that has something to contribute. At the present time, the Hadely Centre in England is funded at more than GFDL and NCAR CCSM combined, this in a country with 10 percent of the GDP of the U.S. By this standard, the U.S. should have ten or twenty modeling centers each with its own supercomputer, most interacting with the external community. Some of these centers should be regional centers concentrating on the climate problems of the regions in which they are sited.

Question 3. Several witnesses have emphasized the need to integrate observational data into climate models. In your opinion, in addition to incorporating this data, do we need *additional* observational data?

Answer. What we need is *sustained and accurate* data in the atmosphere, ocean, land and cryosphere adequate to define the long term climate patterns: annual cycle, El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation, and physical climate impacts: soil moisture, stream flow, and glacier and ice sheet evolution. This is a finite (but expensive) aim. It would also be desirable to have data on ecological impacts, especially fisheries, forests, and disease vectors. We also need to be able to deal with opportunities as they arise—at the moment, the melting of the Greenland Ice sheet is so much on scientists' and the public's mind that one would expect our science agencies to undertake a large and concerted effort to measure the melting of Greenland—so far this hasn't happened.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN F. KERRY TO DR. DANIEL A. REED

Question 1. In your written testimony, you discuss the need to integrate observational data into our climate models. What are the limitations in our ability to do that today?

Answer. Data assimilation, the integration of observational data with computational models at each cycle, remains a technically challenging problem, both mathematically and technically. We have made progress, but much work remains. My climate modeling colleagues can best speak to the modeling issues, but I can comment on the computational and observational aspects. The diversity and scale of data—from current satellites to geological records—make the problem complex. Moreover, the spatial and temporal data gaps exacerbate the integration problems. Finally, there is simply the matter of scale. The volume of data we must manage and integrate grows daily.

Question 2. How many different climate models do we need, here in the U.S. as well as internationally? Should we be collaborating with international partners on model development, or is there value in having separate models in separate countries?

Answer. Again, this is a question best answered by my climate modeling colleagues. However, it is important to remember that any model is an approximation of the actual system. By necessity, each model includes simplifying abstractions that may fail to capture salient aspects of the real system. These simplifications make the model tractable and allow us to evaluate the models computationally in a reasonable time on available high-performance computing systems. Thus, the accuracy of any model depends on our current knowledge and understanding of climatic processes, the skill of the model builders and available computing resources. Advances in any of those areas can improve model accuracy. For this reason, we often evaluate ensembles of models, examining the common and differing behaviors to illuminate potential errors.

Thus, I believe we need multiple models, with differing assumptions and approaches, enabled by a broad international collaboration. These models can and should be configured and specialized to understand regional climatic effects.

Question 3. You describe the need for an integrated, interagency effort to address the range of research, software, data storage and computing challenge associated with climate modeling. How should that be structured? Should it be led by NSF, NOAA or another agency? Is the Global Change Research Program capable of managing such an effort?

Answer. Many Federal agencies support climate change research, with differing scales and approaches. This has historically been the strength of the U.S. research funding environment. However, assessing the impact of climate change is an outcome-driven activity. I believe this is best managed by a single agency with the resources and the mandate to deliver detailed global and regional assessments, not a basic research agency.

Question 4. In your written testimony, you say that “climate change modeling is a deep and challenging scientific problem that requires computing infrastructure at the largest scale.” The National Center for Atmospheric Research (NCAR) in Boulder is the only supercomputing facility focused strictly on climate change, but you indicate that NCAR cannot deliver timely and accurate predictions. Should we focus on establishing NCAR as the premier climate modeling center in the country and expanding our capabilities there? Or do we need a structure that supports advanced climate modeling at various institutions around the country?

Answer. We need a balanced approach based on a pyramid model of computing. The pyramid apex is one or more premier high-performance computing systems for climate change modeling—substantially larger than anything available today. However, the apex must be supported by a diverse set of smaller systems spread across our universities and national laboratories.

NCAR is one of the possible sites for an apex climate change modeling supercomputing center, but there are other viable sites as well (*e.g.,* at one of our national laboratories). The site selection should be derived from a national analysis of available infrastructure (people and facilities), costs and community engagement.

Question 5. Given the apparent limitations of using off-the-shelf parallel processors for the purpose of climate modeling, should we be building special-purpose supercomputers for this purpose? If so, is there any role for the private sector in developing these systems?

Answer. Yes, for this and many other proposes of national importance. We need greater investment in purpose-built supercomputers that have been architected for critical national problems, just as we invest in purpose-built defense infrastructure. Climate modeling is but one critical example of such a national scientific problem; there are many others related to national security, biomedicine, energy research and other domains.

I believe a coordinated program of research, development and production must involve government, academia and private industry. In the end, the systems will be built by industry if the government is a willing supporter and purchaser of the purpose-built systems.

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