Statement of David R. Legates to the Committee on Environment and Public Works
United States Senate, March 13, 2002

I would like to thank the Committee for inviting my commentary on the important topic of the economic and environmental risks associated with increasing greenhouse gas emissions.

As a matter of introduction, my background in global change research has focused primarily on precipitation measurement and an examination of precipitation variability. My Ph.D. dissertation resulted in the compilation of the most reliable, highest resolution, digital air temperature and precipitation climatology available to date. Today, these fields still are being used to evaluate general circulation model (GCM) simulations of present-day climate and to serve as input fields for hydrological and climatological analyses. In particular, my research has focused on the accuracy of and biases associated with precipitation measurement and on the attempt to use existing climatological time-series to determine long-term fluctuations in climate. I also was a member of the United States delegation at the joint USA/USSR Working Meeting on Development of Data Sets for Detecting Climate Change held in Obninsk, Russia on September 11–14, 1989 where a joint protocol for data exchange was signed.

Indeed, an answer to the question, “Do we have the capability to determine whether we are changing our climate?” is of obvious concern to both scientists and policy makers. I agree strongly that we need to enact sensible environmental policy – **one that is based on scientific fact** with foreseeable outcomes that can reasonably be expected to have beneficial results. As a scientist, I choose here to focus my comments on the scientific basis of climate change and the capabilities of the climate models, as that is my area of expertise. In the past, we have recognized a need for cleaner air and cleaner water, demonstrated the problems associated with detrimental human influences, and developed policy that has resulted in our air and water becoming markedly cleaner than they were just thirty years ago. I urge that this issue be treated with the same common-sense approach.

Problems with the Observational Record Leaves Questions Unanswered

In light of my research on climatological observations, particularly precipitation, I have come to realize that looking for long-term trends in climate data is a very difficult undertaking. Precipitation data, for example, exhibit many spurious trends resulting from, in part, biases associated with the process of measuring precipitation. Indeed, attempts to measure snowfall using automatic methods have proven to be largely useless and, given the biases associated with measuring snowfall by traditional human-observed rain gages, our estimates of snowfall can be underestimates by almost a factor of two. Urban development of the environment surrounding the rain gage and, in particular, changes in rain gage design and the location of rain gages over time has adversely affected our ability to ascertain climatic trends in precipitation. Even a cursory examination of our most reliable records of precipitation shows that we frequently move meteorological stations, change instrumentation, and even the environment surrounding the site changes over time, which undermines attempts to answer the question “Is the climate changing?” Furthermore, precipitation is a highly variable field so, from a purely statistical standpoint, **it is difficult to ascertain a small climate change signal from this high year-to-year variability.** Air temperature measurements also are subject to these same measurement difficulties; in fact,

the IPCC agrees that as much as one-fifth of the observed rise in air temperature may be attributable to urbanization effects. As some of this change may be a direct result of natural climatic fluctuations, **attributing a cause to any detected changes also is an extremely difficult undertaking**. Indeed, as has been argued, “the data are dirty”!

Moreover, **nearly all of our surface-based observations are taken from land-based meteorological stations, leaving the nearly 70% of the earth's surface covered by oceans largely unobserved.** In particular, location of these land-based stations is biased toward mid-latitudes, low elevations, wetter climates, and technologically developed nations. **Efforts to use sea surface temperatures over the oceans as a surrogate for air temperature measurements are largely invalid as the two temperatures are not often commensurate.** This “land” bias, in my view, is one of the main limiting factors in using the observational record to infer global trends.

Satellite observations of air temperature and precipitation have proven very useful in addressing the climate change question in that they provide a complete coverage of the earth's surface and are not subject to the biases associated with meteorological observing sites on the ground. **Spencer and Christy's analysis of air temperature changes over the lower portion of the troposphere for the last twenty years exhibits no significant climate change signal as does an analysis using regularly-launched weather balloons. This is in stark contrast to the observed surface air temperature rise of 0.6° ± 0.2°C that has occurred over the entire twentieth century.** A blue-ribbon panel convened to address this apparent discrepancy concluded that the temperature of the lower atmosphere might have remained relatively constant while an increase in near surface air temperature was observed. Some have argued that the surface warming is a delayed response to warming that had earlier occurred in the troposphere, although the abrupt warming of the troposphere is not consistent with expected scenarios of anthropogenic warming. **The National Academy of Sciences (NAS) concluded that the difference between surface air temperatures and those of the troposphere was real but inconsistent with anthropogenic warming scenarios.** In particular, the NAS only considered whether the satellite and surface records could both be correct and yet contradictory; they never addressed the issue of whether the surface records could, in fact, be biased.

Another problem in tying the observed increases in air temperature to an anthropogenic cause is timing. **Most of the warming in the observed record occurred during two periods: 1910 to 1945 and 1970 to present. Much of the warming actually predates the rise in anthropogenic trace gas emissions, which makes it difficult to ascribe anthropogenic causes to the entire record.** Indeed, we know that our observed record began in the late 1800s when air temperature measurements were sparse and more prone to bias. This timing also coincides with the demise of the Little Ice Age – a period of cooler-than-normal conditions that lasted from the middle portion of the last millennium to about the mid-1800s. **Thus, it is unclear how much of the observed warming should be attributed to anthropogenic increases in atmospheric trace gases and how much of it is simply natural variability or measurement bias.**

Modeling the Complex Climatic System is an Extremely Difficult Task

In theory, therefore, climate models should be our best ability to study climate change. With models, we are not constrained by biased and limited observing systems or by contamination by other signals; but rather, we can alter the simulated climate and see "what if" while holding everything else constant. **Such models, however, are predicated on their ability to replicate the real climate – after all, if climate models cannot replicate what we observe today, how can their prognostications of climate change possibly be expected to be transferable to the real world?** Although I am not a climate modeler, much of my research has focused on comparing observations with climate model simulations of present-day conditions. Thus, I am very familiar with what climate models can and cannot do.

I am dismayed by the fact that much of the rather limited success in simulating average conditions by most climate models is achieved at the expense of changing some parameters to highly unrealistic values. For example, some models drastically change the energy coming from the sun to levels that are well beyond those that solar physicists have observed. Many models employ what are called "flux adjustments", which can only be described as finagling factors to make the average, present-day surface air temperatures look reasonable. **One has to question why such overt deviations from reality are necessary if, in fact, the models are able to realistically represent our climate system.**

In defense of climate modelers, I will say that they have a very difficult and daunting task. The climate system is extremely complex. Clouds, land surface processes, the cryosphere (ice and snow), precipitation forming mechanisms, the biosphere, and atmospheric circulation, just to name a few, are complex components of the global climate system that are not well understood or modeled appropriately at the scale employed by general circulation models. In essence, the climate change response can be directly affected by our parameterizations of many of these components. **For example, an important question that now is being asked is "Why is the warming exhibited by transient climate models not being seen in the observed record?"** There has been much discussion on the impacts of aerosols, black soot, high altitude clouds, and other so-called "wild cards" in the climate system – are they masking the climate change signal or should they be adding to it? How climate modelers treat these unknown processes in their models can affect dramatically the model simulations. Indeed, there are likely additional issues that we have not yet encountered.

Climate Models Cannot Reproduce a Key Climatic Variable: Precipitation

Despite these issues, do climate models well represent the earth's climate? On three separate occasions – in 1990, 1996, and again in 2000 – I have reviewed the ability of state-of-the-art climate models to simulate regional-scale precipitation. In general, the models poorly reproduce the observed precipitation and that characteristic of the models has not substantially changed over time. One area where the models have been in continued agreement has been in the Southern Great Plains of the United States. **In all three studies, the varied models I have examined agree that northeastern Colorado receives substantially more precipitation than northwestern Louisiana! That is in marked contrast with reality where Louisiana is obviously wetter than Colorado.** But the important ramification of this is that if precipitation is badly simulated in a climate model, then that will adversely affect virtually every other aspect of the model simulation. Precipitation affects the energy, moisture, and momentum balances of the atmosphere and directly affects the modeling of the atmosphere, the hydrosphere, the biosphere, and the cryosphere. In turn, a bad representation of these components will again adversely impact the precipitation simulation. In short, anything done wrong in a climate model is likely to be exhibited in the model simulation of precipitation and, in turn, errors in simulating precipitation are likely to adversely affect the simulation of other components of the climate system. Given its integrative characteristic, therefore, **precipitation is a good diagnostic for determining how well the model actually simulates reality, especially since simple "tuning" adjustments cannot mask limitations in the simulation, as is the case with air temperature.**

If we examine climate model output a bit further, we uncover another disturbing fact – climate models simply do not exhibit the same year-to-year or even within-season variability that we observe. Precipitation in a climate model does not arise from organized systems that develop, move across the earth's surface, and dissipate. Instead, modeled precipitation can best be described as "popcorn-like", with little if any spatial coherency. On a year-to-year basis, both air temperatures and precipitation exhibit little fluctuation, quite unlike what we experience. This is particularly important because it is the climatic extremes and not their means that have the biggest adverse impacts. **Simply put, climate models cannot begin to address issues associated with changes in the frequency of extreme events because they fail to exhibit the observed variability in the climate system.**

I attach a piece I wrote regarding the climate models used in the National Assessment and their evaluation with my climatology, which further highlights our uncertainties in climate models. In fact, the National Assessment itself recognized that **both the Canadian Global Coupled Model and the Hadley Climate Model from Great Britain used by the Assessment provide more extreme climate change scenarios than other models that were available and that had been developed in the United States. Neither model is reasonably able to simulate the present-day climate conditions.**

Our Observational Capabilities Are in Jeopardy

Given that our observational record is inconclusive and that model simulations are fraught with problems, on what *can* we agree? In my view, there are two main courses of action that we should undertake. First, we need to continue to develop and preserve efforts at climate monitoring and climate change detection. Efforts to establish new global climate observing systems are useful, but we need to preserve the stations that we presently have. There is no surrogate for a long-term climate record taken with the same instrumentation and located in essentially the same environmental conditions. Modernization efforts of the National Weather Service to some extent are undermining our monitoring of climatic conditions by moving and replacing observing sites, thereby further introducing inhomogeneities into these climate records. Some nations of the world have resorted to selling their data, which has adversely impacted our assessments of climate change. **However, given that oceans cover nearly three-quarters of the earth's surface, we need to exploit and further develop satellite-derived methods for monitoring the earth's climate.** We also need to better utilize the national network of WSR-88D weather radars to monitor precipitation.

But foremost, we need to focus on developing methods and policy that can directly save lives and mitigates the economic devastation that often is associated with specific weather-related events. Climate change discussions tend to focus on increases in mean air temperatures or percentage changes in mean precipitation. But it is not changes in the mean fields on which we need to place our efforts. It would be rather easy to accommodate even moderately large changes in mean air temperature, for example, if there were no year-to-year variability. Loss of life and adverse economic impact resulting from the weather occurs not when conditions are "normal"; but rather, as a result of extreme climatic events: heat waves, cold outbreaks, floods, droughts, and storms both at small (tornado, thunderstorm, high winds, hail, lightning) and large scales (hurricanes, tropical storms, nor'easters). The one thing that I *can* guarantee is that regardless of what impact anthropogenic increases in atmospheric trace gases will have, extreme weather events will continue to be a part of our life and they will continue to be associated with the most weather-related deaths and the largest economic impact resulting from the weather.

Ascertaining anthropogenic changes to these extreme weather events is nearly impossible. Climate models cannot even begin to simulate storm-scale systems, let alone model the full range of year-to-year variability. Many of these events are extremely uncommon so that we cannot determine their statistical frequency of occurrence from the observed record, let alone determine how that frequency may have been changing over time. While we need to continue to examine existing climate records for insights and to develop reliable theory to explain plausible scenarios of change, the concern is whether we can enact policy now that will make a difference in the future.

However, is there cause for concern that anthropogenic warming will lead to an enhanced hydrologic cycle; that is, will there be more variability in precipitation resulting in more occurrences of floods and droughts? The IPCC Summary for Policy Makers states:

> "Global warming is likely to lead to greater extremes of drying and heavy rainfall and increase the risk of droughts and floods that occur with El Niño events in many different regions."

However, if one reads the technical summary of Working Group I, we find that:

> "There is no compelling evidence to indicate that the characteristics of tropical and extratropical storms have changed. Owing to incomplete data and limited and conflicting analyses, it is uncertain as to whether there have been any long-term and large-scale increases in the intensity and frequency of extra-tropical cyclones in the Northern Hemisphere. Recent analyses of changes in severe local weather (*e.g.*, tornadoes, thunderstorm days, and hail) in a few selected regions do not provide compelling evidence to suggest long-term changes. In general, trends in severe weather events are notoriously difficult to detect because of their relatively rare occurrence and large spatial variability."

The IPCC goes on to further state "there were relatively small increases in global land areas experiencing severe droughts or severe wetness over the 20th century". Karl and Knight, who conducted a detailed study on precipitation variability across the United States, concluded that as the climate has warmed, variability actually has decreased across much of the Northern Hemisphere's midlatitudes, a finding they agree is corroborated by some computer models. Hayden, writing for the Water Sector of the US National Assessment, agrees that no trend in storminess or storm frequency variability has been observed over the last century and that "little can or should be said about change in variability of storminess in future, carbon dioxide enriched years." Soden concluded, "even the extreme models exhibit markedly less precipitation variability than observed." In addition, Sinclair and Watterson have noted that, in fact, climate models tend to indicate that increased levels of atmospheric trace gases leads to a "marked decrease in the occurrence of intense storms" outside the tropics and they argue that claims of enhanced storminess from model simulations are more the result of models that fail to conserve mass. **Clearly, claims that anthropogenic global warming will lead to more occurrences of droughts, floods, and storms are wildly exaggerated.**

Thus, I believe it stands to reason that we need to focus on providing real-time monitoring of environmental conditions. This will have two benefits: it will provide immediate data to allow decision makers to make informed choices to protect citizens faced with these extreme weather events and, if installed and maintained properly, it will assist with our long-term climate monitoring goals. Such efforts are presently being developed by forward-looking states. For example, I am involved with a project, initiated by the State of Delaware in cooperation with FEMA, the National Weather Service, and Computational Geosciences Inc. of Norman, Oklahoma, to develop the most comprehensive, highest resolution, statewide weather monitoring system available anywhere. Louisiana and Texas also have expressed interests in using our High-Resolution Weather Data System technology for real-time statewide weather monitoring. Regardless then of what the future holds, employing real-time monitoring systems, with a firm commitment to supporting and maintaining long-term climate monitoring goals, proves to be our best opportunity to minimize the impact of weather on human activities.

Final Thoughts: The Science Is Not Yet In

In 1997, I had the pleasure to chair a panel session at the *Houston Forum* that included seven of the most prominent climate change scientists in the country. At the close of that session, I asked each panelist the question, "In 2002, given five more years of observations, five more years of model development, and five more years of technological advances and knowledge about the climate system, will we have an answer to the question of whether our climate is changing as a result of anthropogenic increases in trace gas emissions?" The panel, which consisted of both advocates and skeptics, agreed that we would have a definitive answer probably not by 2002, but certainly by 2007. I disagreed then and I continue to disagree today. I fear that the issue has become so politically charged that the political process will always cloud the true search for scientific truth. But more than that, I feel **the climate system is far more complex than we ever imagined** – so much so that we still will not have a definitive answer by 2007.

I again thank the Committee for inviting my commentary on this important topic.

A Layman's Guide to the General Circulation Models Used in the National Assessment

by

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Executive Summary

The U.S. National Assessment of the Potential Consequences of Climate Variability and Change for the Nation intends to "provide a detailed understanding of the consequences of climate change for the nation." This report argues that the National Assessment will not be able to provide policymakers and the public with useful information on climate change because of its reliance on flawed computer climate models. These models, which are intended to describe climate only on a very large scale, are currently used by the National Assessment to describe possible scenarios of regional climate change in the U.S. Because current models cannot accurately represent the existing climate without manipulation, they are unlikely to render reliable global climate scenarios or provide useful forecasts of future climate changes in regions of the United States as small as the Midwest, West or South.

The Guide explains how General Circulation Models (GCMs) describe changes in the complex factors that make up our climate, such as atmospheric changes, interaction of the land, sea, and air, and the role of clouds in climate. The strengths and weaknesses of climate models are discussed and the report shows how researchers attempt to answer the important questions about global warming as they refine their use of GCMs.

The two climate models used in the U.S. National Assessment are then described with reference to their similarities and differences. The limitations of these models – the Canadian Global Coupled Model and the Hadley Climate Model from Great Britain– are outlined with special emphasis on their inability to provide useful regional scenarios of climate change. The report concludes with an analysis of how well these two models reproduce the present-day climate as a benchmark for their ability to reproduce future climate.

Key findings in this report include:

- The utility of current GCMs is limited by our incomplete understanding of the climate system and by our ability to transform this incomplete understanding into mathematical representations. It is common practice to "tune" GCMs to make them represent current conditions more accurately, but the need for this manipulation casts serious doubt on their

ability to predict future conditions. Because all factors are interconnected in climate modeling, an error in one field will adversely affect the simulation of every other variable.

- To reduce complexity and computational time, GCMs treat surfaces as uniform and average the flows of moisture and energy between the land surface and the atmosphere over large areas. But the extensive variability of the land surface and the effects that even small-scale changes can have make modeling land-surface interactions quite difficult.
- The National Assessment itself recognized that both the models that it selected provide a more extreme climate change scenario than other models that were available and that had been developed in the U.S.
- Both models offer incomplete modeling of the effects of individual greenhouse gases, including water vapor and atmospheric sulfates. The CGCM1 in particular fails to model sea ice dynamics and offers a simplistic treatment of land-surface hydrology. Predicted temperature increases over various regions of the United States differ considerably between the two models; these predictions fail to correspond with observed precipitation variability and contradict each other.
- In general, the Hadley model simulation is closer to the observed climate in the United States than the Canadian simulation, although both models produced considerable differences from observations. This, again, cast serious doubt on the models' ability to simulate future climate change.

Conclusion: Given these uncertainties, using the available GCMs to assess the potential for climate change in specific regions is not likely to yield valid and consistent results. GCMs can provide possible scenarios for climate change, but at the present level of sophistication, they are not reliable enough to be used as the basis for public policy. Using GCMs to make predictions about local climate change in the United States is not legitimate.

A Layman's Guide to the General Circulation Models Used in the National Assessment

INTRODUCTION

What is a General Circulation Model (GCM)?

The word "model" usually conjures up images of a miniature replica of a real object. Model trains, automobiles, and airplanes, for example, are intended to be scale-reduced versions of the original. Models are judged by their attention to detail, and sometimes functionality, with respect to their real counterparts and are quite distinct from "toys", which also are intended to resemble the original but lack the attention to detail and functionality.

In science, the word "model" has a similar, but broader, meaning. Models can be physical replicas; for example, a model may be a smaller version of a larger habitat for a given animal or plant species. A model also, however, can be a working representation of a difficult concept, such as a model of an atom, for example. In this case, the model is simply a more useful way to describe and analyze a portion of nature that is only partially understood and observable. Usually, such models can be described by a set of mathematical equations – some from fundamental laws, and some empirical – rather than being a true physical replica.

General circulation models (or GCMs) are a further example of the latter definition. They are not physical reproductions of the earth and its climate system but instead are mathematical representations of the physical laws and processes that govern and dictate the climate of the earth. As such, they are *computer models* – computer programs that are able to solve the complex interactions among these mathematical equations to derive fields of air temperature, humidity, winds, precipitation, and other variables that define the earth's climate. General circulation models are limited both by our understanding of what drives, shapes, and affects the climate of the earth as well as how the earth's climate responds to a variety of external forces -- in addition to the speed and capabilities of modern-day computers.

The Concept of Space in GCMs

If we were to build a GCM, our first and fundamental decision would be the selection of the model's concept of space – how we choose to physically describe the three-dimensions of the atmosphere. Here we have two fundamental choices: the model can either be a *Cartesian grid* model or it can be a *spectral* model.

Conceptually, the Cartesian grid climate model is easier to understand and grasp, although it is less flexible and recently seems to be the less desirable choice among climate modelers. Consider a set of building blocks that might be toys for a young child. We could arrange the blocks in the form of a regular lattice where the face of every block is flush against another block. We could make this wall of blocks several blocks high and several blocks wide. Thus, each block in the center of the wall is adjacent to six other blocks – one above, one below, and four adjacent to each horizontal face.

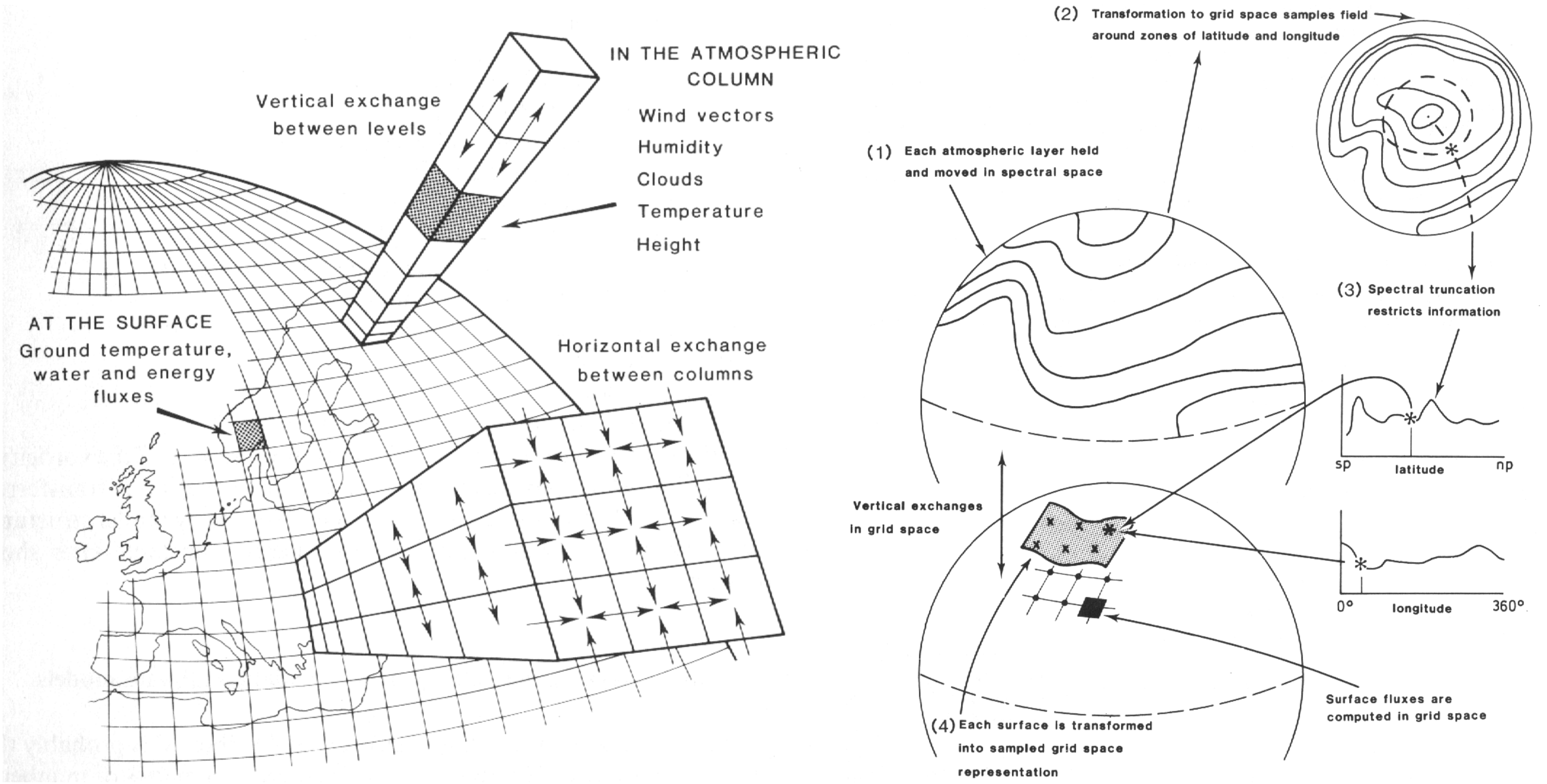
In a Cartesian grid model, we extend the concept of these building blocks to represent hypothetical "blocks" of atmosphere, stacked adjacent to and on top of each other in the same manner we stacked the child's building blocks (Figure 1). Since the earth's surface is a sphere, however, we extend these blocks around the globe until they reach the blocks on the other end. Thus, in our climate model, every block has an adjacent partner on each of its four horizontal faces – our "wall" of blocks extends around the globe and covers the entire earth's surface. The only edges that exist are the blocks on the bottom and those on the top. Here, however, the blocks on the bottom are in contact with the earth's surface and can be used to describe the interactions between the atmosphere and the land surface. Although the atmosphere really has no "top" (air simply becomes thinner with height until its density approaches zero), the blocks on top of our stack can be used to represent the vertical extent of the atmosphere.

Since each block has six faces, we will simply describe (mathematically) the flows of energy, mass, and other physical quantities between one of our atmospheric boxes and the six adjacent boxes. We assume that each box is homogeneous; temperature, humidity, and other atmospheric variables can only vary between boxes and not within a box. Each of these variables is associated with the location (both horizontally and vertically) of the center of the box. As the box centers form a lattice or a grid around the earth's surface, the name "Cartesian grid model" is justified.

A typical Cartesian grid model will employ a lattice of approximately 72 boxes by 90 boxes (2½º of latitude by 4º of longitude) stacked about 15 boxes high. The more boxes that are employed, more spatial resolution is obtained but at the expense of increased computer time. This choice of resolution is usually appropriate to allow sufficient spatial variability within a reasonable amount of computer run time.

By contrast, the *spectral* model does not use the concept of "boxes" at all but relies on a framework that is harder to grasp. Imagine a tabletop covered by several sheets of paper stacked on top of one another. Each sheet represents a different atmospheric layer. Vertically, the interaction between the layers is similar to the vertical interaction between the boxes that we saw with the Cartesian grid model. However, the horizontal representation of the field is not described by interactions among boxes; but rather, it is presented and manipulated in the form of waves. Just as energy is carried through the ocean in the form of oceanic waves, we can represent flows of energy and mass along each atmospheric layer using a series of waves having different amplitudes and frequencies (called *spherical harmonics*). Although these waves are difficult to describe, one can think of them as a series of sine and cosine curves (true really only in the east-west direction) that, when taken together, can be used to represent the spatial variability of any field (Figure 2). Grid values, akin to the representation of the Cartesian grid model, are computed from these waves and the horizontal and vertical resolutions become commensurate with those of Cartesian grid models.

At the same spatial resolution, spectral models have the advantage in that they can more easily (or compactly) describe a field than a Cartesian grid model. Thus, computation times are reduced. Moreover, spatial resolutions can be changed more easily with a spectral model, which allows for more flexibility and adaptability. Some have argued that Cartesian grid GCMs are



Representation of three-dimensional space in general circulation models (GCMs). Cartesian GCMs (left) use a concept similar to a series of stacked boxes, while spectral GCMs (right) use a series of waves and smoothly varying functions. Both representations, however, use the Cartesian analog (*i.e.*, stacked boxes or stacked waves in their representation of the vertical dimension. (Figure taken from Henderson-Sellers and McGuffie, 1987).

more satisfactory than their spectral counterparts for a variety of reasons, including the fact that it is possible for spectral models to violate some of the fundamental laws of physics (to produce negative mass, a physical impossibility, for example). This can occur since the use of waves (as in a spectral model) implies the field must be smoothly varying – a constraint that is often inappropriate for many atmospheric fields. Precipitation, for example, exhibits significantly steep spatial gradients, which makes the representation of a precipitation field using smoothly varying wave patterns very difficult. In 1987, McGuffie and Henderson-Sellers wrote that Cartesian grid models will, in time, be favored over spectral models owing to increased computational power and the need to reduce these gradient anomalies associated with spectral modeling. The computational advantage gained from the use of spectral models over the past decade, however, led to a proliferation of spectral GCMs, which still represent the majority of the GCMs used today.

Describing Atmospheric Processes in a GCM

Having chosen our framework for spatial representation, the next step is to describe the atmospheric processes that govern the earth's climate. First, we must define the equations that drive atmospheric dynamics – processes that lead to atmospheric motions. We must require that the model conserve energy, since we know from the first law of thermodynamics that energy cannot be created nor destroyed. Our GCM also must conserve mass; although Einstein showed that matter may be converted into energy, that occurrence is insignificant in the atmosphere. Momentum also must be conserved since an object in motion tends to remain in motion. We also use the *ideal gas law*, which states that the pressure of the atmosphere is proportional to both its density and temperature. There are additional equations that describe more complicated atmospheric properties that also must be conserved.

Next, we define equations describing the physics of the atmosphere – processes that describe energy exchanges within the atmosphere. In GCMs, three-dimensional, time-dependent equations govern the rate of change of atmospheric variables including air temperature, moisture, horizontal winds and the height for each atmospheric layer, and surface air pressure. These equations describe, for example, the effect of vertical air motions and absorbed energy on air temperature, the rate of atmospheric pressure changes with respect to height in the atmosphere, relationships between atmospheric moisture, cloud formation and condensation/precipitation, and the interaction between clouds and the energy balance. Clouds can play a key role in the energy balance of the earth since they reflect incoming energy from the sun, but trap outgoing "heat" energy from the earth. Thus, modeling of clouds and their effects on the energy and moisture balances is important to GCM prognostications of climate change scenarios.

Except for the representation and treatment of clouds, all spectral GCMs at this point are essentially the same, and so too are all Cartesian GCMs. The reason is that there really are not many ways (only minor variations on the theme exist) to describe the dynamics and physics of the atmosphere within our chosen spatial framework. Where models within their respective classes differ substantially is with regard to their modeling of atmospheric interactions with the earth's surface.

Modeling Surface Processes in a GCM

The critical component of most GCMs is their treatment of interactions between the atmosphere and the earth's surface. Oceans, lakes, and other bodies of water provide substantial amounts of moisture and energy to the atmosphere. Modeling them is important since nearly three-quarters of the earth is covered by water and the ocean is a fluid -- always in constant motion. Thus, in addition to the atmosphere, the oceans provide an important mechanism for the redistribution of energy around the earth. Their circulation must be modeled and the energy and moisture transfers between the ocean and the atmosphere must be appropriately described. In addition, much of the world's oceans are saline and quite deep. Interactions between temperature and salinity (called the thermohaline circulation) are extremely important to the earth's climate but are not well understood. Moreover, deep ocean water can store atmospheric gasses, to be released at a much later time when concentration of these gasses is much lower. Modeling of such processes within a GCM is extremely difficult.

With respect to modeling the oceans, sea ice plays an important role in shaping the earth's climate. When air temperatures drop below freezing, the surface of the ocean may become frozen, creating a barrier to energy and moisture flows between the ocean waters and the atmosphere above. In the presence of sea ice, the atmosphere is deprived of moisture and energy from the relatively warmer waters below, thus causing the atmosphere to become colder and drier and cause a positive feedback to sea ice formation. Sea ice, however, moves with the combined forces (often in different directions) of oceanic circulation and surface winds. This causes sea ice to become broken in some places (called leads) and piled up to form hills and ridges in others. Thus, sea ice is not uniform and modeling these interactions is extremely difficult and not well understood.

But the biggest challenge to GCM modeling is the representation of the interactions between the atmosphere and the land surface. If you take a quick glance around your environment, you will see that the land surface is quite heterogeneous -- trees, shrubs, grasses, roads, houses, streams, *etc.* often coexist within a single square mile. In our Cartesian grid GCM, however, our "boxes" are often several *hundred* miles wide and we must assume that everything within the box is homogeneous. Spectral GCMs have similar spatial resolutions and assume that everything, including the land surface, is smoothly varying. Thus, the sheer nature of surface heterogeneity makes modeling the land surface within a GCM very difficult.

Couple that now with the fact that interactions between the land surface and the atmosphere are extremely complex. Plants try to conserve water and so shut down many vital functions when water supplies run low. However, each plant species behaves differently; for example, trees have deeper roots than short grasses and, therefore, their access to water is different. Plant use of water, even in times of ample moisture supply, differs widely among plant species that, of course, often coexist. Snow and ice cover are dictated by air temperature and precipitation, but old snow has different characteristics than newly fallen snow. To reduce complexity, GCMs simply try to simulate the flows of moisture and energy between the land surface and the atmosphere in the aggregate. But given the extensive heterogeneity of the land surface and the effects that even small, sub-resolution scale changes can have -- well, to say that modeling land surface interactions is difficult would be an extreme understatement!

THE GCMS OF THE NATIONAL ASSESSMENT

Rather than discuss all possible ways in which climate models can represent various climate-shaping processes, let us focus on the two models used in the United States National Assessment -- GCMs from the Canadian Centre for Climate Modeling and Analysis and the Hadley Centre for Climate Prediction and Research. Both models are well documented and results from and specifications of both models are widely available to the scientific community. For selection by the National Assessment Synthesis Team (US National Assessment, 2000), climate models were chosen based on the criteria that the model must:

1) be a coupled atmosphere-ocean general circulation model that includes a comprehensive representation of the atmosphere, oceans, and land surface,
2) include the diurnal cycle of solar radiation to provide estimates of fluctuations in maximum and minimum air temperature and to represent the development of summertime convective rainfall,
3) be capable, to the best extent possible, of representing significant aspects of climate variations (*e.g.*, El Nino/Southern Oscillation),
4) provide the highest practicable spatial and temporal resolution -- about 200 miles in longitude and 175 to 300 miles in latitude -- over the central United States,
5) allow for an interface with higher resolution regional modeling studies,
6) must be able to simulate the time-evolution of the climate from at least 1900 (beginning of the detailed historical record) to at least 2100 using a well-documented scenario for changes in atmospheric composition that accounts for time-dependent changes in greenhouse gas and aerosol concentrations,
7) have results that are available in time for use in the National Assessment,
8) have been developed by groups participating in the development of the Third Assessment Report of the IPCC for compatibility and the model must be well documented, and
9) allow for a wide array of results to be openly provided on the WWW.

Items (1-3) are important in that significant influences on the climate (diurnal cycle, oceans, land surface, and other processes) are included, although most models now do include these features and some of the assessments of model performance (*e.g.*, simulation of El Nino/Southern Oscillation) are tenuous, given our limited understanding of the process. As expected, the chosen models must afford the highest spatial and temporal resolution (Item 4) and their results must be useful for regional-scale modeling applications (Item 5). For simulation purposes, the model data must be from a transient climate simulation (*i.e.*, it allows for changes in atmospheric constituents over time) that extends both back and forward in time about 100 years from the present (Item 6). Finally, Items (7-9) are purely administrative criteria, although virtually all modeling groups participate in the IPCC and compatibility with the IPCC really should not be an issue (Item 8). It was deemed important to include at least two models in the National Assessment, to provide a more balanced presentation and allow for a spectrum of model uncertainties and differences. Both the Canadian Centre and Hadley Centre models fit these criteria.

The Canadian Climate Centre Model

The Canadian Global Coupled Model (CGCM1), developed by the Canadian Climate Centre, is a spectrally-based model with a spatial resolution of approximately 3.75° of latitude by 3.75° of longitude (about 260 miles by 185 miles over the United States) and ten vertical atmospheric layers. The ocean model coupled to this atmosphere has a spatial resolution of 1.8° of latitude by 1.8° of longitude (about 125 miles by 90 miles) and twenty-nine vertical layers. Given the complexity and the importance of modeling the oceans, a higher spatial resolution is often required by most ocean model components of GCMs. In the oceans, we are interested in simulating the exchanges of energy and moisture between the ocean and the atmosphere, as well as simulating the redistribution of energy within the oceans. This redistribution of energy occurs both horizontally (ocean circulation) and vertically. Vertical motions also allow for heating and cooling of the deeper ocean waters and their absorption of greenhouse gases. This, of course, is immensely important in a proper simulation of the earth's climate.

Because the ocean responds to different spatial and temporal scales than those which drive atmospheric processes, coupling an ocean model to an atmospheric GCM is a complicated task. Often, the modeling of energy and moisture exchanges results in values that are completely unreasonable -- they differ considerably from observations. To rectify such conditions, GCMs often resort to a "flux-adjustment" of ocean-atmosphere interactions; that is, they force the exchanges of heat and moisture between the simulated oceans and the simulated atmosphere to meet prescribed distributions. This flux-adjustment process is used to dictate that the coupled model correctly simulates the oceanic circulation of salinity and temperature (*i.e.*, the thermohaline circulation). In the case of the CGCM1, the model is flux adjusted.

Sea ice modeling is even more tenuous than ocean modeling, but certainly as important. Many models incorporate both the formation and movement of sea ice (dynamics) as well as their inhibition of the exchange of heat and moisture between the ocean and the atmosphere (thermodynamics). In the case of the CGCM1, the thermodynamics are modeled, but sea ice dynamics are not. Seasonal distributions of sea ice are prescribed to be consistent with seasonal observations.

Equally difficult is the modeling of land surface interactions -- exchanges of energy and moisture between the atmosphere and the vegetation/soil surface. Land surface models can be highly simplistic, where the surface color, temperature, and moisture characteristics correspond to average conditions and variations. In such formulations, the land surface hydrology is modeled by what is termed the "bucket method". Soil water is held in a theoretical "bucket" -- water can be put into the bucket (through precipitation) and removed from the bucket (through evaporation and plant transpiration). A simple resistance function models the rate of water removal from the bucket by plant water usage and soil evaporation. The bucket has a finite depth, so that when precipitation overflows the bucket, the excess moisture becomes streamflow (although streamflow is not directly modeled). Land surface components of GCMs can be quite complex, however, where interactions between plants and their responses to changing atmospheric and soil moisture conditions are modeled. Within the CGCM1, the land surface hydrology is modeled by a modified bucket method. Seasonal and diurnal fluctuations in solar energy are usually included in most models used today; this is true as well for the CGCM1.

Atmosphere chemistry in some GCMs, and in the CGCM1 in particular, is treated in a rather crude manner. Time-varying effects of individual greenhouse gases (*e.g.*, carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and ozone) are not modeled; but rather, temporal increases in a single greenhouse gas -- carbon dioxide -- are used as a surrogate. Here, the assumption is that atmospheric greenhouse gas concentrations will increase 1% (compounded) per year until 2100. In other models, the individual effect of each greenhouse gas is considered separately. In addition to greenhouse gases, changing concentrations of sulfate aerosols also are important to modeling climate change. Atmospheric sulfates, large sulfur-based particles suspended in the atmosphere, originating from both anthropogenic and natural sources, are widely believed to reflect incoming solar energy, thereby diminishing the potential global warming signal. Although the chemistry can be complex, some models attempt to simulate their direct effects and changes in aerosol concentrations over time. The CGCM1, however, simply models aerosols as a change (increase) in the reflectance of solar energy reaching the surface of the earth, without modeling the actual dynamics and properties of sulfate aerosols.

At equilibrium (when no further change in air temperature occurs), the response of the CGCM1 model to a doubling of concentrations of greenhouse gases (specifically, carbon dioxide) is an increase of 3.5°C (6.3°F) in the globally averaged air temperature (Boer *et al.*, 1992), which occurs by about 2050 (Figure 2). Over the United States by 2030, the model simulates summer increases of between 1° and 3°C (1.8° to 5.4°F) over the entire United States. Winter increases of 2° to 4°C (3.6° to 7.2°F) are modeled over western and central areas of the United States while 0° to 2°C (0.0° to 3.6°F) changes are modeled over eastern portions. Winter precipitation increases in the west and decreases elsewhere while summer changes are largely unpredictable (both increases and decreases are observed).

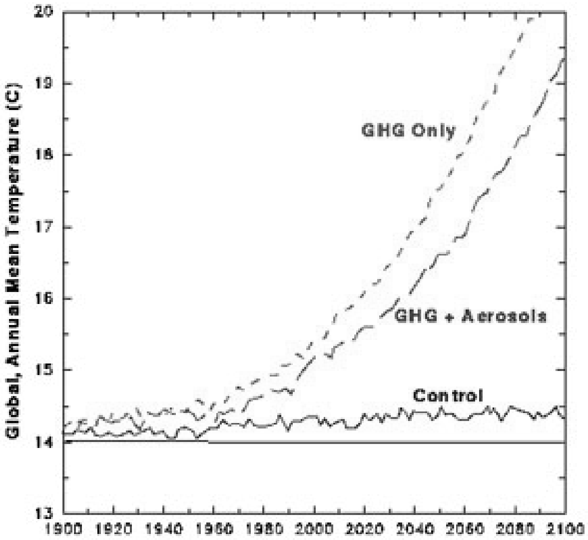


Figure 2: Simulations of climate change using the CGCM1 model with changes in greenhouse gas concentrations (GHG Only), greenhouse gases and atmospheric aerosols (GHG+Aerosols), and with no changes (Control). (Figure from Boer *et al.*, 1992).

The Hadley Centre Model

By contrast with the CGCM1, the Hadley Climate Model (HadCM2), developed by the Hadley Centre for Climate Prediction and Research of the United Kingdom Meteorological Office, is a Cartesian grid model with a spatial resolution of approximately 2.5° of latitude by 3.75° of longitude (about 175 miles by 185 miles over the United States) and nineteen vertical atmospheric layers. Its coupled ocean model has the same horizontal resolution with twenty vertical layers and also is flux-adjusted. In the HadCM2, sea ice dynamics are modeled, as well as their influence on the exchange of heat and moisture between the ocean and the atmosphere.

The HadCM2 uses a more sophisticated approach to modeling land surface hydrology. Several soil layers are used and the flow of moisture between these soil layers (through percolation downward through the soil) is modeled. The model provides a more detailed and specific treatment of the plant canopy, including the area of ground covered by leaves and the response of the leaves to water stress. Both seasonal and diurnal cycles of solar energy variations are incorporated into the model.

As with the CGCM1, the HadCM2 GCM applies the same modeling strategy for the treatment of atmospheric chemistry. Temporal increases in carbon dioxide only are specified. Individual effects of other greenhouse gases such as methane, nitrous oxide, and ozone, for example, are not modeled but are incorporated into the effects of a change in carbon dioxide. Atmospheric sulfates are modeled only as a change in the surface reflectance of solar energy (albedo) while their actual dynamics and the individual properties are not included. This is consistent with the formulation used by the CGCM1.

For a doubling of atmospheric carbon dioxide concentrations, the response of the HadCM2 is an increase in the globally averaged air temperature of 2.6°C (4.7°F). Over the United States, the model simulates increases of from 1° to 3°C (1.8° to 5.4°F) over the eastern third of the nation and increases from 1° to 4°C (1.8° to 7.2°F) over the western two-thirds. Precipitation is modeled to increase in the western and eastern thirds of the nation during winter while changes in winter precipitation in the central Great Plains and summer precipitation everywhere is mixed (both increases and decreases are observed).

Table 1: Comparison between the Canadian Climate Centre Model (CGCM1) and the Hadley Centre Model (HadCM2).

Variable	CGCM1	HadCM2
Atmospheric Model		
North-South Resolution	3.75° (about 260 miles)	2.5° (about 175 miles)
East-West Resolution	3.75° (about 185 miles)	3.75° (about 185 miles)
Vertical Resolution	10 layers	19 layers
Oceanic Model	Flux Adjusted	Flux Adjusted
North-South Resolution	1.8° (about 125 miles)	2.5° (about 175 miles)
East-West Resolution	1.8° (about 90 miles)	3.75° (about 185 miles)
Vertical Resolution	29 layers	20 layers
Land Surface Hydrology	Modified Bucket Method	Detailed Plant Canopy
Seasonal Solar Cycle	Yes	Yes
Diurnal Solar Cycle	Yes	Yes
Treatment of Multiple Greenhouse Gases	Carbon Dioxide Used as a Surrogate	Carbon Dioxide Used as a Surrogate
Treatment of Atmospheric Aerosols	Change in Surface Reflectance Only	Change in Surface Reflectance Only
Equilibrium Change for a Doubling of Carbon Dioxide	3.5°C (6.3°F)	2.6°C (4.7°F)

THE UTILITY AND LIMITATIONS OF GCM SCENARIOS

Limitations in climate modeling

GCMs are designed to be descriptions of the full three-dimensional structure of the earth's climate and often are used in a variety of applications, including the investigation of the possible role of various climate forcing mechanisms and the simulation of past and future climates. Given what we have seen regarding the abilities of GCMs, it appears that such models have the potential to simulate accurately changes in the real climate. However, we must remember several important issues. First, GCMs are limited by our incomplete understanding of the climate system and how the various atmospheric, land surface, oceanic, and ice components interact with one another. But in addition, GCMs are further limited by our ability to transform this incomplete understanding into mathematical representations. We may have a general feel for the complex interrelationships between the atmosphere and the oceans, for example, but expressing this understanding in a set of mathematical equations is much more difficult. Second, GCMs are limited by their own spatial and temporal resolutions. Computational complexity and finite restrictions on computing power reduce GCM simulations to coarse generalities. As a result, many small-scale features, which may have significant impact on the local, regional, or even global climate, are not represented. Thus, we must recognize that GCMs, at best, can only present a gross thumbnail sketch. Regional assessments over areas encompassing many GCM grid cells are the finest scale resolution that can be expected. It is inappropriate, and grossly misleading, to select results from a single grid cell and apply it locally. It cannot be over emphasized that GCM representations of the climate can be evaluated at a spatial resolution no finer than large regional areas, seldom smaller than a region defined by a square a thousand miles (at least several GCM grid cells) on a side. Even the use of "nested grid models" (models which take GCM output and resolve it to finer scale resolutions) does not overcome this limitation since results from the GCM simulation drives such models and no mechanism is available to feedback the results of such finer-scale models to the GCM.

A third limitation in GCMs is that given the restrictions in our understanding of the climate system and its computational complexity, some known phenomena are simply not reproduced in climate models. Hurricanes and most other forms of severe weather (*e.g.*, nor'easters, thunderstorms, and tornadoes) simply cannot be represented in a GCM owing to the coarse spatial resolution. Other more complex phenomena resulting from interactions among the elements that drive the climate system may be limited or even not simulated at all. Phenomena such as El Ninõ and La Ninã, the Pacific Decadal Oscillation, and other complex interrelationships between the ocean and the atmosphere, for example, are inadequately reproduced or often completely absent in climate model simulations. Such indicators should be flags that something fundamental is lacking in the GCM. These phenomena should be produced in the model as a result of our specification of climate interactions and driving mechanisms; their absence indicates a fundamental flaw in either our understanding of the climate system, our mathematical representation of the process, the spatial and temporal limitations imposed by finite computational power, or all three of the above.

An assessment of the efficacy of any climate model, therefore, must focus on the ability of the model to simulate the present climate conditions. If a model cannot simulate what we know to be true, then it is unlikely that model prognostications of climate change are believable. However, a word of caution is warranted. It is common practice to "tune" climate models so that they better resemble present conditions. This is widely acceptable, because many parameters in GCMs cannot be specified directly and their values must be determined through empirical trial-and-error. However, this raises the concern that a GCM may adequately simulate the present climate, not because the model correctly represents the processes that drive the earth's climate; but rather, because it has been tuned to do so. Thus, the model may appear to provide a good simulation of the earth's climate, when in fact the model may poorly simulate climate change mechanisms. In other words, a GCM may provide an adequate simulation of the present-day climate conditions, but it does so for the wrong reasons. Model efficacy in simulating present-day conditions, therefore, is not a guarantee that model-derived climate change scenarios will be reasonable. To address this question, modelers often employ simulations of past climates, such as the Holocene or the Pleistocene, to see if the model provides the kind of climate that we can infer existed during such epochs. Of course, our knowledge of pre-historical climate conditions is tenuous and extremely crude, which limits the utility of such evaluations.

A final limitation in climate modeling is that in the climate system, everything is interconnected. In short, anything you do wrong in a climate model will adversely affect the simulation of every other variable. Take precipitation, for example. Precipitation requires moisture in the atmosphere and a mechanism to cause it to condense (causing the air to rise over mountains, by surface heating, as a result of weather fronts, or by cyclonic rotation). Any errors in representing the atmospheric moisture content or precipitation-causing mechanisms will result in errors in the simulation of precipitation. Thus, GCM simulations of precipitation will be affected by limitations in the representation and simulation of topography, since mountains force air to rise and condense to produce orographic (mountain-induced) precipitation (*e.g.*, the coastal mountain ranges of Washington and Oregon). Incorrect simulations of air temperature also will adversely affect the simulation of precipitation since the ability of the atmosphere to store moisture is directly related to its temperature. If winds, air pressure, and atmospheric circulation are inadequately represented, then precipitation will be adversely affected since the atmospheric flow of moisture that may condense into precipitation will be incorrect. Plant transpiration and soil evaporation also provide moisture for precipitation; therefore, errors in the simulation of soil moisture conditions will adversely affect the simulation of precipitation. Simulation of clouds solar energy reaching the ground will affect estimates of surface heating which adversely affects the simulation of precipitation. Even problems in specifying oceanic circulation or sea ice concentrations will affect weather patterns, which affect precipitation simulations. In sum, the simulation of precipitation is adversely affected by inaccuracies in the simulation of virtually every other climate variable.

However, inaccuracies in simulating precipitation, in turn, will adversely affect the simulation of virtually every other climate variable. Condensation releases heat to the atmosphere and forms clouds, which reflect energy from the sun and trap heat from the earth's surface -- both of which affect the simulation of air temperature. As a result, this can affect the simulation of winds, air pressure, and atmospheric circulation. Since winds drive the circulation of the upper layers of the ocean, the simulation of ocean circulation also is affected. Air temperature conditions also contribute to the model simulation of sea ice formation, which would be adversely affected. Precipitation is the only source of soil moisture; hence, inadequate simulations of precipitation will adversely affect soil moisture conditions and land surface hydrology. Vegetation also responds to precipitation availability so that the entire representation of the biosphere can be adversely affected. Clearly, the interrelationships among the various components that comprise the climate system make climate modeling difficult. Keep in mind, however, that it is not just the long-term average and seasonal variations that are of interest. Demonstrating that precipitation is highest over the tropical rainforests and lowest in the subtropical deserts is not enough. Climate change is likely to manifest itself in small regional fluctuations. Moreover, we also are interested in intra-annual (year-to-year) variability. Much of the character of the earth's climate is in how it varies over time. A GCM that simulates essentially the same conditions year after year clearly is missing an important component of the earth's climate. Thus, the evaluation of climate change prognostications using GCMs must be made in light of the model's ability to represent the holistic nature of the climate and its variability. Interestingly, the National Assessment admits, "results suggest that the GCMs likely do not adequately include all of the feedback processes that may be important in determining the long-term climate" (United States National Assessment, 2000:23).

It should be noted that GCMs are not weather prediction models. Their utility is not in predicting, for example, whether it will rain in southern England on the morning of July 14, 2087. Rather, we are interested in determining whether the probability of precipitation will be substantially different from what it is today -- in both the frequency and intensity of precipitation events. In general, we want to know whether the summer of 2055 is likely to be warmer or colder than present conditions, and by how much. As such, GCMs are only used appropriately to address the likelihood of changes over large spatial and temporal scales -- assessing changes for specific dates or locations is beyond the scope of GCM utility.

How the National Assessment employs models

In the United States National Assessment, three approaches are used to determine the anthropogenic effects of climate change. The first approach is to examine the historical record, back to the late 1800s, to look for trends or changes that might possibly be linked to human sources. Unfortunately, the climate record reflects not just changes linked to anthropogenic activities, but a whole host of fluctuations caused by natural sources and uncertainties induced by changes to the instrumentation, station network and its environment, *etc.* The second approach is to use "sensitivity/vulnerability analysis" -- address the degree of change required to cause significant impacts in areas of critical human concern and its probability of occurrence. Such speculations are based, in large part, on the results of analysis from both the historical record and model prognostications.

Our focus here is on the third approach used in the National Assessment -- the use of climate models (GCMs in particular) to assess the potential for anthropogenic climate change. While GCMs provide quantitative assessments of such changes (*i.e.*, they assign numerical values to changes and their probabilities), the limitations discussed above can lead to some skepticism of such assessments. In particular, we need to pay close attention to the uncertainties or "error bars" associated with the numbers generated by the models. Indeed, the Draft of Chapter 1 of the National Assessment indicates that GCMs are not perfect predictors of future climates, but argue that they "can be used to provide important and useful information about potential long-term climate changes over periods of up to a few centuries on hemispheric scales and across the [United States], but care must be taken in interpreting regionally specific and short-term aspects of the model simulations" (US National Assessment, 2000:23). Although the National Assessment goes on to highlight all of the caveats associated with the use of model projections, model results are nevertheless shown in high resolution and without assessment of uncertainties, which allows many results gleaned from the models to transcend these caveats and concerns.

In the National Assessment, as well as in most modeling applications, GCM estimates of climate change scenarios are developed by taking the difference between the model simulated change and the model representation of the present climate conditions. For example, if the model simulated a present climate of 10°C (50°F) that was to change to 15°C (59°F) under a given climate change scenario, then the climate change prognostication would be for an increase of 5°C (9°F). For precipitation, the rate is computed as a percentage, not as a difference; thus, if for the present climate, we have a precipitation rate of 4 mm per day that changes to 6 mm per day under climate change, the climate change prognostication would be for an increase in precipitation of 50%. Note that the observed values are not used -- thus, it is important that the model be compared to the observations to determine how reasonable these changes might be.

Limitations in interpreting results from the models used in the National Assessment

It is laudable that the National Assessment considered more than a single model although it is recognized that the evaluation of too many models would have become unwieldy. It is also was significant that the two models be of different type -- one a spectral GCM and the other a Cartesian grid GCM. As previously discussed, and as pointed out in Chapter 1 of the National Assessment, interpretation of the results from these two models must be accompanied by a great deal of care, owing to the inherent limitations in applying the results from GCM simulations. In particular, however, the choice of the two models recommended for use in the National Assessment, namely, the Canadian Climate Centre (CGCM1) and Hadley Centre (HadCM2) models is rather odd. It is widely recognized, and even mentioned by the National Assessment, that the CGCM1 provides a more extreme climate change scenario than other models that were considered but not used. To a large extent, this same criticism holds for the HadCM2 as well. It also is particularly intriguing that neither of the two selected models was developed by a group within the United States, especially when viable alternatives exist.

In part, the extreme scenarios developed by these two models result from the use of overly simplistic formulations of key model components. For example, the CGCM1 has the simplest treatment of land surface hydrology of all models considered; namely, a bucket model for soil moisture. Other models use a soil layer model with an explicit treatment of vegetation interactions. It has been widely demonstrated that bucket models overly simplify and grossly bias the representation of the hydrological cycle. Since precipitation, soil evaporation, and plant transpiration are components of not only the water balance, but the energy balance as well, such simplistic treatments greatly undermine the ability of the model to represent the climate. It is surprising that the National Assessment used a model employing such a simplistic treatment of land surface hydrology, particularly in light of the fact that clearly better alternatives exist.

With respect to sea ice models, the CGCM1 has the most simplistic treatment of all the models considered -- it lacks a dynamic component that other models possess. Although sea ice modeling is very difficult, a proper sea ice model is important to simulate the fluxes of energy and moisture between the atmosphere and the ocean at high latitudes. Since virtually all models indicate the greatest response of air temperature by greenhouse gas forcing will occur in the high latitudes, selection of a model that incorporates an inferior sea ice component is extremely puzzling. This is likely to overemphasize the effect of high latitude warming, which, in part, may be a major reason why prognostications of the CGCM1 are on the extreme side.

Furthermore, the CGCM1does not treat all greenhouse gases independently (the effect of them is lumped into an "effective" CO_2 surrogate) and includes the effect of atmospheric aerosols only changing the surface reflectance of solar energy. Given the potential importance of sulfur masking/mitigation of the anthropogenic greenhouse gas change signal, and decreasing concentrations of methane, this overly simplistic treatment may overstate the effect of such an important component of the anthropogenic global warming issue.

In considering the effect of greenhouse gases, it must be remembered that the most important greenhouse gas is not carbon dioxide, but water vapor. As we saw earlier, treatment of the oceans and, in particular, the land surface hydrology play an important role in determining correct levels of atmospheric humidity. Inaccuracies in precipitation rates also adversely affect atmospheric concentrations of water vapor. But couple this with the fact that the two models tend to provide estimates of surface air temperatures that are several degrees too cold. Since the amount of water vapor in the air at a relative humidity of 100% (saturated conditions) increases exponentially with increasing air temperature, the atmospheric moisture content is likely to be underestimated by a cold model. Water vapor has a relatively high specific heat -- meaning it takes more energy to raise the temperature of a water vapor molecule. Dry air is easier to warm; hence it is easier to achieve warming in a model that starts out with less water vapor in its atmosphere. Furthermore, it takes energy to evaporate water -- energy that with a drier atmosphere would contribute to additional warming.

In an evaluation of the intra-annual variability in climate models, Soden (2000) compared observations of precipitation variability with several GCMs, including those used in the National Assessment (Figure 3). He concluded, “Not only do the GCMs differ with respect to the observations, but the models also lack coherence among themselves…even the extreme models exhibit markedly less precipitation variability than observed.” Virtually no climate model adequately resolves the intra-annual climate variability.

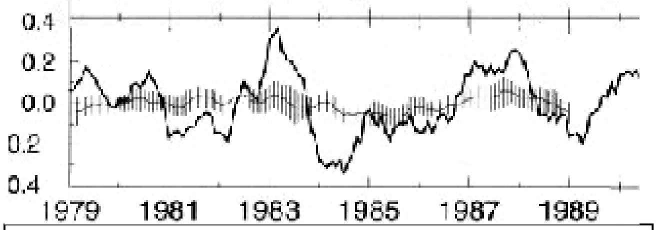


Figure 3: Precipitation rate in mm day^{-1} as observed (thick solid line) and as simulated by an ensemble of GCMs (thin solid line). Vertical lines on the GCM ensemble show the intra-annual variability among the GCMs mean. (from Soden, 2000)

Earlier it was mentioned that it is important to evaluate the efficacy of the GCMs with respect to their ability to reproduce the present-day climate. Doherty and Mearns (1999) have provided a comparison of historical simulations of the two models used in the National Assessment against observational data. In general, they conclude that both models have significant problems in their representation of topography -- the western United States is represented simply as one large hill beginning at sea level along the West coast and descending into the Great Plains. This problem manifests itself in cold and wet biases over the Rocky Mountains. When these problems with topography are coupled with the high spatial variability and the coarse spatial resolution of the models, results of climate change scenarios for detailed regions in the western United States is, in their words, "highly questionable". In general, the HadCM2 simulation is closer to the observed climate than that of the CGCM1, although both models exhibit considerable differences from the observations. They conclude, "researchers should exercise extreme caution in the conclusions they draw from impacts analysis using the output from these climate models, given the uncertainty of the model results, especially on a regional scale."

With regard to air temperature, Doherty and Mearns (1999) mapped the differences between the model mean climatology and an air temperature climatology developed by Legates and Willmott (1990b). In addition to the overall cold bias of both models, Doherty and Mearns found that air temperatures over the northern United States and Canada differ from the observations by as much as 12°C (21.6°F)! Topographically induced underestimates in air temperature are obvious in both models over the Rocky Mountains. In the central Plains, both models overestimate air temperature by up to 6°C (10.8°F) in summer, which is likely to overestimate summer drying, leading to an overestimate of drought frequency. Overall, both models exhibit similar patterns of biases in air temperature with warmer-than-observed conditions in winter and autumn in the northern United States and colder-than-observed conditions in the western United States in all seasons. Both models make the central United States too warm in summer and autumn.

Precipitation is difficult to simulate in a GCM, owing to the interrelationships among other climate variables noted earlier. In addition, precipitation mechanisms occur at scales well below the spatial and temporal resolution of most GCMs, the precipitation forming process is not fully understood, and numerical instabilities may arise with small amounts of moisture. Doherty and Mearns (1999) also mapped differences between the model mean climatology and a precipitation climatology developed by Legates and Willmott (1990a). As with air temperature, considerable overestimates exist over the Rocky Mountains in both models as a direct result of their inadequate representation of topography -- differences are as much as 6 mm day^{-1} (7.1 inches per month) are observed in parts of the Rocky Mountains. Note that this is twice the mean monthly precipitation in some areas! Overestimates also are observed in the northeastern United States in spring and summer by as much as 3 mm day^{-1} (3.5 inches per month) while precipitation in the southeastern United States and lower Mississippi River Basin during winter and summer is underestimated by as much as 3 mm day^{-1} (3.5 inches per month). Both models exhibit similar patterns of biases, although the regions of bias tend to be somewhat smaller in the HadCM2.

One conclusion of the National Assessment is of an enhanced hydrologic cycle over the United States -- increased precipitation variability and storminess. The ramifications are obvious; more floods and droughts will increase the potential losses and uncertainty of our future world. However, is this a rational conclusion? Karl *et al.* (1997) noted, "Variability in much of the Northern Hemisphere's midlatitudes has decreased as the climate has become warmer. Some computer models also project decreases in variability." This seems to be in direct opposition to the claims of both the Intergovernmental Panel on Climate Change (IPCC) and the National Assessment. Hayden (1999), in a paper written for and presented at a national conference to discuss the content of the National Assessment (and later published in a refereed journal), indicated that the observations show "there has been no trend in North America-wide storminess or in storm frequency variability found in the record of storm tracks for the period 1885-1996 … It is not possible, at this time, to attribute the large regional changes in storm climate to elevated atmospheric carbon dioxide." With regard to the model projections, he states, "[Model] projections of North American storminess shows no sensitivity to elevated carbon dioxide. It would appear that statements about storminess based on [model] output statistics are unwarranted at this time. … It should also be clear that little can or should be said about change in variability of storminess in future, carbon dioxide enriched years." Sinclair and Watterson (1999) further go on to conclude that for areas such as the United States, "doubled CO_2 leads to a marked decrease in the occurrence of intense storms." Both in general and in particular, GCMs do not exhibit an enhancement of the hydrologic cycle; nevertheless, the National Assessment decided to ignore this fact.

Concluding statements

In light of our discussion, climate models should be thought of as useful tools to assess our understanding of the climate system and to examine interrelationships among various components of the climate system. At present, and at least into the near foreseeable future, the uncertainties associated with model simulations make their projections only a single possible scenario, at best. Historically, assessments of climate change have steadily become less extreme as more climate feedback mechanisms are included in the models. Overall, it appears that anthropogenic climate change estimates are still uncertain (given the discrepancies between most models) and, when coupled with the slower-than-predicted warming present in the historical record, the true climate changes are likely to be at or below the lowest model estimates, with some of these changes having potentially beneficial effects.

Table 2: Selected projections from the Canadian Climate Centre Model (CGCM1) and the Hadley Centre Model (HadCM2) over the United States by 2030 (taken from Doherty and Mearns, 2000)

	Air Temperature					
	Winter			**Summer**		
	Eastern	Central	Western	Eastern	Central	Western
CGCM1	0° to 2°C	2° to 4°C	2° to 4°C	1° to 3°C	1° to 3°C	1° to 3°C
HadCM2	1° to 3°C	1° to 4°C	1° to 4°C	0° to 1°C	0° to 3°C	1° to 2°C
	Precipitation (in mm per day)					
	Winter			**Summer**		
	Eastern	Central	Western	Eastern	Central	Western
CGCM1	-2.0 to 0.0	-2.0 to 0.0	0.0 to +3.0	-1.0 to +0.5	-1.0 to +0.5	-0.5 to +0.5
HadCM2	0.0 to +1.0	-0.5 to +1.0	0.0 to +2.0	-0.5 to +1.0	-0.5 to +1.0	-0.5 to +1.0

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United States National Assessment (2000): *Chapter 1 -- Scenarios for Climate Variability and Change*. National Assessment Synthesis Team Document, Washington, DC, *Draft Report Version*.

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March 2002

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Research Interests

Climatology	*Computational Methods*
Hydroclimatology/Surface Water Hydrology	Statistical/Numerical Methods
Precipitation and Climate Change	Spatial Analysis and Spatial Statistics
Global and Regional Climatology	Digital/Numerical Cartography

Education

Ph.D.	Climatology, University of Delaware, Newark, Delaware. Received: August 1988. Dissertation: *A Climatology of Global Precipitation*.
M.S.	Climatology/Geography, Univ. of Delaware, Newark, Delaware. Received: June 1985. Thesis: *Interpolation of Point Values from Isarithms*
B.A.	Mathematics and Geography (Double Major), University of Delaware, Newark, Delaware. Received: June 1982. Graduated: *Cum Laude.*

Professional Experience

1999–	Associate Professor, University of Delaware, Newark, Delaware. (2000–present: Associate Director of the Delaware Space Grant Consortium) (2001–present: Associate State Climatologist in charge of the Delaware Mesonet) (2001–present: Director, Center for Climatic Research)
1998–1999	Associate Professor, Louisiana State University, Baton Rouge, Louisiana.
1998–1999	Research Scientist, Southern Regional Climate Center, Baton Rouge, Louisiana.
1994–1997	Associate Professor, University of Oklahoma, Norman, Oklahoma.
1995–1997	Chief Research Scientist, Center for Computational Geosciences, Norman, Oklahoma.
1995–	Vice President for Research, Computational Geosciences Inc., Norman, Oklahoma.
1995–1996	Visiting Associate Professor, University of Virginia, Charlottesville, Virginia.
1988–1994	Assistant Professor, University of Oklahoma, Norman, Oklahoma.
1991	Visiting Research Scientist, National Climatic Data Center, Asheville, North Carolina.
1982–1988	Graduate Research Assistant, University of Delaware, Newark, Delaware.
1986–1987	University of Delaware Graduate Fellowship, University of Delaware, Newark, Delaware.
1984	Instructor, University of Delaware, Newark, Delaware.
1981–1982	Undergraduate Research Assistant, University of Delaware, Newark, Delaware.

Selected Awards, Grants, and Projects

2000–2001	"Enhancements to the High Resolution Weather Data System (HRWxDS)", Duke Energy Corporation, Charlotte, North Carolina, co-Principal Investigator (K.R. Nixon, PI), $150,000.
2000	Awarded *Certified Consulting Meteorologist* status by the American Meteorological Society.
1999–2000	"Doppler Radar Irrigation Scheduling System: DRISS – Phase II", USDA Small Business Innovation Research Grant, United States Department of Agriculture, co-Principal Investigator (K.R. Nixon, PI), $230,000.

1999–2001	“Searching for Anthropogenic Climate Change Signals Using Non-Correlation-Based Approaches”, National Oceanic and Atmospheric Administration and Department of Energy's Climate and Global Change Program, Principal Investigator (R.E. Davis and S.M. Robeson), $50,001.
1999–2002	“The Great Plains Regional Earth Science Applications Center (GP-RESAC): A Consortium to Transfer Remote Sensing Products and Technology to Support the Great Plains Agroecosystem”, Regional Earth Science Applications Center, National Aeronautics and Space Administration, co-Principal Investigator (E. Martinko, PI, K. Price, and M.E. Jakubauskas), $75,000.
1999	“Monitoring Precipitation for the St. Johns River Watershed During June 1999”, St. Johns River Water Management District, co-Principal Investigator (K.R. Nixon, PI), $5,000.
1998–1999	“Doppler Radar Irrigation Scheduling System: DRISS – Phase I”, USDA Small Business Innovation Research Grant, United States Department of Agriculture, co-Principal Investigator (K.R. Nixon, PI), $65,000.
1998	Listed in *Who’s Who in Science and Engineering, 5th Edition -- 2000-2001.*
1998	Awarded the Alpha Lambda Delta Freshman Honor Society Award for Superior Instruction of Freshman Students -- Fall 1998. Louisiana State University.
1997–1998	“Development of an Intelligent Geographic Information System to Support Spatiotemporal Queries, Analysis, and Modeling in Hydrology”, United States Department of Defense, National Imagery and Mapping Agency, University Research Initiatives (NURI), co-Principal Investigator (M. Yuan, PI, J. Canning), $596,919.
1997–2001	“Interaction Between Land Cover/Land Use Dynamics and Climatological Variability in the Western Oklahoma/Kansas/Texas Indicator Region”, National Institute for Global Environmental Change, co-Principal Investigator (M.E. Jakubauskas, PI), $301,081.
1997–1998	“Expansion and Analysis of the Comprehensive Pacific Rainfall Data Base”, National Oceanic and Atmospheric Administration's Climate and Global Change Program, co-Principal Investigator (M. Morrissey, PI), $163,740.
1997–1998	“Rapid Tornado Damage Assessment”. Natural Hazards Research Applications and Information Center's Quick Response Research Program, Principal Investigator (with M.D. Biddle), $3000.
1995–1998	“Accuracy Assessment of the 4km x 4km Hourly WSR-88D GCIP Precipitation Data Using Raingage Measurements as Baseline Data”, NOAA Climate and Global Change Program, co-Principal Investigator (M.L. Morrissey, PI, and C.E. Duchon), $244,000.
1995–1997	“Water Resource Decision Support System – Phase II”. USDA Small Business Innovation Research Grant, United States Department of Agriculture, Consulting Hydroclimatologist (K.R. Nixon, PI), $100,000.
1995–1999	“Acquisition of Equipment to Create the Environmental Computing Applications System”, National Science Foundation's Academic Research Infrastructure Program, co-Principal Investigator (with thirteen researchers at the University of Oklahoma, K.K. Droegemeier, PI), $580,000.
1995	University of Oklahoma nominee for an International Affairs Fellowship from the Council on Foreign Relations.
1994–1997	“WSR-88D Radar Precipitation Interface”, Duke Power Company, Charlotte, North Carolina, co-Principal Investigator (K.R. Nixon, PI), $504,016.
1994	“Water Resource Decision Support System – Phase I”, USDA Small Business Innovation Research Grant, United States Department of Agriculture, Consulting Hydroclimatologist (K.R. Nixon, PI), $100,000.

1993–1994 “Development of an Interdisciplinary GIS Teaching Laboratory”, Instrumentation and Laboratory Improvement Program, National Science Foundation, co-Principal Investigator (G.L. Thompson, PI), $15,700.

1992–1994 “The Impact of Doubling Atmospheric Carbon Dioxide on Precipitation Frequency and Intensity in the Southern Great Plains Region”, Bureau of Reclamation, United States Department of the Interior, Principal Investigator, $122,020.

1992–1995 “Surface Hydrology Research Cluster”, EPSCoR program, National Science Foundation and the State of Oklahoma EPSCoR Program, co-Principal Investigator (with seven researchers at the University of Oklahoma and Oklahoma State University, T.H.L. Williams, PI), $871,335.

1992 University of Oklahoma nominee for the National Science Foundation's Presidential Faculty Fellow and Young Investigator Awards.

1991–1993 “Compilation of an Unbiased Precipitation Data Set and Its Use in the Evaluation of the Natural Variability and GCM-Simulated Climates for the United States”, Climate Dynamics Division, National Science Foundation, Principal Investigator, $25,839.

1990–1991 Consultant to the Global Precipitation Climatology Project sponsored by the World Meteorological Organization at Deutscher Wetterdienst (German Weather Service).

1989 “An Objective Approach to the Selection of a Precipitation Frequency Distribution”, Research Fellowship, University of Oklahoma, Principal Investigator, $5000.

1986–1987 Awarded Competitive University Fellowship for Graduate Studies, University of Delaware.

Participation in National and International Presentations, Workshops, and Institutes

2001 Invited speaker by the George C. Marshall Institute, January 23, Washington, DC.

2000 Invited speaker at “Global Warming: Science and Public Policy”, Rayburn House Office Building, April 3, Washington, DC.

1998 Moderator of and participant in “Global Warming: The Science Behind the World’s Hottest Environmental Issue”, The Houston Forum, September 25, Houston, Texas.

1998 Invited speaker at a “Cooler Heads” Luncheon for House and Senate Staff Members, Rayburn House Office Building, June 5, Washington, DC.

1997 Invited participant at the Conference on “Global Climate Change: What Does It Mean for the Central Southwest?”, October 30, Dallas, Texas.

1996 Invited participant at the Twin Cities Conference on Global Climate Change by the Minnesota Environmental Coalition of Labor and Industry, December 11, Minneapolis, Minnesota.

1996 Invited participant at the NPOESS Climate Requirements Workshop, February 27–29, College Park, Maryland.

1995 Invited participant at the ACSYS Solid Precipitation Climatology Project Workshop, September 12–15, Reston, Virginia.

1995 Invited speaker at the 20th Annual Energy Conference of the Western Fuels Association, July 27, Baton Rouge, Louisiana.

1995 Invited panelist at the NOAA Experts Meeting on Documenting and Detecting Long-Term Climate Change: Monitoring Requirements, January 9–11, Asheville, North Carolina.

1994 Invited lecturer at the NATO Advanced Study Institute on the Role of Water and the Hydrological Cycle in Global Change, May 27–June 6, Il Ciocco, Italy.

1994 Invited participant at the UCAR Workshop on Databases for Terrestrial Biosphere Modeling, May 9–11, Boulder, Colorado.

1993 Invited participant at the NATO Advanced Research Workshop on Global Environmental Change and Land Surface Processes in Hydrology: The Trials and Tribulations of Modeling and Measuring, May 17–21, Tucson, Arizona (chaired panel discussion).

1993 Invited participant at the NOAA Workshop on Environmental Information Needs: Precipitation-Sensitive Systems, May 4–7, Boulder, Colorado.

1992 Invited participant at the joint GEWEX/WGNE Workshop on Global Observations, Analyses and Simulation of Precipitation, National Meteorological Center, October 27–30, Washington, DC.

1991 Invited participant at the NATO Advanced Research Workshop on Opportunities for Hydrological Data in Support of Climate Change Studies, August 26–30, Lahnstein, Germany.

1989 Invited participant at the joint USA/USSR Working Meeting on Development of Data Sets for Detecting Climatic Change, September 11–14, Obninsk, USSR.

1987 Invited participant at the 1987 Summer Supercomputing Institute, National Center for Atmospheric Research, Boulder, Colorado.

Service on National and International Committees and Boards

Panel Member, National Science Foundation, Geography and Regional Science, 2000–2002.

Associate Editor, *Climate Research*, 2000 – present

Editorial Board, *The Professional Geographer*, 1998–2000.

Vice President, Central Louisiana Joint Chapters of the American Meteorological Society and the National Weather Association, 1998–1999.

Member, Annual Meetings Program Committee, Association of American Geographers, 1996.

Chair, Climate Specialty Group, Association of American Geographers, 1994–1996.

Board of Directors, Climate Specialty Group, Association of American Geographers, 1992–1994.

National Expert, International Organizing Committee (OC) for the WMO Solid Precipitation Measurement Intercomparison Project, 1989–1993.

Membership in Professional Organizations and Honorary Societies

American Geophysical Union
American Meteorological Society
American Water Resources Association
Association of American Geographers

Phi Beta Kappa
Phi Kappa Phi
Pi Mu Epsilon (Mathematics)

Refereed Publications

Jakubauskas, M.E., D.R. Legates, and J.H. Kastens (2001). Harmonic Analysis of Time-Series AVHRR NDVI Data. *Photogrammetric Engineering and Remote Sensing*, **67**(4):461–470.

Jakubauskas, M.E., and D.R. Legates (2001). Crop Identification Using Harmonic Analysis of Time-Series AVHRR NDVI Data. *Computers and Electronics in Agriculture*, forthcoming.

Legates, D.R. (2000). Real-Time Calibration of Radar Precipitation Estimates. *The Professional Geographer*, **52**(2):235–246.

Legates, D.R. (2000). Remote Sensing in Hydroclimatology: An Introduction to a Focus Section of *The Professional Geographer*. *The Professional Geographer*, **52**(2):233–234.

Jakubauskas, M.E., D.R. Legates, and J.H. Kastens (2000). Harmonic Analysis of Time-Series AVHRR NDVI Data for Characterizing US Great Plains Land Use/Land Cover. *International Archives of Photogrammetry and Remote Sensing*, **33**(B4):384–389.

Legates, D.R., and G.J. McCabe, Jr. (1999). Evaluating the Use of "Goodness of Fit" Measures in Hydrologic and Hydroclimatic Model Validation. *Water Resources Research*, **35**(1):233–241.

Davis, R.E., M.B. Lowit, P.C. Knappenberger, and D.R. Legates (1999). A Climatology of Snowfall-Temperature Relationships in Canada. *Journal of Geophysical Research*, **104**(D10): 11,985–11,994.

Komuscu, A.U., and D.R. Legates (1999). Effects of Rainfall Variability on Spatial Accumulation of Peak Runoff and Excess Runoff Depth: Little Washita River Basin, Oklahoma, USA. *Journal of Environmental Hydrology*, **7**, Paper 18, November.

Legates, D.R., K.R. Nixon, T.D. Stockdale, and G.E. Quelch (1998). Use of the WSR-88D Weather Radars in Rangeland Management. *Specialty Conference on Rangeland Management and Water Resources*, American Water Resources Association, 55–64.

Legates, D.R., and R.E. Davis (1997). The Continuing Search for an Anthropogenic Climate Change Signal: Limitations of Correlation-based Approaches. *Geophysical Research Letters*, **24**(18):2319–2322.

Legates, D.R. (1997). Comments on “Global and Terrestrial Precipitation: A Comparative Assessment of Existing Climatologies” — A Reply. *International Journal of Climatology*, **17**:779–783.

Legates, D.R., K.R. Nixon, T.D. Stockdale, and G.E. Quelch (1996). Soil Water Management Using a Water Resource Decision Support System and Calibrated WSR-88D Precipitation Estimates. *Symposium on GIS and Water Resources*, American Water Resources Association, 427–435.

Janowiak, J.E., P.A. Arkin, P. Xie, M.L. Morrissey, and D.R. Legates (1995). An Examination of the East Pacific ITCZ Rainfall Distribution. *Journal of Climate*, **8**(11):2810–2823.

Legates, D.R. (1995). Global and Terrestrial Precipitation: A Comparative Assessment of Existing Climatologies. *International Journal of Climatology,* **15**:237–258.

Groisman, P.Ya., and D.R. Legates (1995). Documenting and Detecting Long-Term Precipitation Trends: Where We Are and What Should be Done. *Climatic Change*, **31**:601–622.

McCabe, G.J., Jr., and D.R. Legates (1995). Relationships Between 700 hPa Height Anomalies and 1 April Snowpack Accumulations in the Western USA. *International Journal of Climatology*, **15**:517–530.

Legates, D.R., T.L. DeLiberty, and J.M. Salisbury (1994). Implications of Doubled Trace Gas Concentrations on Summer Precipitation Variability in the Southern Great Plains. *Symposium on the Effects of Human-Induced Changes on Hydrologic Systems*, American Water Resources Association, 755–762.

Groisman, P.Ya., and D.R. Legates (1994). Accuracy of Historical United States Precipitation Data. *Bulletin of the American Meteorological Society*, **75**(2):215–227.

Legates, D.R. (1993). The Effect of Domain Shape on Principal Components Analyses: A Reply. *International Journal of Climatology*, **13**:219–228.

Legates, D.R., and T.L. DeLiberty (1993). Measurement Biases in the United States Raingage Network. *Symposium on Geographic Information Systems and Water Resources*, American Water Resources Association, 547–557.

Legates, D.R., and T.L. DeLiberty (1993). Precipitation Measurement Biases in the United States. *Water Resources Bulletin*, **29**(5), 855–861.

Willmott, C.J., and D.R. Legates (1993). A Comparison of GCM-Simulated and Observed Mean January and July Global Surface Air Temperature. *Journal of Climate,* **6**:274–291.

Legates, D.R., and J.R. Mather (1992). An Evaluation of the Average Annual Global Water Balance. *Geographical Review,* **82**:253–267.

Legates, D.R., and C.J. Willmott (1992). A Comparison of GCM-Simulated and Observed Mean January and July Precipitation. *Global and Planetary Change*, **97**:345–363.

McCabe, G.J., Jr., and D.R. Legates (1992). General Circulation Model Simulations of Winter and Summer Sea-Level Pressures Over North America. *International Journal of Climatology*, **12**:815–827.

Legates, D.R. (1991). The Effect of Domain Shape on Principal Components Analyses. *International Journal of Climatology*, **11**:135–146.

Legates, D.R. (1991). An Evaluation of Procedures to Estimate Monthly Precipitation Probabilities. *Journal of Hydrology*, **122**:129–140.

Willmott, C.J., and D.R. Legates (1991). Rising Estimates of Terrestrial and Global Precipitation. *Climate Research*, **1**:179–186.

Legates, D.R., and C.J. Willmott (1990). Mean Seasonal and Spatial Variability in Gauge-Corrected, Global Precipitation. *International Journal of Climatology*, **10**(2):111–127.

Legates, D.R., and C.J. Willmott (1990). Mean Seasonal and Spatial Variability in Global Surface Air Temperature. *Theoretical and Applied Climatology,* **41**(1):11–21.

Legates, D.R., and C.J. Willmott (1986). Interpolation of Point Values from Isoline Maps. *The American Cartographer*, **13**(4):308–323.

Willmott, C.J., S.G. Ackleson, R.E. Davis, J.J. Feddema, K.M. Klink, D.R. Legates, J. O'Donnell, and C.M. Rowe (1985). Statistics for the Evaluation and Comparison of Models. *Journal of Geophysical Research*, **90**(C5):8995–9005.

Legates, D.R., and C.J. Willmott (1983). A Comparative Evaluation of Principal Components-Based and Information Theory Methods of Precipitation Regionalization. *Archives for Meteorology, Geophysics, and Bioclimatology, Series B,* **32**:381–394.

Book Chapters, Monographs, and Reports

Legates, D.R. (2000). A Brief Guide to the Global Climate Models Used in the National Assessment. The George C. Marshall Institute, 16pp.

Legates, D.R., and M.D. Biddle (1999). Warning Response and Risk Behavior in the Oak Grove – Birmingham, Alabama Tornado of 08 April 1998. Natural Hazards Research Application and Information Center, Final Report.

Legates, D.R. (1998). Applications of the Wind-Bias Assessments to Precipitation Data in USA and Global Archives. *WMO Solid Precipitation Measurement Intercomparison: Final Report*, B.E. Goodison *et al., eds.*, WMO Instruments and Observing Methods Report No. 67, WMO/TD-No.872, 73–75.

Legates, D.R. (1998). *Lab Exercises for Physical Geography: The Atmosphere.* Louisiana State University, Baton Rouge, Louisiana, 130pp. (Revised in 2000)

Legates, D.R., and D.C. Goodrich (1997). The Challenges We Face: Panel Discussion on Precipitation (edited by H.V. Gupta and S. Sorooshian). *Global Environmental Change and Land Surface Processes in Hydrology: The Trials and Tribulations of Modeling and Measuring*, S. Sorooshian, H.V. Gupta, and S.C. Rodda, *eds.*, NATO Advanced Science Institute on Global Environmental Change, Springer-Verlag, Berlin, 169–180.

Legates, D.R., and T.L. DeLiberty (1996). Precipitation in the Southern Great Plains: Observations and Model Simulations of Present-Day and Doubled Atmospheric CO_2 Concentrations. *Global Climate Change Response Program*, United States Department of the Interior, Bureau of Reclamation, Denver, Colorado, 80pp.

Groisman, P.Ya., and D.R. Legates (1996). Documenting and Detecting Long-Term Precipitation Trends: Where We Are and What Should Be Done. *Long-Term Climate Monitoring by the Global Climate Observing System*, T.R. Karl, *ed.*, Kluwer Academic Publishers, The Netherlands, 471–492.

Legates, D.R., and C.J. Willmott (1995). Evaluating the Terrestrial Water Balance from the Historical Climate Record. *The Role of Water and the Hydrological Cycle in Global Change*, NATO ASI Series, Springer-Verlag, The Netherlands, 23–58.

Legates, D.R. (1994). Issues in the Interpolation of Spatially-Continuous Data. *Opportunities for Hydrological Data in Support of Climate Change Studies*, Internationales Hydrologisches Programm der UNESCO Operationelles Hydrologisches Programm der WMO in der Bundesrepublik Deutschland, Sonderheft 7, Koblenz, 199–206.

Legates, D.R. (1994). The Use of Precipitation Time-series in Hydrologic Analyses. *Opportunities for Hydrological Data in Support of Climate Change Studies*, Internationales Hydrologisches Programm der UNESCO Operationelles Hydrologisches Programm der WMO in der Bundesrepublik Deutschland, Sonderheft 7, Koblenz, 95–102.

Legates, D.R. (1993). *Lab Exercises for an Introduction to Physical Geography*. Custom Academic Publishing, Norman, Oklahoma, 130pp.

Legates, D.R., and G.J. McCabe, Jr. (1992). General Circulation Model Estimates of Regional Precipitation, in *Global Climate Change: Implications, Challenges and Mitigation Measures*, S.K. Majumdar *et al.*, eds., The Pennsylvania Academy of Science, 302–314.

Legates, D.R. (1989). A High-Resolution Climatology of Gage-Corrected, Global Precipitation, in *Precipitation Measurement,* B. Sevruk (ed.), Swiss Federal Institute of Technology and the World Meteorological Organization, 519–526.

Legates, D.R. (1987). A Climatology of Global Precipitation. *Publications in Climatology,* **40**(1), 84pp.

Legates, D.R. (1984). Interpolation of Point Values from Isarithms. *Publications in Climatology,* **37**(1), 66pp.

Papers in Proceedings of Professional Meetings

Legates, D.R., D.J. Leathers, J.H. Talley, T.L. DeLiberty, G.S. Donaldson, K.R. Nixon, A.P. Janke, and G.E. Quelch (2002). Integrating Weather Information into an Integrated Transportation Management System. *Proceedings, AMS Conference on ...*, Orlando, FL.

Jakubauskas, M.E., D.L. Peterson, and D.R. Legates (2001). Fourier Decomposition of an AVHRR NDVI Time Series for Seasonal and Interannual Land Cover Change Detection. *Proceedings, First International Workshop on the Analysis of Multitemporal Remotely Sensed Images*, Trento, Italy.

Nixon, K.R., D.R. Legates, A.P. Janke, G.E. Quelch, T.D. Stockdale, and A.C. Yung (2001). A High-Resolution Weather Data System. *Proceedings, 25th Annual Conference of the Association of State Floodplain Managers*, Charlotte, NC.

Nixon, K.R., D.R. Legates, A.P. Janke, and G.E. Quelch (2001). A High-Resolution Weather Data System. *Proceedings, Conference on Decision Support Systems for Water Resource Management,* Snowbird, UT.

Legates, D.R., R.E. Davis, S.M. Robeson, and O.W. Frauenfeld (2000). A Non-Correlation-Based Approach to the Search for Anthropogenic Climate Change Signals. *Proceedings, Fifteenth Conference on Probability and Statistics in the Atmospheric Sciences*, Asheville, NC, 14 –17.

Legates, D.R., K.R. Nixon, and T.D. Stockdale (2000). Real-Time Calibration of WSR-88D Precipitation Estimates. *Proceedings, Twelfth Conference on Applied Climatology* and the *Fifteenth Conference on Probability and Statistics in the Atmospheric Sciences,* Asheville, NC, J38 –J39.

Jakubauskas, M.E., D.R. Legates, and J.H. Kastens (2000). Crop Identification using Harmonic Analysis of Time-Series AVHRR NDVI Data. *Proceedings, Second International Conference on Geospatial Information in Agriculture and Forestry,* Lake Buena Vista, FL.

Yung, A.C., K.T. Vogel, K.R. Nixon, and D.R. Legates (2000). The Use of NEXRAD Data for Hydrologic Modeling of Historic Flood Events. *Proceedings, Association of State Floodplain Managers Annual Conference,* Austin, TX.

Legates, D.R. (1999). Precipitation Variability in the United States: Status, Trends, and Canadian Global Coupled Model Simulations. *Proceedings, Conference on Potential Consequences of Climate Variability and Change to Water Resources of the United States,* American Water Resources Association, Atlanta, GA, 97–100.

Legates, D.R., M.E. Jakubauskas, and R. Ayala (1999). Interactions Between Climate Variability and Land Cover/Land Use Dynamics in Western Oklahoma/Kansas/Texas. *Proceedings, Conference on Potential Consequences of Climate Variability and Change to Water Resources of the United States,* American Water Resources Association, Atlanta, GA, 297–300.

Legates, D.R., K.R. Nixon, G.E. Quelch, and T.D. Stockdale (1999). Environmental Modeling and Monitoring using a High-Resolution Weather Data System (HRWxDS). *Proceedings of the Fourth International Conference on GeoComputation*, Fredericksburg, VA, on CD-ROM.

Legates, D.R., K.R. Nixon, G.E. Quelch, and T.D. Stockdale (1999). A High-Resolution Hydrometeorological Data System (HRHDS) for Environmental Modeling and Monitoring. *Proceedings of the EPA National Conference on Environmental Problem Solving with Geographic Information Systems*, Cincinnati, OH, 76–77.

Legates, D.R., K.R. Nixon, G.E. Quelch, and T.D. Stockdale (1999). Real-time and Historical Calibration of WSR-88D Precipitation Estimates. *Proceedings, Eleventh Conference on Applied Climatology*, American Meteorological Society, Dallas, TX, 76–77.

Mahmood, R., K.S. Humes, and D.R. Legates (1999). Scale-Aggregation of Landsat-TM Data and Information Loss. *Proceedings, 1999 ASPRS Annual Conference*, American Society of Photogrammetry and Remote Sensing, Portland, OR, 733–742.

Muller, R.A., D.R. Legates, and J.M. Grymes III (1999). Application of the Climatic Water Budget for K-12 Education, Monitoring Climatic Variability, and Applied Research. *Proceedings, Eighth Symposium on Education* and *Proceedings, Eleventh Conference on Applied Climatology*, American Meteorological Society, Dallas, TX, 17–18.

Nixon, K.R., R.L. Elliott, D.R. Legates, G.E. Quelch, and T.D. Stockdale (1999). Doppler Radar Irrigation Scheduling System (DRISS). *Proceedings, USCID/ASCE Workshop on Modernization of Irrigation Water Delivery Systems*, Phoenix, AZ, forthcoming.

Nixon, K.R., D.R. Legates, G.E. Quelch, and T.D. Stockdale (1999). A High-Resolution Weather Data System for Environmental Modeling and Monitoring of Meteorological Conditions. *Proceedings, Fifteenth International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology* and *Proceedings, Fourteenth Conference on Hydrology*, American Meteorological Society, Dallas, TX, 521–524.

Michaels, P.J., P.C. Knappenberger, R.E. Davis, and D.R. Legates (1997). Global Warming: Subtle or Sulfates? *Proceedings, American Meteorological Society Symposium on Climate Change*, American Meteorological Society, Long Beach, CA, 178–181.

Ray, G.C., and D.R. Legates (1997). Range of Selection Approaches for Marine and Coastal Protected Areas. *Proceedings, Second International Symposium and Workshop on Marine and Coastal Protected Areas: Integrating Science and Management*, National Oceanic and Atmospheric Administration, Tampa, FL, 118–126.

Legates, D.R., and T.L. DeLiberty (1996). Precipitation Frequency and Intensity on the Southern Great Plains: Present-Day Conditions and Doubled Trace Gas Scenarios. *Proceedings, Second International Scientific Conference on the Global Energy and Water Cycle*, Washington, DC, 456–457.

DeLiberty, T.L., and D.R. Legates (1996). The Interannual and Seasonal Variability of Modelled Soil Moisture: A Case Study in Oklahoma. *Proceedings, Second International Scientific Conference on the Global Energy and Water Cycle*, Washington, DC, 269–270.

Legates, D.R. (1995). Precipitation Measurement Biases and Climate Change Detection. *Proceedings, Sixth Symposium on Global Change Studies*, American Meteorological Society, Dallas, TX, 168–173.

DeLiberty, T.L., and D.R. Legates (1995). A Regional-Scale Investigation of Soil Moisture Variability. *Proceedings, Conference on Hydrology*, American Meteorological Society, Dallas, TX, 115–120.

McCabe, G.J., Jr., D.R. Legates, and M.D. Dettinger (1994). Relations Between 700-Millibar Height Anomalies and April 1 Snowpack Accumulations in the Western United States. *Proceedings, Eighteenth Climate Diagnostics Workshop*, National Oceanic and Atmospheric Administration, Boulder, CO, 252–255.

Legates, D.R. (1993). Biases in Precipitation Gage Measurement. *Global Observations, Analyses and Simulation of Precipitation*, Report of the WGNE/GEWEX Workshop, WCRP-78, WMO/TD-No.544, World Climate Research Programme, Camp Springs, MD, 31–34.

Legates, D.R. (1993). Conventional Precipitation Climatologies. *Global Observations, Analyses and Simulation of Precipitation*, Report of the WGNE/GEWEX Workshop, WCRP-78, WMO/TD-No.544, World Climate Research Programme, Camp Springs, MD, 23–29.

Legates, D.R., and T.L. DeLiberty (1993). Estimation of Biases in Precipitation Gage Measurements: An Example Using the United States Raingage Network. *Proceedings, Eighth Symposium on Methods of Instrumentation* and *Proceedings, Eighth Conference on Applied Climatology*, American Meteorological Society, Anaheim, CA, J48–J51.

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