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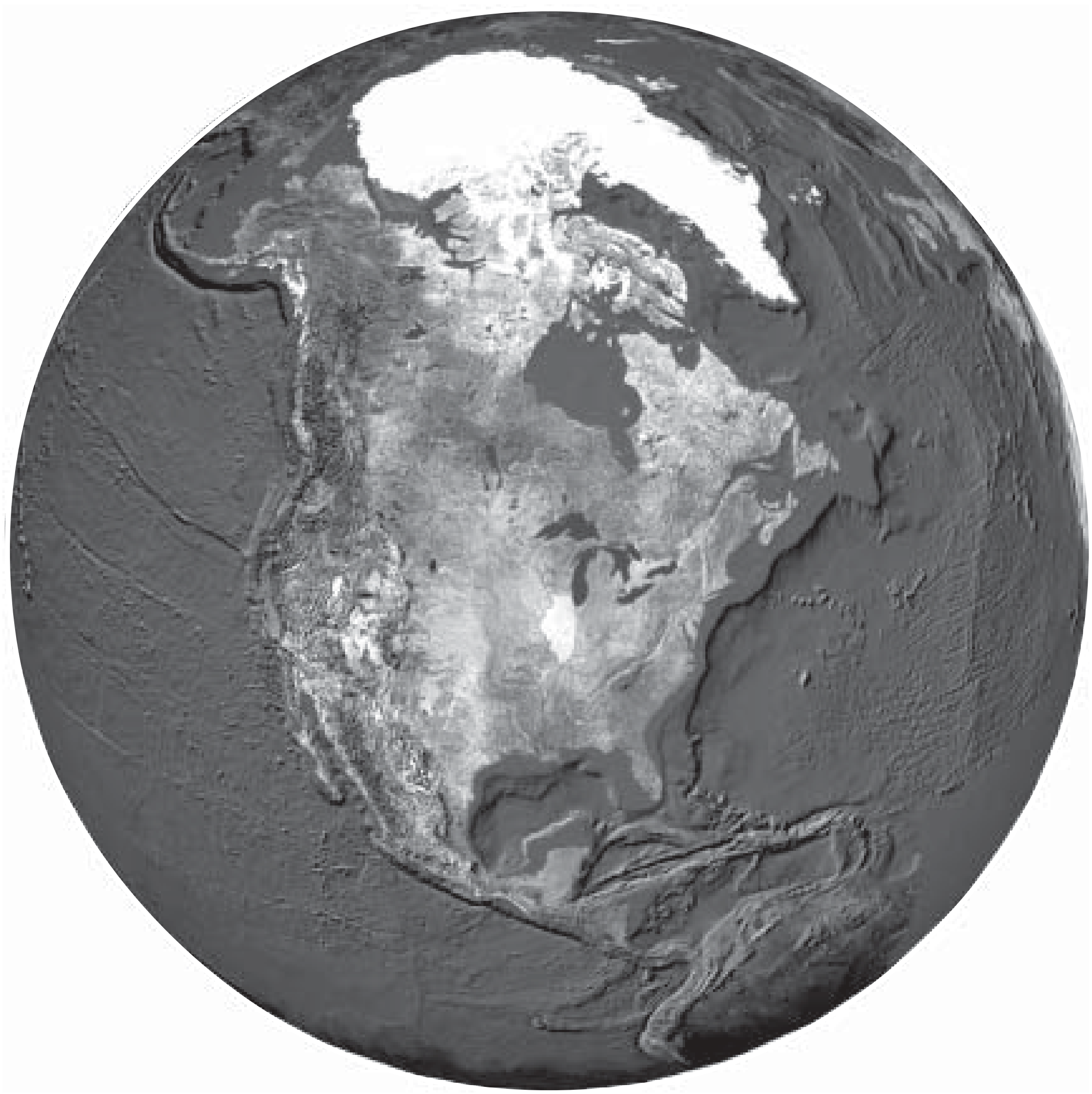
Illinois State Water Survey

# Insights to Key Questions about Climate Change



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# Executive Summary

This report presents extensive information from recently published findings related to the following two critical questions about climate change:

- What will the future climate be like?
- What will the effects be, both good and bad?

**Chapter 1** introduces the two main chapters of the report that provide insights to the above two critical questions about climate change.

**Chapter 2** provides examples from a wide spectrum of scientists, scientific organizations, and the media of contradictions and confusion about whether human-induced climate change is predictable over the time scale of a century. It then explains why such climate change is unpredictable in the traditional deterministic sense. It describes the climate system and documents major improvements and remaining uncertainties of global climate models relevant to evaluating human-induced climate change on the century time scale.

Key determinants of human-induced climate change are emissions of greenhouse gases, aerosols, and land-cover changes. Quantifying these agents 100 years from now is based on subjective assumptions and value judgments about human behavior, technologies, resource management, economic development, and policies. Incomplete science and model limitations, together with uncertainties about, for example, world population (6.9-15.1 billion), world wealth (197-550 x $10^{12}$ 1990 US dollars per year), and primary energy (514-2737 x $10^{18}$ Joules per year) lead to large uncertainties in estimated accumulations of greenhouse gases and aerosols in the atmosphere, land-cover changes, and climate change (~1 to ~6$^{o}$C) in 2100. Even with perfect science and perfect climate models, large uncertainties about future climates always will remain due to inherent uncertainties associated with the socioeconomic drivers.

Currently, climate models are reported to simulate regional climates in a less than acceptable manner, but the models often are judged to perform well in their simulation of global mean climate conditions. It is recommended that simulations of global climate conditions by global climate models be judged to be acceptable when they simulate faithfully all important processes governing the evolution of climate and simulate correctly historical and current regional climate conditions. When descriptions of climate change are represented as the difference between simulated current climates and projected climates, biases and errors in simulating current climate conditions should be specified.

The public and decisionmakers will be better served by improving communication among scientists and by the media, including better communication of uncertainty. Fundamental to improving communication is greater consistency by scientists and the media in defining and using key terms. Climate cannot be predicted in a deterministic sense, so it is unwise to call the output of climate models “climate predictions”. It is recommended that climate-change modeling studies be described as “climate experiments”, and the resulting climate-change representations as “climate-change scenarios” or “pictures”, consistent with definitions and usages by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations and the United States Climate Change Science Program (USCCSP).

National and international climate assessments frequently draw on historical climate records that span a few decades or a century. However, such climate records often are too short to establish an adequate baseline for evaluation of climate change due to human activities. Climate measurements in Illinois since the mid-19th century document major climate swings not evident in a 50- to 100-year record. Illinois is no warmer or wetter today than it has been over the last 150 years, and extreme precipitation events across the country are reported to be no more frequent than they were a century ago. Important conclusions from these data are that i) regional climate trends over the past 50-100 years that are consistent with theoretical expectations of an enhanced greenhouse effect (for example, higher precipitation and more heavy rainfall events in northern mid-latitudes) do not necessarily establish causality; and ii) global warming has not resulted in warming in all parts of the globe.

There is a great need to define, quantify, and communicate uncertainty about past and possible future climate changes.

**Chapter 3** focuses on the issue of economic impacts of weather and climate in the United States (US). The first section addresses known financial impacts of recent (1950-2000) weather and climate conditions. Descriptions follow of temporal trends of weather and climate extremes and their impacts, causes for on-going increases in economic impacts, and estimates of future financial impacts under a changed climate.

Two major weather-sensitive sectors in the US are agricultural production and energy use. National data were assessed to define 1950-1997 annual losses and gains relating to weather fluctuations, showing average annual agricultural losses of $2.6 billion and gains of $1.9 billion (1997 dollars). Energy usage tied to weather variations over this period resulted in average annual costs to consumers of $4.6 billion and gains of $3.9 billion (1997 dollars). Agricultural-based trends in losses over this period increased 3 percent, whereas costs for natural gas and electricity declined by 1.3 percent and 4.1 percent, respectively.

Storms and climate extremes such as droughts and heat waves also have major economic impacts. Trends in these climate extremes and associated losses exhibit major differences. The frequency of most types of storms and droughts either has not changed or has decreased during 1940-2000. Yet, losses (1997 dollars) for most storm types have increased over time, including those due to hurricanes, floods, hail, droughts, tornadoes, heat waves, and winter storms. Hurricanes lead in losses with an annual average of $4.2 billion, followed by flood losses of $3.2 billion, thunderstorm-related losses of $2.5 billion, winter storms at $0.3 billion, and wind storms at $0.2 billion (all 1997 dollars).

Certain recent major weather-climate events have had major financial impacts, including the drought in 1987-1989, Hurricane Andrew in 1992, major Midwestern floods in 1993, El Niño in 1997-1998, and the record warm winter in 2001-2002. Extensive economic assessments of these events have documented both losses and gains related to these events.

A series of 72 weather disasters in the US during the 1990s caused insured property losses of $55 billion (1997 dollars). Possible causes for increased losses include a shift in climate related to global warming, questionable insurance practices, and aging infrastructure. Study also shows increasing losses due to societal factors, including population growth, more people residing in more weather vulnerable areas, shifts in business-product development that are weather sensitive, and growing wealth.

Various studies of weather- and climate-induced economic impacts were used to develop national loss and gain estimates. When damaging conditions occur, average annual losses for the nation are $35 billion (2003 dollars), a value in close agreement with results of earlier assessments. Losses of $35 billion a year represent 2 percent of the total federal expenditures in 2003 and 0.4 percent of the nation's Gross Domestic Product (GDP).  Average annual gains resulting from weather conditions amount to $25 billion, and two recent warm, dry winters each produced $20 billion gains.

Some economists have attempted to estimate the economic impacts related to possible future climates altered by global warming.  Many believe economic models are incapable of such estimates and that any economic projections are as uncertain as those of the climate pictures painted by climate models.  Projections for the US, depending upon varying assumptions about the future climate (combinations of warmer, wetter, drier, or more storms), show annual losses ranging from $2 billion to $69 billion, and others estimate annual gains of $30 billion to $40 billion.  In all cases, the projected outcomes are small in relation to the expected GDP.

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# Chapter 1:
# Introduction

Climate change is an important issue for Illinois. Climate changes in Illinois, the Midwest, the rest of the nation, and the world have had and will continue to have direct and indirect impacts on Illinois.

Over the past 15 years, various scientists and institutions have issued a variety of prognostications of major changes in global and regional climates resulting from human activities. These include a specter of disastrous shifts in global and national climate condition with more intense droughts, increased flooding and weather extremes, and much higher temperatures. The Intergovernmental Panel on Climate Change (IPCC), a body of the United Nations, and other scientific institutions project a future with damaging weather for the world (IPCC, 2001). Three-hundred scientists conducted a major national assessment of the projected consequences of climate change for the United States (US). This assessment involved a two-step process: developing *estimates* of how climate may change in the future, and developing *estimates* of how the estimated changed climate conditions would affect the environment and society, including how society might respond (NAST, 2001). This process was based on the two most critical questions surrounding the climate change issue:

- What will the future climate be like?
- What will the effects be, both good and bad?

The assessment also recommended further studies on the above two critical questions (NAST, 2001).

A recent assessment of climate change and the potential impacts of future climate change in the Great Lakes region, sponsored by the Union of Concerned Scientists and the Ecological Society of America, includes predictions and projections of extreme future climate conditions (Kling et al., 2003). In looking to the future, the study foresees mainly disastrous outcomes for all Midwestern activities. These predictions and projections are different than the modeling scenarios issued by the National Assessment Synthesis Team.

In 1991, the Illinois General Assembly established a special task force to address the issues raised by the potential for future anthropogenic-generated climate changes. The task force's goals were twofold: 1) to assess the potential for serious impacts on the state's economy and environment; and 2) to establish a basis for developing state policy about emerging nationwide proposals for reducing climate change. The General Assembly also directed that the "Illinois State Water Survey serve as the State's center for scientific research and information relating to global climate change."

The nine-year lifetime of the task force led to assessments of the science and the potential state impacts (Changnon and Wendland, 1994), reviews of state policies relating to climate change (Changnon, 1995a; 1996), investigations of the state's climate during the 20$^{th}$ century (Changnon, 1995b; Changnon et al., 1997), and to recommendations for the state's policy position (Task Force on Global Climate Change, 1999). These recommendations were transmitted to the Illinois General Assembly and Illinois members of the US Congress. Two of the five recommendations serve as the basis for this report: 1) Illinois needs to monitor developments in climate change science and provide information to its citizens and policymakers; and 2) the science of global climate change remains uncertain, and research is needed on future climate changes and their impacts. Authorization for the task force expired in 2000.

In 2002, an Illinois Interagency Workgroup on Climate Change (IWOCC) was established as a subcommittee of the Energy Cabinet. The IWOCC (2002) prepared an inventory of climate action opportunities for Illinois consistent with a voluntary approach to reducing the emissions of greenhouse gases and sequestering carbon.

This report presents recently published data and findings that will be informative to decisionmakers and the public.

Chapter 2 focuses on the scientific unpredictability of future climate conditions. It describes the climate system and then documents major improvements and remaining uncertainties of global climate models relevant to evaluating climate change over the next century. Annual precipitation and temperature in Illinois and the levels of Lakes Huron and Michigan since the mid-19th century also are documented.

Chapter 3 focuses on the issue of the economic impacts of weather and climate. It draws on recent studies that have documented in detail the financial outcomes from the weather and climate conditions of recent decades. There is considerable emphasis on losses and gains associated with extremes and how society has responded to these. These economic impacts were assessed in light of the nation's economy to gain a perspective on the possible seriousness of perhaps greater future impacts on the nation's economy.

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# Chapter 2: Experiments to Paint Pictures of Unpredictable Climates

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## Introduction

There is high regard for the credibility of a magazine such as *National Geographic* and a news organization such as the British Broadcasting Corporation (BBC). On January 30, 2002, Hillary Mayell, writing for the *National Geographic News*, reported that "[t]wo separate teams of scientists are predicting more extreme rainfall and greater flooding in this century.... They also predict the Asian monsoon region will experience a five-fold increase of very wet summers" (http://news.nationalgeographic.com/news/2002/01/0130_020130_greatfloods.html; January 31, 2003). Alex Kirby, Environment Correspondent for *BBC News*, reported the long-range weather forecast given to delegates at a United Nations climate conference in Bonn, Germany: "Here is the European weather forecast for the next century and it has several surprises. Average temperatures across the continent are expected to rise between 0.1 and 0.4 degrees Centigrade each decade. Very hot summers will become at least twice as frequent as they are now and perhaps 10 times more frequent. Except in the far north of Europe, they will also be drier than they are now. By 2080, very cold winters will almost have disappeared. Across Europe, winters will become wetter by one to two percent per decade" (http://news.bbc.co.uk/1/hi/sci/tech/505115.stm; January 31, 2003). Newspaper reports also are full of stories of what climate models predict will happen; for example, *Las Vegas Sun*, April 17, 2002; *Ottawa Citizen*, November 14, 2002; *AP Online* (AP Worldstream), November 21, 2002; *San Francisco Chronicle*, January 28, 2003; *San Francisco Chronicle*, February 17, 2003; and *The News-Gazette*, Champaign, IL, April 9, 2003.

When media giants predict what will happen over the next century, the public automatically assumes that, because of the conventional understanding of the word prediction, there must be a sound scientific basis and a significant level of skill and confidence behind such predictions. But it is not only news media who lead the public to believe that long-range (up to 100 years) climate predictions are possible and scientifically sound. Government agencies and scientists also talk about climate prediction. Accurate prediction of climate change on decadal and longer time scales is a major scientific objective of the United States (US) Department of Energy's Environmental Sciences Division (http://wwwscience.doe.gov/production/grants/Fr01_09.html; January 29, 2003) and the National Oceanic and Atmospheric Administration (http://www.osp.noaa.gov/; April 7, 2003). In the United Kingdom (UK), the Hadley Centre for Climate Prediction and Research provides predictions of changes in precipitation and temperature expected in 2080 (http://www.met-office.gov.uk/corporate/pressoffice/prclimatechange.html; January 29, 2003). Main objectives of the UK Terrestrial Initiative in Global Environmental Research are to improve the prediction of climate and the overall effects of climate change on the natural environment.

The main means of predicting future climate are stated to be general circulation models or GCMs (http://www.nwl.ac.uk/tiger/; January 30, 2003). In a Canadian report, Hengeveld et al.

(2002) include a chapter on "Predicting Climate" that includes discussion of climate predictions, projections, forecasts, expectations, possibilities, estimates, and experiments. The American Geophysical Union talks about predicting climate while recognizing major uncertainties (http://www.agu.org/sci_soc/policy/climate_change_position.html; March 12, 2003). The American Association of State Climatologists states that climate prediction is difficult and complex (http://lwf.ncdc.noaa.gov/oa/aasc/AASC-Policy-Statement-on-Climate.html; February 27, 2003), but presumably achievable.

The national assessment of climate change impacts in the US reports as a main conclusion that the scenarios examined indicate that "... temperature in the US will rise by about 3-5°C on average in the next 100 years, which is more than the projected *global* increase" (USGCRP, 2000, p. 6). This reads like a deterministic prediction, despite the recognition in the assessment that scenarios are no more than "... plausible alternative futures ... of what might happen under particular assumptions, that "... we cannot predict many aspects of our nation's future climate," (p. 4), and that "[r]eal uncertainties remain in the ability of models to simulate many aspects of the future climate" (p. 15).

The National Research Council (NRC, 2001, p. 15) describes a climate system model as "... an important tool for interpreting observations and assessing hypothetical futures." The NRC also recognizes that "... we cannot predict either the course of human populations, technology, or societal transitions with any clarity" (pp. 22-23). Nevertheless, a particular emissions scenario is said to lead to a "... predicted temperature increase ..." (p. 18), the IPCC estimates are referred to as "predictions", and current models are stated to yield "predictions" of global climate change, while recognizing that current "estimates" of future warming should be regarded as "tentative" (p. 1). In a Commentary in *Nature* magazine, Klaus Hasselmann, Max Planck Institute of Meteorology in Germany, talks about improving predictions while recognizing that "...model predictions of future greenhouse warming are still uncertain ....", due mainly to the coarse resolution of computer models (Hasselmann, 1997).

In the UK, the Climate Impacts Programme states that predictions of future climate are not yet possible (http://www.cru.uea.ac.uk/link/ukcip/Sum_Rep.pdf; January 29, 2003). In the US, at the National Center for Atmospheric Research in Boulder, Colorado, Kevin Trenberth, in a paper on the IPCC assessment of global warming, acknowledges in a section entitled "Prediction of climate change" that "... the actions of humans are not predictable in any deterministic sense, ..." and "[a]ccordingly, they are not truly predictions..." (http://www.cgd.ucar.edu/cas/GLOB_CHANGE/ipcc2001.html; pp. 8-9, February 24, 2003). The US Environmental Protection Agency (USEPA) describes climate models as "unreliable" (http://yosemite.epa.gov/oar/globalwarming.nsf/content/ClimateFutureClimateUSClimate.html; May 28, 2003). Despite the prestigious IPCC of the United Nations reporting that "... the long-term prediction of future climate states is not possible" (Moore III, 2001, p. 771), Goody et al. (2002, p. 874) report that "... predictions of global warming 50-100 yr from now are being made, most importantly by the United Nations Intergovernmental Panel on Climate Change (IPCC) ...."

Clearly, the various claims and counterclaims about the scientific ability to predict future climate and the use of various terms to describe climate change create confusion and contradictions. Key questions become: With what level of confidence can scientists foretell climate conditions 100 years from now? Does use of the word "predict" in the context of climate change instill to the nonspecialist an undue sense of confidence in the ability of scientists to foretell climate conditions 100 years from now?

To begin discussing the predictability or unpredictability of climate change, a question is posed: What do the Club of Rome's report "Limits to Growth" (Meadows et al., 1972), James Lovelocks's "Gaia Theory" (Lovelock, 1988), fertility rates, and labor productivity rates have to do with foretelling climate change? Everything. The "Limits to Growth" and "The Gaia Theory" use the concept of global system dynamics and assumptions about how the global system is structured and operates to paint pictures about how the Earth's planetary system might react to human-induced perturbations. Foretelling climate change 100 years from now also requires a global systems approach that integrates the physical, biological, and chemical worlds with demographic, societal, technological, economic, and policy changes. Fertility and labor productivity rates are two fundamental factors that drive the emissions of greenhouse gases and aerosols, which in turn can change the chemistry of the atmosphere and climate. Therefore, to answer whether scientists can or cannot predict climate, one has to ask whether social scientists, demographers, economists, and engineers can predict social change, labor productivity, fertility rates, and technologies 100 years from now.

The focus of the "global warming" debate is on increasing global mean temperature, accelerated sea-level rise, and changing regional climates over decades and centuries due to human activities. Before looking to the future, one must look to the past and establish how well climate models simulate observed climate conditions, and how well limited climate observations represent longer-term climate conditions. Here, some examples will suffice to introduce these concepts, with more detailed discussion in subsequent sections.

The IPCC (2001) reports that the global average surface temperature has increased by 0.6 $\pm 0.2^{o}C$ since the late $19^{th}$ century in association with about a 50 percent increase in the atmospheric concentration of greenhouse gases (expressed as carbon dioxide equivalents), natural forcing, and a small amount of urban warming. Stott et al. (2000) report satisfactory simulations of the observed increase in global mean surface temperature since 1860. The IPCC reports that "... confidence in the ability of these models to provide useful projections of future climate has improved due to their demonstrated performance on a range of space and time scales" (IPCC, 2001, p. 9). The IPCC also concludes that "... most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (2001, p. 10). Natural factors and urban warming also contribute to century-scale global warming (IPCC, 2001). The reliability of these reconstructions of climate conditions over the past 140 years depend on the fidelity and completeness of *estimates* of changes in anthropogenic and natural radiative forcing.

An important subject of scientific debate in recent years has been reported differences between temperature changes at the surface and in the middle troposphere. Since the start of the satellite record in the late 1970s, global average surface temperature has increased by about $+0.15^{o}C$ per decade (IPCC, 2001, p. 4). However, Christy et al. (2003) demonstrate that satellite measurements show global atmospheric warming of only about $0.06^{o}C$ per decade. Santer et al. (2003) report that satellite estimates of tropospheric temperature changes depend critically on which satellite data set is used. Trends from various weather-balloon records range from $-0.02^{o}C$ per decade to $0.05^{o}C$ per decade (The Independent Institute, 2003). The USCCSP (2002, pp. 30-31) reports that "[t]he failure of the troposphere to warm at the same rate as the surface during the last few decades has called into question both our understanding of the causes of any change, in particular the impacts of enhanced greenhouse gas concentrations, and the data used to calculate temperature trends".

Some investigators conclude that recent Northern Hemisphere warming may be more directly related to the thermal structure of natural atmospheric circulation regimes than to any anthropogenic forcing pattern itself (Corti et al., 1999).

Another important subject of scientific debate is whether recent decades are the warmest in the last millenium. Whereas the IPCC reports that "... the rate and duration of warming of the 20$^{th}$ century has been much greater than in any of the previous centuries" (IPCC, 2001, p. 3), another report concludes that "[a]cross the world, many records reveal that the 20$^{th}$ century is probably not the warmest nor a uniquely extreme climatic period of the last millenium" (Soon and Baliunas, 2003, p. 89). These authors also demonstrate the difficulties and challenges of combining proxy indicators into a hemispheric or global quantitative composite. Mann et al. (2003) challenge Soon and Baliunas' conclusion, and McIntyre and McKitrick (2003) challenge Mann et al. Thus, there is diversity of opinion on the extent to which hemispheric and global climates have changed as a result of human activities.

Acceleration in the rate of global-sea -level rise in the latter half of the 19$^{th}$ century is also one of the commonly anticipated impacts of global warming. The *IPCC Summary for Policymakers* reports an observed rise in sea level, and also concludes that "[w]ithin present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20$^{th}$ century" (IPCC, 2001, p. 10). Lack of significant acceleration in the rate of sea-level rise may be important because there is evidence that suggests that sea-level rise began before major industrialization (Church and Gregory, 2001).

Based on theory and on model simulations of possible future climates, there is reported to be scientific consensus that global mean temperature and sea level will continue to rise as a result of human activities, but there is considerable uncertainty as to the magnitude and timing of the projected increases. The USGCRP (2002, p. 1) reports that "... various global climate models project significantly different increases in the global average surface temperature: from approximately 1$^{o}$C during the 21$^{st}$ century to more than 4$^{o}$C during the same period." The US (n.d., p. 5) reports that "[l]arge computer-driven models predict that the equilibrium change in the average temperature of the globe's atmosphere as a consequence of doubling of $CO_2$ or its equivalent is unlikely to lie outside the range of 1.5-4.5$^{o}$C with a best estimate of 2.5$^{o}$C." Forest et al. (2000) conclude that the 95 percent probability range for a doubling of carbon dioxide is 0.7-5.1$^{o}$C. The USGCRP and the IPCC project a temperature increase to the year 2100 in the range ~1.0-5.8$^{o}$C (USCCSP, 2002, p. 7; IPCC, 2001, p. 13). The IPCC does not provide a best estimate, but notes that the range of climate projections resulting from the full set of emissions scenarios would be larger (Cubasch and Meehl, 2001, p. 555). Using their own emissions scenarios and their Integrated Global System Model (IGSM), Webster et al. (2001) project a global surface mean temperature increase of 0.9-4.0$^{o}$C in 2100 and find that the IPCC scenarios "... are biased in the direction of higher global mean temperature change by the end of the next century" (p. 22). Simulating the IPCC emissions scenarios through the IGSM, they find a 1.3-3.6$^{o}$C temperature change range in 2100. Michaels et al. (2002) question many of the assumptions behind the IPCC projections and conclude on the basis of new calculations that 21$^{st}$ century warming will be modest and near the low end of the IPCC projections.

The credibility of all these projections rests on the validity and comprehensiveness of the scientific content of the models and of the emissions and land-cover scenarios used to drive climate change. And, superimposed on all the prognostications of human-induced climate change must be possible changes due to natural and urban factors. The large range of differences in these prognostications by scientists and scientific institutions leads to one conclusion: a great deal of uncertainty surrounds the issue. The American Meteorological Society (2003, p. 511) does not use the term model predictions and finds that "... uncertainty remains regarding the magnitude, timing, and regional distribution of anticipated changes."

Large uncertainties surrounding the magnitude and timing of possible global and regional climate changes are central issues in policy debates over what should be done about climate change. Some policymakers favor taking action now to curb the emissions of greenhouse gases. Others emphasize the need to reduce scientific uncertainties as a basis for making sound policy decisions. In both cases, policy and management strategies for dealing with climate change could be very different if it could be determined with confidence that climate is more likely to warm 1°C or 6°C over the 21st century.

So far, discussion has focused on global climate change. Indeed, scientists, politicians, and the public are rightly concerned about threats to the global environment, and decisions on climate change made by the international community largely reflect concern over threats to the global environment. Nevertheless, everybody lives in a particular country in a particular region of the world, and perception of how climate within each country has changed in the past and may change in the future also influences policy debate. This is why this report addresses global and regional climate changes with a focus on regional climate change in Central North America (CNA), especially Illinois.

This introduction illustrates the uncertain and controversial world of foretelling climate change over the course of a century. An important goal of this chapter is to identify improvements made and remaining limitations in scientists' abilities to foretell global and regional climate changes. A case also is made for more careful and consistent communication by scientists and the media when describing these abilities.

Five major factors constrain the ability of scientists — climatologists, physicists, ecologists, oceanographers, biogeochemists, and computer modelers — to foretell human-induced climate change with accuracy and precision. *First*, the climate system is a coupled, nonlinear chaotic system. *Second*, scientists do not yet fully understand how the global climate systems works. *Third*, some important climate processes either are not included in climate models or are simplified, and some are not simulated faithfully. *Fourth*, models do not simulate major components of the global climate system (regional climates) correctly. And *fifth*, and perhaps most important, it is impossible for sociologists, demographers, engineers, and economists to predict with reasonable confidence pollution levels and land-cover changes five generations from now. This is of central importance, because pollution levels and land-use changes are reported to be the basic driving forces of human-induced climate change.

This chapter follows a path of increasing complexity. A description of the climate system identifies the major pieces of the global-climate jigsaw puzzle that must be pulled together for scientists to foretell future climates and how human activities may cause climates to change. A summary and recommendations follow a discussion of climate model improvements and limitations, and how well climate models simulate current global and regional climates and foretell future climates.

## The Climate System

Climate conditions are the result of the interplay of many components and processes of the climate system: the atmosphere, oceans, cryosphere, biosphere, geosphere, and land surface, together with the transfer of water, energy, chemicals, and mass among the components. Radiation from the sun drives the Earth's climate, although volcanic eruptions and internal instabilities in the oceans also influence climate variability and climate change.

All components of the climate system are interconnected, and inaccuracies in simulating key variables can have ripple effects throughout the system. The climate system also is a nonlinear system in which feedbacks are very important. A feedback is "a natural process internal to the climate system that can amplify (positive feedback) or damp (negative feedback) the direct response to greenhouse gases" (http://www/ametsoc.org/AMS/POLICY/draftstatements/climatechange_draft102102.html; January 20, 2003). Schneider and Dickinson (1974) discuss some possible feedback mechanisms that must be included in a "realistic" climate model. An example of a positive feedback is that as temperature increases from the buildup of greenhouse gases, evapotranspiration increases, the water-vapor content of the atmosphere increases, and temperature increases further because water vapor is the most important of the greenhouse gases. The IPCC recognizes that feedbacks largely control climate sensitivity and that, according to current models, positive water-vapor feedback accounts for most of the simulated and projected warming (Stocker, 2001). An example of a negative feedback is that as temperature and water vapor increase, the number, size, and lifetime of clouds can increase, reflect more incoming solar radiation, and cool the climate. However, "[a]t present, it is generally believed that there is insufficient observational evidence to determine whether clouds have a positive or negative net feedback on the climate" (Lawford et al., 2002, p. 16).

Human activities can alter the climate system in many ways. For example, the burning of fossil fuels, deforestation, agriculture, construction of landfills, and a host of other activities release greenhouse gases and aerosols (liquid or solid particles) to the atmosphere. The increased concentration of these gases and aerosols in the atmosphere can change the energy balance by increasing or decreasing radiative forcing (IPCC, 2001, Figure 3), which can lead to climate warming or cooling. Gases such as carbon dioxide, methane, nitrous oxide, halocarbons, and low-level ozone generally act to warm the climate. Stratospheric ozone, biomass burning, and aerosols from fossil-fuel combustion can cool the climate. The direct radiative effects of aerosols relate to their scattering and absorption of solar and infrared radiation in the atmosphere. The indirect effects of aerosols involve cloud formation processes, cloud properties, and cloud lifetimes. It is the indirect effects of aerosols that are least understood and are associated with large uncertainties. Large-scale changes in land cover also cause continental-scale changes in climate (Pitman, 2003).

Fundamental to understanding and modeling the climate system is accurate quantification of the Earth's annual and global mean energy balance and temperature. In a complex web of interactions, energy from the sun [an average of 342 Watts per square meter ($Wm^{-2}$) at the top of the atmosphere] is reflected by clouds, aerosols, the atmosphere, and the Earth's surface; absorbed by the atmosphere and the Earth's surface; emitted from the Earth's surface; and ultimately lost to space. The IPCC reports that "[t]his exchange of energy between surface and atmosphere maintains under present conditions a global mean temperature near the surface of $14^{o}C$, ..." (Baede, 2001, p. 89). "The natural greenhouse effect is part of the energy balance of the Earth ..." (p. 90).

The concept of radiative forcing is central to climate assessments (Ramaswamy, 2001). This concept was first developed to investigate the global mean surface temperature response to radiative perturbations. For example, an increase in the concentration of greenhouse gases and aerosols in the atmosphere can modify the radiation and energy balance of the climate system.

Using measurements or estimates of changes in atmospheric chemistry and physics, scientists calculate resulting changes in radiative forcing and the energy budget of the climate system. Climate change is a system response to these and other radiative forcings expressed in units of $Wm^{-2}$. Changes in radiative forcing and the energy budget of the climate system since pre-industrial times have not been measured. Changes in radiative forcings are calculated or estimated, and subjective judgments are made about the reliability of the estimates, which lack a rigorous statistical basis (Ramaswamy, 2001). Uncertainties in the estimates of radiative forcing are due to many factors, including uncertainties in emissions estimates, pollutant concentrations and lifetimes in the atmosphere, land-cover and albedo changes, and the effects of pollutants and land-cover changes on the radiation and energy balance of the climate system. The IPCC also recognizes that "... [t]he climate sensitivity for some of the forcings that have potentially occurred in the industrial era have yet to be comprehensively investigated" (Ramaswamy, 2001, p. 354).

The impact of gases, aerosols, and land-cover changes on climate are varied and complex. Some greenhouse gases such as carbon dioxide and nitrous oxide reside in the atmosphere many years, are thoroughly mixed in the atmosphere, and their concentrations are very much the same anywhere around the world. A molecule of nitrous oxide absorbs more radiation than a molecule of carbon dioxide, there is a lower concentration of nitrous oxide than carbon dioxide in the atmosphere, but nitrous oxide resides in the atmosphere much longer than carbon dioxide. Overall, the IPCC reports that carbon dioxide has had an order of magnitude greater impact on radiative forcing and climate since 1750 than nitrous oxide (Ramaswamy, 2001). Other gases such as sulfur dioxide and the resulting sulfate aerosol typically reside in the atmosphere for only days and, therefore, are not thoroughly mixed in the atmosphere. Concentrations of aerosols vary greatly from region to region; consequently, the greatest impacts of aerosols on the climate system are likely to be more regional than global in nature.

The IPCC reports that "[t]he radiative forcing due to increases of the well-mixed greenhouse gases from 1750 to 2000 is estimated to be 2.43 $Wm^{-2}$..." (IPCC, 2001, p. 7). It also reports that the radiative forcing is estimated to be 0.35 $Wm^{-2}$ for low-level ozone and -0.4 $Wm^{-2}$ for the direct radiative effect of sulfate (IPCC, 2001, pp. 7 and 9). However, because the emissions of sulfur dioxide and the concentrations of the sulfate aerosol and ozone vary regionally, these estimates of the radiative forcing for sulfate and ozone are the global aggregates of many different regional values. Thus, as Ramaswamy (2001, p. 355) notes, "[t]he global, annual average forcing estimate for these species masks the inhomogeneity in the problem such that the anticipated global mean response (via Equation 6.1) may not be adequate for gauging the spatial pattern of the actual climate change. For these classes of radiative perturbations, it is incorrect to assume that the characteristics of the responses would be necessarily co-located with the forcing, or the magnitudes that would follow from the forcing patterns exactly (e.g., Cox et al., 1995; Ramaswamy and Chen, 1997b)." Plausible estimates of geographical distributions of annual average radiative forcing due to aerosols and land-cover changes are shown to exceed -4.5 $Wm^{-2}$ in some regions of the world (Ramaswamy, 2001, Figure 6.7). Absolute values are not provided. Monthly values can be much larger than the annual average values: for example, Kiehl and Rodhe (1995) computed the direct radiative forcing due to sulfate aerosol and reported July values of -11 $Wm^{-2}$ in central Europe and -7.2 $Wm^{-2}$ in Eastern China. The predominantly regional nature of inhomogeneous forcings such as aerosols, low-level ozone, and land-cover changes raises the question of the meaning of a global mean climate sensitivity for these forcings, and identifies the importance of quantifying these forcings to evaluate regional climate changes (Ramaswamy, 2001).

Figure 3 in the IPCC *Summary for Policymakers* identifies most of the external agents that force climate to change (IPCC, 2001, p. 8). One of the most profound conclusions of the IPCC is that "[t]he simulations of this assessment report (for example, Figure 5) indicate that the estimated net effect of these perturbations is to have warmed the global climate since 1750. [Based upon Chapter 6, Figure 6.6]" (IPCC, 2001, p. 8). The largest contribution to increased radiative forcing and, hence, global warming is shown to be the increase in the concentrations of greenhouse gases, especially carbon dioxide.

The large magnitude of the uncertainties for estimates of radiative forcing can be illustrated by examining the IPCC data. The caption to Figure 3 in the *Summary for Policymakers* states that the second indirect effect of aerosols on cloud lifetime is not shown, and the possible magnitude of this negative forcing is not stated (IPCC, 2001, p. 8). However, the caption to the "same" figure in the *Technical Summary* (p. 37) and the "same" figure in Chapter 6 (Ramaswamy, 2001, p. 392), state that there is "... very little confidence in the simulated quantitative estimates" of this second indirect effect of aerosols. It is also stated that "[a]ll the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. As in the SAR, it is emphasized that the positive and negative global mean forcings cannot be added up and viewed *a priori* as providing offsets in terms of the complete global climate impact." However, in the caption to Figure 15, the IPCC states that "[t]he net anthropogenic forcing at 1990 was 1.0 $Wm^{-2}$ including a net cooling of 1.0 $Wm^{-2}$ due to sulphate aerosols. The net natural forcing for 1990 relative to 1860 was 0.5 $Wm^{-2}$ ..." (IPCC, 2001, p. 58). Thus, it appears that the IPCC has produced its own first-order perspective on a global, annual mean scale to obtain the climate response to identified natural and anthropogenic forcings.

The IPCC does report that the indirect radiative effect of aerosols is highly uncertain with a range of radiative forcing of up to -2 $Wm^{-2}$ for the first indirect effect. The IPCC also states that "... GCM calculations suggest that the radiative flux perturbation associated with the second aerosol indirect effect is of the same sign and could be of similar magnitude compared to the first effect" (Ramaswamy, 2001, p. 351; IPCC, 2001, p. 45). Hence, using data at the high end of the uncertainty range, it can be concluded that negative radiative forcing from identified natural and anthropogenic agents since 1750 could exceed 6 $Wm^{-2}$, whereas the upper bound of positive radiative forcings shown in Figure 3 is only about 5 $Wm^{-2}$. This means that negative radiative forcing associated with natural and human agents since 1750 could exceed positive forcing, and the first-order climate response could be cooling rather than warming.

Whereas the IPCC *Summary for Policymakers* states categorically (IPCC, 2001, Figure 3, p. 8) that "... the estimated net effect of these perturbations is to have warmed the global climate since 1750. [Based upon Chapter 6, figure 6.6]", such a conclusion cannot be drawn with a high degree of confidence from Figure 6.6. Indeed, data presented in the IPCC report indicate that scientists cannot determine with confidence from a first-order perspective whether there has been a net positive or negative forcing, and hence whether global mean surface temperature should have warmed or cooled since 1750. Schwartz (2003) drew a similar conclusion. A conclusion that there must have been net positive radiative forcing because global mean surface temperature is reported to have increased is not necessarily valid. What scientists need to present along a causal chain are estimates of all radiative forcings, together with uncertainty bounds, and the calculated range of possible climate responses to these forcings. If the climate record is inconsistent with the best estimates of radiative forcing, then it could mean that the climate record is biased, that not all radiative forcings are known and/or documented, estimates of radiative forcing are in error, or that important feedback processes are not adequately accounted for.

Quantifying the many climate forcings over the past two centuries is fraught with a high degree of uncertainty, as are estimates of climate sensitivity attributed to such forcing. Gregory et al. (2002) developed an observationally based estimate of climate sensitivity over the period 1861-1900 to 1957-1994, while recognizing that the radiative estimates they employ are imprecise and incomplete.

A challenge for climatologists is to measure the Earth's radiation balance and temperature sufficiently accurately to identify and filter out from the ~342 $Wm^{-2}$ of natural climate forcing a small human signal of perhaps several $Wm^{-2}$ and absolute temperature changes of fractions of a degree C. Limited measurements of the many components of the global climate system, incomplete knowledge of forcings, and system complexities make this a very difficult challenge. Limited observational data also hinder the development and validation of comprehensive and accurate climate models. Pielke (2003) recommends that the IPCC should use a heat balance perspective to diagnose the Earth's radiative imbalance, including presentations of the magnitudes of planetary energy imbalances simulated by all climate models.

## Climate Models and Climate Prognostications

Climate models are essential tools for synthesizing observations, theory, and experimental results to investigate how the Earth's system operates and how human activities affect it (USCCSP, 2002). There is a hierarchy of climate models (IPCC, 2001, pp. 46-55; Baede, 2001, pp. 94-96; McAveney, 2001), with coupled atmospheric-oceanic GCMs being the most complete. These global models are based on the fundamental physical, biological, and chemical principles governing the global climate system and have been a central part of the US climate research program since the 1970s. The models are used to explain the climate response to greenhouse gases, aerosols, and land-cover changes in terms of physical, chemical, and biological processes.

Even though GCMs take a long time to run on the biggest, fastest computers in the world, they are still simplifications of the highly complex climate system. Mathematical equations are solved and interactions among components of the climate system are calculated at spacings of 200-400 kilometers (km) in the horizontal and 1 km or more in the vertical, a resolution too coarse to simulate directly many small-scale processes. About 20 GCMs operate throughout the world, but they were not developed independently of one another, and the IPCC recognizes that "such an ensemble does not constitute an independent unbiased sampling of possible model formulations" (Stocker, 2001, p. 423).

The level of skill in foretelling future climate is reflected in the accuracy of the prognostications and, hence, is an indication to the public and decisionmakers of the confidence they should have in the prognostications. The public is familiar with weather predictions and forecasts, and increasingly hears predictions and forecasts of climate change. But it is doubtful whether the general public understands that climate predictions and forecasts are constructed very differently than weather predictions and forecasts, or that the skill level for foretelling climate change is in some ways akin to crystal-ball gazing.

In communicating with decisionmakers, the public, and the media about important, highly complex, and controversial topics such as climate change, the semantics of scientists are important and can be very misleading. To comprehend scientists' ability to foretell the future, one must understand their language and recognize that scientists often are, perhaps inadvertently, inconsistent among themselves in describing what they can and cannot do.

Climate change often is defined as a significant difference in climate statistics between two 30-year periods. It can refer to a change in average conditions (for example, temperature or rainfall), or a change in the frequency of specified events, such as heat waves, floods, or droughts. The change may be abrupt, from one 30-year period to the next, or may be evident as a more gradual trend over decades or centuries. The outputs from climate models often are used to construct climate statistics and generally are not concerned with specific sequences of weather events. However, one view is that the best climate models must produce a realistic weather event (Xin-Zhong Liang, June 17, 2003, personal communication). The Illinois State Water Survey (ISWS) is committed to developing improved climate models to reduce the uncertainties of future climate change. Scientists at the ISWS are enhancing the Weather and Research Forecast model as a basis for developing a regional Climate-Weather Research and Forecast model.

To the extent that climate processes and forcings uniquely determine future climate conditions, future climate conditions and climate change can be said to be predicted deterministically. However, as will be shown later, the climate models either exclude or simplify some important climate processes. Climate forcings also cannot be determined uniquely. Further, the IPCC reports that "[t]he climate system is a coupled non-linear chaotic system ..." (Moore III, 2001, p. 771). For these reasons, climate conditions on the century scale cannot be predicted deterministically. Even with perfect science and perfect climate models, future climates always will remain unpredictable due to inherent uncertainties associated with socioeconomic drivers.

In 1998, James E. Hansen, a scientist with the National Aeronautics and Space Administration, and colleagues reported that climate prediction is impossible because "[t]he forcings that drive long-term climate change are not known with an accuracy sufficient to define future climate change" (Hansen et al., 1998, p. 12753). The IPCC also acknowledges that "... the long-term prediction of future climate states is not possible. Rather the focus must be upon the prediction of the probability distribution of the system's possible future states..." (Moore III, 2001, p. 771), but this clear and important statement is not included in the *Summary for Policymakers*. The USCCSP also acknowledges that scientists cannot predict future climate (USCCSP, 2002, p. 7).

As leading scientists and scientific bodies recognize that climate cannot be predicted, it is illogical to call the output of climate models "climate predictions". What then are scientists telling the public and decisionmakers about climate change? What is the nature of the ability of climatologists to foretell future climates?

The USCCSP acknowledges that scientists can project the climate and environmental consequences of different combinations of basic human driving forces (USCCSP, 2002, p. 7). When scientists make a set of *assumptions* about the future world, they are said to create *scenarios.* These scenarios are "... experiments that make it possible to begin to explore the potential implications of different technological and institutional conditions for future emissions, climate, and living standards" (USCCSP, 2002, p. 7). The USCCSP uses the term "scenario" to refer to "... any description of the world as it *might evolve* or be made to evolve in response to decisions" (USCCSP, 2002, p. 45). Scenarios of future climates, then, are experiments that "paint a picture" of what might happen under particular assumptions (USCCSP, 2002, p. 44). The USCCSP reports that "[t]he Intergovernmental Panel on Climate Change (IPCC) has made extensive use of scenarios to drive climate models ..." and that "[o]ther qualitative and quantitative scenarios have been used extensively in controversial assessments of the potential consequences of climate change for particular sectors and regions in the United States" (USCCSP, 2002, p. 46). Then is the "construction of climate scenarios" the correct term to use to describe how scientists foretell climate change?

Unfortunately, there is no simple answer. The IPCC uses the term "scenarios" in a dual context. First, "emissions scenarios" are constructed as inputs to drive climate models. These emissions scenarios are used to generate estimates of future pollution levels that are used in climate models to "project" future climate conditions. "Each [emissions] scenario represents a specific quantification of one of the four storylines .... Four different narrative storylines were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification .... All the scenarios based on the same storyline constitute a scenario 'family'.." (IPCC, 2001, p. 62).

Climate projections, according to the IPCC, are "... descriptions of the modeled response of the climate system to scenarios of greenhouse gas and aerosol concentrations ..." (Mearns and Hulme, 2001, p. 741). Using a combination of products from science and crystal-ball gazing about pollution levels and land-cover changes from future human activities, scientists calculate hypothetical future climate conditions.

The IPCC uses the term "climate scenarios", but these are different than climate projections. According to the IPCC, a climate scenario is "[a] plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as data on the observed current climate. A *climate change scenario* is the difference between a climate scenario and the current climate" (IPCC, 2001, p. 789).

Thus, the IPCC cascade of uncertainties progresses from unknown future emissions of greenhouse gases and aerosols to emissions scenarios (or "narrative storylines" ), climate projections, climate scenarios, and on to climate change scenarios. The true purpose of the IPCC scenarios is stated to be "... to illuminate uncertainty..." (Mearns and Hulme, p. 744), while recognizing that climate scenarios do not fully represent the uncertainties inherent in climate prediction. The IPCC scenarios are generally treated as having a uniform probability and often annotated with a list of caveats. This may be confusing and difficult to understand, so further explanation of climate projections and scenarios is warranted.

Figure 2-1 simplifies the major steps used by the IPCC to generate climate scenarios using climate models. These components can be integrated in one comprehensive model of the global climate system (e.g., http://web.mit.edu/globalchange/www/if.html; January 30, 2003), or they constitute separate models, or submodels, that interact.

The IPCC recognizes that "[i]n order to make quantitative projections of future climate change, it is necessary to use climate models that simulate **all the important processes** [emphasis added] governing the future evolution of the climate" (IPCC, 2001, p. 48). Furthermore, "[t]o estimate the response properly, we must represent **faithfully** [emphasis added] the physical

1. Socioeconomic-technology-energy-land cover assumptions

↓

2. Scenarios of emissions of gases and particles and land-use practices

↓

3. Scenarios of atmospheric concentrations of gases and particles

↓

4. Scenarios of radiative forcings due to human activities and natural factors

↓

5. Run global climate models to generate climate scenarios or climate pictures

Figure 2-1. Simplified representation of major steps to generate climate scenarios or paint climate pictures, based on assumptions about future human behavior and technologies; feedback and policy responses are not shown.

processes in models. Not only must the **whole system model** [emphasis added] perform reasonably well in comparison with observations (both spatial and temporal), but so too must the **component models** [emphasis added] and the **processes** [emphasis added] that are involved in the models" (Stocker, 2001, p. 421). Thus, the IPCC sets forth credible criteria that can be used to evaluate model performance.

The IPCC recognizes that "[t]he degree to which the model can simulate the response of the climate system hinges to a very large degree on the level of understanding of the physical, geophysical, chemical, and biological processes that govern the climate system" (IPCC, 2001, p. 46). The accuracy of GCM outputs in simulating current and future climates depends on the extent to which all these key processes are included realistically in the models and the climate forcings are specified accurately.

As a prelude to later documenting scientific assessments of model performance, the remainder of this section documents major improvements and remaining sources of error, bias, and uncertainty in climate models, and provides some insights to the wide range of assumptions that are used in specifying climate forcing scenarios.

## Climate Model Improvements

A main finding of the IPCC is that confidence in the ability of models to project future climate has increased, due largely to improvement in understanding of climate processes and their incorporation in climate models, including water vapor, sea-ice dynamics, and ocean heat transport (IPCC, 2001, p. 9). "Coupled models, as a class, are considered to be suitable tools to provide useful projections of future climates" (IPCC, 2001, p. 54).

The following quotations, taken from that IPCC (2001) report and the draft USCCSP (2002) report and its associated white papers, document many major model improvements.

- “Many basic climate processes of importance are well-known and modeled exceedingly well” (IPCC, 2001, p. 46)

- “Advances in land surface models have led to a much improved capability of simulating coupled atmosphere-land system” (Lawford et al., 2002, p. 21).

- “Our ability to model the carbon cycle has improved dramatically in the past decade. In the next five to ten years, research should advance to allow these models to be used with measurable confidence in projecting the future course of carbon cycling” (Wickland et al., 2002, p. 36)

- “Coupled models can provide credible simulations of both the annual mean climate and the climatological seasonal cycle over broad continental scales for most variables of interest for climate change” (McAvaney, 2001, p. 511).

- “Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20$^{th}$ century” (IPCC, 2001, p. 9).

- “The atmosphere-ocean coupled system shows various modes of variability that range widely from intra-seasonal to inter-decadal time scales (see Chapters 2 and 7)” (McAvaney, 2001, p. 503).

- “The growth in systematic intercomparisons of models provides the core evidence for the growing capabilities of climate models” (IPCC, 2001, p. 55).

- “Radiative transfer calculations are performed with different types of radiative transfer schemes ranging from line-by-line models to band models (IPCC, 1994). The agreement between the surface measurements and the line-by-line model is within 10% for the most important of the greenhouse gases...” (Ramaswamy, 2001, p. 356).

- “Some recent models produce satisfactory simulations of current climate without the need for non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface used in earlier models” (IPCC, 2001, p. 9). “This is due to a better representation of key processes in both atmosphere and ocean components of climate models, and improved spatial resolution. However, while simulated SSTs generally agree well with observations (deviations of less than 2$^{o}$C), there are large areas where consistent errors of SST occur in the models ...” (Stocker, 2001, p. 450).

- “Overall, differences have been seen in the climate change response of flux adjusted and equivalent non-flux adjusted models (Fanning and Weaver, 1997b; Gregory and Mitchell, 1997), but it is not clear whether the differences are due to the flux adjustment itself, or to the systematic errors in the non-flux adjusted model” (McAvaney, 2001, p. 479).

- "The latest results of the zonal mean ocean heat transports ... agree within error estimates (Table 7.1). This suggests that the models are now converging on the correct values for the zonally averaged heat fluxes" (Stocker, 2001, p. 450).

- "Recent ensemble results (Rodwell et al., 1999; Mehta et al., 2000) have been able to reproduce the decadal North Atlantic atmospheric variations from observed SSTs but with much reduced amplitude" (Stocker, 2001, p. 451).

- "The inclusion of changes in solar irradiance and volcanic aerosols has improved the simulated variability found in several AOGCMs" (McAvaney, 2001, p. 503).

- "Analysis of and confidence in extreme events simulated within climate models are still emerging, particularly for storm tracks and storm frequencies" (IPCC, 2001, p. 54).

- "The general ability of models to simulate extra-tropical storms and storm tracks is most encouraging" (McAvaney, 2001, p. 508).

- "The performance of coupled models in simualting ENSO has improved; however, its variability is displaced westward and its strength generally is underestimated" (IPCC, 2001, p. 54).

- "Theoretical understanding of the atmospheric hydrological cycle has also increased. As a result, observational tests of how well models represent the processes governing water vapor content have become more sophisticated and more meaningful. Since the SAR, appraisal of the confidence in simulated water vapor feedback has shifted from a diffuse concern about upper-tropospheric humidity to a more focused concern about the role of micrphysical processes in the convection parameterizations, and particularly those affecting tropical deep convection" (Stocker, 2001, p. 427).

- "Since the SAR, several coupled climate models have incorporated an explicit treatment of openings in sea ice, often in conjunction with ice dynamics. Other developments since the SAR include updated parameterizations of snow ageing and associated albedo changes and the implementation in some models of a multi-layer formulation of heat conduction through the ice. Although sea-ice thermodynamic processes are crudely approximated in many coupled climate models (see Chapter 8, Section 8.5.3.), it is unclear how these approximations contribute to errors in climate model simulations." (Stocker, 2001, p. 445).

- "The vital processes for improved monsoon circulation in models are those associated with the hydrological cycle, especially in the tropics. The difficulties of assembling all of these elements together has led to problems in simulating mean precipitation as well as interannual monsoon variability, although improvements are evident (Webster et al., 1998, and see Chapter 8, Section 8.7.3.)" (Stocker, 2001, p. 452).

- "Through PMIP experiments, it is now well-established that all atmospheric models are able to simulate several robust large-scale features of the Holocene climate but also that they all underestimate these changes" (McAvaney, 2001, p. 496).

- “The results show some agreement with the available observations [of extreme precipitation] but the comparatively low model resolution is an inhibiting factor” (McAvaney, 2001, p. 508).

- “In summary, high horizontal resolution AGCMs (or AOGCMs) are able to simulate some aspects of “tropical cyclone-like vortices” with some degree of success, but it is still too computationally expensive to use such models for long experiments” (McAvaney, 2001, p. 509).

## Remaining Sources of Error, Bias, and Uncertainty in Climate Models

The IPCC identifies three major sources of uncertainty in projected climate change: “... uncertainty in forcing scenarios, uncertainty in modeled response to given forcing scenarios, and uncertainty due to missing or misrepresented physical processes in models” (Cubasch and Meehl, 2001, p. 536). All current climate models are incomplete in that some important components of the climate system and processes are not included, or are simplified. The incompleteness of the climate models is a major source of uncertainty in model simulations. This raises the question: When working on a large and complex jigsaw puzzle, without having access to the picture on the box, how many pieces can be missing for one to describe the full picture accurately? Also, the fact that all current climate models must parameterize, or simplify, the representation of key processes raises the question: How far can one simplify all the processes in an engine and still get the engine to operate as designed? Below, extracted mainly from the IPCC (2001) report and the draft USCCSP (2002) report, is a list of some of the missing and/or simplified processes that are sources of error, bias, and uncertainty in climate model output. Also included are a few examples of difficulties and challenges related to limitations of the observational record and to model initialization.

### *Missing and/or Simplified Processes*

Largely because of incomplete scientific data and understanding, and because of computing limitations, many processes and agents of climate change either are not incorporated in climate models, or they are represented in a simplified manner. The following list illustrates that the state-of-the-science in climate modeling, despite many improvements, still has many shortcomings and limitations. These shortcomings and limitations must be overcome in order to increase the credibility of the models. The list will allow the reader to evaluate the extent to which climate models simulate faithfully all important processes governing current and future climates, an IPCC requirement.

- “While improved parameterizations have built confidence in some areas, recognition of the complexity in other areas has not indicated an overall reduction or shift in the current range of uncertainty of model response to changes in atmospheric composition” (Stocker, 2001, p. 419).

- There are “[l]arge uncertainties in estimates of internal climate variability from models and observations” (IPCC, 2001, p. 59). “Models tend to underestimate natural climate variability derived from proxy data over the last few centuries” (McAvaney, 2001, p. 512).

- Failure to adequately simulate key processes and feedbacks indicates that "... the major problems are generic, affecting all climate models". These processes include ocean mixing, atmospheric convection, hydrologic processes, and representation of clouds and "... contribute significantly to model uncertainties" (USCCSP, 2002, p. 48). "In addition, climate models exhibit serious bias due to their inability to fully represent small-scale cloud and precipitation processes" (Lawford et al., 2002, p. 21). "Furthermore, it is not clear how the production of precipitation from these clouds will be altered as a result of forcing" (Lawford et al., 2002, p. 17).

- "In general, available models do not explicitly incorporate the effects of human activities in an interactive system representation; the human impacts are one-way and static. This limits their utility for representing the future state of the carbon cycle and of future climate" (Wickland et al., 2002, p. 37).

- The Earth's atmosphere is a heat engine driven primarily by solar radiation. Despite frequent reference to a solar "constant", the global climate model experiments acknowledge that total solar irradiance (TSI) is, in fact, a variable that ranges from 1354 to 1370 $Wm^{-2}$ (http://www-pcmdi.llnl.gov/cmip/Table.htm; May 5, 2003 ). In discussing the estimate of solar radiative forcing since 1750, the IPCC reports that "...because of the large uncertainty in the absolute value of TSI and the reconstruction methods our assessment of the 'level of scientific understanding' is 'very low'" (Ramaswamy, 2001, p. 382). "Other mechanisms for the amplification of solar effects on climate ... may exist but do not yet have a rigorous theoretical or observational basis" (Ramaswamy, 2001, p. 352).

- "Unfortunately, there are no global estimates of surface flux that do not rely heavily on models. The best model-independent estimates come from the Global Energy Balance Archive (GEBA), a compilation of observations from more than 1,000 stations (Gilgen et al., 1998). Compared with GEBA observations, surface solar insolation is overestimated in most AGCMs (Betts et al., 1993; Garratt, 1994; Wild et al., 1997, 1998; Garratt et al., 1998). Downwelling long wave radiation, on the other hand, is underestimated (Garratt and Prata, 1996; Wild et al., 1997). The shortwave discrepancy is of more concern: it is more than a factor of two larger than the long-wave discrepancy, and could be due to missing absorption processes in the atmosphere." "If the observations are correct, then improving the models will reduce the energy available for surface evaporation by 10-20% with a corresponding reduction in precipitation (Kiehl et al., 1995) and a general weakening of the hydrological cycle" (McAvaney 2001, p. 484).

- "... conventional comprehensive GCMs have a systematic imbalance of about 2 $Wm^{-2}$ between the incoming and outgoing radiation ..." which mainly is due to "the lack in boundary layer dissipation" (Becker, 2003, p. 519).

- "There are unresolved differences between the observed and modeled temperature variations in the free atmosphere" (Mitchell and Karoly, 2001, p. 729).

- "Coupled models indicate that, in mid-latitudes, the predominant process is the atmosphere driving the ocean as seen by the surface fluxes and as observed, yet when an atmospheric model is run with specified SSTs, the fluxes are reversed in sign, showing the forcing of the atmosphere from the now infinite heat capacity of the ocean (implied by specified SSTs)" (Stocker, 2001, p. 451).

- "ENSO is not simulated well enough in global climate models to have confidence in projected changes with global warming (Chapter 8). It is likely that changes in ENSO will occur, but their nature, how large and rapid they will be, and their implications for regional climate change around the world are quite uncertain and vary from model to model (see this chapter and Chapter 9)" (Stocker, 2001, p. 453).

- "In the extra-tropics, a key question remains the sensitivity of the mid-latitude atmosphere to surface forcing from sea ice and sea surface temperature anomalies. Different modeling studies with similar surface conditions yield contradictory results (e.g., Robertson et al., 2000a,b). The crude treatment of processes involving sea ice, oceanic convection, internal ocean mixing and eddy-induced transports and the coarse resolution of most coupled climate models, adds considerably to the uncertainty" (Stocker, 2001, p. 451).

- "Feedbacks between atmospheric chemistry, climate, and the biosphere were not developed to the stage that they could be included in the projected numbers here. Failure to include such coupling is likely to lead to systematic errors and may substantially alter the projected increases in the major greenhouse gases" (Prather and Ehhalt, 2001, p. 242).
- "...there are central components which affect the system in a non-linear manner and potentially could switch the sign of critical feedbacks" (Moore III, 2001, p. 2).

- "For example, scientists do not know how the amount and distribution of clouds will change, both vertically and horizontally, as the water vapor in the atmosphere changes. More importantly, they do not know how the associated changes in radiative forcing and precipitation will affect climate. The feedback to the Earth's radiative balance and cloud structure from increased upper tropospheric water vapor is potentially quite large and could be positive or negative" (USCCSP, 2002, p. 21).

- "The level of scientific understanding that affects the quantitative estimates of the global annual mean forcing of climate change is very low for aerosols, contrails and aviation induced cirrus, land cover (albedo), and solar irradiance (Ramaswamy, 2001, Table 6.12). Even the sign of cloud feedbacks is unknown" (Stocker, 2001, p. 419).

- "Through landcover changes over the last 300 years, we may have already altered the climate more than would occur associated with the radiative effect of a doubling of carbon dioxide" (Roger Pielke Sr.; http://earthobservatory.nasa.gov/Newsroom/NasaNews/2002/2002100110834.html; April 17, 2003).

- "There are some obvious gaps in these projections where processes influencing the greenhouse gas abundances have been omitted. One involves coupling of tropospheric chemistry with the stratosphere. For one, we did not include the recovery of stratospheric ozone expected over the next century" (Prather and Ehhalt, 2001, p. 275).

- "Global measurements are not available for many aerosol properties, so models must be used to interpolate and extrapolate the available data" (Penner, 2001, p. 291).

- "Estimation of the uncertainty in the complete (i.e., the first and second indirect effects) radiative forcing is not currently feasible due to a lack of analytical relationships to treat the indirect forcing of the second kind" (Penner, 2001, p. 328). "However, only idealized scenarios of only sulphate aerosol have been used" (McAveney, 2001, p. 473). "The largest estimates of negative forcing due to the warm-cloud indirect effect may approach or exceed the positive forcing due to long-lived greenhouse gases" (Penner, 2001, p. 334).

- "... models of both organic and black carbon aerosol species are in early stages of development. They are not well tested because there are few reliable measurements of black carbon or organic aerosols" (Penner, 2001, p. 291).

- "This analysis leads to an overall uncertainty estimate for fossil fuel aerosols of 89% (or a range from -0.1 to -1.0 $Wm^{-2}$) while that for biomass aerosols is 85% (or a range from -0.1 to -0.5 $Wm^{-2}$)" (Penner, 2001, p. 291).

- "Many processes involving atmospheric chemistry, and the coupling of atmospheric chemistry with other elements of global change, have been proposed in the scientific literature. These are generally based on sound physical and chemical principles, but unfortunately, there is no consensus on their quantitative role in atmospheric chemistry on a global scale ..." (Prather and Ehhalt, 2001, p. 277).

- "The representation of land-ice processes in global climate models remains rudimentary" (IPCC, 2001, p. 50).

- "...probably the greatest uncertainty in future projections of climate arises from clouds and their interaction with radiation. Clouds represent a significant source of potential error in climate simulations" (IPCC, 2001, p. 49). "The sign of the net cloud feedback is still a matter of uncertainty, and the various models exhibit a large spread. Further uncertainties arise from precipitation processes and the difficulty in correctly simulating the diurnal cycle and precipitation amounts and frequencies" (IPCC, 2001, p. 50).

- "However, significant problems remain to be solved in the areas of soil moisture processes, runoff prediction, land-cover change and the treatment of snow and sub-grid scale heterogeneity" (IPCC, 2001, p. 51).

- "However, large uncertainties still persist on the quantitative impact of large-scale deforestation on the hydrological cycle, particularly over Amazonia" (IPCC, 2001, p. 51).

- “Limitations in resolution and relatively poor representation of some stratospheric processes adds uncertainty to model results” (IPCC, 2001, p. 50).

- “The possibility for rapid and irreversible changes in the climate system exists, but there is a large degree of uncertainty about the mechanisms involved and hence also about the likelihood or time-scales of such transitions” (IPCC, 2001, p. 53).

- “The atmospheric response time of carbon dioxide is subject to substantial scientific uncertainties, due to limitations in our knowledge of key processes. When carbon dioxide is used as the reference, as it often is, the numerical value of all global warming potential of all greenhouse gases can change substantially” (Ramaswamy, 2001, p. 386).

- “Temperatures during mid-winter in the stratopause and mesopause regions at the South Pole are 20-30 K colder than current model predictions” (Pan et al., 2002).

- The American Meteorological Society acknowledges that feedbacks are poorly understood and that “[t]he full suite of potentially important feedback processes is yet to be adequately understood and quantified” (AMS, 2003, p. 512).

- “Current models do not simulate many aspects of the global climate well, and many of the model shortcomings are related to poor representation of the GWC [global water cycle]. For a given increase in $CO_2$, different climate models produce vastly different cloud, precipitation and soil moisture (both in magnitude and sign) depending on their parameterization of basic water cycle processes” (Lawford et al., 2002, pp. 8-9).

- “The coupled model fresh water flux estimates are more problematic. For example, the inter-tropical convergence zone may become skewed and spuriously migrate from one hemisphere to another, seriously distorting the precipitation fields (Doney et al., 1998; Gordon et al., 2000)” (Stocker, 2001, p. 450).

- Correct specification of the dynamic circulation is defined by the initial condition. “However, systematic model biases and incomplete observations make realistic GCM initialization impossible at this time” (Liang et al., 2002, p. 2560).

- “Our attempts to evaluate coupled models have been limited by the lack of a more comprehensive and systematic approach to the collection and analysis of model output from well-coordinated and well-designed experiments” (McAvaney, 2001, p. 511).

- “... there has been no systematic evaluation of results involving comparisons with observations” (Goody et al., 2002, p. 875).

- “... the models’ ability to quantitatively simulate decadal changes in ocean temperatures and thus thermal expansion has not been adequately tested” (Church and Gregory, 2001, p. 665).

In addition, a long list of research questions posed by the USCCSP identifies, by definition, what is unknown or not understood, or at least not well known and not well understood. Below are some examples of these research questions (USCCSP, 2002; Lawford et al., 2002).

- How predictable are water cycle variables at different temporal and spatial scales?
- How can uncertainty in the prediction of water cycle variables be characterized and communicated to water resource managers?
- What are the magnitudes and distributions of carbon sources and sinks, and what are the processes controlling their dynamics?
- What are the global anthropogenic and natural sources of methane, nitrous oxide, and nitrogen oxides?
- What are the sources of atmospheric aerosols, and what are their magnitudes and variability?
- What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality?
- What are the time scale and other characteristics of the recovery of the stratospheric ozone layer?
- What is the sensitivity of climate change projections to feedbacks in the climate system?
- What are the key feedbacks in the climate system?
- What are the primary natural mechanisms for abrupt climate changes?
- What are the main climatic and hydrological causes of floods and droughts?
- To what extent does the water cycle vary and change with time?
- What are the key mechanisms and processes responsible for maintaining the global water cycle?
- What are the primary drivers of land-cover change?
- How have changes in land cover affected trends in regional and global water cycles?

These and many other research questions identify the need for improved knowledge and understanding of the climate system as a basis for painting clearer pictures about possible future climate changes. The IPCC also reports that "[n]o attempt has been made to quantify the uncertainty in model projections of climate change due to missing or misrepresented physics"

(Cubasch and Meehl, 2001, p. 536). The above lists of major limitations and key research questions clearly reveal the enormity of this issue.

### *Uncertain Climate Forcing Scenarios*

Explaining the complexities of foretelling future climate change begins by identifying the challenges to estimating emissions of greenhouse gases 100 years from now. Greenhouse gases are emitted from natural sources, especially water vapor from oceans, and in increasingly large quantities from a range of human activities. The main greenhouse gases that contribute to an enhanced greenhouse effect are carbon dioxide, nitrous oxide, methane, halocarbons and related compounds, and ozone. Emissions of these gases and their precursors, and particles also come from a wide range of human activities, including the combustion of fossil fuels at home, by industry, in transportation and commerce, and with deforestation and the construction of landfills. The IPCC identifies the major driving forces of future emissions as demographic, technological, and economic developments (IPCC, 2000, Preface). Recent emissions of these pollutants can be measured or estimated within reasonably well-defined uncertainty bounds, but simply extrapolating or projecting historical trends forward for a century is filled with errors.

So how do scientists estimate emissions and pollutant concentrations 100 years from now? They create visions of future worlds and translate these visions into hypothetical changes in emissions and other agents that affect the climate system. Emissions of specific pollutants emanate from a broad suite of human activities, and scientists have to guesstimate, for example, the number of human beings that will live on Earth 100 years from now, the type and level of economic activity they will generate, the energy supplies they will use, the technologies they will develop and implement, the quantities of specific pollutants they will emit, and how they will exploit or conserve resources and protect the environment. Alcamo et al. (1994) report that the major source of variability in emissions projections arises from “key model input” assumptions such as population and labor productivity. Wexler (1996, p. 17) finds that long-term population growth effects per capita income growth and that “[u]ltimately, total GDP, not population, is the variable that determines emissions from energy and industry.”

Changes in land cover also can influence climate in a number of ways, and the challenges in foretelling land-cover changes 100 years from now are equally daunting. Land-cover changes can influence climate by emitting gases and particles that can either warm or cool climate. They can change the reflectivity of the Earth’s surface, which can change the energy budget and climate. Also, they can change evapotranspiration, which can change the moisture balance and climate. To account for the effects of changes in land cover on climate, scientists and others must again resort to crystal-ball gazing to estimate deforestation, reforestation, irrigation, desertification, arable land, pastureland, rangeland, and urban sprawl. There is now enormous urban sprawl in the US, but will this continue over the next 50 or 100 years? The Royal Society in the UK states that future emissions of greenhouse gases and aerosols are dependent on “unknown socio-economic behaviour” (http://www.royalsoc.ac.uk/templates/search/websearch.cfm?mainpage=/policy/cur_clim.htm; June 11, 2003).

Table 2-1 provides examples of the ranges of key variables that the IPCC reports will influence climate in 2100. It is evident that the ranges of uncertainty are large. Overall, the nature of the linkages among changes in societies, economic systems, technology systems, population dynamics, and the environment are complex and unclear (O’Neill and Balk, 2001). This is why

**Table 2-1. Examples of Climate Driving Forces to 2001 Used in the IPCC Emissions Scenarios (IPCC, 2001)**

| *Variable* | *Units* |
|---|---|
| World population (billions) | 6.9-15.1 |
| World GDP ($10^{12}$ 1990 US$/yr) | 197-550 |
| Final energy intensity ($10^{6}$J/US$) | 1.4-7.3 |
| Primary energy ($10^{18}$J/yr) | 514-2737 |
| Share of coal in primary energy (%) | 0-53 |
| Share of zero carbon in primary energy (%) | 22-85 |
| Cumulative carbon dioxide 1990-2100 (GtC) | 772-2538 |
| Sulfur dioxide (MtS/yr) | 11-93 |
| Methane ($MtCH_4$/yr) | 236-1069 |

scientists cannot and probably never will be able to make firm climate predictions and why they have no choice but to resort to crystal-ball gazing.

Imagine being alive in 1880 and facing the challenge of foretelling population and economic growth and technology developments to 1980. Who could foretell the development of computers, aircraft, rockets, space travel, the Internet, nuclear power, hydroelectric power, and automobiles? Who could foretell life expectancies of more than 70 years, the Green Revolution, corn yields of nearly 200 bushels per acre, vast acreage of soybeans in Illinois, and the United Nations?

Perhaps the relevance of "The Limits to Growth" and "The Gaia Theory" is now apparent. These studies, like long-range climate studies, are based on conceptual models and sets of assumptions embodied in scenarios and model structure. They paint pictures about the ways that their authors view the operation of the planetary system, how it may operate in the future, and potential environmental, social, and economic consequences of human behavior. A major assumption in "Limits to Growth" is of no major change in the physical, economic, or social relationships that historically have governed the development of the world system. Basic interactions between these subsystems are structured mainly around positive feedback processes, and the system dynamics produce an overshoot-and -collapse mode. "The Gaia Theory", a unified view of the Earth and life sciences, on the other hand, has many more negative feedbacks and assumes a self-regulating planetary environment over long periods of time. Lovelock regards the current carbon dioxide concentration in the atmosphere and Earth's mean temperature to be well below the optimum for plant life, but recognizes possible serious consequences of disturbing a system that already may be on the verge of failure.

Views on how the world operates and is likely to change during the 21st century and beyond vary considerably. Unlike the behavior of the atmosphere, which is fundamentally constrained by basic laws of physics, future emissions scenarios do not have similar fundamental constraining factors. A multitude of world views form the basis for constructing a multitude of emissions and radiative forcing scenarios that give rise to great uncertainty in foretelling climate change.

This is why foretelling climate change is, to a large extent, akin to gazing into a crystal ball. It is art as much as science.

When one looks at some of the prognostications made only a few decades ago, the difficulties and errors in predicting the future are readily apparent. For example, the response of Nathan Keyfitz to his own question, "How much economic development is possible?" reflected a "Limits to Growth" philosophy: "Indeed, there is doubt whether the 250 million people expected to populate the US in 2000 will be able to live as Americans do today" (Keyfitz, 1976, p. 9). Clearly, this doubt was misplaced.

The reasons for the uncertainty and controversial nature of climate scenarios become apparent when the factors and assumptions that go into foretelling the emissions of pollutants 100 years from now are examined. Pollution scenarios are guided to some extent by historical experience, but are founded largely on assumptions about future human behavior and innovative potential, or the lack of it.

The difficulties and challenges of foretelling population growth, societal and institutional changes, economic development, and technology innovations to 2100 are daunting. Hence, it should not be surprising that climate scenarios are highly uncertain and controversial. Even demographers are uncomfortable making projections more than a few decades into the future, when most of the population will consist of people not yet born (O'Neill and Balk, 2001). O'Neill and Balk report that there is no generally accepted approach to characterizing the uncertainty inherent in population projections, just as there is no generally accepted approach to characterizing the uncertainty inherent in energy projections. Wexler (1996, p. 13) finds that "... the UN projections bounding the IPCC range have no clear meaning or derivation procedure." A continuation of the 1995-2000 fertility rate would, for example, yield a world population of about 53 billion by 2100 (O'Neill and Balk, 2001). The IPCC population scenarios in 2100 range from 6.9 to 15.1 billion (Table 2-1).

Looking at per-capita carbon dioxide emissions, McKitrick (2003) cited data by Marland et al. (2002) to show that average global per-capita emissions of carbon dioxide did not increase from 1970 to 1999, even though per-capita income grew. McKitrick concludes that it is unlikely, therefore, that economic growth over the next few decades could cause global per-capita emissions to suddenly double.

Assumptions about the emissions of aerosols also have a great influence on projected radiative forcing and climate change. All the latest IPCC emissions scenarios assume that policies will be implemented to reduce sulfur emissions and, hence, the negative radiative forcing and cooling associated with the sulfate aerosol. These assumptions lead to higher projected temperature than in earlier IPCC assessments (IPCC, 2001, p. 13). However, Webster et al. (2002) recognize that there is substantial uncertainty in current annual global emissions of sulfur and assume that the ability or willingness to implement sulfur emissions reduction policies is a key uncertainty. In their uncertainty analysis of one climate assessment modeling framework, these authors find that in the absence of greenhouse gas emissions restrictions, there is a one in 40 chance that global mean surface temperature change will exceed 4.9$^{o}$C by 2100. This approach uses formal techniques to elicit expert judgments about uncertainties in projections, while recognizing that uncertainty in future anthropogenic emissions may be irreducible.

Although climate change is a global concern, the most tangible impacts of climate change are in the regions where people live. It is important, therefore, to ask how well computer models reproduce historical and current climate conditions in different regions of the world, and if the models can foretell future regional climates reliably. From a scientific perspective, regional climates can be viewed as pieces of the global climate jigsaw puzzle that must be simulated correctly to provide credibility to models that simulate the whole system. Given the above listed uncertainties and other limitations and sources of uncertainty, biases, and errors in climate models, it is necessary to examine how well climate models reproduce current global mean and regional climates and then how well they can foretell future climates.

## How Well Can Models Reproduce Current Global and Regional Climates?

Understanding and successfully simulating climate processes, dynamic circulations, and past and current climate conditions are keys to developing confidence in the output of climate models. Remember again that the IPCC's stated position is that in order to make quantitative projections of future climate change, it is necessary to use climate models that **simulate faithfully all important processes governing the future evolution of climate.** A further condition is that having confidence in GCM simulations of future climates "... requires that these models **correctly simulate at least one known equilibrium climate, with the present climate being the best choice** [emphasis added] because of the quantity, quality, and global distribution of contemporary instrumental observations" (Gates, 1985, p. 142). However, Gates goes on to state that "... there is an inherent limitation in our ability to validate the accuracy of GCM perturbation simulations, which thereby affects our confidence in the accuracy of the GCM simulations of $CO_2$-induced climate change." Referring to the quantitative and qualitative differences among model simulations, Gates concludes that "... thus, we know that not all of these simulations can be correct, and perhaps all could be wrong." The IPCC recognizes that "[e]ven if a model is assessed as performing credibly when simulating the present climate, this does not necessarily guarantee that the response to a perturbation remains credible" (McAvaney, 2001, p. 473). The IPCC also recognizes that there is a possibility of "systematic errors or deficiencies shared by all models" (Kattenberg et al., 1996, p. 339).

Reporting on the credibility of climate models, IPCC concludes that "[c]oupled models can provide credible simulations of both the present annual mean climate and the climatological seasonal cycle over broad continental scales for most variables of interest for climate change" (McAvaney, 2001, p. 473). "Credibility" means that the errors in the model-mean surface air temperature rarely exceed 1$^o$C over the oceans and 5$^o$C over the continents, although the models do not simulate clouds, snow cover, or evaporation reasonably (McAvaney, 2001, p. 482).

At the regional scale, most reproductions, or simulations, of current (1961-1990) seasonal mean surface temperatures by GCMs differ from observed values within the range ±4$^o$C and seasonal precipitation biases mostly are between -40 and +150 percent (Giorgi and Hewitson, 2001, figure 10.2). This means that for a region where mean summer temperature is 25$^o$C and mean summer precipitation is 300 mm, various climate models simulate mean summer temperature in the 21-29$^o$C range and mean summer precipitation in the 180-750 mm range. The fact that these regional biases are reported to be smaller than those in the previous IPCC assessment "... strongly suggests that simulation of surface climate at the sub-continental scale has improved" (Giorgi and Hewitson, 2001, p. 592), and that the improvement compared with previous models "... implies increased confidence in simulated climatic changes" (p. 622). Improvements, yes. Increased confidence, yes. But do these simulations represent faithful representations of all important processes and correctly simulate present climate conditions?

Billions of people live in regions of the world dominated by seasonal monsoon conditions. Monsoon circulations are key components of the global climate system, a large part of the global hydrological cycle, and a major avenue of communication between the tropics and the extra-tropics. State-of-the-science climate models "... generally simulate a strong relationship between globally averaged warming and increasing extremes in the hydrological cycle including monsoon strength" (Chase et al., 2003, p. 249). However, Chase et al. "find no evidence to support this model hypothesis ...." In southeastern Asia, western Africa, eastern Africa, and Australasia, they found evidence of significantly diminished monsoonal circulations from 1950 to 1998, and no change in monsoon circulations since 1979, the period of strongest reported warming.

The above data are for many regions throughout the world, so let us look specifically at the climate record and model simulations for CNA where the ISWS is located. The historical climate record shows that annual mean temperature for Illinois has varied over a range of about 4.0°C since 1830, but there has not been an overall trend over this 170-year period. Temperature was generally cool in the 1800s, increased about 2.0°C from the 1870s to the 1930s, and has cooled since that time (Figure 2-2). This 2.0°C increase in Illinois' annual mean temperature from the 1870s to the 1930s is much larger than the increase in the Earth's surface temperature of about 0.3°C over the same period (IPCC, 2001, Figure 2). And, whereas the Earth's surface temperature has increased about 0.4°C from 1930 to the end of the 20th century, the annual mean temperature in Illinois has decreased. In fact, there has been a century-long cooling trend throughout much of east-central, eastern, and southern United States (http://www.sws.uiuc.edu/atmos/statecli/Climate_change/us-change.gif; November 28, 2003).

Annual mean precipitation for Illinois generally was low from about 1890 to 1970 and higher in the mid-19th century and the last three decades of the 20th century (Figure 2-3). Even though there are few precipitation records in the middle 19th century, high regional precipitation is reflected in the high levels of Lakes Michigan and Huron, which at that time were more than 1 meter higher than in the 1930s and even higher than in the 1980s (Figure 2-4).

Two important conclusions can be drawn from these data: i) regional climate trends over the past 50-100 years that are consistent with theoretical expectations of an enhanced greenhouse effect (for example, higher precipitation and more heavy rainfall events in northern mid-latitudes) do not necessarily establish causality; and ii) global warming has not resulted in warming in all parts of the globe.

The IPCC (2001) documents recent climate changes in other parts of the world, including warming, a decrease in daily temperature range, a 2 percent increase in cloud cover over mid- to high-latitude land areas, a reduction in the frequency of low temperatures, a smaller increase in the frequency of extreme high temperatures, a decrease in the extent of snow and ice in mid- and high latitudes of the Northern Hemisphere, a widespread retreat of mountain glaciers in nonpolar regions, more frequent, persistent, and intense El Niño episodes, relatively small increases in global land areas experiencing severe drought and wetness, but with more severe droughts in parts of Asia and Africa. Besides CNA, the IPCC reports that a few other parts of the globe have not warmed, including some parts of the Southern Hemisphere, oceans, and parts of Antarctica. No significant trends in Antarctic sea-ice extent are apparent, and there are no clear trends in the intensity and frequency of tropical and extra-tropical cyclones and severe local storms.

The IPCC *Summary for Policy Makers* takes the position that the performance of climate models has been demonstrated on a range of space and time-scales; hence, confidence in the ability of these models to provide useful projections of future climate has improved. There is

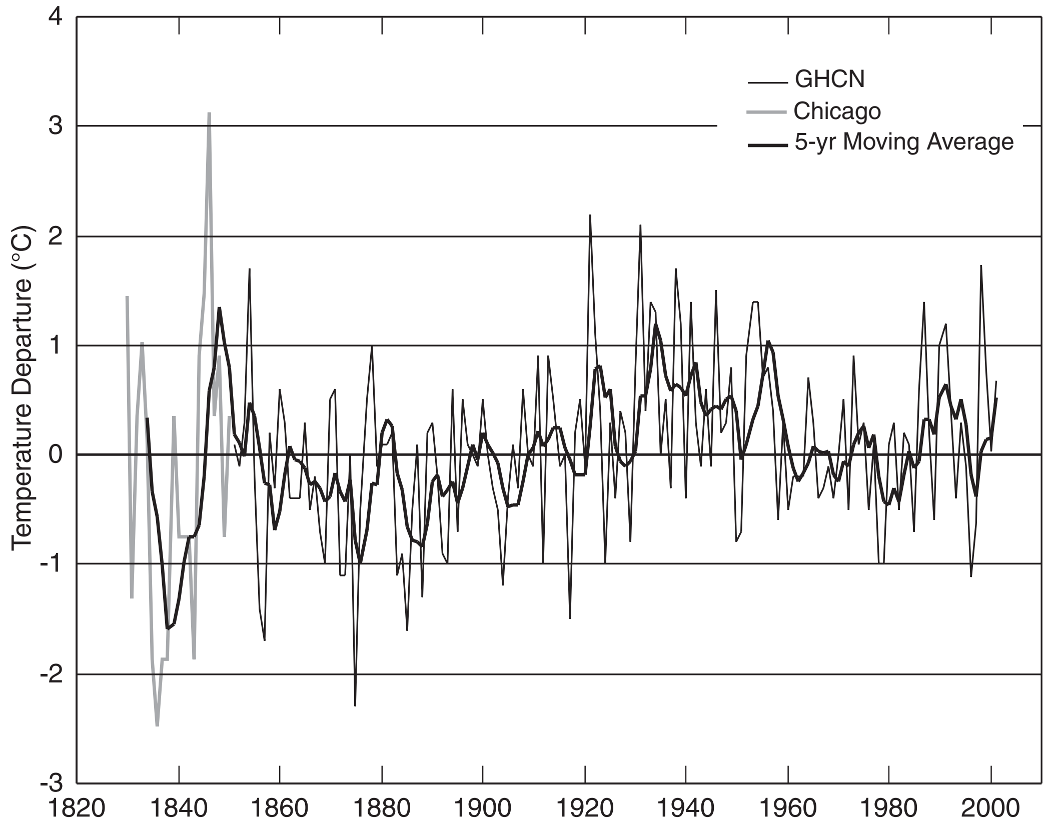


Figure 2-2. The 5-year moving averages of annual mean temperature in Illinois, 1830-2001. The 1830-1850 record, based on Chicago only, was normalized using 1961-1990 Midway Airport data after making an adjustment of +1.8˚C for the Chicago urban effect. The number of stations increased to 10 by 1879 and 31 by 1902. The 1851-1995 Global Historical Climate Network (GHCN) data include St. Louis, MO, and Dubuque, IA. Each station record was normalized by calculating a departure based on the station's 1961-1990 average. Departures then were averaged for Illinois (Jim Angel, ISWS, March 12, 2003, personal communication).

reported to be large-scale consistency between models and observations. Despite recognizing the importance of comparing model output to observations as a basis for establishing the credibility of the output of climate models, and despite presenting much relevant data and information in the technical chapters, the IPCC (2001) does not present in the *Summary for Policy Makers* a summary statement as to how well or how poorly current climate models perform in simulating faithfully all important processes and the global system of regional climates.

Related to the issue of reporting errors and biases is how the IPCC reports projections of climate change: the IPCC reports differences between the simulation of recent climate conditions and a climate scenario as the measure of a climate change scenario. It does not report actual values of, for example, the surface temperature of the Earth or precipitation in Illinois and how these values are expected to change. Substantial discussion by the IPCC on the importance of absolute values and the limitations of not using absolute values is lacking. It would seem reasonable to conclude that more credibility could be attached to the products of climate models that

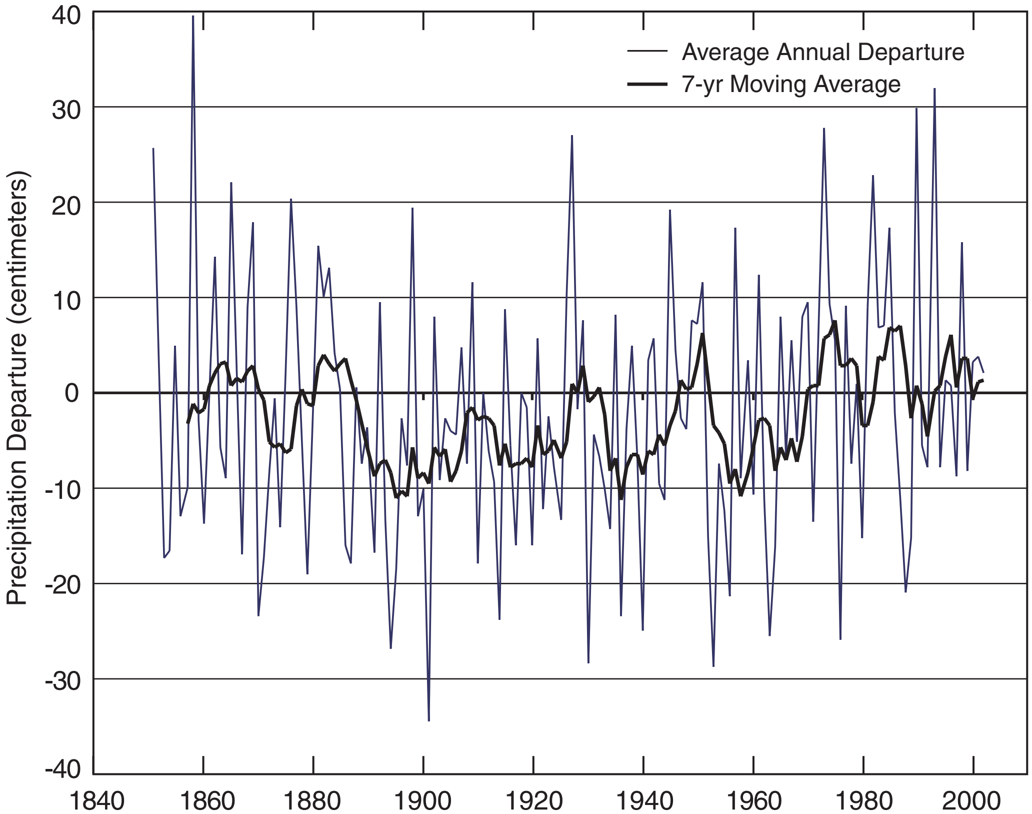


Figure 2-3. Precipitation in Illinois, 1837-2002, showing annual departures from 1961-1990 average and 7-year moving averages. There was one station until 1850 (St. Louis), 10 by 1876, and 40 by 1898 (Jim Angel, ISWS, March 12, 2003, personal communication).

simulate climate processes faithfully and historical climate conditions accurately than to climate models that do not. For example, if models skew the inter-tropical convergence zone and allow it to spuriously migrate from one hemisphere to another, thus seriously distorting current precipitation fields, why should it be assumed that these models have credibility in simulating future climate scenarios? Similarly, if models simulate high pressure and low rainfall in a region that has a high frequency of storms and high rainfall, why should these models be considered credible in simulating future climates? And when climate models do not simulate regional climates accurately (the pieces of the global jigsaw puzzle), why should we believe that they simulate accurately the global-mean climate (the whole jigsaw puzzle, which is the composite of all the pieces), or future climate changes?

Neither the IPCC (IPCC, 2001) nor the US National Assessment Team (USGCRP, 2000) documents 19th century regional climate conditions. Starting the recorded climate history around 1895, both the IPCC and the USGCRP document an increase in precipitation over most of the US during the 20th century. The IPCC also reports that land-surface precipitation has continued to increase in the middle and high latitudes of the Northern Hemisphere, consistent with the increase in water vapor and precipitation associated with an enhanced greenhouse effect (IPCC, 2001, p. 4 and p. 30). In Illinois, from 1895 to 2002, there is a statistically significant increase in

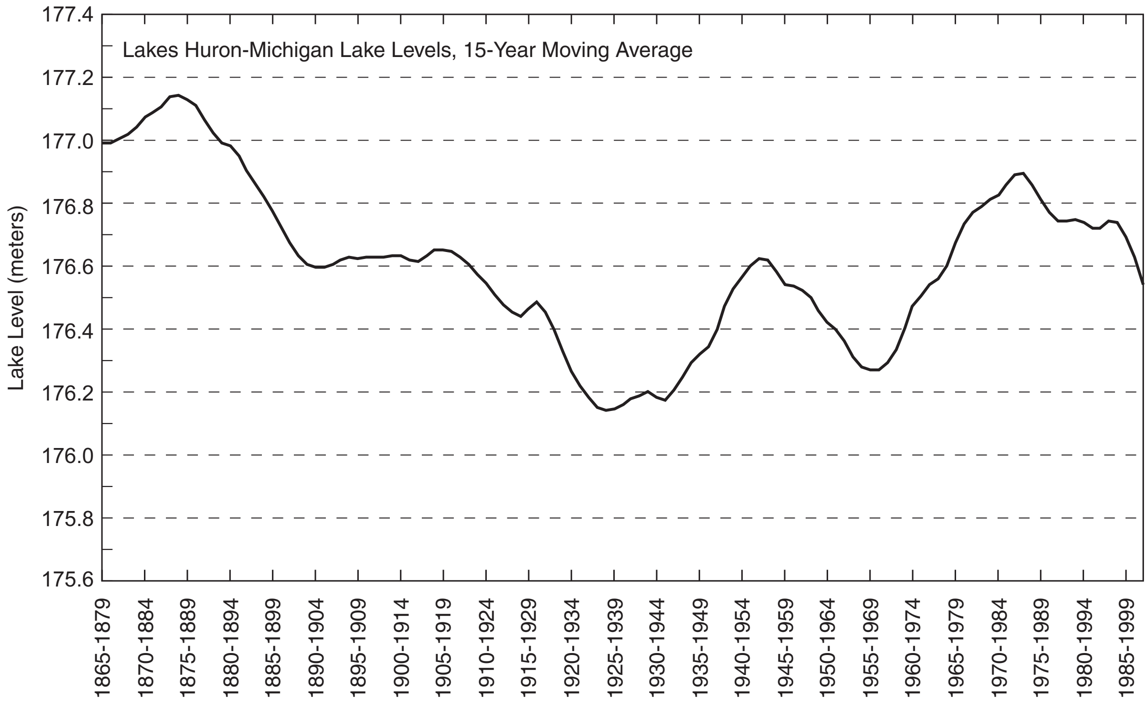


Figure 2-4. Lakes Huron-Michigan lake levels, 15-year moving average (Stan Changnon, ISWS, March 18, 2003, personal communication).

precipitation (**p** = 0.05), consistent with the IPCC and USGCRP conclusions. However, when the longer record from 1850 to 2002 is considered, there is no statistically significant trend in precipitation. These high 19th century precipitation and lake levels in the Midwest cause one to question the IPCC conclusion that precipitation has increased in middle and high latitudes of the Northern Hemisphere consistent with the increase in water vapor and precipitation associated with an enhanced greenhouse effect.

Similarly, the fact that extreme precipitation events are reported to have been about as frequent at the start of the 20th century as at the end of the 20th century (Kunkel, 2003) causes one to question the IPCC conclusion that the frequency of extreme precipitation events has increased.

Before examining possible future climate conditions in CNA, it is necessary to examine how well GCMs simulate current (1961-1990) climate conditions in CNA. The IPCC shows that surface temperature biases in CNA for the 1961-1990 climate simulated by 5 GCMs are ~ -1.3-~+2.6°C in winter and ~+0.4-~+3.5°C in summer. Precipitation biases are ~±20 percent in winter and ~-10-+40 percent in summer (IPCC, 2001, Figure 10.2). This author is not aware of any reported model simulations of Midwest climate for the past 150 years.

Despite reported improvements in the performance of climate models in simulating global mean climate conditions, the models have limited ability to simulate current and recent historical regional climate conditions faithfully and consistently. The USCCSP (2002, pp. 47-48) acknowledges that "[t]he current crop of world-class climate models exhibits an unacceptably large range in climate sensitivity." The IPCC reports that "[a]t the regional scale, area-average biases in the simulation of present day climate are highly variable from region to region and across models" (Giorgi and Hewitson, p. 603).

If there is so much error and/or bias in simulating regional climate conditions throughout the world, are the models simulating global mean climate conditions correctly? Faithful reproduction of the big picture of a jigsaw puzzle requires that all pieces must be the right size, shape, and color, and in the right places. The whole can be no better than the sum of its parts, and if the parts are the wrong size, shape, or color, and are misplaced, then the fidelity of the whole picture must be questioned. Increased credibility could be accorded to climate models if they were evaluated on their ability to simulate the global picture as a composite of all the regional pieces, in addition to simulating global mean conditions. And although comparing simulated climate against the observational record can help establish model credibility, the IPCC (2001) reports that even accurate simulation of current climate does not guarantee the ability of a model to simulate climate change correctly.

## How Well Can Models Foretell Future Climates?

This section starts with the IPCC's description in the *Summary for Policymakers* of the "understanding" of the climate system and "how well" climate models represent key processes and climate projections (IPCC, 2001, Preface, and p. 2 and p. 23). This description is that "... confidence in the ability of these models to provide useful projections of future climate has improved ..." (IPCC, 2001, p. 9).

The following discussion uses mainly data and information contained in the IPCC and the USCCSP reports (IPCC, 2001; USCCSP, 2002) to provide insight on the usefulness of climate models to provide projections of future climate. The IPCC recognizes that although climate models now have some skill in simulating changes since 1850 (IPCC, 2001, Section 8.6.1), these changes are fairly small in comparison with many projections of climate change in the 21st century (McAvaney, 2001, p. 493). Also, it should be noted that the IPCC uses a simple model for the projections of climate change for the next century, and changes in atmospheric composition are specified (Cubasch and Meehl, 2001).

As noted in the Introduction, the USCCSP and the IPCC report model projections of increases in global mean surface temperature in a range from approximately 1°C to more than 5°C during the 21st century. The IPCC also notes that the range of climate projections resulting from the full set of emissions scenarios would be larger, and that some models have climate sensitivities outside the range considered (Cubasch and Meehl, 2001, p. 555). Also, superimposed on the predictions and projections of human-induced climate change must be the possible changes due to natural factors of considerably uncertain magnitude (Mitchell and Karoly, 2001, p. 705).

The IPCC data show projected, seasonal, regional temperature increases in 2071-2100, from a 1961-1990 base, generally in the 2-8°C range, with precipitation changes ±40 percent (Giorgi and Hewitson, 2001, Figures 10.3 and 10.5). In a region with current mean summer precipitation of about 300 mm, future projections of mean annual precipitation range from ~180 mm to 420 mm. The biases of 1961-1990 base climate simulations also need to be considered. This means that if a climate model simulates base climate with a mean summer temperature 3°C higher than a 20°C observed base temperature and projects an increase of 6°C, then the model projection for the end of the 21st century could be 29°C. Alternatively, if the model simulates base climate with a mean temperature of 17°C and projects an increase of 3°C, then the model projection for the end of the 21st century could be 20°C. Similarly with precipitation, if a climate model simulates a base climate with mean summer precipitation 100 mm higher than the 300 mm observed base and projects an increase of 100 mm, then the model projection for the end of the 21st century could be 500 mm. Alternatively, if the model simulates base climate with mean summer precipitation of 200 mm and projects a 100 mm increase, then the model projection for the end of the 21st century could be 300 mm. As stated above, IPCC and most other descriptions of climate change are represented as the difference between the simulated base climate and the projected climate.  They do not represent explicitly the biases and errors in simulating current climate conditions. Also, Figure 10.5 of Giorgi and Hewitson shows that models often exhibit opposing precipitation biases in different seasons that cancel each other out in simulations of annual precipitation. This is one reason why simulations of annual precipitation can give the right answer for the wrong reason.

With such bias and/or error in the simulation of base climates and projections of future climate, the USCCSP concludes that "... modeled projections of the future regional impacts of global climate change are often contradictory and are not sufficiently reliable tools for planning" (USCCSP, 2002, p. 7). "In fact, different model projections are at times contradictory, a symptom of the unreliability of regional-scale projections at this time" (USCCSP, 2002, p. 44). The IPCC recognizes that "[s]imulated changes in mean climate conditions for the last decades of the 21st century (compared to present day climate) vary substantially among models and among regions" (Giorgi and Hewitson, p. 603). The USEPA reports that "[h]owever, scientists are unable to say whether particular regions will receive more or less rainfall; and for many regions they are unable to even state whether a wetter or a drier climate is more likely (http://yosemite.epa.gov/oar/globalwarming.nsf/content/ClimateFutureClimateUSClimate.html Open Document; May 28, 2003). The IPCC even reports that "... there has been an increase in uncertainty in those aspects of climate change that critically depend on regional changes" (IPCC, 2001, p. 53).

Cubasch and Meehl (2001, p. 556, Figure 9.15) show results from seven simple climate models that project global temperature change from 1990 to 2100 for seven emissions scenarios. The range of projected temperature increase that is due to the range of emissions scenarios is shown to be ~1.8°-3.0°C.  The range of projected temperature increase for any particular emissions scenario that is due to the use of different models is ~1.2°-2.4°C. This shows that, according to the simple models, more than half of the uncertainty in projected climate change is due to uncertainty about future emissions, and less than half of the uncertainty is due to scientific differences among models.

The above information provides a basis for evaluating the credibility and usefulness of climate models. Scientists look at this information and draw quite different conclusions. The IPCC reports that "... confidence in the ability of these models to provide useful projections of future climate has improved ..." (IPCC, 2001, p. 9).  The USCCSP (2002) concludes that the uncertainty in current climate models is "unacceptable."

## Summary and Recommendations

### *i) Climate change is unpredictable.*

There are five main reasons why century-scale, human-induced climate change is unpredictable in the conventional deterministic sense.

- It is impossible for sociologists, demographers, engineers, and economists to predict with reasonable confidence and accuracy the evolution of the emission of pollutants and land-cover changes that are reported to drive century-scale climate change. The IPCC modeling experiments indicate that more than half of the uncertainty in the specified climate-change scenarios is due to uncertainty about future emissions scenarios and specified climate forcings. Further, not all forcings have been specified and the range and combination of emissions scenarios does not include all possibilities.

- Scientists do not fully understand how the climate system operates.

- Some important climate processes either are not included in climate models or are simplified, and some are not simulated faithfully.

- The climate system is a coupled, nonlinear, chaotic system.

- Models do not simulate the components of the global climate system (regional climates) correctly.

Even with model improvements, major uncertainties, biases, errors, and omissions remain in modeled projections of future climate change.

Key determinants of human-induced climate change are emissions of greenhouse gases, aerosols, and land-cover changes. Quantifying these agents 100 years from now is based on subjective assumptions and value judgments about human behavior, technologies, resource management, economic development, and policies. There are no generally accepted approaches to characterizing the uncertainties inherent in energy, economic, technology, and population projections on the century time scale, and the range of plausible storylines will forever remain large.

Divergent economic, population, technology, and land-cover changes are the main cause of divergent emissions and climate scenarios. Whatever they are called, the reliability of predictions, forecasts, projections, simulations, scenarios, and pictures of climate change emanating from the biggest, fastest, and most resolute computer models today or any time in the future will never be any more reliable and accurate than the ability of demographers, economists, sociologists, and engineers to foresee and model how the world will operate a century or more in the future.

The unpredictability of climate change does not reduce the importance of trying to quantify the possible influences of human activities on global and regional climates, but even perfect climate models will never produce perfect crystal balls. As the IPCC notes, "[f]uture models should certainly advance in completeness and sophistication; however, the key will be to demonstrate some degree of prognostic skill" (Moore III, 2001, p. 772). "The most we can expect to achieve is the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model simulations" (Moore III, 2001, p. 774). Challenges to generating credible probability distributions include development of credible models and credible forcing scenarios.

***ii) Inconsistent descriptions of modeling capabilities by scientists and government agencies lead to confusion of the media, the public, and decisionmakers.***

Climate change is an important policy issue that demands clear communication among scientists and with the media, the public, and decisionmakers.

Traditionally, a reasonably high level of confidence is associated with use of the word "prediction". Although authoritative scientific bodies such as the IPCC and the USCCSP state clearly that human-induced climate change is unpredictable on the century time-scale, some government agencies, scientists, and the media still choose to talk about long-term climate prediction. Because climate change is unpredictable, use of the term "climate prediction" carries a sense of deterministic confidence that is unwarranted in the context of human-induced climate change on the century time scale, and is a basis of misinformation.

There is also a major inconsistency between the IPCC and the USCCSP in that the USCCSP reports the uncertainty in climate models to be "unacceptable," whereas the IPCC reports progress in climate modeling and describes climate projections as "useful." The media, the public, and decisionmakers can only be confused by such inconsistent qualitative characterizations of model performance. Therefore, it is recommended that scenarios, or pictures, of future climates painted by climate models should be accompanied by quantitative comparisons of computer simulations with often limited climate observations and descriptions of the assumed socioeconomic and technology futures, and discussions of the strengths and weaknesses of the models and observations.

The media, public, and decisionmakers need to be better informed about the inherent limitations and uncertainties in foretelling future climates, and what science can and cannot do to reduce these uncertainties. As Ryan (2003) notes, serving the public will be done through increasing communication skill, including better communication of uncertainty. Fundamental to improving communications is greater consistency by scientists and the media in defining and using key terms. In recognition of the scientific unpredictability of century-scale climate change, climate-change modeling studies are more correctly described as "climate experiments" and the resulting climate-change representations as "climate-change scenarios" or "pictures", consistent with the IPCC and USCCSP definitions.

***iii) Global climate models should not be judged to be credible when there are large uncertainties, errors, and biases in their simulation of regional climates.***

Currently, climate models are reported to simulate regional climates in an unacceptable manner, but the models often are judged to be performing well in their simulation of global mean climate conditions. It is recommended that the simulation of global mean climate conditions be judged to be acceptable only when their simulations of historical and current regional climates also are judged to be acceptable. This would allow decisionmakers to have some confidence that global climate models are simulating all the major components and processes of the global climate system correctly. Also, when descriptions of climate change are represented as the difference between simulated current climates and projected climates, the biases and errors in simulating current climate conditions should be specified. This would allow evaluation of the extent to which the models simulate correctly at least one known equilibrium climate. Such documentation and quantification of model performance would provide a more objective basis for determining the credibility and usefulness of models than evaluations such as “models have improved”, “models are useful”, or “models are unacceptable”. Still, reasonable people always will have varying opinions about how faithful and complete climate simulations should be for climate models to be judged credible and useful.

***iv) Climate records for 50 to 100 years often are too short to establish a baseline against which to evaluate climate change due to human activities.***

Regional climates change naturally on all time scales. Most observational climate data are available only for the last 50 to 100 years and, therefore, cannot document changes over longer time scales. Climate and lake-level measurements since the mid-19th century provide documentation of major climate shifts that are not evident in a 50-100-year record. Illinois today is no warmer or wetter today than it has been over the last 150 years. Precipitation and lake levels were as high or higher in the 19th century as in recent decades. And it is reported that across the US, extreme precipitation events were about as frequent at the start of the 20th century as at the end of the 20th century. These revelations raise questions about the magnitude, timing, and cause of climate changes in other parts of the nation and world prior to the 20th century. An important message from these data is that regional climate trends over the past 50-100 years that are consistent with theoretical expectations of an enhanced greenhouse effect, e.g., higher precipitation and more heavy rainfall events in northern mid-latitudes, do not necessarily establish causality.

***v) It is generally accepted that further research can reduce scientific uncertainties and improve the scientific basis for decisionmaking, but just the opposite has been reported to have been the case in climate-change research.***

Although the performance of climate models has improved, the many gaps in knowledge and the research questions identified by the IPCC, the USCCSP, and others illustrate the need for improved knowledge and understanding of the climate system and improved modeling capabilities as a basis for conducting experiments to paint clearer pictures about future climates. However, a finding by the Office of Management and Budget (OMB) questions the commonly held assumption that research, at least over the time span of a decade, will reduce scientific uncertainties. The OMB, in an information box called “Why the Increasing Uncertainty About Global Change?”, recognizes in a budget report for the National Aeronautics and Space Administration that “[s]ince 1990, many billions of dollars has been devoted to research on climate change, yet predictions regarding the range of possible changes in temperature due to increasing carbon dioxide concentrations has become broader, rather than narrower. This is not a failure of the research community. Scientists have gained a great deal of knowledge over the past decade. A big part of that new knowledge has been that the Earth’s atmosphere is much more complex—and unpredictable—than originally thought” (http://www.whitehouse.gov/omb/budget/fy2003/bud27.html; January 30, 2003). Goody et al. (2002, p. 874) expect that “the list of forcings will be longer 10 yr from now. Unknown physics cannot be evaluated.” It is hoped that future research can revise the trend and reduce the uncertainties about possible future climate changes.

***vi) Uncertainty associated with climate prognostications is not defined or quantified.***

The documentation of historical climates and scientific understanding of future climate change are fraught with uncertainty, but uncertainty needs to be defined and quantified for risk analysts and decisionmakers. Webster (2003) and Manning (2003) discuss the methodological, institutional, and philosophical challenges and difficulties of defining and quantifying uncertainty. Recently, a National Research Council Panel on Climate Change Feedbacks deliberated "...the scientific definition of uncertainty, its quantitative evaluation, and its relation to the development of policy options regarding climate change" (National Research Council, 2003, p. viii). Their deliberations did not make it into the final report, so the challenges and difficulties of defining, quantifying, and communicating uncertainty appear to be as great as ever.

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# Chapter 3
# Economic Impacts of Weather and Climate Conditions in the United States: Past, Present, and Future

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## Introduction

A key issue resulting from the prognostications about a forthcoming change in the global climate involves the potential impacts of these changes. Major global climatic shifts are projected to occur during the 21st Century, and there is great concern about expected negative economic impacts resulting from such changes. Furthermore, the United States (US) experienced major losses from several weather extremes during the 1990s, a situation that helped climate change scientists and the insurance industry to believe that the expected climate change with more extremes had begun and that the financial impacts would be severe.

To address these future economic issues, this section examines how weather and climate have affected the nation's economy over the past 50 years and how these impacts have been changing in recent years and may change in the future, with and without a change in climate.

Comparison of current direct economic impacts of the nation's weather and climate with the nation's total economy provides a basis for deciding what types of future actions may be necessary. This study did not investigate impacts to human health, the physical environment, or their possible monetary values. Past climate conditions that produced major US economic impacts have fluctuated over time scales ranging from a decade to centuries. For example, the 1930s and 1950s experienced the worst droughts of the past 200 years, and the 1960s and 1970s had the best Midwestern crop-weather conditions of the 20th Century (Thompson, 1986).

Weather-sensitive US activities experience both economic gains and losses, depending on the climate conditions. Good growing-season weather conditions bring high crop yields, whereas cold winters bring high heating costs. All major storms produce damages that translate into economic losses, but some individuals and institutions also experience financial gain in the aftermath of a damaging event (Changnon, 1996). Thus, the net effect of extremes is not always loss. Winners often are found later in the storm area and in unaffected regions because most extreme conditions do not cover all or much of the nation. For example, rebuilding homes after a damaging hurricane benefits the construction industry, and farmers producing crops in unaffected areas during a serious drought benefit from increased incomes as prices are driven upwards by the drought's crop losses (Hewings and Mahidhara, 1996). The post-event rebuilding process often brings improvements with stronger new structures, better rules and procedures for dealing with future storms, and other societal benefits. Seldom are the economic gains resulting from extremes assessed; and often when they are assessed, they are incomplete (NAS, 1999). A few comprehensive impact-oriented studies of recent major events, such as the 1988 drought (Riebsame et al., 1991), Hurricane Andrew (Pielke, 1995), and the Midwest flood of 1993 (Changnon, 1996), found the value of the gains ranged from 30 to 55 percent of the losses.

The complex issue of economic impacts due to weather and climate has never been studied extensively. The National Academy of Sciences (1999) assessed the economic impacts of natural hazards, noting the paucity of national efforts to collect loss and gain data systematically. However, increasing attention to the economic impacts of climate during recent years by scientists and economists has led to the collection of data on several events and to studies defining many climate impacts (Changnon, 2003b). Nevertheless, many economic impacts are measured poorly, and much existing loss information is based on estimates rather than actual measurements. Many weather extremes only affect parts of the nation. Hence, the national scale approach herein does not address regional impacts, but rather attempts to measure net collective national impacts, losses, or gains during a particular year or a series of years.

This section focuses on published results that have carefully assessed the economic impacts from weather and climate conditions particularly during the past 50 years. Fortunately, recent studies of past losses have made careful adjustments to the raw data. Studies of past economic impacts require careful attention and adjustments for shifting changes in the "target" such as varying crop varieties/hybrids over time, for inflation, and to other changing societal and technological conditions that affect the measurement of impacts. Comparison of property insurance loss data from a Florida storm in 1950 and losses from a similar storm in 1990 requires adjustment for the changes in the area's population density, in the types and quality of the structures, and in the level of insurance coverage. These critical normalization activities are identified where appropriate in the text. The resulting economic impacts of weather and climate across the nation are evaluated against the totality of the nation's economy to gain a perspective on just how serious future impacts could become, given a change in climate.

Gains and losses resulting from weather and climate conditions during 1950-1997 in two weather-sensitive national sectors, agricultural production and energy use, are defined and addressed first. Temporal behavior of various extreme climate and weather conditions during 1950-2000 is then assessed. Next, national annual losses from damaging extremes, including floods and hurricanes, during 1949-1997, are reviewed. Financial losses and gains are identified for six recent major weather extremes, including the 1988 drought, the 1993 flood, and the extreme winter from El Niño 1997-1998. This information, coupled with financial findings presented earlier in the chapter, serves as basis for interpreting economic gains and losses from weather and climate extremes, particularly recent increased losses during the 1990s. Various reasons for recent increased losses, including societal shifts, are assessed. The final section summarizes national losses and gains, how the impacts rate in the nation's economy, and future impacts resulting from possible future climate change.

## National Impacts of Weather and Climate on Agricultural Production and Energy Use

### Data and Analysis

#### *Crop Yield Values*

Data on major US crops, provided by the US Department of Agriculture, were interpreted and analyzed to define weather effects, which are principally above or below average growing-season moisture and temperature conditions. Data were obtained for the nation's four major crops (corn, soybeans, wheat, and cotton) and their yields for 1950-1997 (Changnon and Hewings, 2000) which represent 92 percent of the total agricultural crop value during that period.

Assessment of how various weather conditions affected corn and soybean yields in the central United States revealed that excessive precipitation (high or low) and associated temperature extremes accounted for 71 percent of the annual crop losses due to weather (Changnon, 1972). Hail and high winds accounted for much of the remaining loss (26%), and early or late frost caused 3 percent of the losses. The record 1988 drought affected large parts of the nation and all four crops; agricultural losses (including government payments) amounted to $24 billion (Riebsame et al., 1991). Depression of crop yields below expected levels, as defined by average weather conditions and agricultural technology levels, serves as a meaningful measure of drought impacts, as well as a measure of overly wet field conditions. For example, overly wet soils from widespread heavy growing-season rainfall in 1993 across the Midwest depressed crop yields significantly, and total agricultural damages amounted to $8.9 billion (Changnon, 1996).

The national annual crop yield values had to be made comparable over time because ever-changing farming practices, seed varieties, and agricultural technologies have created continuing, ever-changing increases in yields. This normalization of annual yield values was accomplished by expressing the annual values as a percentage of the expected yield value. The expected yield value in any year was determined by statistically fitting curves to the array of historical yield values. Such curves reflect the yield expected due to agricultural technology under average weather conditions (Thompson, 1986; Offutt et al., 1987). Figure 3-1 shows the best-fit curve and its equation, as calculated for the 1950-1997 corn yields. These yield values illustrate upward trends over time but quite different time distributions. Figure 3-2 shows these departures as calculated for the soybean yields during 1950-1997. By this process, four annual yield data sets were created, including the percent of expected national corn yields for 1920-1997, cotton yields for 1910-1997, soybean yields for 1924-1997, and the percent of expected national wheat yields for 1910-1997 (Changnon and Hewings, 2000). The equation for each crop was determined for the period of yield record.

Annual departures above or below expected yields, expressed as percentages, for a given crop were compared with the year's total crop production to determine the amount of production lost or gained due to weather. These production amounts for a given year were expressed in financial terms by using the year's financial value of a unit of production (bushels for corn, soybeans, and wheat, and pounds for cotton). These annual dollar loss and gain values were adjusted to 1997 dollar levels by using the implicit price deflator of the Gross National Product (GNP). For example, the national corn yield in 1955 was determined to be 7 percent below the expected yield (with average weather), and the year's production (2,872,959,000 bushels) was calculated to be 217 million bushels less than the expected production of 3,089,203,225 bushels (actual production divided by 93%). The 1955 price was $1.35 per bushel, representing a 1955 loss of $292.95 million. This value was adjusted to the 1997 level by the price index, creating a loss of $1.530 billion in 1997 dollars.

### *Energy Consumption Values*

The national economic effects of temperatures that deviate from the average values over prolonged periods (one or more seasons) on the consumption of electricity and natural gas across the United States were assessed annually for the 1950-1997 period. The national approach to assessment identifies those years when the effects of either high or low temperatures were sizable and predominant across large parts of the nation. Annual data on the national residential and commercial consumption and prices of each energy form were obtained from the Energy Information Administration in Washington, DC. Industrial use of electricity and natural gas was not included because these values are heavily tied to demands other than weather conditions (Changnon and Hewings, 2000).

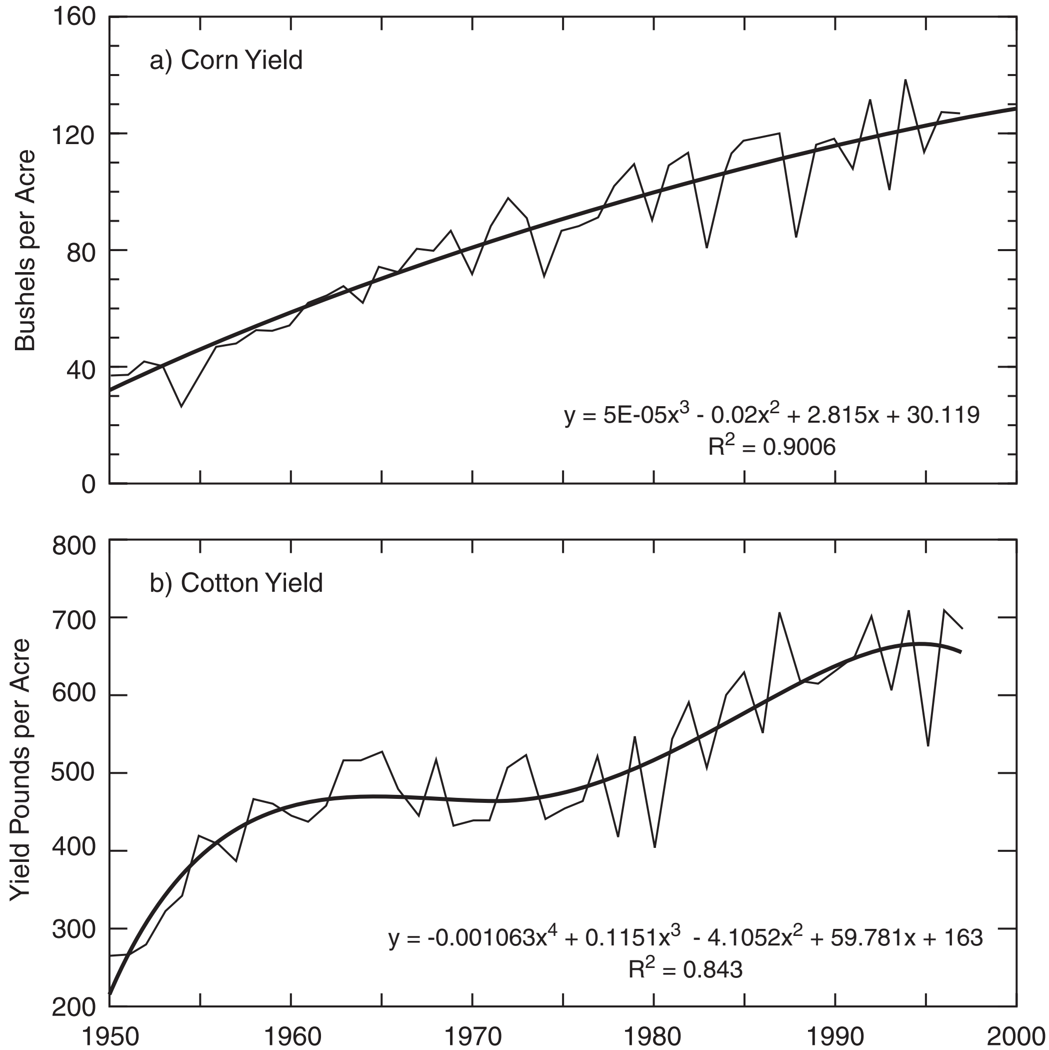


Figure 3-1. Distribution of yields during 1950-1997 for two of the four major US crops showing the best-fit curves, as an expression of changing farm practices and technology, and the equation of the best-fit curves (Changnon et al., 2001)

The annual values of national consumption from 1949 to 1997 were first adjusted to ever-changing and generally increasing usage due to shifting demand resulting from the nation's population growth, technological changes, and shifting economic factors that collectively affect usage and price. A technique that has been used successfully in agriculture to assess weather effects on crop yields was used to adjust for these energy-related variables to assess the weather effect on energy consumption. Curves were statistically fit to the temporal distributions of the annual consumption values for electricity and natural gas for 1949-1997. These curves represented the combined influences of shifting economy, changes in energy usage, and any technological changes affecting consumption. Hence, the values on the curve with the best fit represent the expected consumption values in each year with average temperature conditions and existing technologies. For those years when the annual consumption values were above or below the

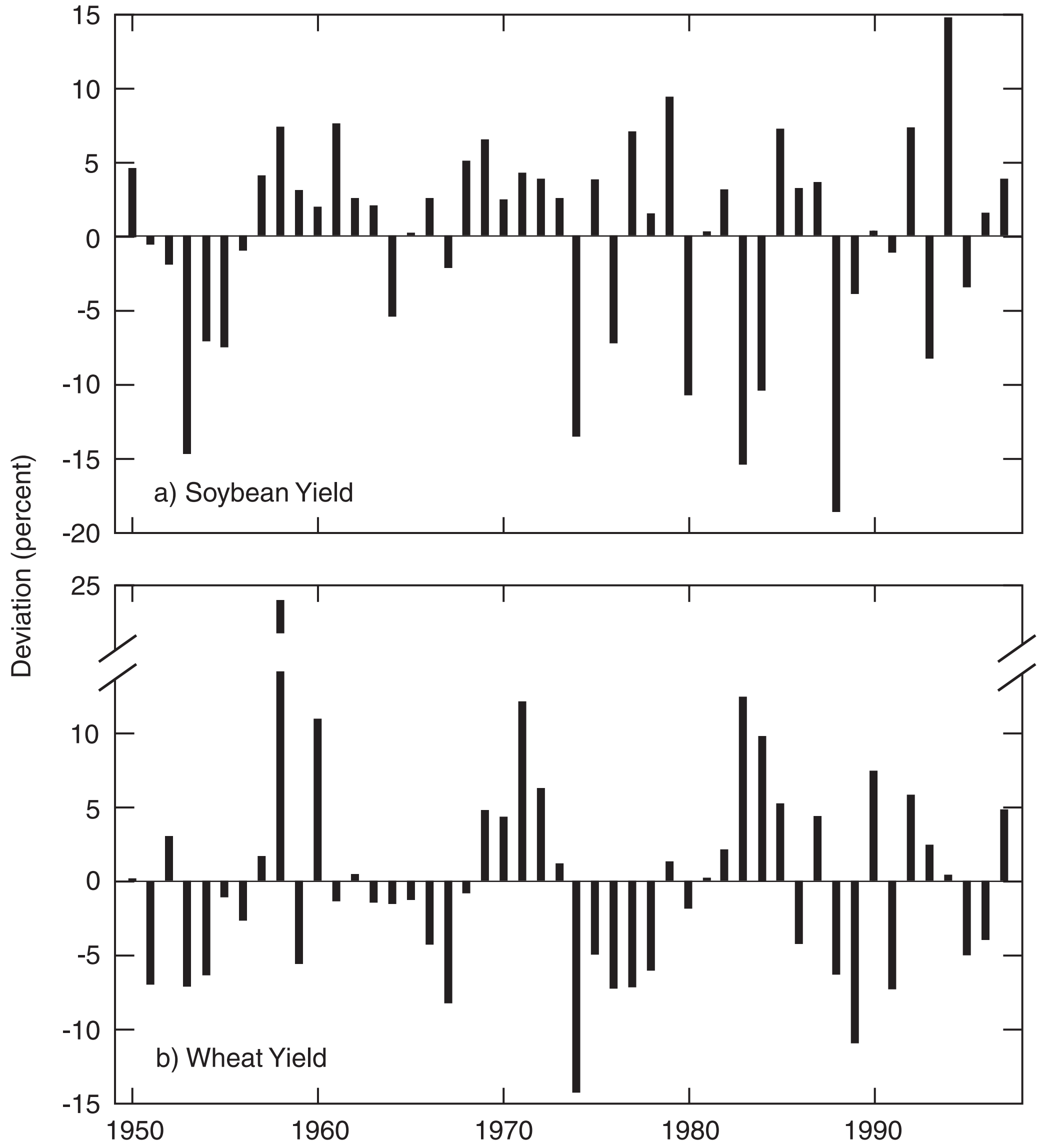


Figure 3-2. Percent departure of actual annual yields from best-fit curves, or expected yields with average weather, soybeans and wheat, 1950-1997 (Changnon et al., 2001)

expected value, the difference was calculated and considered to be the effect of temperature conditions during the year.

Figure 3-3 shows the best-fit curve, a third-order fit to the distribution with an $R^2$ (square of the correlation coefficient) of 0.997, the equation, and the annual values (points) for the national electricity consumption from 1949 to 1997. If values were below the curve, such as in the mid-1960s, they reflected milder than expected temperatures nationally, and the values above the curve, or expected value for the year, were a result of high-temperature extremes. The actual consumption values in each year also were expressed as a percentage of the expected value. The resulting percentage was considered to be the expression of the influence of weather conditions during the year such as hot summers, cold winters, or both. The years with values that exceeded

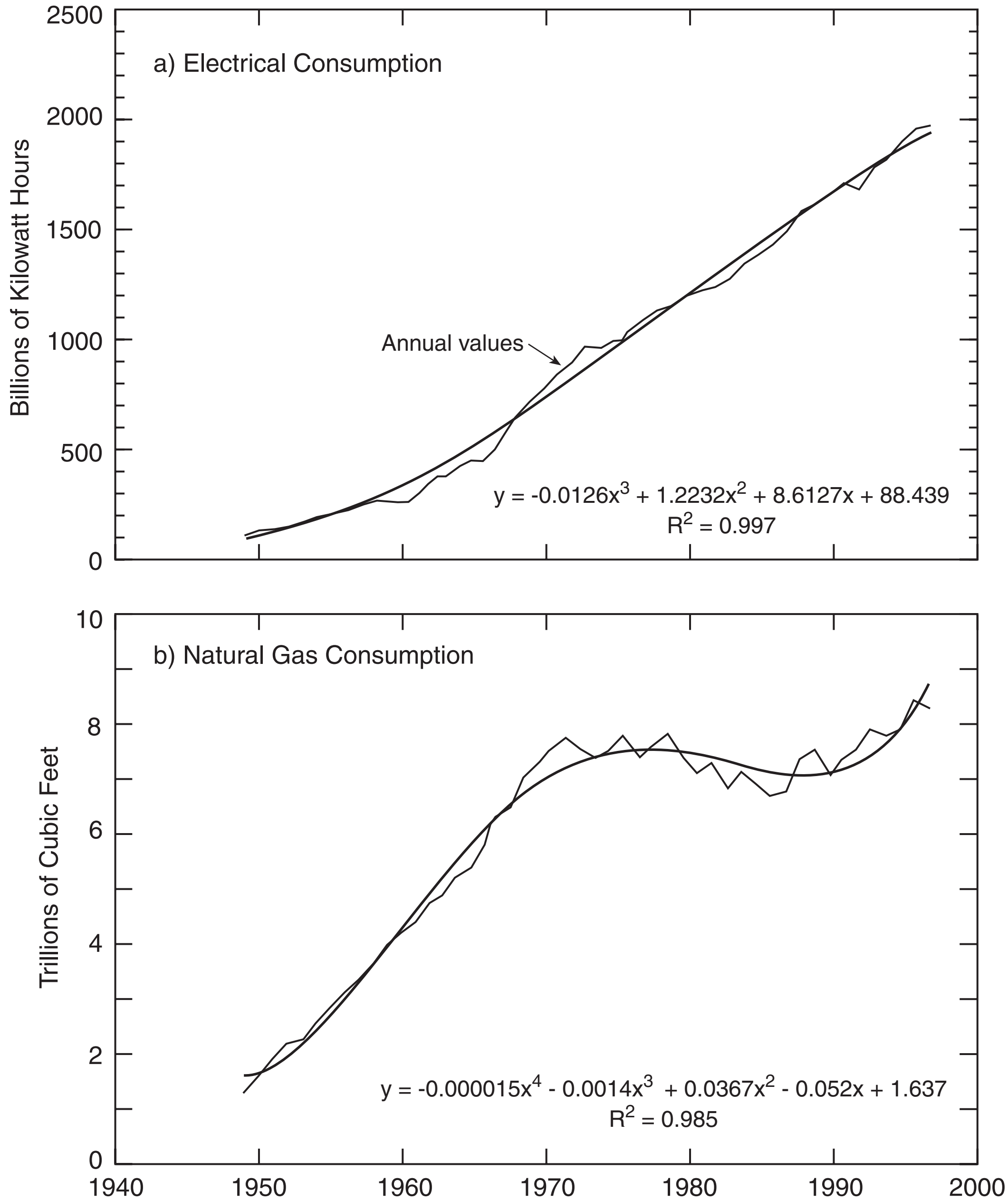


Figure 3-3. Best-fit curves and their equations, as determined for distributions of annual electric consumption values and natural gas consumption values (residential and commercial), 1950-1997 (Changnon et al., 2001)

the expected value of electricity or natural gas usage represented additional (above average) costs due to temperature extremes, whereas those below the curve represented reduced usage, or gains, due to mild temperatures. The actual differences above expected consumption levels for both electricity and natural gas were the variables assessed for benefits (gains) and costs due to temperature extremes.

Based on the annual calculations of differences in consumption due to temperature extremes, the national annual electricity values during 1949-1997 were calculated. These departures, expressed as a percent of the expected annual value, ranged from 1 to 14 percent of the expected values. The departures in kilowatt hours for each year were measured, and costs and gains were assessed based on electric prices in that year. These annual gains/costs then were adjusted to 1997 dollars using the implicit price deflator of the GNP.

Natural gas values during 1949-1997 also shifted over time, reflecting changing demand due to population, commercial growth, the oil embargo of the early 1970s, and other economic factors. Annual values of consumption were also statistically best fit by a fourth-order polynomial function, and the resulting curve (Figure 3-3) depicts for each year the expected gas consumption (residential and commercial) with average temperatures (Changnon et al., 2001). The natural gas excesses for the years when gas usage deviated from the expected level were measured, and these ranged from 1 to 11 percent. The costs for each year were determined using the year's gas price. These annual added cost values were then set to 1997 dollar levels by adjusting for inflation. An example of the calculations, as done for each year, is shown in Table 3-1 for 1970.

## Gains and Losses

Depressions below expected yields of corn, soybean, wheat, and cotton crops during 1950-1997 were analyzed to define weather-caused loss in the nation's primary agricultural production and its value, and yield values above expected levels were defined as weather-caused gains. The percentage departures for each year were used to assess the lost/gained production each year, and the annual values were adjusted to 1997 dollar levels. The resulting loss values for the 1950-1997 period are shown in Table 3-2. The average annual loss for all crops was $2.599 billion. This loss, plus the average crop-hail losses of $270 million, represent between 7 and 9 percent of the annual net cash income for US agriculture in the 1990s.

Values of crop insurance payments and disaster payments for 1981-1994 crop losses were compared with the calculated losses as a means of judging the adequacy of the calculated values (Changnon and Hewings, 2001). Calculated loss values should exceed the two loss payment values since many farm losses are uninsured, and federal relief is only awarded in major disasters. Many crop losses are due to small-scale summer droughts, or to small intense rainstorms that do not cause enough statewide loss to qualify for federal aid (Changnon et al., 1996a). The 14-year payments averaged $1.65 billion per year, compared to calculated losses of $2.66 billion

**Table 3-1. Calculations of the National Cost of Natural Gas, 1970**

| *Variable* | *Difference* |
|---|---|
| Actual consumption | 7.24 trillion cubic feet |
| Expected use with normal temperatures | 6.86 trillion cubic feet |
| Difference due to low temperatures | 0.38 trillion cubic feet |
| Difference value in 1,000 cubic feet | 380 million |
| Cost of gas per 1,000 cubic feet | $6.94 |
| Cost of added use of gas (difference in 1000 cubic feet times unit cost) | $2,637 million |
| Adjustment factor to convert 1970 values to 1997 values | 3.562 |
| Cost of added use of gas in 1970 converted to 1997 | $9,393 million |

**Table 3-2. Financial Losses (1997 dollars) during 1950-1997 Calculated for Major US Crops Based on Weather Extremes**

| *Crop* | *Total loss ($ billions)* | *Average annual loss ($ billions)* |
|---|---|---|
| Corn | 53.850 | 1.122 |
| Soybeans | 27.305 | 0.569 |
| Cotton | 22.982 | 0.479 |
| Wheat | 20.570 | 0.429 |
| Totals | 124.707 | 2.599 |

per year during 1981-1994. Peak insurance and disaster payment periods were $6.56 billion (1988-1989) and $4.15 billion (1993-1994), and the calculated national losses for these two-year periods were $13.204 billion and $6.149 billion, respectively. These results help confirm that the calculated national crop loss values had an appropriate magnitude, well in excess of the total based on crop insurance and federal disaster payments.

Stressful weather conditions causing low crop yields nationally often were matched by other growing seasons with near perfect conditions and high, above expected crop yields (Changnon and Winstanley, 1999). The impacts of better than average growing season conditions on crop yields and the related financial gains also were assessed. Annual economic gains were calculated using the same procedures used to calculate losses. Resulting gains during 1950-1997 were determined and then compared with the losses to gain insights as to their relationship.

Table 3-3 shows the magnitude of the financial gains and losses for each of the four major US crops due to good crop-weather during the 1950-1997 period. The average annual gain from the four crops was $1.901 billion. Corn had the largest gain, and data in Table 3-3 show corn gains occurred in 26 years during the 48-year period. Comparison of the average annual losses with the average annual gains of all four crops reveals that losses exceeded gains. One reason for this outcome is that the annual unit (bushel) prices in good crop years are often lower than those in bad yield years. During this 48-year period there were more loss years than gain years for wheat, but more gain years for corn and cotton. The total national gain in crops from good weather extremes during 1950-1997 amounted to $92.9 billion (1997 dollars), as compared to losses of $124.7 billion.

Economic gains and losses in energy usage associated with extremes, such as cool/warm summers and warm/cold winters, have been assessed (Changnon and Hewings, 2001). Losses were defined as higher costs to consumers but were actually gains for the utilities. Table 3-4 presents the energy usage loss and gain values for 1950-1997. Electric users nationwide benefitted in 22 years largely due to cool summers and mild winters, compared to above average costs in 26 years. The average annual gain was $2.260 billion (1997 dollars) and represented 91 percent of the average annual loss. Total costs for 1950-1997 were $118.984 billion, resulting in an annual average of $2.479 billion for that period.

The natural gas gains to consumers from 22 years with mild cold seasons and much lower heating costs amounted to $1.651 billion (1997 dollars) per year, and represented 76 percent of the average loss experienced (Table 3-4). Both electricity and natural gas usage during 1950-1997 had a few more years with losses than with gains. Collectively, the climate extremes of

**Table 3-3. National Gains and Losses (1997 dollars) Experienced in Crop Yields Due to Weather, 1950-1997**

| *Crop* | *Annual average ($ millions)* | *Number of years of each type* |
|---|---|---|
| Corn | | |
| Losses | 1,122 | 22 |
| Gains | 769 | 26 |
| Cotton | | |
| Losses | 479 | 23 |
| Gains | 261 | 25 |
| Soybeans | | |
| Losses | 569 | 24 |
| Gain | 482 | 24 |
| Wheat | | |
| Losses | 429 | 29 |
| Gains | 389 | 19 |
| 4-crop totals | | |
| Losses | 2,599 | – |
| Gains | 1,901 | – |

**Table 3-4. National Gains and Losses (1997 dollars) Due to Temperature Effects on Energy Usage, 1950-1997**

| *Energy use* | *Annual average ($ millions)* | *Number of years of each type* | *Monetary gains ($) as percent of losses* |
|---|---|---|---|
| Electricity | | | |
| Losses | 2,479 | 26 | – |
| Gains | 2,260 | 22 | 91 |
| Natural gas | | | |
| Losses | 2,171 | 26 | – |
| Gains | 1,651 | 22 | 76 |
| Totals | | | |
| Losses | 4,650 | – | – |
| Gains | 3,911 | – | 84 |

temperature during 1950-1997 produced gains in energy usage that together averaged $3.911 billion per year, as compared with losses that averaged $4.650 billion per year.

## Temporal Trends

The temporal distributions of crop yields and energy use during 1950-1997 were examined (Changnon et al., 2001). One meaningful expression of yield change due to stressful weather conditions is the temporal distribution of the yield departures below the expected annual values, or losses. The temporal distributions of the departures (loss years) in the four crop yields all had relatively flat time trends for their period of record. As shown in Figures 3-4 and 3-5, the timing and magnitude of the fluctuations of the corn and wheat yields are quite different. Low corn yield departures in recent years (1983 and 1988) match those of the 1930s, all at about 70 percent of expected values. Recent wheat departures below the trend are not as low as those experienced in the 1930s and 1950s. Table 3-5 presents the average departures as percentages of the yields of the four crops for 1950-1973 and 1974-1997. The magnitude of the weather-induced low yields has increased over time for corn (from 6.4% to 9.4%), soybeans, and cotton, but has decreased for wheat.

The time distributions based on the annual departures of natural gas consumption and electricity consumption appear in Figures 3-6 and 3-7, respectively. Both the natural gas and the

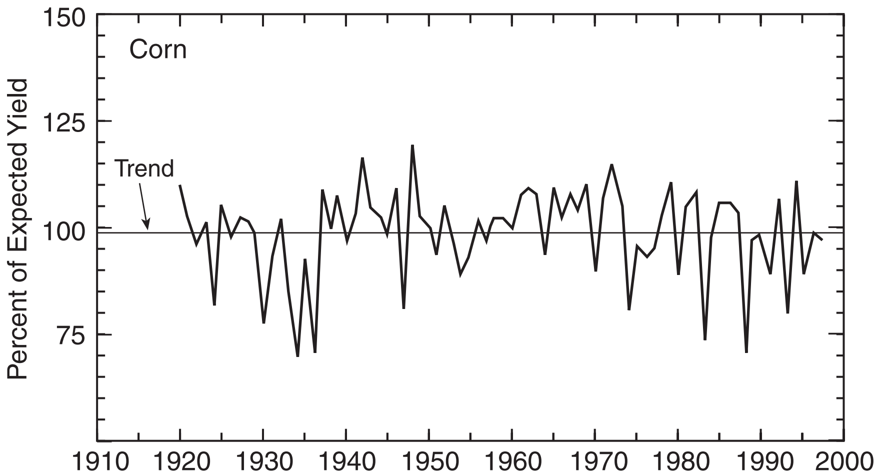


Figure 3-4. Annual departures (%) of US national corn yields from expected values with average weather conditions, 1920-1997, and the linear trend (Changnon and Hewings, 2000)

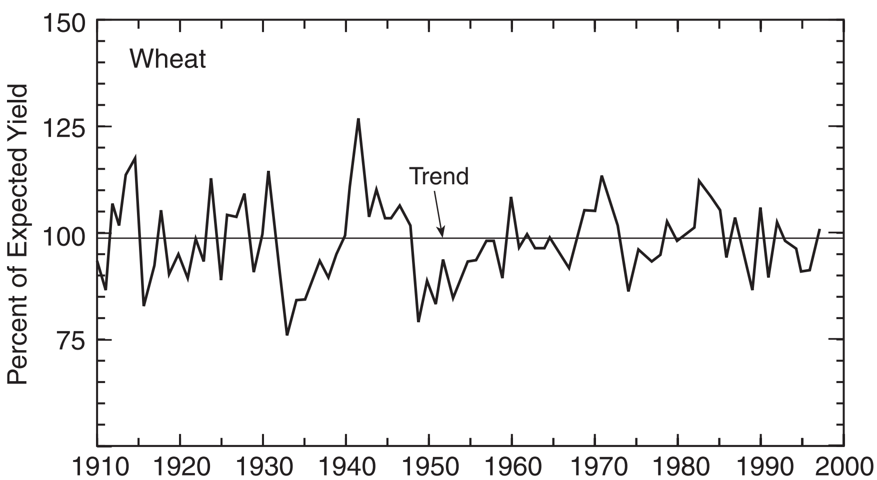


Figure 3-5. Annual departures (%) of US national wheat yields from expected values with average weather conditions, 1910-1997, and the linear trend (Changnon and Hewings, 2000)

**Table 3-5. Average Departures (%) of National Crop Yields below Expected Yield Values (Losses), 1950-1973 and 1974-1997**

| *Period* | *Corn* | *Cotton* | *Soybeans* | *Wheat* |
|---|---|---|---|---|
| 1950-1973 | 6.4 | 10.7 | 5.3 | 6.1 |
| 1974-1997 | 9.4 | 13.9 | 8.1 | 5.8 |
| Difference | +3.0 | +3.2 | +2.8 | -0.3 |

electricity use departures decreased over time during 1950-1997, and the 48-year declines in natural gas and electricity use were both statistically significant at the 5 percent level.

To further examine the temporal changes, the departures above the natural gas and electricity curves, representing years of higher consumption due to weather demands, were compared for 1950-1973 and 1974-1997. Table 3-6 presents the average percentage departures above the expected values for these two 24-year periods for natural gas consumption and electricity consumption. The values further illustrate that weather-induced expenditures for electricity and natural gas substantially decreased over time.

## Temporal Fluctuations in Weather and Climate Extremes

A necessary aspect for assessing the economic impacts of climate conditions, particularly with reference to changes over time, is to assess the temporal behavior of individual weather and climate conditions. This information provides a basis for comparing the temporal behavior and economic impacts attributed to particular conditions. If losses related to a given weather condition are increasing, but the condition itself is decreasing, the difference helps point to other nonatmospheric factors affecting the losses.

Following are the highlights drawn from the findings from two major studies of the temporal behavior of various extreme climate conditions. Kunkel et al. (1999b) assessed trends in both impacts and several climate conditions, and another study (Changnon and Hewings, 2001) measured fluctuations in several storm conditions.

### Floods

While excess precipitation is the fundamental cause of hydrologic floods, other factors play an important role, for example, antecedent soil moisture, rate of melt in snowmelt floods, and the physical characteristics (size, topography, and control structures) of basins. However, most studies of climate trends have focused on precipitation only. Several recent studies have indicated a trend to more frequent heavy precipitation events. Karl et al. (1995) found that 1-day heavy precipitation events exceeding 5.1 centimeters (2 inches) have made an increasingly large contribution to annual precipitation over the United States since 1910. Heavy precipitation events of 7-day duration are closely related to hydrologic flooding occurrences on small to medium-sized rivers, and trends in 7-day heavy precipitation events for the entire country were examined (Kunkel et al., 1999a). They found (Figure 3-8) increases in the frequency of heavy events when averaged over the entire United States.

Measures relating to annual extreme wet conditions were based on the national values developed for the Palmer Drought Severity Index (PDSI). This widely used meteorologically

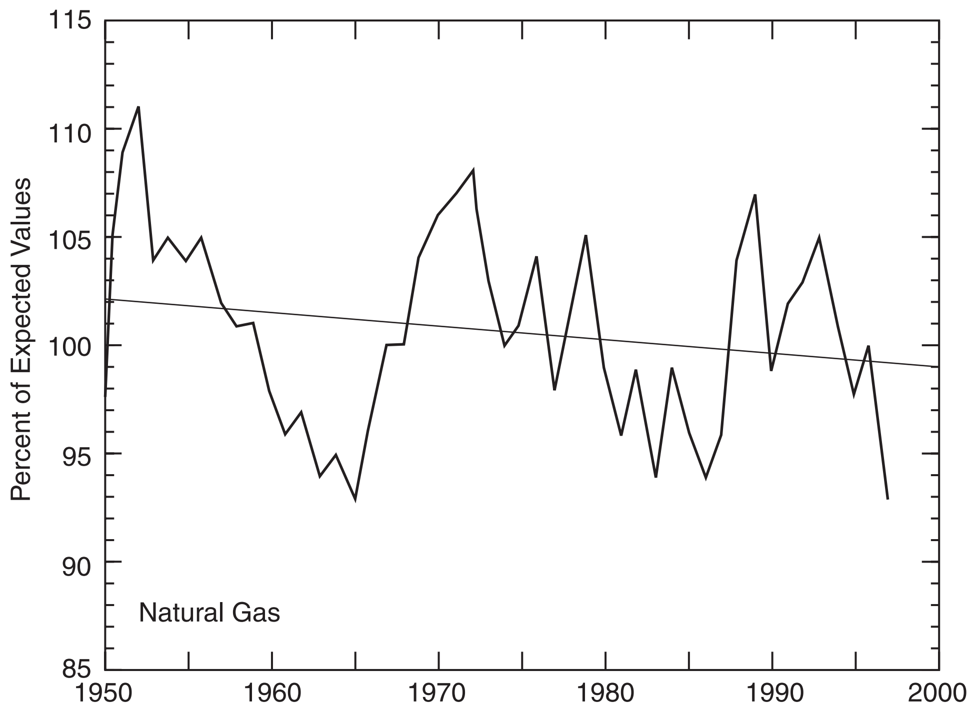


Figure 3-6. Annual US natural gas usage, expressed as a percent of annual expected value with average weather conditions, 1950-1997, and the trend line (Changnon et al., 2001)

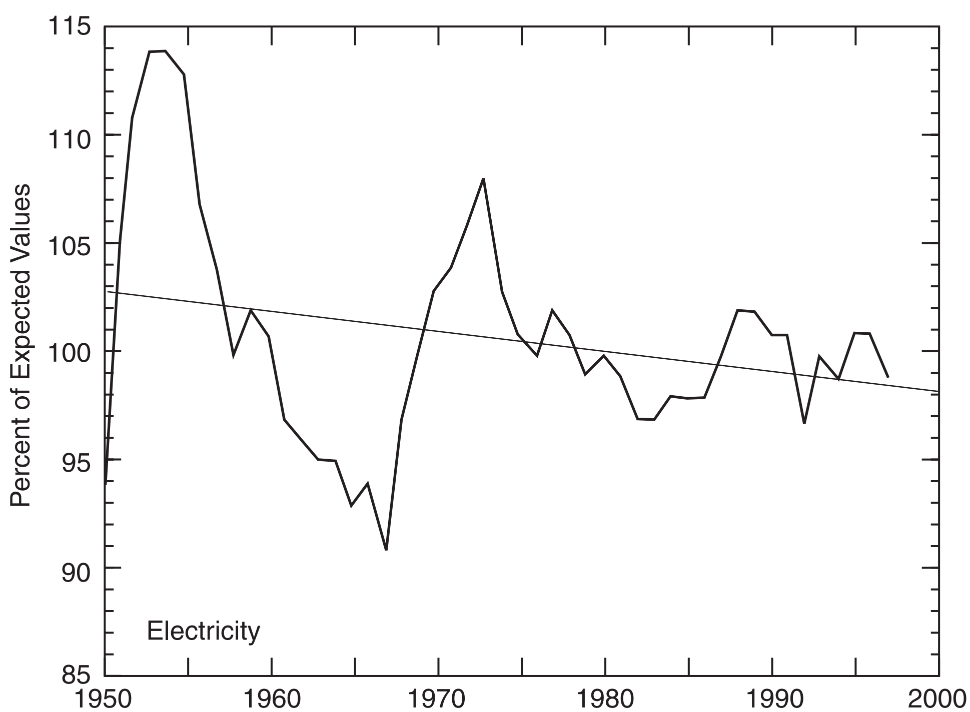


Figure 3-7. Annual US electricity usage, expressed as a percent of annual expected value based on average weather conditions, 1950-1997, and the trend line (Changnon and Hewings, 2000)

**Table 3-6. Average Departures (%) of National Annual Electric Use and Natural Gas Use above Expected Values, 1950-1973 and 1974-1997**

| *Period* | *Natural gas* | *Electricity* |
|---|---|---|
| 1950-1973 | 4.4 | 5.5 |
| 1974-1997 | 3.1 | 1.5 |
| Difference | -1.3 | -4.0 |

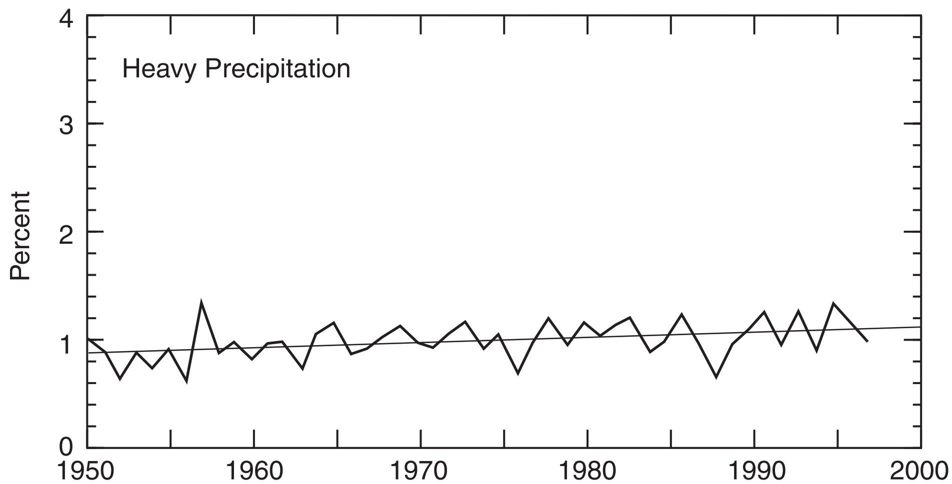


Figure 3-8. Annual percent of the United States experiencing heavy precipitation amounts over 7-day periods that met or exceeded the once in 5-year frequency levels, 1950-1997, and the trend line (Changnon and Hewings, 2000)

based index uses precipitation and temperature data to estimate soil moisture conditions on a monthly basis and for various US locations. Departures from average conditions are quantified and values of 3 (or greater) on the wet side are labeled as a “severe moisture surplus”. These values were used to calculate for each year what percent of the United States was experiencing such a surplus. Annual values were available for 1901-1997, and Figure 3-9 shows the percent of the US area experiencing severe soil moisture surplus using the PDSI. Since about 1970, the percent area has been high relative to the long-term mean.

Lettenmaier et al. (1994) and Lins and Slack (1997) found upward streamflow trends, consistent with the observed upward trends in heavy precipitation. Changnon and Kunkel (1995), in a study of peak streamflows for selected Midwestern US basins, found upward trends for many locations in the upper portion of the Mississippi River basin. Although all these studies are revealing, extensive human modification of river basins makes it very difficult to assess long-term trends in peak flows on a national basis and relate this to flood damage. Figure 3-10 shows the timing of major floods on the Mississippi River at St. Louis since 1840. Two measures are shown: peak stages (height of the river level) and peak discharges (volume of water passing). Development of a major levee system on the river over time greatly has influenced the stages by

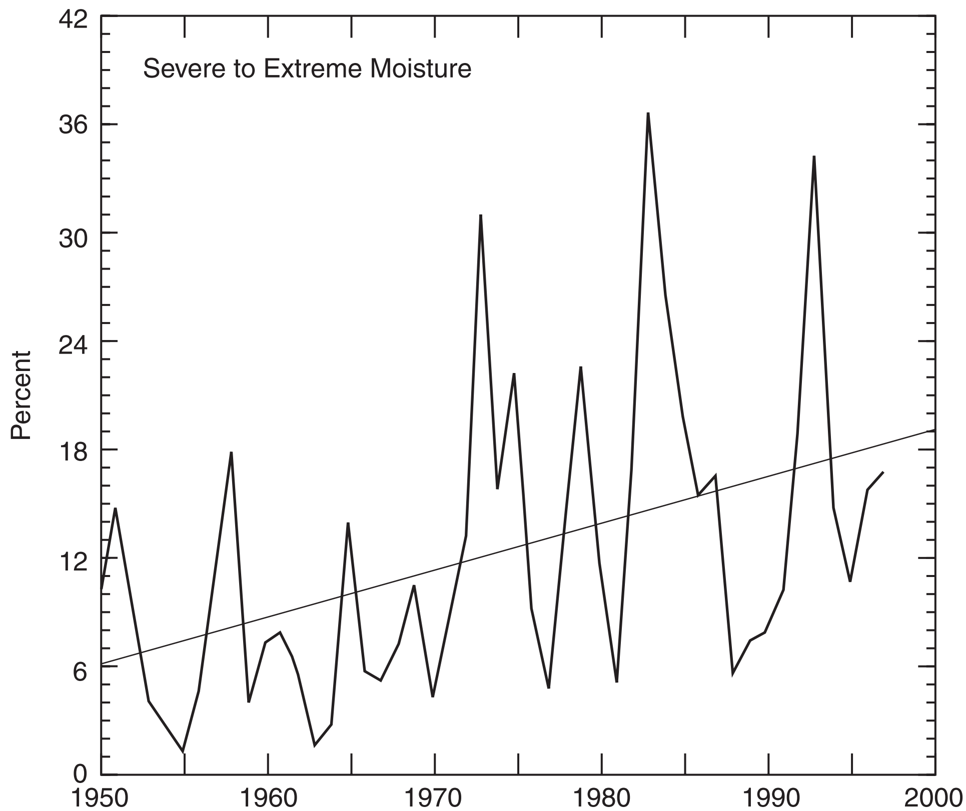


Figure 3-9. Annual percent of the United States experiencing severe to extreme moisture surplus, 1950-1997, and the trend line (Changnon and Hewings, 2000)

forcing the river to stay in its channel and rise increasingly higher, relatively speaking. Peak stages (Figure 3-10a) have been concentrated over the last 50 years. However, the peak discharge (Figure 3-10b) is less affected by human intervention in the basin's land use than the crest. Major floods, as measured by the volume of water, have a very different temporal distribution. The largest flood on record, by this measure, occurred in 1844, followed by the floods in 1903 and 1993. More importantly, the temporal distribution of the major discharge floods reveals that they are well distributed over the 160-year period, with no obvious long-term trend.

In sum, available data indicate that flood-related damages have increased in recent decades. There is a corresponding increase in the frequency of heavy precipitation events and in the percentage of area experiencing excessively moist conditions. However, because of the limited nature of the impacts data (Downton and Pielke, 2001), little can be said about the relative contributions of physical forcing (i.e., increases in flood-producing precipitation) and changes in societal vulnerability as causes of the impacts trends.

## Hurricanes

Two measures of hurricane activity were assessed: all land-falling hurricanes and those classified as intense based on peak winds. The frequency of land-falling hurricanes over time decreased (Kunkel et al., 1999b). The annual incidences of intense land-falling hurricanes, rated

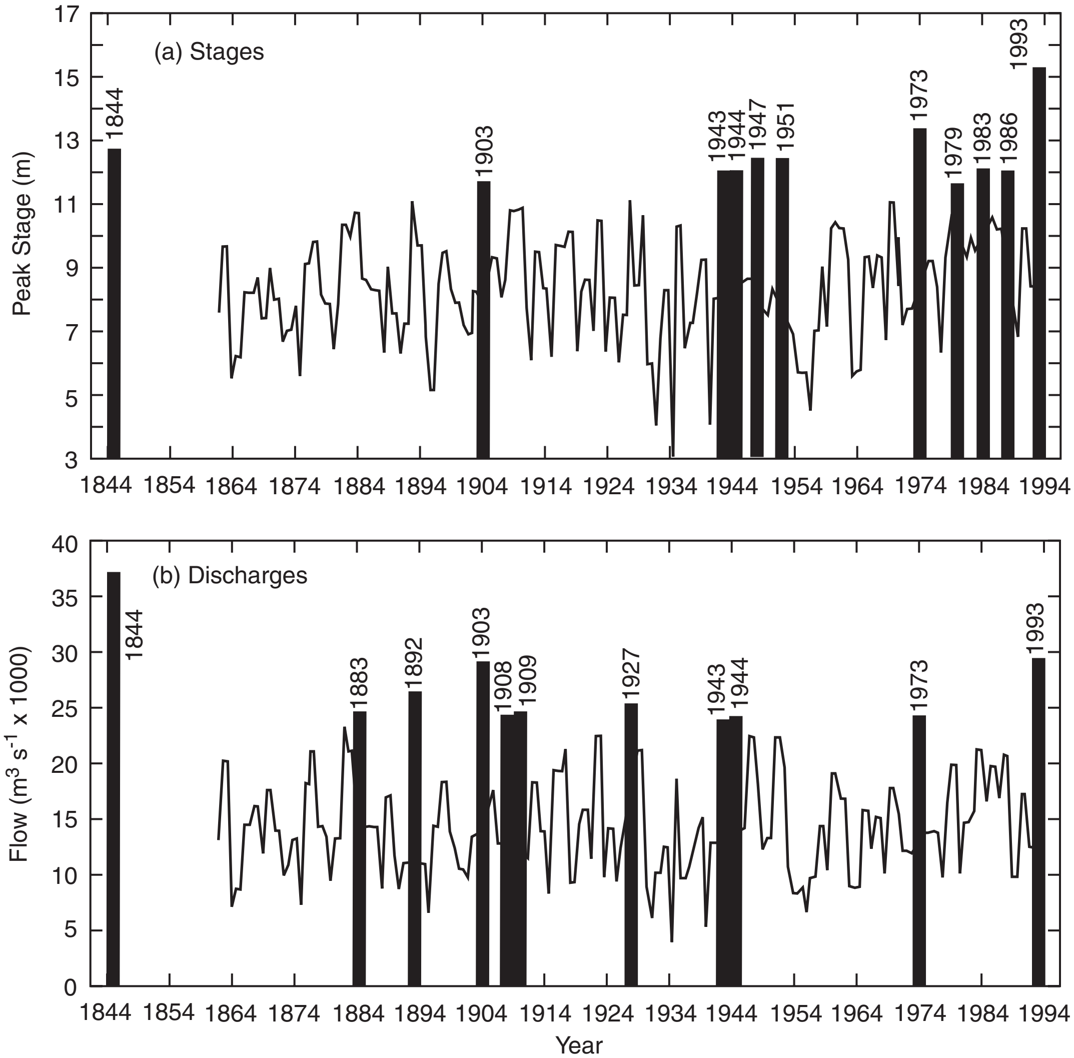


Figure 3-10. Annual values of a) peak stage (m) and (b) peak discharge ($m^3$ $s^{-1}$ x 1000) on the Mississippi River at St. Louis, MO, for 1844-1993 (Kunkel et al., 1999)

as 3, 4, or 5 on the Saffir/Simpson hurricane scale, account for 80 percent of all hurricane losses (Pielke and Landsea, 1998). The scale of 3 and higher depends on the storm's central pressure being less than 27.91 inches, wind speeds above 111 mph, and storm surges of 9 feet or higher. Figure 3-11 shows their 1950-1997 frequency, revealing a major decrease significant at the 1 percent level (Changnon and Hewings, 2000).

The increase in hurricane damages (unadjusted) over recent decades has occurred almost entirely during an extended period of decreasing hurricane frequencies and intensities. This means that fewer storms are responsible for the increased damages, and these storms are no stronger than those of past years. Clearly, the primary factor responsible for the increase in damages is the rapid population growth and development in vulnerable coastal locations, rather than storm numbers and strength (Pielke and Landsea, 1998).

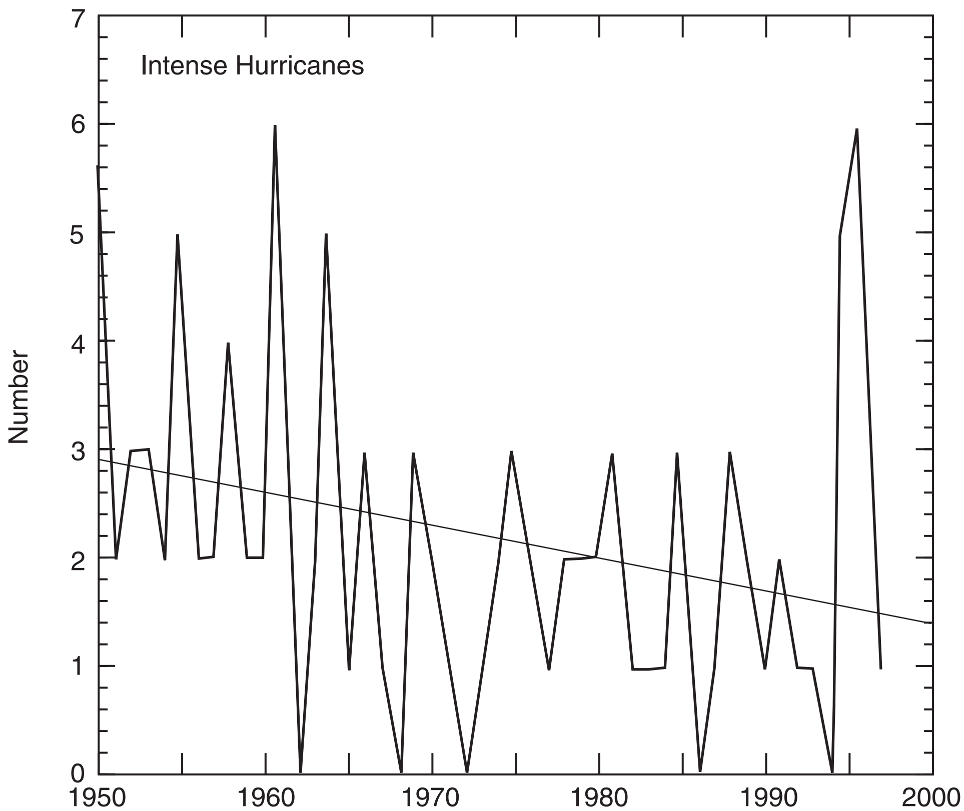


Figure 3-11. Annual number of intense hurricanes (level 3, 4, or 5 on Saffir/Simpson scale), 1950-1977, and the trend line (Changnon and Hewings, 2000)

## Thunderstorms

Based on data from 160 first-order weather stations located around the nation, the national average number of thunderstorm days during 1910-1997 had a downward trend (Figure 3-12). Annual averages declined over time from 40 days in 1910 to 38 days in 1997, an outcome similar to the trends in the frequencies of hail days and killer tornado days. The thunder-day decline was statistically significant at the 2 percent level, and agreed with the downward trend in national thunderstorm losses over time (see Figure 3-21). Changnon (2001) found that thunderstorm-created losses had increased in Florida and the West Coast, but storm frequencies had not increased in these areas. This suggested the increased losses were a result of the large regional growth of population and wealth in these areas.

## Hail

The US Weather Bureau began to compile records of all incidences of hail at all weather stations in 1896, and these serve as a means for comparison with the crop-hail and property-hail loss data. The average number of hail days per year for 1910-1996, based on data from 1,012 US weather stations where 93 percent of all insured losses occur, had a downward trend (Figure 3-13). This agreed with the temporal downward trend in the crop-hail loss distribution, but property losses from hail had a major increase during the past 15-20 years, and mainly in large cities.

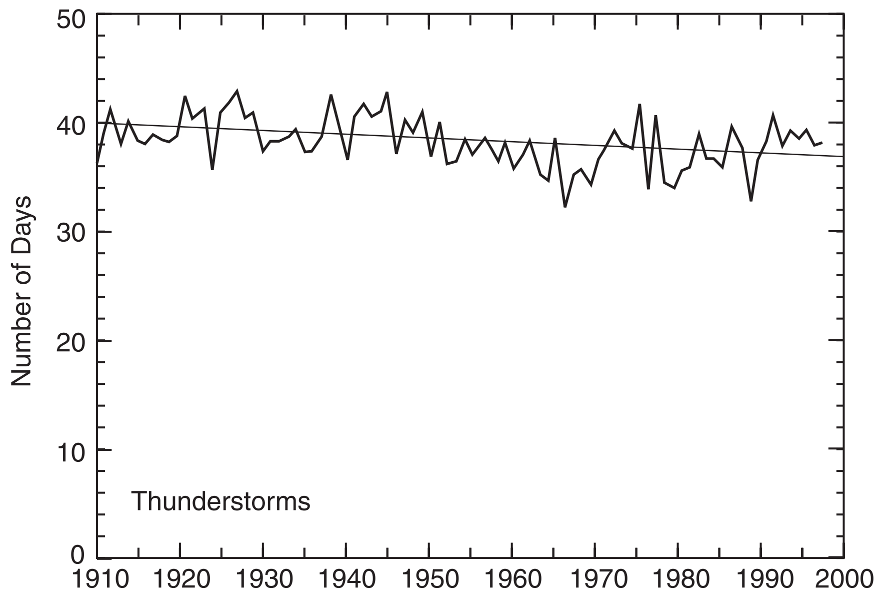


Figure 3-12. Annual average number of thunderstorm days in the United States, 1910-1997, and the trend line (Changnon and Hewings, 2000)

## Tornadoes

The number of tornado days reported nationally during 1953-1997 shows a slight increase over time until 1970, and a flat trend thereafter. Unadjusted tornado losses also showed a temporal increase. However, the national number of killer tornadoes, those tornadic storms leading to one more deaths during 1953-1997, showed a marked temporal decrease. Violent tornadoes, defined as those having reached a wind speed of F4 or F5 (speeds > 207 mph) also were analyzed. Annual data for these intense events (Figure 3-14) for the 1950-1997 period revealed a steady decline over time (Changnon and Hewings, 2000). The increases noted for all tornadoes and their losses are considered a result of growing population and more attention to tornado occurrences, collectively leading to more tornadoes seen over time (Kunkel et al., 1999b).

## Winter Storms

Winter storm losses, based on insurance data for 1950-1997, have undergone a marked increase over time. Extratropical cyclones (ECs) are primarily responsible for the oft damaging winter season storms. Very strong ECS develop along the nation's East Coast because of strong horizontal temperature gradients, which provide the energy for ECs, and are often present, a result of the warm Gulf Stream to the east and cold air to the west that forms over the snow-covered continental interior. The high population density and extensive coastal development make this region particularly vulnerable to damage from high winds, coastal flooding, heavy snow, and icing. The frequency of strong, damaging East Coast ECs, termed nor'easters, generally increased from 1965 into the 1980s (Davis et al., 1993). One of the most damaging aspects of nor'easters is coastal flooding caused by strong onshore wind flow. The steady increase in the frequency of high water levels from the early 1900s into the 1990s was attributed to sea-level rise (Zhang et al., 1997). Thus, observed increases in damage may not be due only to an increased

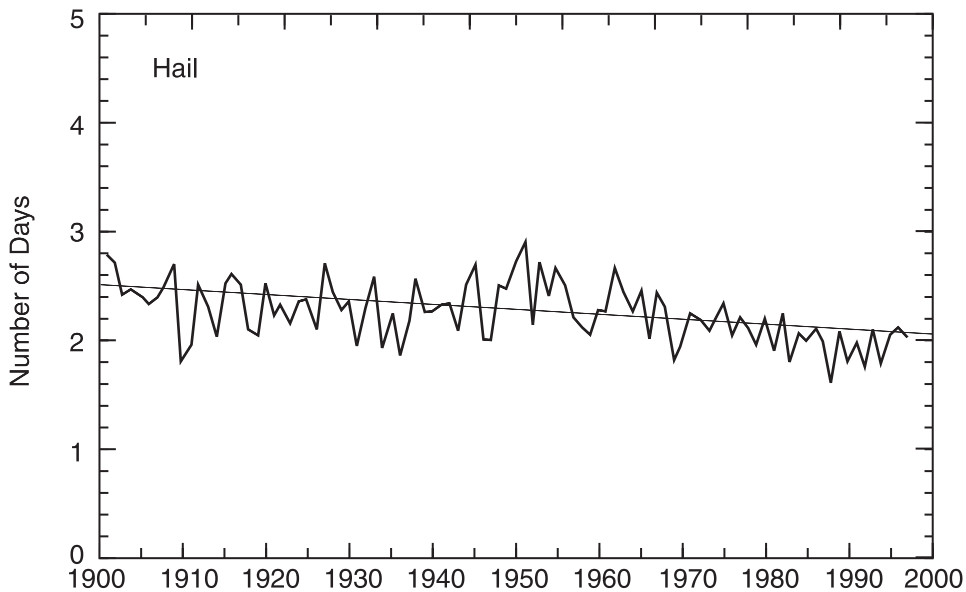


Figure 3-13. Average annual number of US hail days, 1900-1997, and the trend line (Changnon and Hewings, 2000)

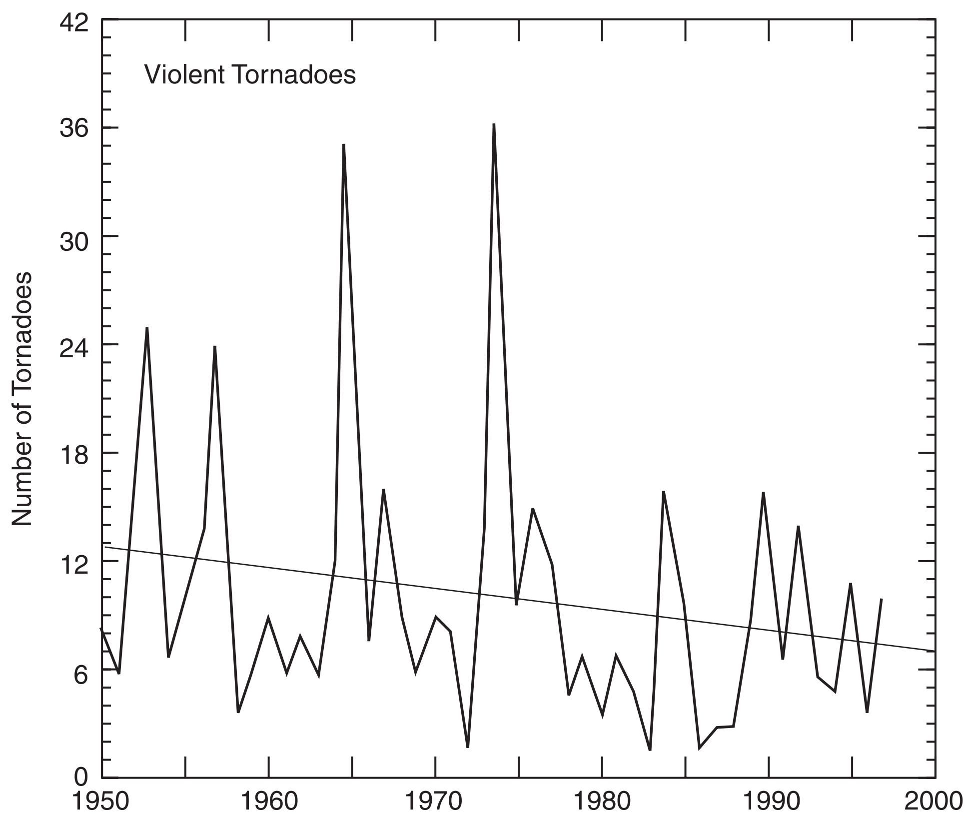


Figure 3-14. Annual number of violent tornadoes (F4 or F5), 1950-1997, and the trend line (Changnon and Hewings, 2000)

frequency of strong nor'easters, but also due to a more vulnerable coastline. The increase in winter storm losses is associated with both societal and climatological factors, but further research is needed to discern the relative contribution of each (Kunkel et al., 1999b).

### Droughts

Departures from average conditions on the PDSI are quantified, and values of 3 (or greater) on the dry side are labeled as a severe drought. These values were used to calculate what percent of the United States was experiencing severe drought each year. Annual values of each condition were available for 1901-1997. Figure 3-15 shows the PDSI for 1950-1997, revealing a steady decline over time.

Droughts defined using the impacts created in the hydrologic cycle for the nation from 1895 to 1990 are shown (Figure 3-16). The hatched areas are based on hydrologic drought indices exceeding 3, which means that streamflows were significantly decreased. Nationally, these decreases reflect the prolonged hydrologic droughts of the 1930s and the 1950s. All other hydrologic droughts of the past 100 years were shorter (1-2 years), and were scattered throughout the entire 1895-1990 period. There is no indication of a shift in hydrologic drought frequency over time. The two major events of the mid-century dominate the distribution.

### Extreme Heat and Cold

Extremes of temperature cause losses to crops and property. Rogers and Robli (1991) conducted a study of winter freezes that damaged Florida citrus areas. They found a cluster of severe freezes since the late 1970s, the most frequent occurrence of freezes since the late 19$^{th}$ Century. They identified six major freezes during 1977-1989, which resulted in a significant

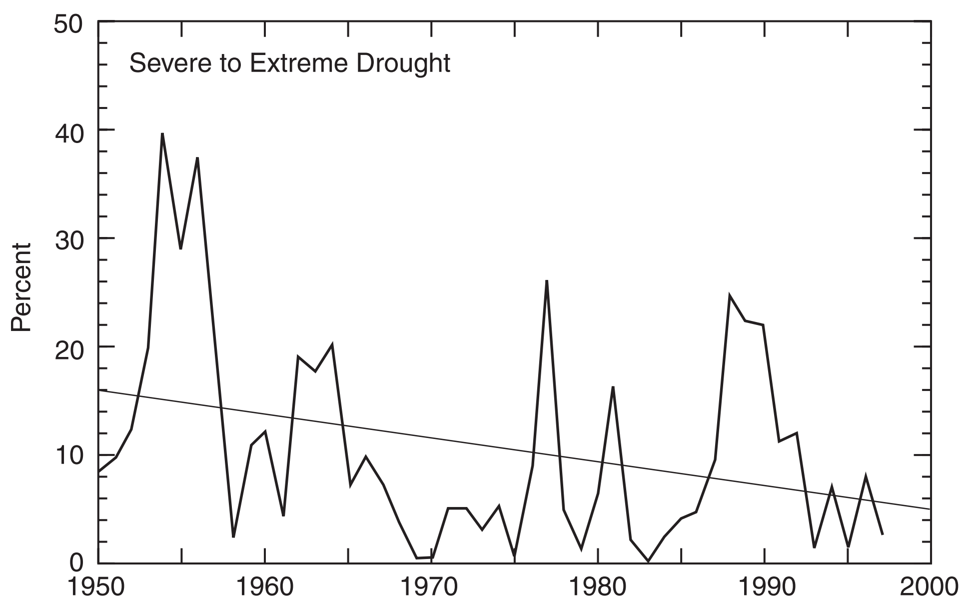


Figure 3-15. Annual percent of the United States experiencing severe to extreme drought, 1950-1997, and the trend line (Changnon and Hewings, 2000)

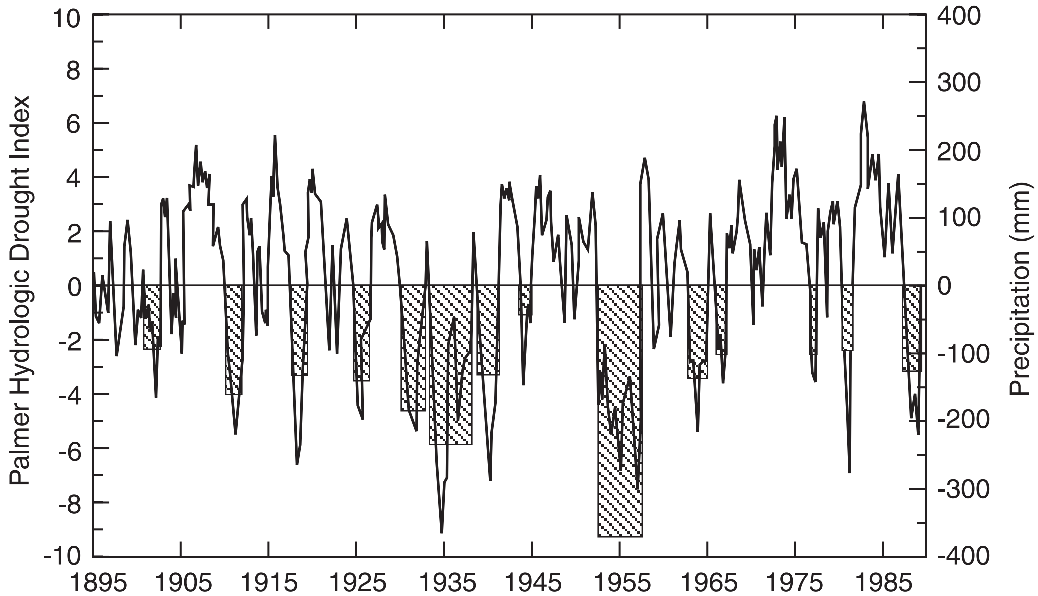


Figure 3-16. Palmer Hydrologic Drought Index values for the United States, 1895-1990 (Kunkel et al., 1999b)

decrease in citrus production (Miller, 1988). During the earlier part of the 20th Century, severe freezes occurred only about once per decade.

The ten warmest four-day periods in the central United States were identified using long-term temperature data. A heat wave frequency index was produced by averaging each year's frequency of heat waves for all area stations (Figure 3-17). The dominant feature is the high frequency during the 1930s. The year with the highest frequency since then was 1988. The 1995 heat wave that killed 770 persons barely registers on this graph, because it was of relatively small spatial extent; unfortunately, it was most intense over the region's largest population center, Chicago. Overall, there is no indication of a trend on a regional basis. A national heat wave index computed back to 1931 (not shown) also showed no evidence of an upward or downward trend. A recent study of trends in extreme temperatures for the northeast United States for the period 1951-1993 found a statistically significant decrease in the number of days with temperatures exceeding 95°F (DeGaetano, 1996). The study also found a general increase in the number of days with temperatures below freezing; however, this trend was not statistically significant. By contrast, Balling and Idso (1990) studied trends in extreme high summer temperatures in the United States for the period 1948-1987, and they found that the frequency had increased. Cooling degree-days, on a national scale, decreased from 1950 to 1997 (Changnon et al., 2001).

An index of winter freezing for the central United States (Figure 3-18), computed in a similar manner to the heat wave frequency index, shows evidence of an increase since 1953. In particular, intense cold waves in the 1970s stand out. On a national basis, this recent increase is not as evident, although the 1983 and 1989 events were widespread. Heating degree-days, on a national scale, decreased from 1950 to 1997 (Changnon et al., 2001).

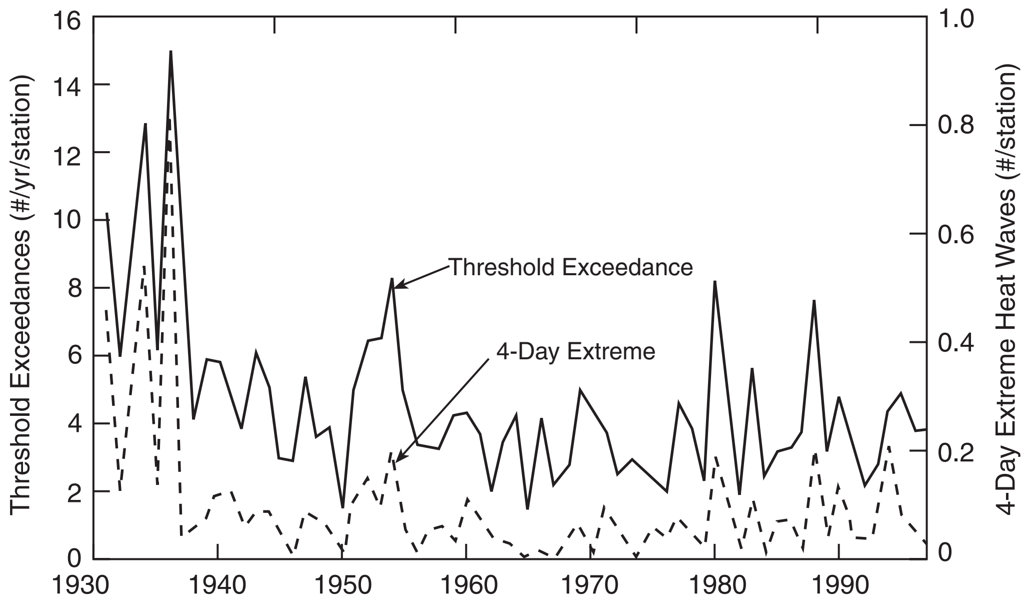


Figure 3-17. Number of days with a maximum temperature above the threshold for a 1.5 percent daily exceedance probability (solid line) and number of 4-day heat waves with an average temperature exceeding the threshold for a one in 10-year recurrence (dashed line); each curve represents an average of 876 long-term stations (Kunkel et al., 1999)

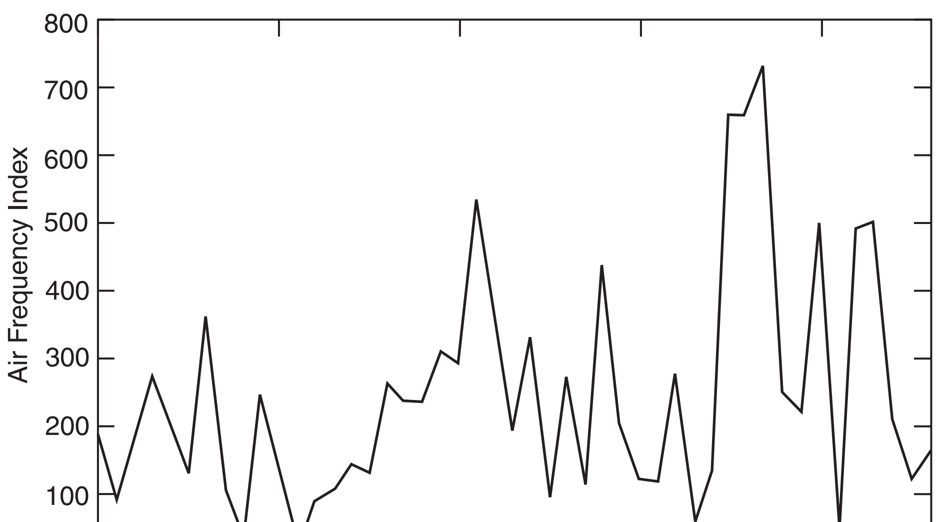


Figure 3-18. Winter freezing indices for St. Louis, 1941-1942 to 1987-1988 (Kunkel et al., 1999)

## Summary

The temporal results for US conditions agree with the findings of a recent IPCC report. Studies have documented various increasing and decreasing regional trends in the frequency or magnitude of extreme events. It is difficult for scientists to discern global trends in extreme events, however. As the IPCC (1996) notes: Overall, there is no evidence that extreme weather events, or climate variability, has increased, in a global sense, through the 20$^{th}$ Century, although data and analyses are poor and not comprehensive. On regional scales, there is clear evidence of changes in some extremes and climate variability indicators. Some of these changes have been toward greater variability; some have been toward lower variability.

Short summaries of findings for specific types of extremes and their economic impacts follow.

1) Flood damages, after normalization, have been higher over the last 25 years than during the previous 65 years. The last 25 years also have been characterized by a high frequency of heavy rain events. Thus, there is some atmospheric evidence to support that the observed impacts trends are at least partially the result of climate trends. However, there have been increases in societal exposure to floods, coupled with human changes in major rivers (for example, levee systems), that collectively would increase flooding losses. Flood losses over time increased at a greater rate than did precipitation shifts.

2) There has been a steady and substantial increase in hurricane losses. However, there has been no corresponding upward trend in hurricane frequency or intensity. Observed loss increases are due entirely to increased societal exposure (population and structures) along vulnerable coastlines. In fact, the hurricane loss data, when normalized for exposure, do not show an increase over time (Figure 3-19).

3) Convective storm conditions (hail and tornadoes) display mixed outcomes. The number of hail days and crop-hail losses have decreased over time, but property losses from hail have increased. Tornado losses show an increase over time, but the number of intense tornadoes has actually decreased over time. These differences between the property losses and the storm frequencies suggest that societal factors have increased the risk of property damage from these storms.

4) Winter storm damages have increased over the last 10-15 years. There is evidence that increased frequency of intense nor'easters partially may be to blame for the increased losses. However, such factors as sea-level rise and coastal development have increased societal vulnerability to such storms. Increased losses related to winter storms appear largely related to societal changes.

5) While the drought of 1988 stands out for its large losses, there is no evidence of a long-term trend in drought-related losses in the United States. There is evidence of a recent downward trend in climatological drought conditions. Droughts during the 1930s and 1950s remain the dominant features of this century.

6) Recent heat waves have caused extensive deaths. Comparison with severe heat waves of the 1930s suggests that society is at increased risk for a variety of reasons, such as an

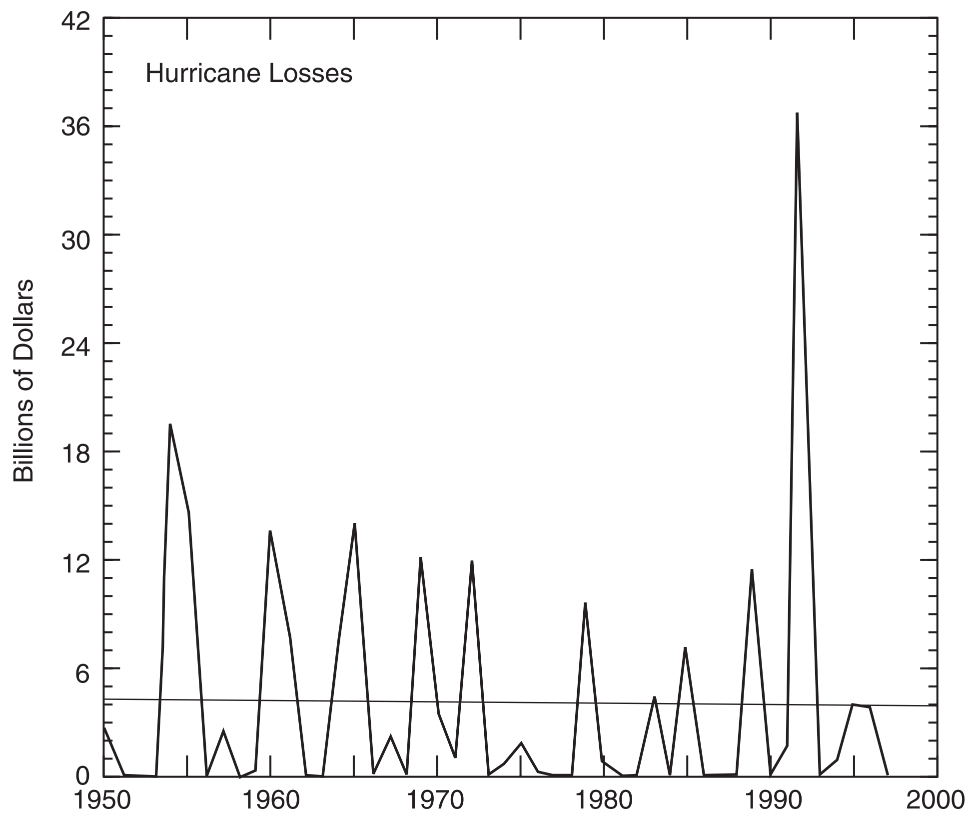


Figure 3-19. Annual normalized hurricane losses (billions of 1997 dollars), 1950-1997, and the linear trend (Changnon et al., 2001)

aging population and cultural changes. Further, there is no evidence that the frequency of high temperatures and severe heat waves has increased. The high frequency of intense heat during the 1930s dominates a time series of heat waves. During the last 15 years, there have been several intense cold waves, and the time series suggests an upward trend in the central United States. However, there is no compelling evidence for any national trend. Heating and cooling degree-days both display downward trends over time.

## National Impacts of Damaging Storms

### Data and Analysis

Various sources of data on the economic impacts of storms were assessed and used in this analysis (Changnon and Hewings, 2000). Various types of insurance data and data from the National Weather Service (NWS) were included.

#### *Property Insurance Data on Weather Catastrophes*

Property insurance industry records of storm catastrophes for 1949-1997 are considered the nation's premier property loss data (NAS, 1999). Catastrophes are defined by the insurance industry as events that cause sufficient insured losses to exceed a threshold set by the insurance industry. Catastrophe losses include damages to property and to the contents of damaged facilities, costs of business interruptions, and additional living expenses due to loss of residence. Catastrophe losses were assessed for those due to hurricanes, tornadoes, severe thunderstorms (lightning, high winds, and heavy rains), hail, winter storms, and windstorms. Catastrophe data are limited because they do not represent all the property damage. Insurance experts have estimated that between 5 and 15 percent of all property loss is uninsured against weather hazards, excluding floods (R.J. Roth, personal communication, May 1999). Further, some property losses occur in weather events that did not qualify as catastrophes. Catastrophes account for approximately 90 percent of all weather-caused insured property losses (E. Lecomte, personal communication, May 1999).

The dollar level used by the insurance industry to define catastrophes has changed over time to adjust for inflation ($1 million for 1949-1982, $5 million for 1983-1996, and $25 million in 1997). Further, individual catastrophe values available for this study, approximately 1,000 events during 1949-1997, each had been modified by insurance experts to adjust for shifts in insurance coverage (where the damaging event occurred), changes in property value, and shifts in costs of repairs. The need to adjust for these changes is revealed by the fact that a $1 million storm catastrophe was typically defined by 6,000 claims in 1950-1970, whereas a $5 million catastrophe typically was based on only 3,000 claims in 1997, reflecting the shifts in wealth and insurance coverage (G. Kerney, personal communication, June 1999). All adjusted storm (catastrophe) values also were normalized to 1997 dollar values.

Analysis of catastrophes was based on those that produced losses >$5 million, a level chosen to provide uniformity in events selected from 1949 through 1997. The sampling adequacy of using the $5 million catastrophes was investigated using the 1950-1982 data. During this period, the insurance industry had used $1 million as the baseline for selecting a loss event as a catastrophe. Inspection of the adjusted loss values during this 33-year period revealed that catastrophes producing less than $5 million in losses represented only 3.7 percent of the 751 catastrophes during this period, and their losses accounted for only 0.4 percent of the total losses. Annual catastrophe loss values were further adjusted to 1997 values to account for changing population density in the nation. In 1950 the US population was 43 persons per square mile, but this had increased to 74 persons per square mile by 1997, a 72 percent increase in density. The past annual catastrophe loss values were adjusted based on population adjustment factors determined for each year, the ratio of the year's population to that in 1997. For example, the population in 1997 was 1.3015 times that in 1970; hence, the catastrophe losses in 1970 were multiplied by 1.3015 to adjust them to 1997 values.

### *Crop-Hail Insurance Loss Data*

Data from the crop-hail insurance industry measured the nation's insured hail and wind crop losses. Since 1948, this industry has computed the national annual total losses, total liability, and a loss cost value, which is the annual losses ($) divided by annual liability ($) multiplied by $100. This value normalizes the loss to exposure and changing dollar values, making it comparable between years (Changnon and Changnon, 1997). The loss cost values were used to adjust the historical crop-hail loss values to the 1997 level. Hail and wind account for 26 percent of the losses to corn and soybean yields (Changnon, 1972). Data analyzed were the national annual crop-hail losses, adjusted to 1997 dollars, for 1948-1997.

### *Hurricane, Tornado, and Flood Losses*

Measures of the annual monetary losses caused by hurricanes, tornadoes, and floods, which had been normalized for each condition and developed for use in temporal assessments of losses, were those used herein (Pielke, 1999). The normalization method addresses inflation and changes in storm area wealth and population, and is described in Pielke and Landsea (1998). Loss normalized data included annual US flood damages for 1903-1997, annual hurricane losses for 1900-1997, and annual tornado losses for 1950-1997.

## Magnitude of Total Losses

The total losses and annual averages (normalized to 1997 dollars) for the 1950-1997 period and for each storm type appear in Table 3-7. The leading cause of loss was hurricanes, and normalized hurricane losses for 1900-1997 were $491 billion, with an annual average of $5.05 billion. However, the 1950-1997 average was less, $4.235 billion. Data on losses due to flood damages ranked as second largest. The NWS has collected flood loss data since 1932, and annual values were adjusted to 1997 dollars. The 1932-1997 loss from floods was $174.5 billion, and that for 1950-1997 was $152.7 billion. Flood losses averaged $3.182 billion annually for 1950-1997 (Table 3-7).

The only consistently good economic data on losses from severe thunderstorms (heavy rainfall, lightning, and high winds) were derived from 1949-1997 catastrophe data. These catastrophes, each costing >$5 million, produced a 1950-1997 period total of $78.335 billion in insured property losses. This resulted in an annual average loss of $1.632 billion, third highest (Table 3-7).

Data on tornado losses, as collected by the Nuclear Regulatory Agency for the 1950-1994 period (and the NWS since 1994), adjusted to 1997 dollar values (Pielke 1999), produced an average annual loss of $448 million.

**Table 3-7. National Losses/Costs (1997 dollars) Due to Storm Damages, 1950-1997**

| *Weather extreme* | *1950-1997 total ($ billions)* | *Annual average ($ billions)* |
|---|---|---|
| Hurricanes | 203.280 | 4.235 |
| Floods | 152.770 | 3.182 |
| Thunderstorm catastrophes | 78.335 | 1.632 |
| Tornadoes | 20.160 | 0.448 |
| Crop-hail losses | 12.960 | 0.270 |
| Hail catastrophes | 8.530 | 0.174 |
| Winter storm catastrophes* | 8.452 | 0.282 |
| Wind storm catastrophes | 8.062 | 0.168 |
| Totals | 492.549 | 10.391 |

**Note:** *The winter storm values are based on 1968-1997 data; no winter storm losses were reported in 1950-1967.

Hail and associated wind losses to crops, as measured by the insurance industry for the 1949-1997 period, averaged $270 million annually (adjusted to 1997 dollars). Property losses from hail averaged $174 million per year. The only consistent long-term data on losses from winter storms available were based on 59 insured catastrophes (>$5 million each) for 1968-1997. These storms produced property losses amounting to $8.452 billion over 30 years, averaging $282 million yearly since 1968. Windstorms also produce considerable property damage in the United States, and these typically occur along the East and West Coasts in the colder half-year (October-March). The only quality economic data available for these events were insurance-based catastrophes since 1949, and annual losses averaged $168 million (Table 3-7).

## Temporal Trends in Losses

The temporal distributions of the storm variables were assessed to define their long-term fluctuations and trends. Normalized hurricane losses (Figure 3-19) exhibit a minor downward trend from 1950 to present that was not statistically significant. After normalization, flood losses (Figure 3-20) had an upward trend that was statistically significant at the one percent level.

The trend for insured property losses due to thunderstorm catastrophes is slightly downward (Figure 3-21), but not significant. Winter storm losses continued to increase over time, and were statistically significant at the one percent level. Crop losses due to hail and associated high winds (Figure 3-22) showed a significant (10 percent level) decline over time. This differs from the upward trend found for hail-caused catastrophe losses to property. The normalized tornado losses had a flat trend over time for 1950-1997 (Figure 3-23). Losses from windstorm catastrophes had a statistically significant downward trend during the 1949-1997 period.

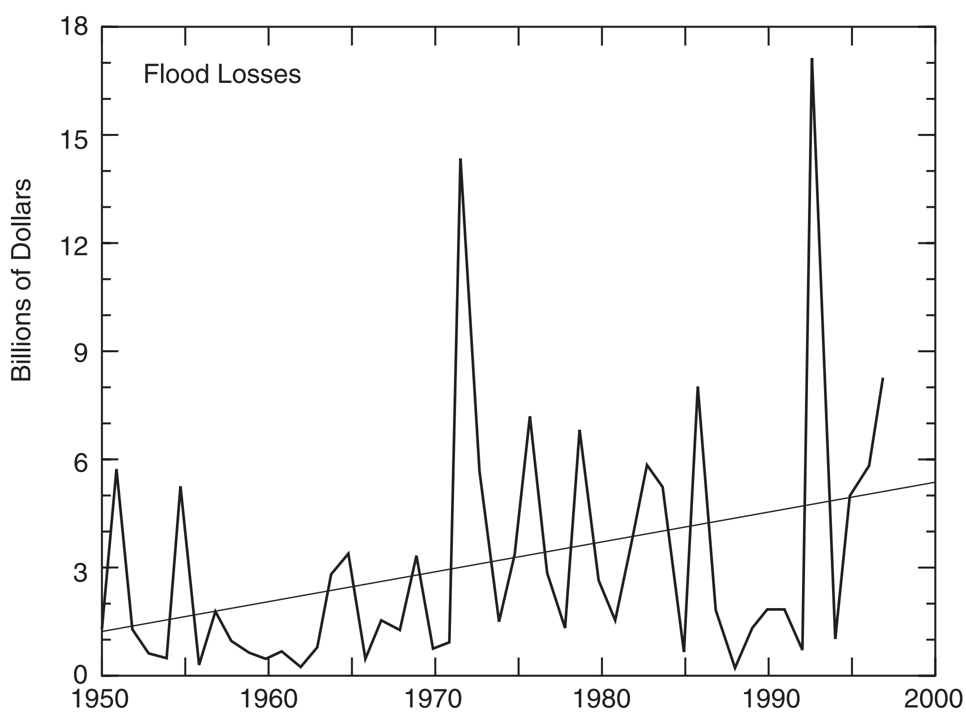


Figure 3-20. The annual adjusted flood losses (billions of 1997 dollars), 1950-1997, and the trend line (Changnon and Hewings, 2001)

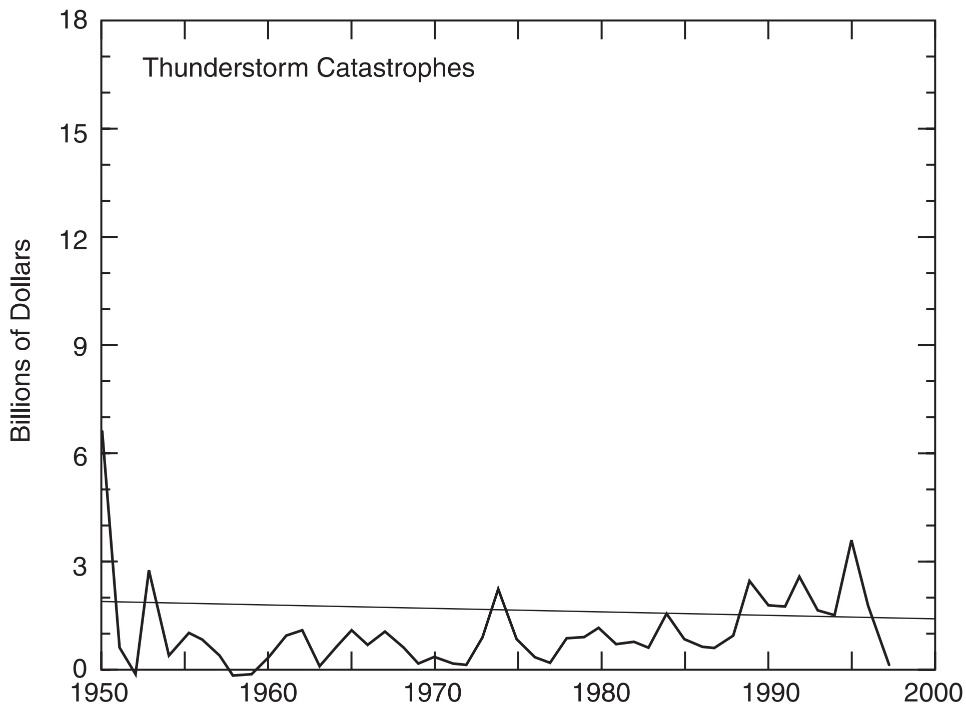


Figure 3-21. Annual losses (billions of 1997 dollars) caused by thunderstorm catastrophes, 1950-1997, and the trend line (Changnon and Hewings, 2000)

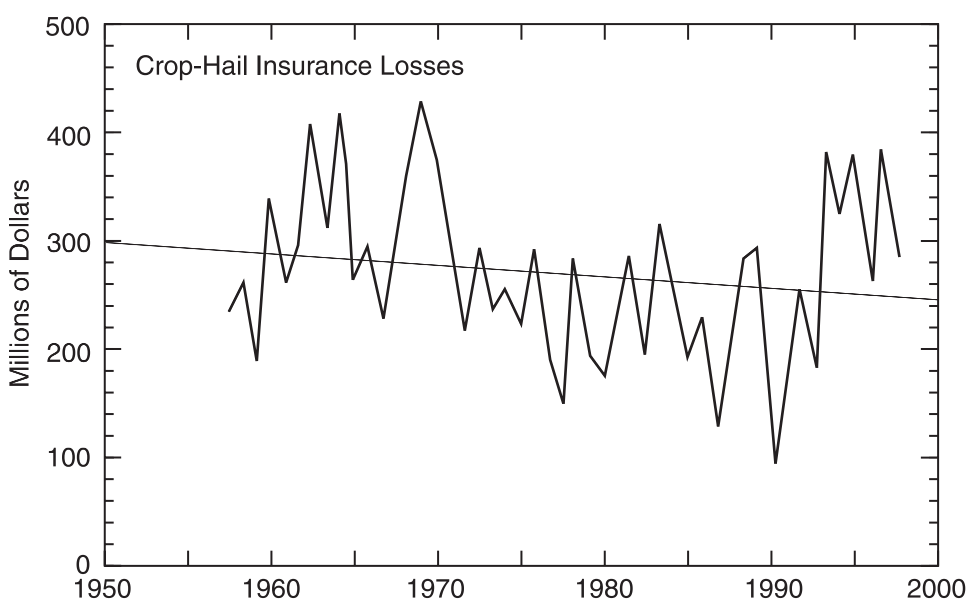


Figure 3-22. Annual crop-hail insurance losses (millions of 1997 dollars), 1950-1997, and the trend line (Changnon and Hewings, 2000)

Another set of data on losses from storms and climate extremes assessed was the federal disaster relief payments made since 1953 (Changnon and Hewings, 2000). These data were adjusted to the 1997 dollar values, and annual values were available for 1953-1997 (Sylves, 1998). An inherent problem in these annual values relates to the fact that payments for losses in any given year often continue into succeeding years. Federal disaster relief payments, which began in 1953, had a statistically significant upward trend with a dramatic increase in the 1990s (Figure 3-24). Payments peaked at nearly $7 billion in 1994, partly a result of large carryover payouts for losses due to Hurricane Andrew in 1992 and the Midwestern flood of 1993.

## Impacts of Major Recent Extremes

Six recent major weather events and climate extremes were extensively studied to define their impacts, including both financial losses and gains. This section presents data relating to the assessment of the economic impacts of each event.

### Drought of 1987-1989

In mid-1987, a drought began developing in the High Plains and Midwest. By mid-1988, 40 percent of the United States was experiencing severe drought, and drought conditions persisted through most of 1989. Measures of drought intensity and areal extent at a national scale showed that the 1987-1989 drought was one of the ten worst droughts of the century (Riebsame et al.,

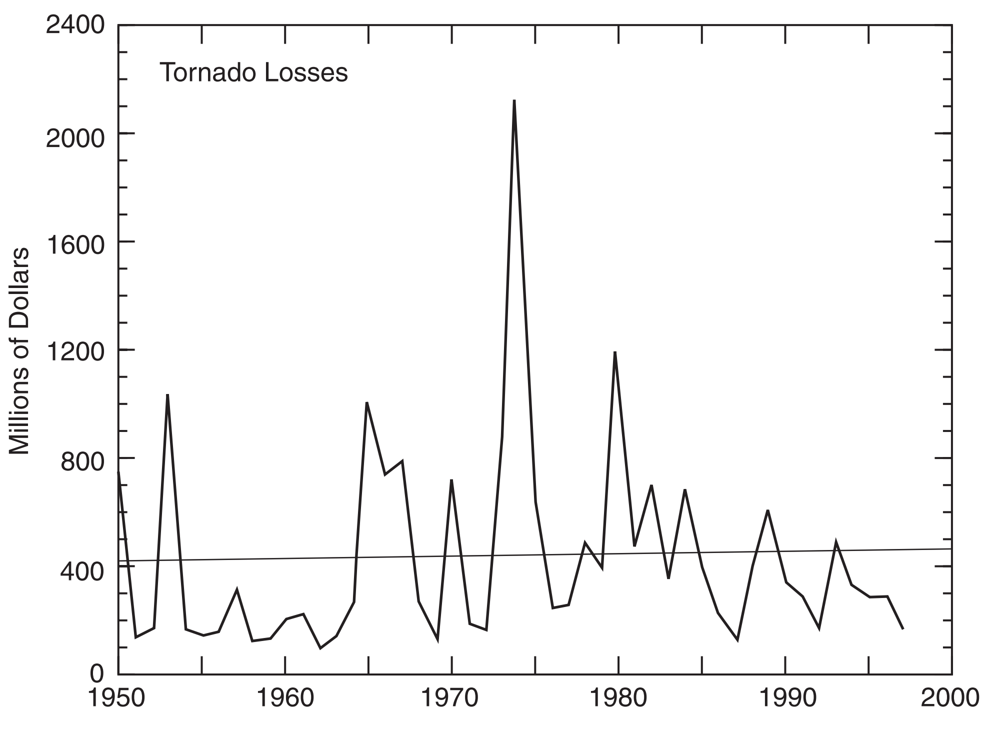


Figure 3-23. Annual normalized tornado losses (millions of 1997 dollars), 1950-1997, and the associated trend line (Changnon et al., 2001)

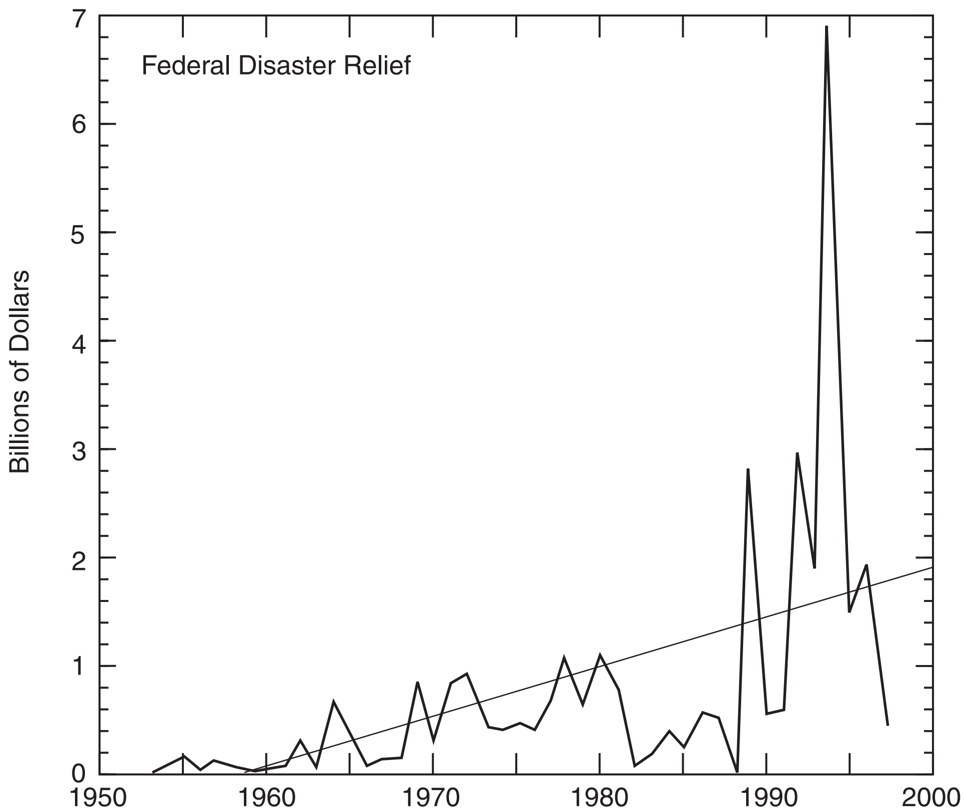


Figure 3-24. Annual federal disaster relief payments (billions of 1997 dollars), 1953-1997, and the trend line (Changnon and Hewings, 2000)

1991). The year 1988 was the fourth driest year of the 20th Century. In some regions like the Midwest and northern High Plains, the magnitude of the drought was a rare extreme event, matching the conditions of the 1930s Dust Bowl. While the 1987-1989 drought was not unprecedented, it stood in sharp contrast to the unusually wet conditions that had existed over much of the nation in the previous two decades, a situation that made some of the drought's impacts appear extreme to many. The pervasive drought created economic, social, and environmental impacts.

Sectors affected and losses (1997 dollars) associated with the drought are shown in Table 3-8. There were extensive losses in the agricultural sector, but agricultural producers in non-drought areas gained $3.6 billion from their normal yields and the high prices caused by the drought. Some gains related to increased power sales resulting from the high summer temperatures, water development firms, and railroads gained $300 million because barge shipments were limited due to low flows in major rivers.

The 1988 drought's $40 billion in losses and costs, one of the most costly weather events of the 20th Century, was not a major factor in the nation's economy (Riebsame et al., 1991). The GNP had a 0.4 percent downturn attributed to the drought; the Consumer Price Index in 1988 rose 5 percent, but economists assigned only 0.3 percent to drought effects.

**Table 3-8. National Losses/Costs (1997 dollars) Associated with the 1987-1989 Drought**

| *Sectors* | *Losses/costs ($ billions)* |
|---|---|
| Federal disaster assistance | 4.3 |
| Federal crop insurance | 3.1 |
| Transportation | 1.0 |
| Farm production uninsured | 15.0 |
| Energy production | 0.2 |
| Food costs | 10.5 |
| Forests | 5.2 |
| Agricultural services and sales | 0.8 |
| Total | 40.1 |

## Hurricane Andrew in 1992

On August 24, 1992, Hurricane Andrew struck the Florida coast just south of Miami, continued westward across the Gulf of Mexico, and made a second landfall in Louisiana. Costly impacts in Florida were assessed in detail to provide information to help illustrate the importance of better preparedness to reduce vulnerability to extreme weather events (Pielke, 1995).

Various losses and costs associated with the storm in Florida are listed (Table 3-9), revealing a storm total of nearly $30 billion. The storm assessment pointed to various actions for better preparedness and to mitigate future hurricane losses. A study of past US hurricanes of the 20th Century had normalized the damages of each storm (Pielke and Landsea, 1998), revealing that Hurricane Andrew losses and costs were the second highest hurricane losses, trailing those of a 1926 hurricane with normalized losses of $72 billion.

## Record Midwestern Floods of 1993

The record Midwestern flood of 1993 inundated 10,000 square miles in nine states, creating a multitude of environmental effects and sizable economic impacts (Changnon, 1996). As the 1993 flood developed, the considerable uncertainty over whether it qualified as a 50-year, 100-year, or 500-year event helped reveal that floods, like droughts, are defined not just by their geophysical dimensions, but by the damages they ultimately inflict. That the flood of 1993 qualified as a record flood by the damages it created is not open to question: it was the nation's record-setting flood of all time. However, parts of agriculture, business, and transportation sectors also benefitted from the flood. For example, farmers in unflooded areas with good yields got higher prices for their harvested crops because the losses in the Midwest drove the prices up.

The 1993 floods produced environmental effects, economic impacts, impacts to and responses by government at the local, state, and federal levels, and floodplain impacts. The economic impacts of the floods of 1993 involved losses to individuals in and near flooded communities, to floodplain farmers, and to Midwestern businesses and industries. Business losses affected regional sales, agricultural production, utilities, manufacturing, transportation, tourism, and recreation. Delayed losses of $2 billion appeared a year or more after the flood and included those resulting from pollutants released by floodwaters, soil losses, groundwater damages, and environmental changes. The resulting total losses (Table 3-10) were $20.8 billion, very significant but only half the losses/costs of the 1987-1989 drought.

Although losses were extensive over the nine-state flooded area from the most costly flood ever, the flood had little impact on the nation's economy as a whole. Economic impact analyses to predict 1994 conditions, with and without the 1993 flood, revealed several interesting outcomes. The flood did not change the nation's gross domestic product (GDP) in 1993, but it was predicted to increase the GDP by 0.01 percent in 1994 due to expenditures for repairs. The flood did not change the 3.3 percent rate of inflation in 1993, but the rate increased from 3.5 to 3.6 percent in 1994 as corn and soybean losses in 1993 caused wholesale farm prices to rise 6 percent. Corporate profits in 1993 dropped by 0.01 percent due to the flood losses and insurance costs, but profits increased by 0.8 percent in 1994 due to rebuilding and cleanup efforts. Although the initial assessment of losses in Iowa was $6.8 billion, a year after the flood, nearly $3 billion had been spent on reconstruction, a boon to the local construction industry and an improved infrastructure (Hewings and Mahidhara, 1996).

**Table 3-9. Losses/Costs (1992 dollars) Associated with Hurricane Andrew in Florida (Pielke, 1995)**

| *Damaged entity* | *Losses/costs ($ billions)* |
|---|---|
| Private property | 16.85 (16.5 insured) |
| Public infrastructure | 1.397 |
| Environmental areas | 2.124 |
| Agriculture | 1.520 |
| Federal aid | 6.596 |
| Aircraft | 0.020 |
| Red Cross | 0.070 |
| Defense Department | 1.412 |
| Total | 29.989 |

**Table 3-10. Losses/Costs (1993 dollars) Due to the 1993 Flooding in the Midwest**

| *Activity* | *Losses ($ billions)* |
|---|---|
| Agriculture | 8.900 |
| Transportation | 1.900 |
| Business and industry | 0.955 |
| Federal and state aid | 6.930 |
| Delayed losses (business and environment) | 2.100 |
| Total | 20.785 |

Although the flood's economic impacts were the greatest on record for any flood ($20.8 billion), the flood actually had very little effect on the nation's economy. The greatest economic losses occurred to regional agriculture and to transportation, commerce, and industry along the major Midwestern rivers.

### El Niño of 1997-1998

A comprehensive assessment of the impacts of the unusual cold season weather of 1997-1998 related to a strong El Niño event was conducted (Changnon, 1999a). El Niño-influenced atmospheric conditions created a considerable amount of damaging weather in the southern US. In March 1998, a leading NWS scientist stated that El Niño 1997-1998 was "the most damaging ever" (Friday, 1998). A series of weather disasters from October 1997 through May 1998 were attributed to the record large El Niño of 1997-1998, and these weather disasters were noteworthy for their variety and wide distribution across the nation. In assessing losses, the events and weather conditions included as being El Niño-related were those that had been so identified by government atmospheric scientists acting in an official capacity.

When the El Niño oceanic conditions grew to record proportions in the tropical Pacific during June-August 1997, the West Coast was assaulted by a series of coastal storms and heavy rains, causing floods, numerous landslides, and agricultural damages, with California losses totaling $1.1 billion statewide. Losses in excess of $0.5 billion were attributed to a record early snowstorm across the High Plains and upper Midwest in October, and an extremely severe ice storm that struck the Northeast in January. Both events were attributed to El Niño's influence on the atmosphere.

Flooding devastated several fruit and vegetable crops, and national prices for fresh produce rose 7.9 percent in January, retreated in February, and then rose 5 percent in March. Floods and storm damages in California were cited as the main reason for a 0.4 percent food price increase in February. The nation's tourist business suffered from a 30 percent drop in income. As shown in Table 3-11, national losses totaled $4.2 billion.

The mild, almost snow-free winter in the northern United States produced by El Niño's influence on the atmospheric circulation over North America resulted in several major economic gains, particularly in the northern sections of the nation (Changnon, 1999a). El Niño's influence on the atmosphere led to the elimination of major Atlantic hurricanes during 1997. Annual US

**Table 3-11. National Losses/Costs (1998 dollars) from Weather Conditions Attributed to El Niño, 1997-1998**

| *Activity* | *Losses/costs ($ billions)* |
|---|---|
| Property losses | 2.800 |
| Federal relief payments | 0.410 |
| State costs | 0.125 |
| Agricultural losses | 0.650 |
| Lost sales (snow-related equipment) | 0.060 |
| Tourist industry losses | 0.200 |
| Total | 4.245 |

hurricane damages had been averaging $5 billion per year in the 1990s. This lack of hurricanes meant savings for home and business owners in hurricane-prone areas, the government, and insurers. Abnormal warmth during the 1997-1998 winter led to major reductions in heating costs with less use of natural gas and heating oil, a savings of $6.7 billion. Generally good weather with little precipitation and temperatures averaging 4°C above normal, also had a major influence on construction, retail shopping, and home sales. Record seasonal sales of goods and homes brought sizable added incomes to retailers, realtors, and homeowners; and summation of the various reported gains produced a national total estimated at $5.6 billion above normal expenditures. The federal government, which normally faces large relief costs related to hurricane and flood damages, benefitted from the lack of hurricane losses and no losses from major spring snowmelt floods.

The net effect on the nation's economy was detectable. For example, the Federal Reserve Board announced in February that the warm January caused a 4 percent drop in production at the nation's electric and gas utilities, ending a run of months with production increases that economists had expected to be +0.3 percent in January. El Niño's net influence on the weather and the Asian financial crisis combined in February to eliminate inflation in the prices paid by wholesalers, as food processors and manufacturers charged wholesalers 0.1 percent less than in January for finished goods. Inflation was zero during January-March, the first time in 10 years, and the Consumer Price Index went unchanged due to the falling energy prices. The GNP rose at a rate of 4.2 percent during the first quarter of 1998, as compared to the 3.4 percent expected (US Department of Commerce, March 1998). The national gains are listed (Table 3-12).

Utilities that used the accurate forecasts for a mild winter and waited to purchase their natural gas supplies on the spot market during the winter, as prices fell rapidly, also reaped sizable benefits for their customers. One Iowa-based utility saved $39 million by using the predictions, and two utilities in Michigan reported forecast-based savings, $48 million and $147 million, respectively.

Assessment of the national impacts, both losses and benefits from Tables 3-11 and 3-12, reveals that economic benefits (nearly $20 billion) outweighed losses ($4.2 billion). This mixture of regionally different weather extremes over a 6-month period reveals how US climate conditions can produce a mix of economic gains and losses.

**Table 3-12. Economic Gains (1998 dollars) Attributed to Weather Conditions Caused by El Niño, 1997-1998**

1. Reduced heating costs ($6.7 billion)
2. Increased sales of merchandise, homes, and other goods ($5.6 billion)
3. Reduced costs of street-highway removal of ice/snow ($350 million to $400 million)
4. Reduced normal losses due to lack of snowmelt floods and no Atlantic hurricanes ($6.3 billion)
5. Income from increased construction and related employment ($450 million to $500 million)
6. Reduced costs to airline and trucking industry ($160 million to $175 million)
7. Total benefits ($19.8 billion)

## Record Warm Winter of 2001-2002

The winter of November 2001-January 2002, the nation's warmest on record since 1895, was 2.4$^{o}$ C above the national long-term average, which led to reduced energy demand and kept natural gas prices much below normal (Changnon and Changnon, 2002). Consumers benefitted from more disposable income. Large parts of the nation had below average precipitation, and snowfall was below normal throughout most of the northern United States. Midwestern cities, such as Chicago and Detroit, reported record high numbers of hours of sunshine. The warm and dry trend throughout most of the nation persisted through February, resulting in a uniquely warm, dry, snow-free, and sunny four-month winter. The climatological winter, December-February, was rated the nation's fifth warmest in the past 100 years, and many states in the Midwest and Northeast had their record warmest winter.

Economic impacts were either direct, almost totally due to the weather, or less direct, or mixed, resulting from the weather and other economic factors. The more direct impacts were the lower heating costs, reduced transportation delays, lower road/highway maintenance costs, added construction activities, and reduced insurance losses. More indirect impacts included retail sales, home sales, and tourism.

Expenditures for homes and retail products during November-February ranged from $4 billion to $5 billion above expected, normal levels. At the end of winter, federal, state, and local highway/street departments reported 50 to 80 percent reductions in costs of snow removal and use of salt. Housing starts were up by 6.3 percent in January to a seasonally adjusted rate of 1.68 million units, the highest level in two years, and February housing starts reached their highest level since 1948. These winter increases represented an additional $2 billion income for the construction industry.

A major area of impacts largely attributable to the weather was heating costs. Natural gas prices fell significantly during the winter. Extremely high prices for natural gas and electricity had developed during the prior (2000-2001) winter, which led many major users to set early season gas contracts at prices that were too high, given the mild winter and low prices that ensued. The winter's low heating bills were a bonanza for consumers, but big utilities lost large sums. One East Coast utility reported a revenue loss of $92 million, an 8.3 percent decrease. However, consumers in the Chicago metropolitan area saved $1 billion, and national savings were $7.5 billion in lower energy costs (Changnon, 2002b). The lack of bad weather with only one winter storm catastrophe also had positive impacts for the property insurance industry, and winter property losses were 78 percent below average. The nation's transportation sector benefitted greatly from the mild, largely storm-free winter: airlines suffered fewer delays, and reduced fuel and operating costs were valued at $145 million.

The national gains and losses from the mild, almost snow-free winter 2001-2002 are listed in Table 3-13. The total benefits ranged from $19.6 to $20.6 billion. Estimated winter losses ranged from $320 to $400 million. The outcome was similar to that with the warm, dry El Niño winter of 1997-1998. The similarity in magnitude of the benefits of the two exceptionally warm winters suggests that a future climate with warmer US winters, as postulated under global warming scenarios, would be a positive outcome.

The unusual weather of 2001-2002 across the nation created huge and generally positive impacts on the nation's economy at a critical time. Some economists claimed the mild weather and its impacts were a factor in getting the nation's economy out of an on-going recession (Greenspan, 2002).

**Table 3-13. National Gains and Losses (2002 dollars) Resulting from November 2001-February 2002 Weather**

*Gains*

- Reduced heating costs ($7.5 billion)
- Sales of merchandise, vehicles, and homes ($4 billion-5 billion*)
- Reduced costs of highway/street snow removal ($750 million)
- Construction income ($2 billion)
- Reduced costs to airlines, trucking, and railroad industries ($255 million)
- Reduced insurance payments for weather losses ($3.8 billion)
- Reduced losses from lack of snowmelt floods ($1.3 billion)

*Losses*

- Tourist industry ($200 million-$270 million*)
- Snow equipment and winter clothing sales ($80 million to $90 million)
- Snow removal ($40 million)

**Note:** *Values affected by other economic factors such as lowered mortgage and interest rates, government incentives to spend, and fears relating to the September 11 attacks.

## Record-High Insured Storm Losses during the 1990s

The United States experienced record-setting high insured property losses from numerous weather catastrophes during 1990-1996. The seven-year total insured loss, after adjusting for inflation and other factors, was $39.65 billion of which $15 billion was due to Hurricane Andrew (Changnon, 1999b). Insured losses in the United States typically represent between 60 and 70 percent of the total national losses from weather hazards (Changnon et al., 1997).

One analysis focused on catastrophes causing $100 million or more in losses, done to match the level used in a previous study of the 1950-1989 catastrophe data (Changnon and Changnon, 1991). Although catastrophes causing $100 million (1991 dollars) or more represent only 30 percent of all catastrophes during 1990-1996, their losses accounted for 85 percent of the total loss produced by all catastrophes experienced during that period. There were 72 catastrophes during 1990-1996, slightly more than half the 142 catastrophes in the prior 40-year period. The 1990-1996 frequency of catastrophes causing $100 million or more in damages averaged 10.3 catastrophes annually, significantly higher than the annual average of 3.6 catastrophes for 1950-1989.

Annual insured losses during 1990-1996 averaged $5.665 billion. However, Hurricane Andrew caused sizable insured losses totaling $15.1 billion in 1992 and 38 percent of the seven-year loss total of $47.5 billion (1997 dollars) caused by all 240 catastrophes during the 1990s. If the high losses of Hurricane Andrew are excluded from the seven-year total, the resulting 1990-1996 losses would have averaged $3.543 billion per year. The 1950-1989 annual loss value (1997 dollars) from catastrophes causing $100 million or more damages was $1.7 billion, much less than the 1990-1996 value with or without Hurricane Andrew's losses. Thus, the early to mid-1990s experienced a major increase in the number of catastrophes and in the magnitude of the annual losses. This anomaly had major economic impacts on the insurance industry (Changnon et al., 1996).

## Causes for Recent Increases in Weather-Climate Extremes

Assessment of the various findings presented in the first four parts of this chapter reveal several factors and conditions that have been identified as responsible for recent increases in economic losses from weather and climate extremes. Obviously, one potential condition is a shift in climate conditions that create more extremes, more intense extremes, or both. Another factor identified is related to the insurance industry and its handling of recent weather losses (Roth, 1996). Several societal factors have been noted as playing a significant role in the recent escalation of losses (Changnon et al., 2000). Population growth is clearly one factor. Another factor is demographic changes as the nation's population density shifts to more weather-vulnerable locations. Growing wealth with more valuable personal property is another societal factor (Pielke, 1999). A factor noted in several storm studies relates to the nation's infrastructure of aging facilities and inadequately constructed buildings and homes (Hooke, 2000).

Review of the comparisons of the temporal trends of losses and of climate conditions, as presented in the previous section, revealed many informative differences. Major differences between a given condition's trend of losses and its frequencies were found for hurricanes, floods, hail, tornadoes, and heat waves. Major regional differences were also noted for hurricanes, hail, and thunderstorm losses with major upward trends in losses occurring in areas where population and wealth had been rapidly growing.

### Insurance Industry Problems

Record-high insured property losses during the 1990s created immense concern among crop insurance, property insurance, and reinsurance industries. They sought explanations for the causes. One that surfaced quickly was that the peaking of losses represented the start of a climate change due to global warming (Swiss Re, 1996; Lecomte, 1993), whereas others believed the shift was due to natural fluctuations in climate (Changnon et al., 1999). However, studies of storm frequencies (Changnon and Changnon, 1998; Kunkel et al., 1999b) did not reveal a major increase in storm frequency or intensity. Extensive analysis of when and where the insured losses had increased pointed to shifts in insured risks for which the insurance industry had not adjusted for in their rates (Roth, 1996). Once the historical loss data were adequately adjusted for shifting coverage, inflation, and evolving construction practices, it was found that the losses of the 1990s were matched by equally high losses in the 1950s, as shown in Figure 3-25 (Changnon, 1999b). The upward trend in insured property losses due to catastrophes during 1949-1994 without adjustment show a close relationship with the trend in the nation's population (Figure 3-26). Thus, the recent increase in insured losses was not unique (Figure 3-25) and partly resulted from a lack of adjustment by the industry for population growth and shifting risks (Kunreuther, 1998).

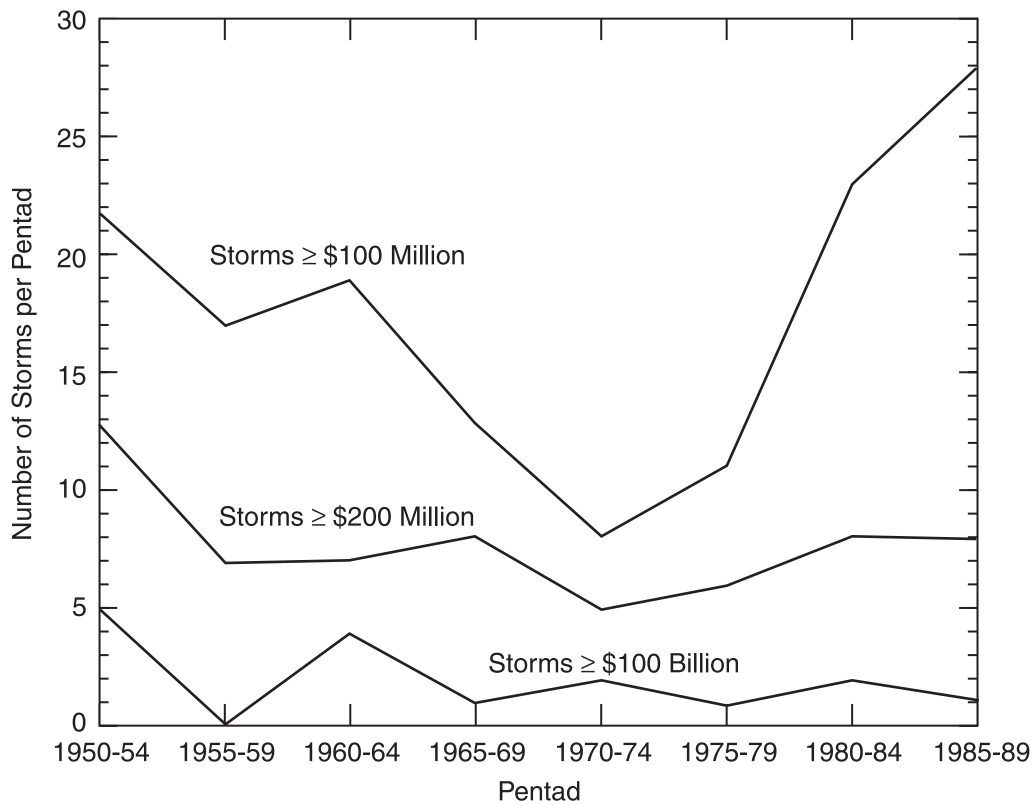


Figure 3-25. Frequencies of national storm catastrophes causing losses at three levels: ≥ $100 million, ≥$200 million, and ≥$1 billion (all values adjusted, 1990 dollars), 1950-1989 (Changnon and Changnon, 1992)

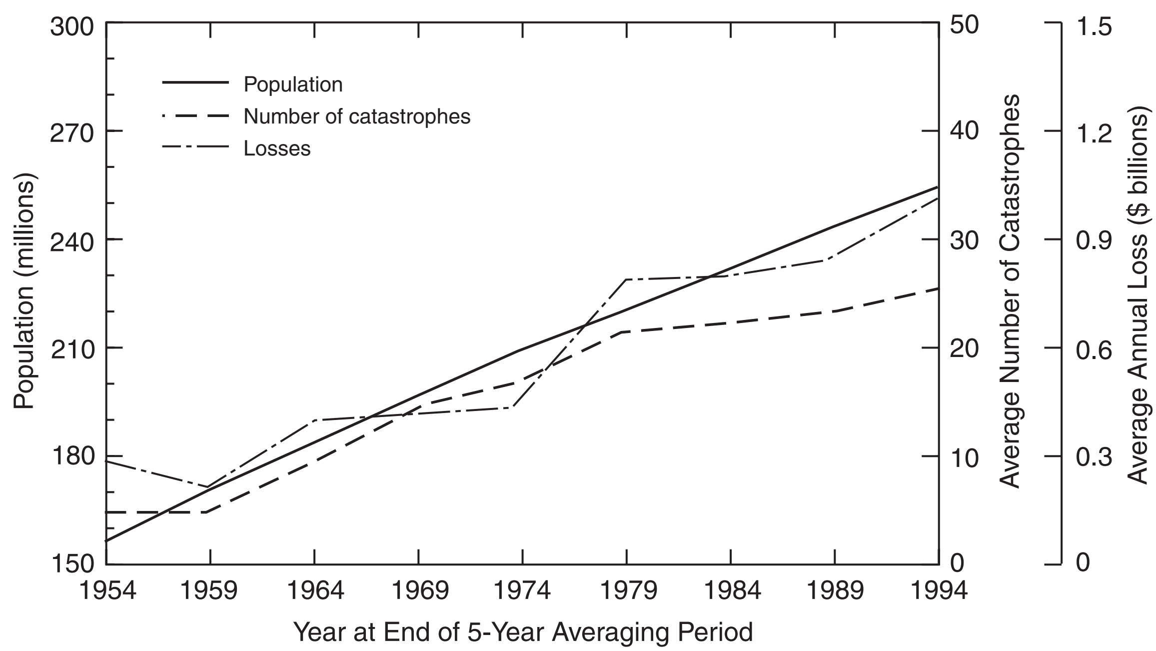


Figure 3-26. Time distributions of catastrophes that caused losses between $10 million and $100 million [adjusted for 5-year periods of number of catastrophes, amount of loss (1997 dollars) from these catastrophes, and the US population] (Changnon et al., 1997)

## Sensitivity to Climate: Adjustments to Recent Climate Fluctuations and Losses

The nation experienced a "climatologically quiet" period from the late 1950s through the early 1970s. It was largely devoid of climatic extremes, such as severe droughts or wet periods that had preceded it during the 1920s, 1930s, 1940s, and 1950s. This "lull before the storm" or quiet regime, reflected in Figure 3-25, was sufficiently long for many weather-sensitive operations, including the insurance industry, to be designed, financed, and operated based on conditions largely free of extremes (Roth, 1996). Many weather-sensitive operations and managers became attuned to functioning in a period with few major extremes.

Conditions began to change during the late 1970s, as climate aberrations again became common nationwide, comparable to conditions in the 1920-1960 period. Suddenly, many managers of weather-sensitive activities faced problems they did not understand. A run of cold, snowy winters that began in 1976 heralded the beginning of a parade of climate aberrations. The list below describes the run of extremes from the mid-1970s to the 1990s.

1. The late 1970s had a series of four winters that were abnormally severe in the central United States.

2. The early 1980s included the wettest five years on record in the nation, producing record high lake levels on the Great Lakes and Great Salt Lake, with attendant major shoreline damages around the lakes. Many structures had encroached to the "average weather" levels defined by 1960-1980 conditions.

3. Droughts developed in the southeast in 1986 and covered half the nation in 1988-1989. California had its six consecutive driest years on record before the drought broke in 1992.

4. The summers of 1992 and 1993 became the two worst years for hail loss to both crops and property in the High Plains. Prolonged storminess throughout both growing seasons created billions of dollars in crop losses with major hail damages in Denver (1990), Wichita (1992), Dallas-Ft. Worth (1994-1995), and St. Louis (2001).

5. Record Midwestern flooding, in duration and areal extent, occurred in 1993 at the same time that the Southeast had an extreme warm season drought. Severe flooding occurred again in 1996 and 1997 in Chicago, California, along the Ohio River, and in the Dakotas.

6. Major winter storms and prolonged record cold made the winter 1993-1994 the worst on record in the East Coast and parts of the Midwest. Damages reached billions of dollars as the parade of bad storms continued into 1996-1997.

After being benign for about 20 years, the US climate became "nasty" again, with conditions more typical of the nation's long-term climate. The enormity of the losses caused by this array of climate anomalies since 1975 is an important part of the story of society's vulnerability to climate (van der Link et al., 1998). Over time, the nation's society and infrastructure had become more susceptible to climate anomalies (Changnon, 2003a). The ever-growing population, with its concomitant demands for food, water, energy, and other weather-influenced resources, was more vulnerable to extremes that reduce these resources. In addition to the increased population, or target at risk, there were other reasons for this increased vulnerability to extremes.

For example, production systems had become increasingly disaggregated. Hence, reliance on timely transportation had grown. Most such forms of production can handle short weather delays but not multi-week or monthly stoppages such as those in the 1993 flood, or in the winters of 1976-1979 or 1993-1994. Unavailability of raw supplies stopped production and crippled business.

An aging infrastructure susceptible to prolonged weather extremes also made society more vulnerable. For example, the nation's large urban water-supply systems replete with major leakages, safety concerns about water in old dams during prolonged wet periods, and aged water transportation arteries often were unable to cope with damages from prolonged flooding, or major demands during droughts (Changnon, 2000).

Agriculture also became financially more sensitive to weather extremes. Ever larger farm units with greater indebtedness resulting from land acquisition and the need for new facilities and costlier farm machinery were extremely vulnerable when multiple years of low yields occurred. Dispersed farm holdings were a good way to insure against small-scale severe weather threats such as hailstorms but useless during droughts or floods, and incorrect long-range forecasts of extremes added to the problems (Changnon, 2002a).

The nation's utilities exhibited a decreasing capacity to provide the necessary power, a result of many economic problems and deregulation. The net effect was less capability to deal with demands during prolonged periods of extremely high temperatures over large areas, or prolonged low temperatures in winter. Brownouts occurred, and industrial/commercial losses resulted.

The impacts of these events on the government, and in turn on the taxpayer, were seen as sizable. Relief programs have been employed to help with the trauma of losses, but the multi-billion dollar relief bills to pay for climate-induced losses since 1987 were seen as a threat to the ever-growing national debt. Furthermore, many federal policies relevant to handling these climate anomalies in more sensible fiscal approaches were found to be flawed (Hooke, 2000). The floodplain management program was recognized as inadequate as the floods of 1993, 1996, and 1997 each had less than 10 percent of those experiencing property damage had flood insurance. The crop-weather insurance program had been modified, but it required multiple agricultural disasters to bring about more effective legislation and a more stable crop insurance program.

## Societal Issues

Societal impacts from weather and climate extremes and accompanying temporal trends in those impacts, are a function of society and climate. Insured property losses due to weather extremes had grown steadily from \$25 million annually in the early 1950s to more than \$5 billion annually in the 1990s (Figure 3-27). Losses caused by catastrophes that exceeded \$5 million in property damages have grown steadily from about \$100 million annually in the 1950s to \$6 billion annually in the 1990s. The annual number of catastrophes jumped from 10 in the 1950s to 35 in the 1990s (Changnon, 1999b). The 1990-1997 total insured losses were \$49 billion, and federal relief payments were \$12 billion. The 1990s experienced a record number of damaging storms, including 72 storms in which damages exceeded \$100 million during 1990-1996, whereas only 142 such storms occurred in the preceding 40 years. Federal relief payments for weather disasters grew from \$670 million during 1956-1970 to \$4 billion in 1991-1995 (Sylves, 1998).

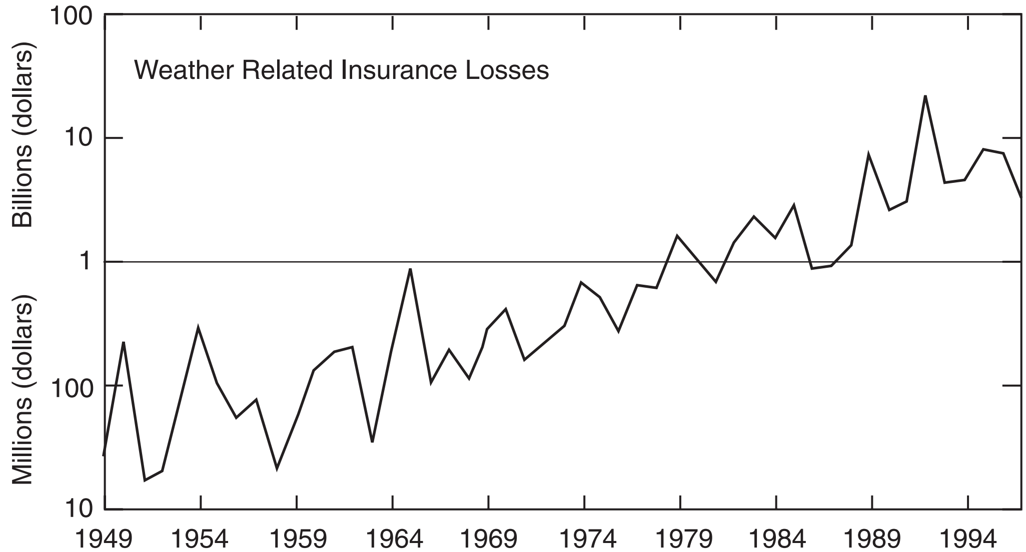


Figure 3-27. Annual losses (1997 dollars) to insured property in the United States from weather extremes, 1949-1997 (Changnon et al., 1997)

Losses due to various individual weather conditions also have grown. Annual hurricane losses grew from $5 billion in the 1940s to more than $40 billion in the 1990s, as adjusted for inflation to 1990 dollars (Pielke and Landsea, 1998). Flood damages also continued to increase from annual losses of $1 billion in the 1940s to $6 billion per year during the 1980-2000 period (Pielke, 1997b). Damaging hailstorms causing urban losses in excess of $300 million became common in the 1990s with such storms at Denver, Dallas-Ft. Worth, St. Louis, Oklahoma City, Wichita, and Orlando. Tornado losses increased from an annual average of $325 million in the 1950s to $370 million in the 1990s.

Trends in insured loss statistics also displayed sharp regional differences. On the West Coast, the Arizona-New Mexico-Colorado-Texas area, and southeastern coastal states, the number of property catastrophes exceeding $100 million in losses during 1990-1997 was double the number in the preceding 40 years (Changnon, 1999b). Elsewhere in the nation, these costly storms had increased by only 20 to 30 percent. Crop-hail insurance losses show major regional differences, with rapid increases in the 1990s in the High Plains, but decreases in the Midwest and on the East Coast.

When annual insured property losses were divided by the US population, a flat trend resulted (Figure 3-28), with isolated peaks in six years that had major hurricanes. This curve is quite different from the unadjusted values used in Figure 3-27. For example, catastrophes exceeding $100 million in losses, after adjustment, averaged $551 million in loss per event in the 1990s, just $12 million more than the average of the 140 catastrophes of the prior 40 years. This reveals no increase in storm intensity. Similar normalization of hurricane loss data produced a flat distribution over time, whereas the raw dollar losses displayed a dramatic temporal increase (Pielke and Landsea, 1998).

Trends in most storm and climate extreme loss data, after careful adjustment for societal and insurance factors, do not display upward trends over time. Comparison of this information with

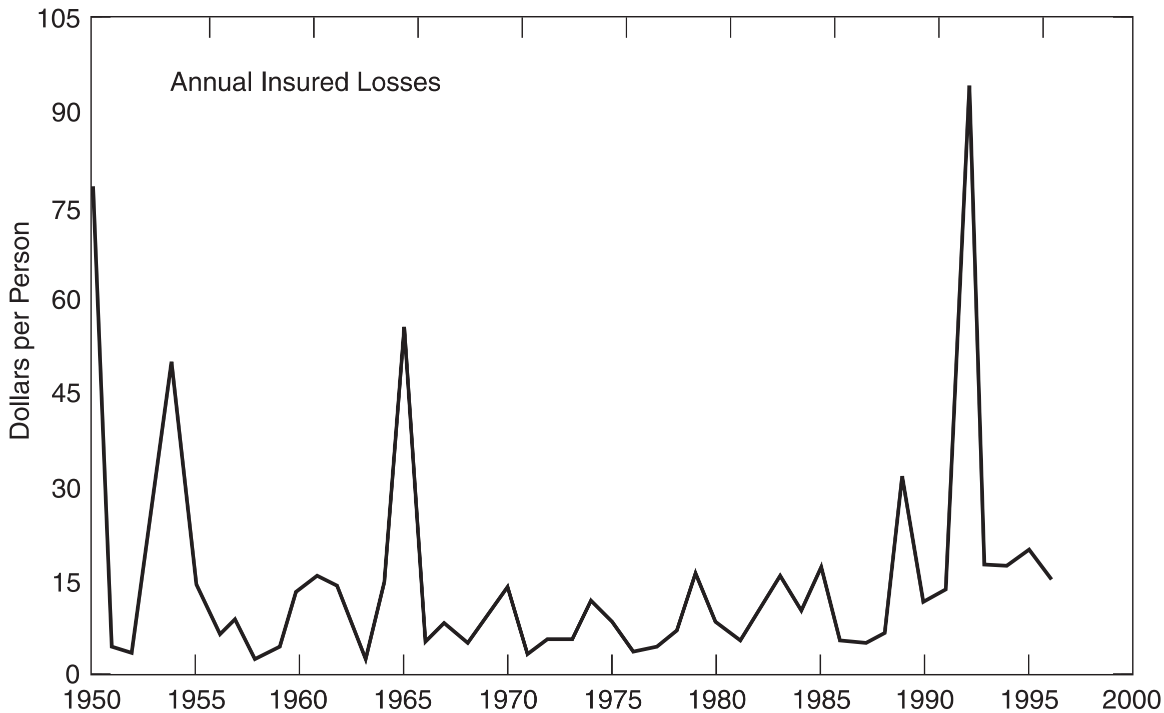


Figure 3-28. Annual losses (1996 dollars) caused by catastrophes causing >$10 million in insured losses normalized by dividing annual losses by the annual US population during 1950-1996; values are in dollars per person (Changnon and Changnon, 1998)

the upward trends in actual dollar losses, and inspection of areas where losses have grown most (Southeast, South, and West), indicates that the major causes of loss trends related to weather and climate extremes are societal factors (Changnon, 2003a). These factors include:

- Increased wealth with more valuable property at risk.
- Increased density of property.
- Demographic shifts to coastal areas and to storm-prone areas that are experiencing increasing urbanization.
- Aging infrastructure, structures built below standards, and inadequate building codes.
- Interdependency of businesses and product development.

Thus, the results from most extensive recent assessment studies show an overall increase in the nation's vulnerability to weather and climate extremes (Kunreuther, 1998). Recent comparative studies of trends in losses and those of weather extremes revealed that most storm activity (tornadoes, thunderstorms, hail days, droughts, and hurricanes) had no long-term increases comparable to the increased losses.

## An Economic Perspective on Weather and Climate Impacts: Past and Future

How do the various economic impacts of weather and climate, losses and gains, rate when compared to measures of the nation's economy? This section addresses this issue.

### Assessment of Past Losses and Gains from Recent Climate Conditions

*Losses*

Annual loss values from all weather extremes and hazards that produce major losses in the United States were assembled. Critical to this endeavor was use of quality loss data with long historical records. Important variables with good data included losses due to floods, hurricanes, and tornadoes, plus weather-induced crop losses and the temperature-driven costs of energy usage. These five variables and four others (severe thunderstorms, hail, windstorms, and winter storms) created a total of nine variables that defined most of the national losses during 1950-1997.

The total losses of the variables, as shown in Tables 3-2, 3-4, and 3-7, create an annual average national loss value of $17.470 billion. Energy use costs ranked highest followed by those due to hurricanes, floods, and crop losses. Each condition's average also was expressed as a percent of the total, and three conditions—hurricanes, energy costs, and floods—accounted for 69 percent of total average loss.

Losses not measured by the variables for which quality data existed also were estimated. For example, losses from these variables incorporated many of the direct losses created, but they did not include the secondary and tertiary losses and costs that develop over time (6 months to 5 years after an event). Estimates derived for conditions not measured by the variables follow.

First, the use of insurance catastrophe data as a measure of property losses from severe thunderstorms, winter storms, and windstorms excluded direct losses from events with property losses under the $5 million loss for catastrophes, as well as uninsured property losses. Roth (1996) and Lecomte (personal communications, May 1999) estimated that weather catastrophes account for about 90 percent of all insured US property losses caused by weather. Three catastrophic storm classes of losses (thunder, winter, and wind) account for $2.082 billion in average losses per year (Table 3-7), and adding 10 percent for omitted losses to this average value indicates that the unmeasured, insured property losses average $230 million annually.

Second, insured residential and commercial property losses caused by wind, hail, and lightning do not account for the uninsured property losses. However, insured losses account for 95 percent of all US property losses due to these conditions because all residential and commercial insurance policies cover these losses and almost all properties are insured for these hazards (Roth, personal communication, May 1999). Interpretation of these values, in light of the estimated total average insured losses for thunderstorms, high winds, and winter storms ($2.082 billion + $230 million = $2.312 billion annually), suggests that the annual uninsured property losses average $115 million ($2.312 x 5%). Thus, unmeasured and measured property losses from these three storm conditions are an estimated $2.427 billion annually, $345 million more than the catastrophe losses accounted for.

Third, crop losses due to precipitation and temperature extremes ($2.603 billion annually) do not include losses to livestock or speciality crops, an estimated $450-$500 million annually (Changnon et al., 2001). Livestock losses in the extremely severe 1988 drought and the record 1993 Midwestern floods were 4 and 3 percent, respectively, of the total agricultural losses.

Adams (1997) noted that record cold temperatures in Florida during winter 1983-1984 caused losses of $1 billion. Specialty crop losses in the Deep South and California from the record-damaging El Niño weather of 1997-1998 were $160 million (Changnon, 1999a). Annual weather losses to the nation's vegetable processing industry average $45 million (Allen, 1997).

Major climate extremes also substantially can reduce retail sales, as they did in California during the stormy, wet winter caused by El Niño in 1997-1998 (Changnon, 1999a). Weather extremes also produce major losses for the nation's transportation systems, including commercial aviation, the trucking industry, riverine shippers, and railroads. For example, the 1993 flood caused record losses of $409 million for the nation's railroads and $610 million for the river-based barge industry (Changnon, 1996). However, gains during the warm winters of 1997-1998 and 2001-2002 averaged $300 million for the transportation sector.

The losses and gains defined from the 11 variables for 1950-1997, coupled with the above adjustments to insured values, and measures of losses and gains from five recent major weather events, were used to develop a list of average annual losses and gains for the nation. Table 3-14 presents the resulting values, with annual losses of $34.74 billion (1997 dollars) resulting from these extremes. The annual loss average from extremes in Canada is $11.6 billion (Bruce et al., 1999).

**Table 3-14. Estimated Annual National Economic Losses/Costs and Gains (billions of 2000 dollars) Resulting from Years with Major Weather and Climate Extremes**

| *Sector* | *Annual losses/costs* |
|---|---|
| Transportation[1] | 1.60 |
| Retail sales[1] | 1.25 |
| Agribusiness[1] | 1.90 |
| Farmers, crops-livestock[2] | 3.32 |
| Energy use[2] | 4.65 |
| Property damages[2] | 10.46 (from storms including floods) |
| Government[1] | 7.00 (from storms including floods) |
| Tourism[1] | 0.20 |
| Property insurance[2] | 4.36 |
| Total | 34.74 |
| | *Annual gains* |
| Construction[1] | 1.50 |
| Farmers[2] | 1.90 |
| Energy use[2] | 3.92 |
| Transportation[1] | 0.30 |
| Property insurance[1] | 6.50 (lack of storms) |
| Government[1] | 6.60 (lack of storms) |
| Tourism[1] | 0.15 |
| Retail sales[1] | 3.80 (winters only) |
| Total | 24.67 |

**Notes:** [1]Based on values from detailed assessments of 1987-1989 drought, 1992 Hurricane Andrew, 1993 flood, El Niño 1997-98, and cold season of 2001-2002.
[2]Based on values derived from 1950-1997 data.

The Chicago Mercantile Exchange (2000) estimated that 20 percent of the nation's $9 trillion economy is "weather sensitive," without explaining how this value was derived or defining what they considered to be weather sensitive. If this estimate were correct, the losses due to major weather extremes accounted for in this study, approximately $34 billion annually, are only 2 percent of weather-sensitive sectors of the nation's economy. Dutton (2002), based solely on his personal opinion, claimed the weather-sensitive components of the nation's GDP add up to $3.8 trillion. A recent report indicated that US industries directly affected by weather account for nearly 10 percent of the GDP, or about $1 trillion (NRC, 2003). That report further claims that annual losses from hurricanes, floods, and tornadoes are $11.4 billion, whereas careful analysis of past losses for 1950-1997 (Table 3-7) shows that losses from these three conditions are much less, an annual average of $7.8 billion. Unfortunately, many weather-related publications often inflate weather-caused economic impacts (Changnon, 2003b). It is relatively easy to identify the sectors of the US economy that are somehow "weather sensitive," but the important question is, "How sensitive and when?"

The measure of losses and gains from major extremes herein puts a good perspective on the level of sensitivity. Maunder (1986) carefully analyzed the nation's economic losses due to adverse weather, and assessed these as part of the gross revenue, as shown in Table 3-15. These percentages are a meaningful measure of sensitivity in various sectors, revealing agriculture is relatively high at 15.5 percent, but weather losses in all other sectors are a small portion, 2 percent or less, of the gross revenue. An assessment of weather impacts to British businesses and industry found most sectors lost 1-5 percent in a major severe winter and 2-4 percent in a severe hot and dry summer (Maunder, 1986).

How does the annual average loss value derived herein relate to other estimates of losses from weather hazards and extremes? Pielke (1997a) estimated that national losses from weather extremes (not including temperature extremes) averaged $300 million per week. This totals $15.6 billion per year, which corresponds well with the $17.47 billion average found herein. A recent major hazards assessment (Mileti, 1999) states, "Dollar losses to crops and property from

**Table 3-15. National Average Annual Losses (1997 dollars) Due to Adverse Weather and Their Portion of Annual Gross Revenue (Maunder, 1986)**

| *Sector* | *Losses ($ billions)* | *Annual gross revenue, percent* |
|---|---|---|
| Agriculture | 8.240 | 15.5 |
| Construction | 0.998 | 1.0 |
| Manufacturing | 0.597 | 0.2 |
| Retail sales | 2.001 | 2.0 |
| Transportation (surface/water) | 0.096 | 0.3 |
| Aviation | 0.090 | 21.1 |
| Communications | 0.077 | 0.3 |
| Electric power | 0.045 | 0.2 |
| Energy | 0.530 | 0.4 |
| Government | 0.008 | 0.01 |
| Total | 12.684 | 21.01 |

natural hazards (1975-1994) were between $230 billion and $1 trillion.  A conservative estimate is $500 billion."  If this value is used, the annual average loss would be $25 billion (1994 dollars). Since the Mileti report states that about 80 percent of all losses are due to "climatological disasters," the resulting total would equal an annual value of $20 billion in losses due to weather extremes. Adjustment of the total for all losses in 1977 (Table 3-15) for inflation produces a value of $37.592 billion (1997 dollars). This is relatively close to the losses based on all extremes herein assessed at $34.7 billion. This close agreement helps support the reality of the loss estimates used herein.

Analysis of the weather conditions causing the maximum loss each year during 1950-1997 revealed six conditions that rated highest in one or more years.  Energy costs were highest in 12 of the 48 years; hurricane losses were highest in 12 years; and flood losses were highest in 11 years.  Crop losses ranked first in eight years, severe thunderstorm losses in four years, and windstorm losses were highest in one year.

Figure 3-29 shows the 48 annual loss values, as determined from the 1950-1997 data, distributed in time and a curve based on averages for 5-year periods (1950-1954, 1955-1959, etc.).  Comparison of the annual values of Figure 3-29 with the annual average of $17.47 billion reveals slightly skewed values with 27 values less than average. The distribution of losses shows a tendency for a sequence of years to include one or two above average years, followed by two to four below average years, followed by an above average year or two.  Pairs of high loss years included 1992-1993 ($73.2 billion), 1972-1973 ($85.3 billion), and 1954-1955 ($79.1 billion).

The distribution of the 5-year average values (Figure 3-29) shows three peaks (1950-1954, 1970-1974, and 1990-1994). Interestingly, all are separated by 20 years.  The highest 5-year value

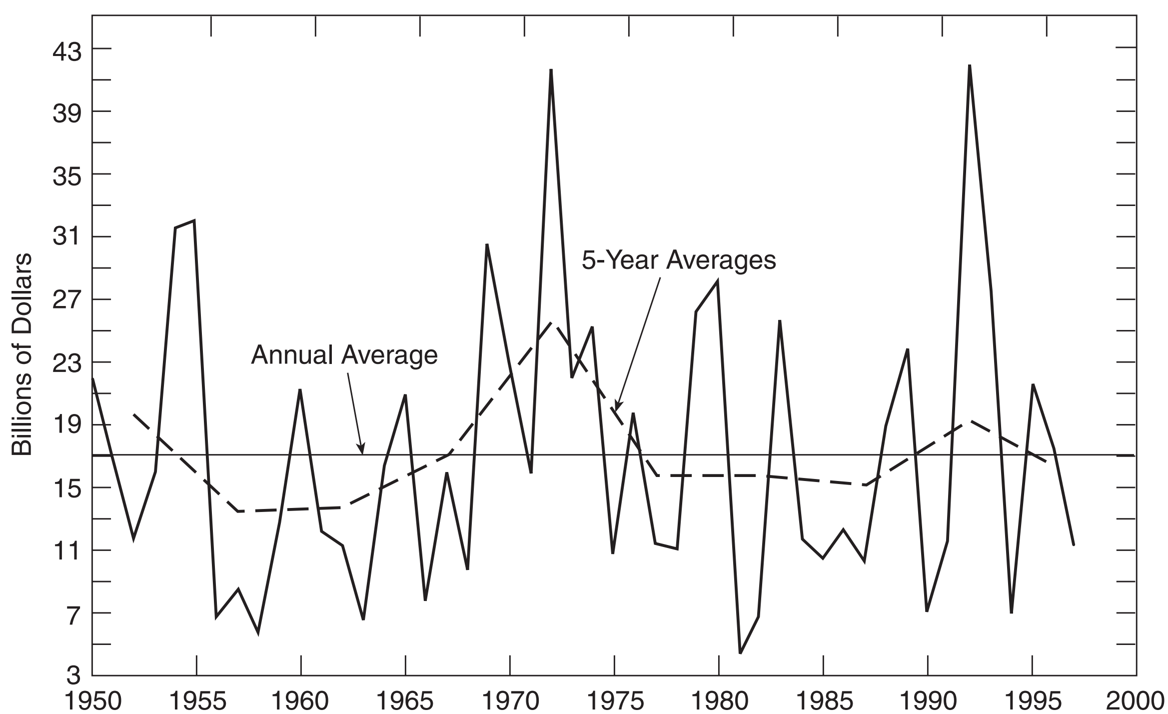


Figure 3-29. Annual and 5-year average National Loss Index values (billions of 1997 dollars), 1950-1997 (Changnon and Hewings, 2001)

in the 48-year period occurred in 1970-1974, with an annual average of $32.499 billion, followed by $25.046 billion (1950-1954), and $20.323 billion (1990-1994). The lowest annual average was $9.936 billion (1960-1964).

Statistical testing of the temporal distribution of the loss values revealed no significant upward or downward trend during 1950-1997. This is not unexpected because certain major loss conditions had upward trends, whereas others had downward trends. Measures of certain intense storm conditions (thunderstorms, tornadoes, and hurricanes) showed temporal decreases, whereas others (floods, winter storms, and heat waves) showed increases over time, reflecting a mixed climatological outcome.

### *Gains*

As explained earlier, assessments of the economic gains due to many weather conditions have been minimal, particularly as they relate to damaging forms of climate extremes. Nevertheless, gains have been identified in most thorough recent studies of major extremes. For example, the studies of the 1987-1989 drought, Hurricane Andrew in 1992, and the 1993 flood revealed economic gains ranging from 30 to 50 percent of the losses. These three events collectively produced losses totaling about $90 billion; hence, gains nationally were between $27 billion and $45 billion. Assessments of economic outcomes from the El Niño cold season and from the record warm winter of 2001-2002 revealed national gains of about $20 billion and losses of $4 billion or less in each event. Crop gains in years with good weather averaged $1.901 billion annually or $93 billion for 1950-1997. Assessment of energy usage also showed 22 years with gains, averaging $3.911 billion per year or 84 percent of the total losses for 1950-1997. These various values were used to construct the estimated gains shown in Table 3-14. When beneficial extremes occur (good growing seasons, warm winters, storm-free conditions, etc.), national economic gains can reach $24.7 billion.

Annual gains exceeded total losses from the various storms in nine years during 1950-1997. This occurred when crop yields were high and energy costs were very low, producing financial gains that collectively exceeded losses due to other weather extremes. Typically, years when gains prevailed had low losses from all types of storms. Years when gains exceeded losses included 1958, 1962, 1963, 1966, 1967, 1968, 1981, 1990, and 1994.

### *Climate Impacts and the National Economy*

The calculated values of financial losses and gains from the weather were assessed against various measures of the nation's economy. However, it must be remembered that the losses and gains determined are direct impacts measured at the time and do not include delayed or indirect financial impacts that may develop months and years after a weather event. Hence, the total financial impacts of weather are even greater than shown. For example, studies of the delayed impacts resulting from the massive 1993 flood indicated that these amounted to roughly a third of the total direct losses (Changnon, 1996).

The $17.47 billion annual average loss for the 1950-1997 period (1997 dollars) was evaluated against two economic measures. It was found to be 1 percent of the total federal expenditures in 1997 ($1.601 trillion), and 0.2 percent of the nation's GDP for 1997 ($8.111 trillion).

The highest one-year loss of $54.4 billion rates as 3.3 percent of the 1997 federal expenditures. The maximum loss year generated using the highest five losses in each sector was $70.7 billion, 4.4 percent of the 1997 federal expenditures. The peak one-year federal assistance payment for weather disasters was $7.1 billion in 1994, 0.5 percent of the 1994 federal expenditures. The Subcommittee on Natural Disaster Reduction (SNDR, 1999) estimated that natural disasters (weather extremes, earthquakes, and other nonweather events) averaged $1 billion in losses per week in the United States, only 0.7 percent of the GDP.

Assessment of the recent major weather extremes presented in a prior section of this chapter, revealed several short-term national-scale economic impacts. The 1987-1989 drought led to a GDP downturn in 1988 of 0.4 percent, and the Consumer Price Index (CPI) rose 0.3 percent. The 1993 flood led the GDP to increase by 0.01 percent in 1994, and corporate profits were down 0.01 percent in 1993, but up by 0.8 percent in 1994. The odd winter weather of El Niño 1997-1998 caused the price of food to increase 0.4 percent in February 1998; inflation held at zero for the first time in 10 years; and the first quarter GDP in 1998 was up 4.2 percent, rather than the 3.4 percent predicted. All of these values are notably small. Agricultural weather losses during 1950-1997 varied between 7 and 9 percent of the annual net cash income for US agriculture in the 1990s (Changnon and Hewings, 2000).

Weather-related economic impacts are more significant regionally where many losses often are concentrated. The $6 billion in flood-related losses in Illinois in 1993 was 2 percent of the Gross State Product (GSP) for 1993. Losses of $21.9 billion in Florida due to Hurricane Andrew in 1992 rated as 10.2 percent of Florida's GSP. The SNDR (1999) indicated that the largest state losses from natural hazards were 5 percent or less of the states' domestic products. Although these impacts are relatively larger than the national impacts, they are not large.

Comparison of weather-climate losses and gains derived using various measures of the nation's economy reveals the changes are extremely small. These findings agree with the economic modeling estimates related to future climate change (Mendelsohn and Smith, 2002), and with the sentiment of the National Assessment Synthesis Team (2001a,b,c).

### Estimating Potential Future Economic Impacts from Climate Change

During the past ten years, a few economists have generated estimates of possible financial impacts resulting from future climate change. At best, these must be considered speculative and uncertain. One simple approach is to examine recent financial impacts and use these as first estimates of future impacts. For example, average and extreme annual losses during 1950-1997 were reviewed as possible precursors to direct economic outcomes from future climate changes because such projections commonly predict more weather and climate extremes. Examination of past values from this study reveals four major loss years during 1950-1997: 1972 ($54.4 billion), 1992 ($43.6 billion), 1954 ($39.8 billion), and 1955 ($39.3 billion). The highest and lowest annual loss values during this period were quite different. The lowest three values were $2.4 billion (1963), $3.1 billion (1966), and $3.4 billion (1968). The lowest value is only 4 percent of the highest value, $54.4 billion. Gains exceeded losses in nine years, and the peak annual gains were $10.9 billion (1981) and $8.3 billion (1992).

If one assumes that the measures of maximum energy use, maximum crop losses, and the losses of the nine storm conditions during 1950-1997 reflect future climate outcomes, then one can estimate part of the economic relevance of the changed climate. For example, the annual loss data for 11 weather/climatic conditions were used to create a scenario of large annual losses. Annual losses of each condition for 1950-1997 were ranked, and the highest five losses were averaged. These 11 "bad year" averages were summed, yielding an annual loss total of $70.7 billion.

Economic modeling has been used to derive estimates of future economic impacts. In the early 1990s, three economists assessed the national economic impacts of global warming. Annual losses generated, in 1988 dollars, were $50 billion (Nordhaus, 1993), $53 billion (Cline, 1992), and $69 billion (Fankhauser, 1993), the latter not unlike the $70 billion value from the scenario using the annual extremes in the 1950-1997 data. The assumed warming in each case was from 2.5°C to 3.0°C, and all three calculations assumed 1988 levels of outputs and composition of goods and services produced. Hewings (1994) noted that the major finding of these studies were that the estimated impact values are small in comparison with the total US economy. A critical issue for estimation of future financial impacts is economic models. Burroughs (1997) evaluated economic models and their use in assessing climate change impacts, pointing to modeling weaknesses and the complexities of integrating the outputs of global climate models with those of macroeconomic models. He further pointed to many other unpredictable factors, such as technology developments over the next 50 to 100 years and their unknown influence on economic impacts of future weather.

A recent economic assessment using three climate scenarios and their estimated impacts on the US economy in 2060 revealed a range of outcomes (Mendelsohn and Smith, 2002). The net national annual economic impact was $36 billion (1998 dollars) in benefits with a climate having a 1.5°C increase and a 15 percent precipitation increase. A scenario with a 5.0°C increase and no precipitation change was estimated to be (for 2060) a national loss of $19.9 billion (1998 dollars), with a range of estimates from $49 billion to $1.6 billion in losses. Mendelsohn and Smith note that these various predicted economic impacts would be about 0.1 percent of the GDP expected by 2060, and they further note their values are about an order of magnitude less than those of the IPCC.

The recent national assessment of climate change was an in-depth investigation of the consequences of climate change in the United States with impacts assessed based on conditions predicted by two global climate models: the Hadley model and the Canadian climate model (NAST, 2001a). Thousands of potential effects were identified (for example, less water, more heat waves, and altered crop seasons, etc.), but few of these impacts were translated into financial outcomes. The agricultural sector assessment found that the projected conditions increased yields of many crops, including corn, wheat, and soybeans. The assessment did quantify the financial outcomes showing that the Canadian model conditions, given various adoption strategies, ranged from losses of $0.5 billion (2000 dollars) annually to gains of $3.5 billion, whereas the Hadley climate model conditions resulted in agricultural benefits ranging between $6 billion and $12 billion (2000 dollars) annually (Reilly et al., 2002). In comparison, the authors' agricultural assessments of the 1950-1997 period presented herein found an average annual benefit of $1.9 billion (1997 dollars) with a one-year peak of $4.8 billion. When losses occurred, the average annual loss was $2.6 billion (1997 dollars).

The NAST water sector assessment found that "Information on economic sectors most susceptible to climate change is extremely weak, as are tools for assessing the socioeconomic costs of both impacts and responses in the water sector" (Gleick, 2000), indicating that the economic impacts from climate-related changes to water resources could not be determined. The concluding chapter of the national assessment report states, "For the nation as a whole, direct economic impacts are likely to be modest" (NAST, 2001c).

The above listed economic estimates of losses and gains from a future changed climate must be considered highly speculative. A recent series of papers by economists, all familiar with the climate change issue, revealed the impossibility of estimating, even crudely, the future economic impacts of global warming and the costs of various approaches for mitigating climate change (Yohe, 2003; Azar and Lindgren, 2003; Hovarth, 2003; Tol 2003). As Yohe (2003) stated, "How could we estimate the distribution of costs and benefits (of mitigating climate change) across the wide range of unknown and unpredictable economic and climate futures."

Furthermore, estimating national impacts based on shifts in the nation's weather and climate does not take into consideration external impacts. Climate changes in other parts of the world, particularly in developing nations, may create financial impacts and major burdens that greatly influence the US economy. All of this adds to the uncertainty in estimating future economic impacts in the United States.

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