ADDENDUM:
Global Climate Change Impacts in the United States

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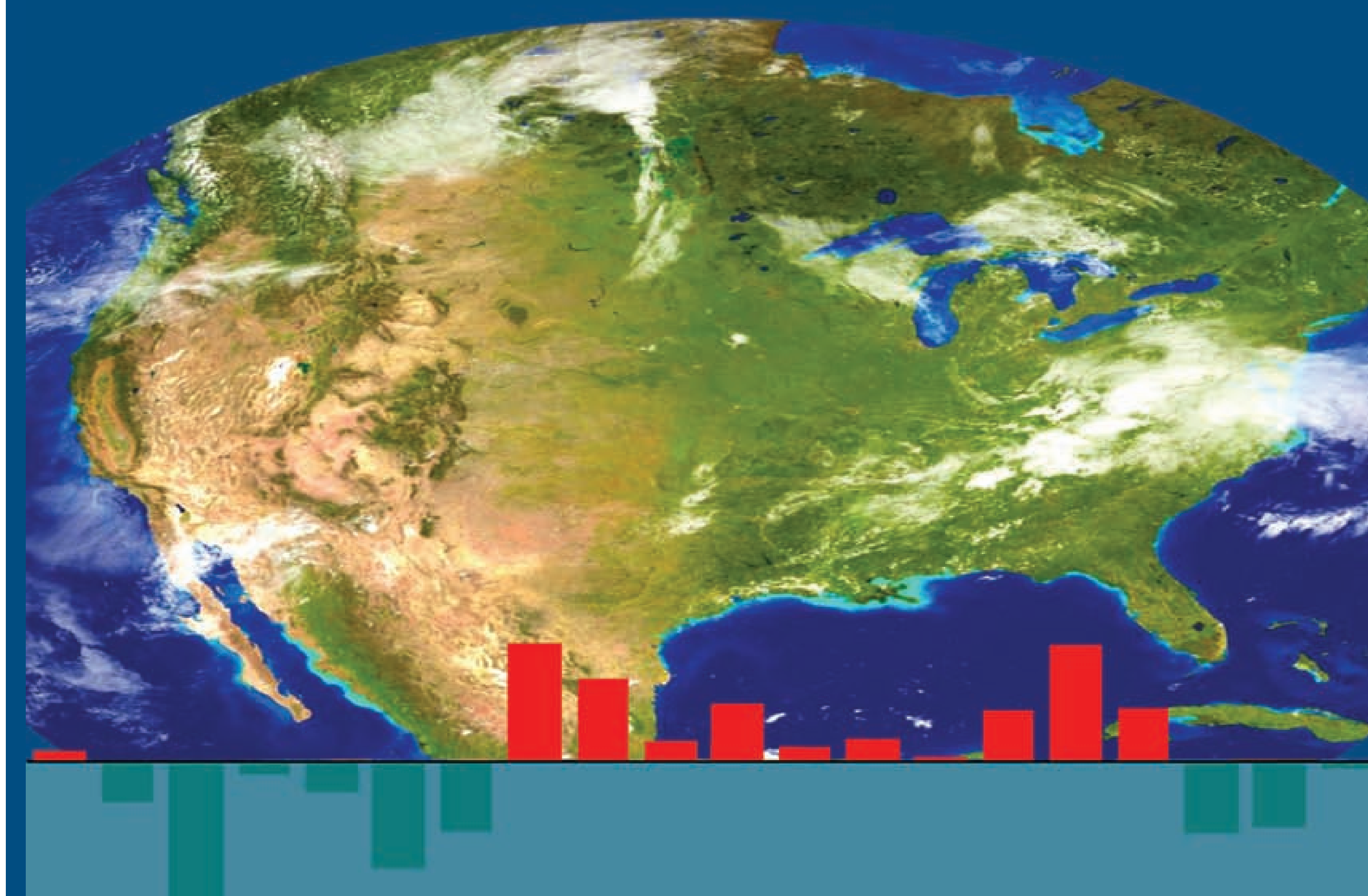

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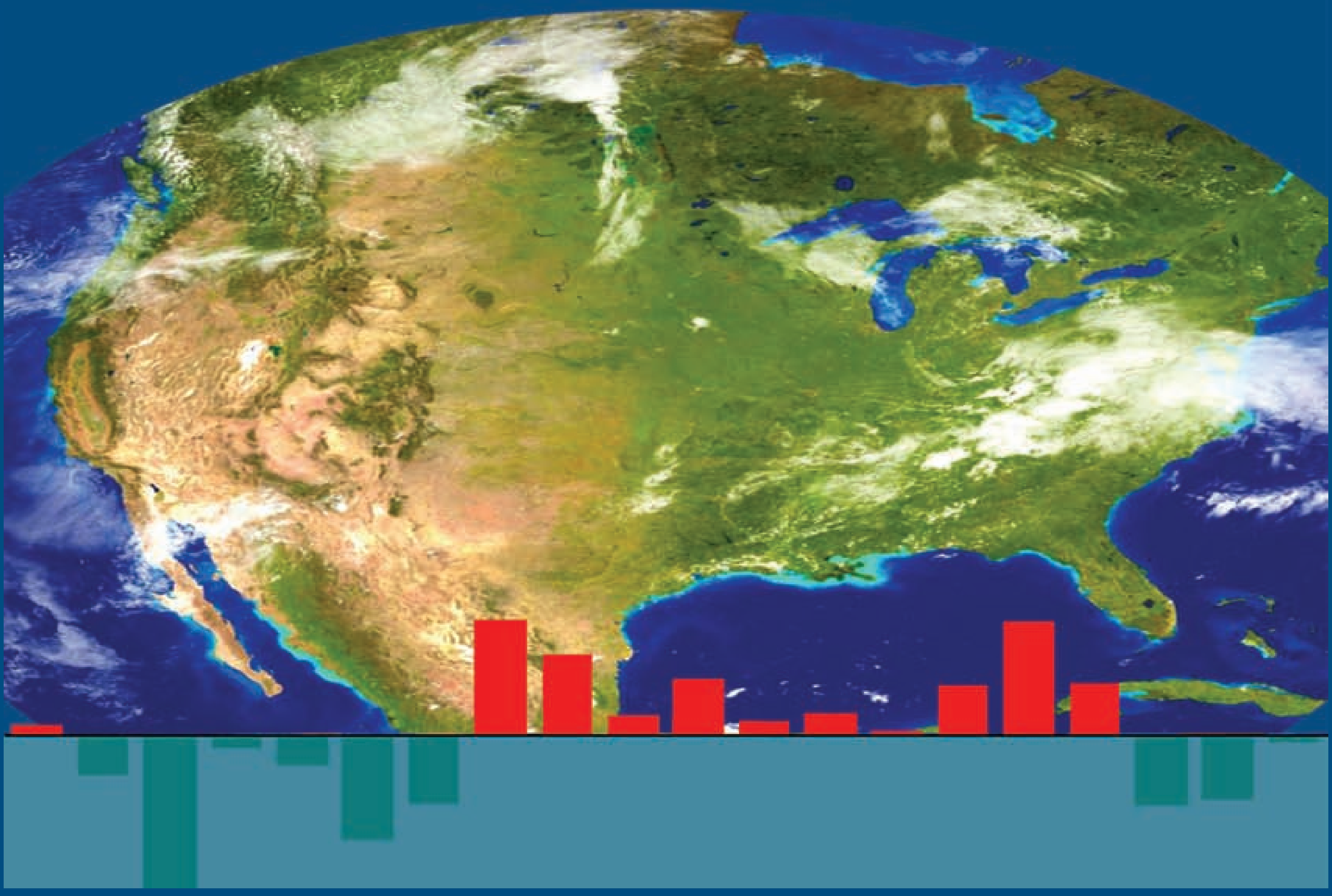

ADDENDUM: Global Climate Change Impacts in the United States

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Acknowledgement

Many thanks to David G. Herro, Peter Goettler, John Bee Mazur, Geoff Pohanka, and Norman Rogers, as well as to the many other donors for their support of the activities of the Center for the Study of Science at the Cato Institute.

The bars at the bottom of the front cover show the U.S. average annual temperature from 1991 through 2010.[1]

September 27, 2012

The Center for the Study of Science at the Cato Institute is pleased to transmit to you a major revision of the report *Global Climate Change Impacts in the United States*. The original document served as the principal source of information regarding the climate of the United States for the Environmental Protection Agency's December 7, 2009, *Endangerment Finding* from carbon dioxide and other greenhouse gases. This new document is titled *ADDENDUM: Global Climate Change Impacts in the United States*.

This effort grew out of the recognition that the original document was lacking in scope and relevant scientific detail. A Cato review of a draft noted that it was among the worst summary documents on climate change ever written, and that literally every paragraph was missing critical information from the refereed scientific literature. While that review was extensive, the restricted timeframe for commentary necessarily limited any effort. The following document completes that effort.

It is telling that this commentary document contains more footnotes and references than the original; indeed, one could conclude that the original *Global Climate Change Impacts* ignored or purposefully omitted more primary-source science than it included.

It is in that light that we present this document. May it serve as a primary reference and a guidepost for those who want to bring science back into environmental protection.

Sincerely,

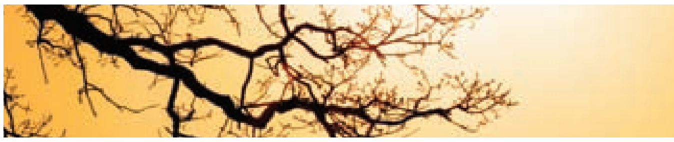
Edward H. Crane
President
Cato Institute

CONTENTS

Climate Change Impacts by Sector

CONTENTS

Regional Climate Change Impacts



About this Report

What is this report?

This report summarizes the important science that is missing from *Global Climate Change Impacts in the United States*, a 2009 document produced by the U.S. Global Change Research Program (USGCRP) that was critical to the Environmental Protection Agency's December, 2009, "finding of endangerment" from increasing atmospheric carbon dioxide and other greenhouse gases. According to the 2007 Supreme Court decision, *Massachusetts v. EPA*, the EPA must regulate carbon dioxide under the 1990 Clean Air Act Amendments subsequent to finding that it endangers human health and welfare. Presumably, this means that the Agency must then regulate carbon dioxide to the point at which it no longer causes "endangerment."

This report discusses climate-related impacts on the same sectors that were in the 2009 report. It is an authoritative report containing more primary science citations and endnotes than its 2009 predecessor. In one sense, it can therefore be hypothesized that the 2009 report ignored more global warming science than it included.

Why was this produced?

Cato Institute staff reviewed various drafts of the 2009 report and provided voluminous commentary indicating a systematic bias in the direction of alarmist findings. In a preface to his review, Senior Fellow in Environmental Studies Patrick J. Michaels noted:

> Of all of the "consensus" government or intergovernmental documents of this genre that I have reviewed in my 30+ years in this profession, there is no doubt that this is absolutely the worst of all. Virtually every sentence can be contested or does not represent a complete survey of a relevant literature...
>
> ...There is an overwhelming amount of misleading material in the CCSP's [the Climate Change Science Program, now the U.S. Global Change Research Program] *Global Climate Change Impacts in the United States*. It is immediately obvious that the intent of the report is not to provide an accurate scientific assessment of the current and future impacts of climate change in the United States, but to confuse the reader by a loose handling of *normal climate* events (made seemingly more frequent, intense, and damaging simply by our growing population, population movements, and wealth) presented as *climate change* events. Additionally, there is absolutely no effort made by the CCSP authors to include any dissenting opinion to their declarative statements, despite the peer-reviewed scientific literature being full of legitimate and applicable reports and observations that provide contrasting findings. Yet, quite brazenly, the CCSP authors claim to provide its readers—"U.S. policymakers and citizens"—with the "best available science." This proclamation is simply false...
>
> ...The uninformed reader (i.e., the public, reporters, and policymakers) upon reading this report will be led to believe that a terrible disaster is soon to befall the United States from human-induced climate change and that almost all of the impacts will be negative and devastating. Of course, if the purpose here is not really to produce an unbiased review of the impact of climate change on the United States, but rather a

> political document that will give cover for EPA's decision to regulate carbon dioxide, then there is really no reason to go through the ruse of gathering comments from scientists knowledgeable about the issues, as the only science that is relevant is selected work that fits the authors' pre-existing paradigm.

This *Addendum* is similar in format to the 2009 USGCRP report, allowing a facile reference for science that was omitted. In some places, we have moved text verbatim from the 2009 report to this *Addendum*.

What are its sources?

This *Addendum* is primarily based upon the peer-reviewed scientific literature, peer-screened professional presentations, and publicly available climate data. We include literature through the begining of 2012, which of course could not be in the 2009 report. But there are also a plethora of citations from 2008 or earlier that were not included in the USGCRP document. Why that is the case is for others to determine.

Does this report deal with options for responding to climate change?

Unlike the USGCRP report, which coupled global warming forecasts with emissions reduction scenarios, this *Addendum* is generally not prescriptive. Readers can determine for themselves whether or not a more complete scientific analysis warrants mitigation programs that may be very expensive (stringent cap-and-trade limitations or a carbon tax) or inexpensive (substitution of natural gas for electrical generation and possibly vehicular propulsion).

How does this report address incomplete scientific understanding?

This report is candid about what is known and what is not. Unlike the USGCRP, it does not include the self-serving section, *An Agenda for Climate Impacts Science*. The Cato Institute traditionally has strong feelings against such rent-seeking behavior by others, including the public-choice-biased global warming science and technology community.

Executive Summary

Observations show unequivocally that there have been two periods of planetary warming in the past 160 years. The first, from roughly 1910 through 1945, likely had very little of a human component, while the second, beginning in 1977, most likely did. Both warmings were of similar magnitude statistically. While there has been no significant warming since 1997, the overall importance of this to global warming science is unclear at this time.

Warming over this century is likely to be near the low end of the range specified in the various reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC). Scaling the IPCC's midrange computer models with observed climate changes yields a warming of approximately 2.9°F. The global average temperature since 1900 has risen about 1.4°F. The U.S. temperature rose by 1.2°F in the same period. The rise in U.S. temperatures in the coming century will likely be equal to or marginally higher than the global average, with a concentration of warming in the winter and in higher latitudes.

Reducing U.S. emissions of carbon dioxide, even by over 80 percent, will have no measurable effect on global mean surface temperature or other climate-change-related phenomena within any policy-forseeable timeframe. This is true even if most developed economies achieve this reduction. The reason for this is because of the dramatic increases in emissions that are occurring in China, India, and the developing world.

Climate changes have been observed by both instrumental and proxy measures. From the latter, for example, we know that droughts much more severe than what we have observed in the instrumental record have occurred in the Colorado River Basin, which provides essential water for much of the southwestern United States. There has been a measured increase in rainfall on the rainiest day of the year—about a quarter of an inch in the last century. Climate extremes have reverted back to where they were in the late 19th and early 20th centuries, after a quiescent period in the mid- and late 20th century.

We can confidently say that climate change will continue. The current low point in hurricane energy cannot be maintained unless tropical cyclone climatology is undergoing some vast, unforeseen change. The slight increase in heavy precipitation may continue to grow. The fact that it was increasing prior to the major emissions of greenhouse gases means it may even reverse. American agriculture, which is adapted to a remarkably wide range of climates, will continue with the expectation of higher crop yields in the future.

This report synthesizes a broad and diverse scientific literature that was ignored or misinterpreted in the report *Global Climate Change Impacts in the United States*, produced by the U.S. Global

Change Research Program (USGCRP). The number of footnotes and references in this report substantially exceeds—932 versus 894—that in the USGCRP document. Whether or not this means that the USGCRP ignored more science than it included is a worthy subject for public discussion, given that it is a taxpayer-supported organization, consuming billions of dollars per year.

This report concentrates on the same sectors and regions as the USGCRP report, with the exception of two brief sections from that report, "coasts" and "islands," that were superfluous in that document. In general, we find strong evidence that people easily adapt to climate and climate change, which should not be surprising, as climate change is a hallmark of the *Homo sapiens* era. If climate changes become larger, incentives to adapt increase. Infrastructure engineering tends to err on the side of caution with regard to environmental disturbance (with the Fukushima nuclear disaster being a telling exception), and will continue to do so.

We expect that "ocean acidification" will become the next global environmental concern, following on the heels of failed gloom-and-doom projections about population, global cooling, acid rain, ozone depletion, and global warming. It is worth noting that atmospheric carbon dioxide concentrations through the vast majority of the time when life has been on earth have been much higher than they are now, and carbonate-secreting organisms thrived in the ocean during those eons.

Markets have largely replaced wars over resource scarcity and can be expected to continue to ameliorate local weather and climate variability.

Projections of future climate change are highly dependent upon the nature of our future energy supply. The history of energy projections reveals that they are largely worthless. "Peak oil" is now a known myth. We were purportedly running out of natural gas. No one knows the utility or the future of nuclear fusion. Things that we cannot imagine today will provide energy tomorrow, as is obvious from a 1900-era vantage concerning 20th-century energy and transportation. Anyone at that time who said that a handful of a nonexistent element, placed in a confined place, would destroy a city, would be branded insane. Imagine if someone said that if this element were placed in less confined circumstances, it could provide electricity for that city for 100 years? Yet, with regard to global warming, EPA assumes no major changes in energy technology or use in the next 200 years!

When examining climate data, where relevant, this report subscribes to the scientific standard that any change in a variable that is not statistically significant is in fact not a change. Consequently, we find much less "climate change" than does the USGCRP, which does not adhere to the this normative principle. In particular, we find that forecasts of future changes in regional precipitation in the United States (with a few exceptions) are of no utility.

This report does not espouse specific emission-reduction strategies for carbon dioxide; instead it concentrates largely on climate change in the United States. One reason is because such policies are likely to have no detectable effect on climate on a time horizon that takes into account the normal changing of energy and transportation technologies.

One aspect of adaptation to climate change that is largely ignored in the USGCRP report is the salutary effect of carbon dioxide on plants. In particular, it is important to note that, as carbon dioxide builds up in the atmosphere, the optimum temperature for photosynthesis also rises. In other words, physiology is not static.

This report does not end with a self-serving list of areas from which its authors can generate even more federal taxpayer funding for themselves. For an example of that, see the original USGCRP volume.

Key Findings

1. Climate change is unequivocal, and human activity plays some part in it.
There are two periods of warming in the 20th century that are statistically indistinguishable in magnitude. The first had little if any relation to changes in atmospheric carbon dioxide, while the second has characteristics that are consistent in part with a changed greenhouse effect. (p. 17)

2. Climate change has occurred and will occur in the United States.
U.S. temperature and precipitation have changed significantly over some states since the modern record began in 1895. Some changes, such as the amelioration of severe winter cold in the northern Great Plains, are highly consistent with a changed greenhouse effect. (pp. 38–56, 187–92)

3. Impacts of observed climate change have little national significance.
There is no significant long-term change in U.S. economic output that can be attributed to climate change. The slow nature of climate progression results in *de facto* adaptation, as can be seen with sea level changes on the East Coast. (pp. 48–49, 79–81, 155–58, 173–74)

4. Climate change will affect water resources.
Long-term paleoclimatic studies show that severe and extensive droughts have occurred repeatedly throughout the Great Plains and the West. These will occur in the future, with or without human-induced climate change. Infrastructure planners would be well-advised to take them into account. (pp. 57–71)

5. Crop and livestock production will adapt to climate change.
There is a large body of evidence that demonstrates substantial untapped adaptability of U.S. agriculture to climate change, including crop-switching that can change the species used for livestock feed. In addition, carbon dioxide itself is likely increasing crop yields and will continue to do so in increasing increments in the future. (pp. 102–18)

6. Sea level rise caused by global warming is easily adapted to.
Much of the densely populated East Coast has experienced sea level rises in the 20th century that are more than twice those caused by global warming, with obvious adaptation. The mean projections from the United Nations will likely be associated with similar adaptation. (pp. 173–74)

7. Life expectancy and wealth are likely to continue to increase.
There is little relationship between climate and life expectancy and wealth. Even under the most dire climate scenarios, people will be much wealthier and healthier in the year 2100 than they are today. (pp. 139–45, 158–61)

8. Climate change is a minor overlay on U.S. society.
People voluntarily expose themselves to climate changes throughout their lives that are much larger and more sudden than those expected from greenhouse gases. The migration of U.S. population from the cold North and East to the much warmer South and West is an example. Global markets exist to allocate resources that fluctuate with the weather and climate. (pp. 154–69)

9. Species and ecosystems will change with or without climate change.
There is little doubt that some ecosystems, such as the desert West, have been changing with climate, while others, such as cold marine fisheries, move with little obvious relationship to climate. (pp. 119–38, 208)

10. Policies enacted by the developed world will have little effect on global temperature.
Even if every nation that has obligations under the Kyoto Protocol agreed to reduce emissions over 80 percent, there would be little or no detectable effect on climate in the policy-relevant timeframe, because emissions from these countries will be dwarfed in coming decades by the total emissions from China, India, and the developing world. (pp. 28, 211)

[1]National Climatic Data Center, U.S. Department of Commerce, at http://www.ncdc.noaa.gov/oa/climate/research/cag3/na.html.

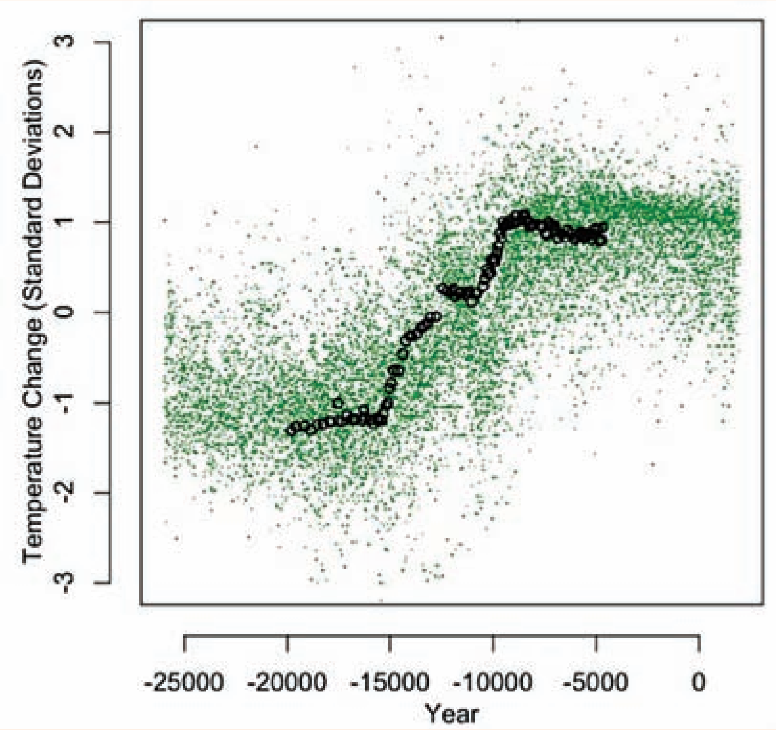
Global Climate Change

Key Messages:

- Human activities have resulted in the emissions of gases that warm the lower atmosphere, as well as particles that counter the resultant warming. We have also changed the surface of the planet in complicated ways that have undetermined net effects on global climate.
- Global average surface temperature measured by an uneven network of thermometers increased approximately 0.7°F early in the 20th century, which was before changing atmospheric composition could have had much influence on climate. In the mid-century, temperatures fell slightly.
- Global average surface temperature rose approximately another 0.7°F from the mid-1970s through the late 1990s, when a very strong El Niño event resulted in the record temperatures measured in 1998. There is conflicting evidence concerning the exact amount of this warming that was caused by changes in atmospheric composition.
- Depending upon the measurement technique used, global sea levels either rose at a constant and modest level during the 20th century, rose at a constant level through the mid-1990s, followed by a slight increase in the rate of rise, or fluctuated cyclically throughout the 20th century.
- Climate will continue to change in the coming century. Emissions reduction policies taken by the United States will largely have no effect on these changes. Currently developing economies, powered mainly by fossil fuels, will contribute most of the emissions of this century.

This introduction to global climate change explains very briefly what has been happening to the world's climate, speculates on why these changes have occurred, and what the future might portend. While this report focuses on climate change impacts on the United States, complete understanding of these changes requires an understanding of the global climate system that we currently do not possess. Climate has always changed and will continue to do so, although human activity may amplify or modify such changes.

In addition to the authors listed on page 1, Indur Goklany contributed to this chapter.



The green dots are the inferred temperature change from 80 different "proxy" climate variables, such as ice cores and ocean sediment records. The black circles are the atmosphere's carbon dioxide concentration.[1] The proxy and carbon dioxide data are all standardized so that their units are commensurate. It is very clear that inferring any lag time between carbon dioxide and the proxy field (as was done in the cited work) is very difficult, unless the noise is artificially removed from the proxy data.

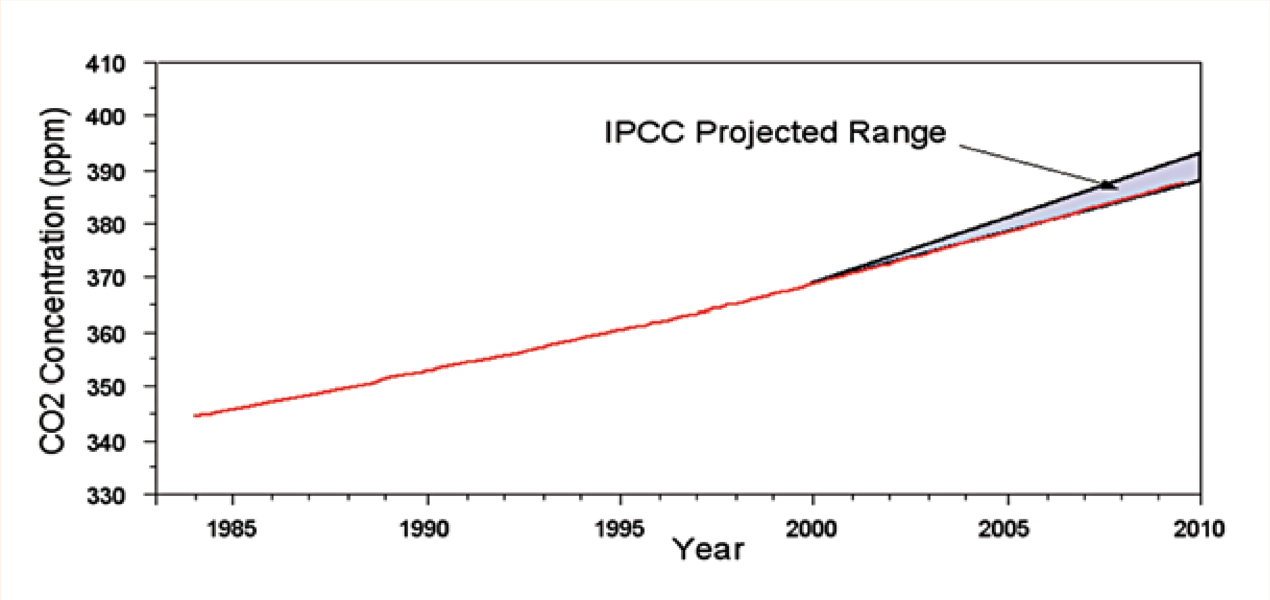
Human activities have led to changes in the concentration of atmospheric constituents that amplify the natural greenhouse effect.

The Earth's climate is determined by many factors, including the energy output of the sun, the amount of solar radiation that is absorbed by the earth-atmosphere system, and the "recycling" of radiation in the lower atmosphere by what are called "greenhouse" gases. They make the lower atmosphere warmer than it would be in their absence. They do not change the overall earth-atmosphere temperature, but rather redistribute it in a different fashion than would occur in their absence. In descending order of importance, these are water vapor, carbon dioxide, methane, industrial halocarbons, ozone, and nitrous oxide. (There are many others that have infinitesimal effects.) Absent these compounds, the Earth's surface temperature would be approximately 60°F lower than it is now. These gases have increased surface temperature beyond its "preindustrial" average, although the amount of increase is dependent upon assumptions of how "sensitive" that temperature is to changes in their concentration. Sensitivity is very difficult to determine from first scientific principles, and there is an ongoing and vigorous debate about precisely what its value is. The increase in carbon dioxide concentration has played some role in the observed warming of surface temperatures by 0.7°F beginning in 1977.

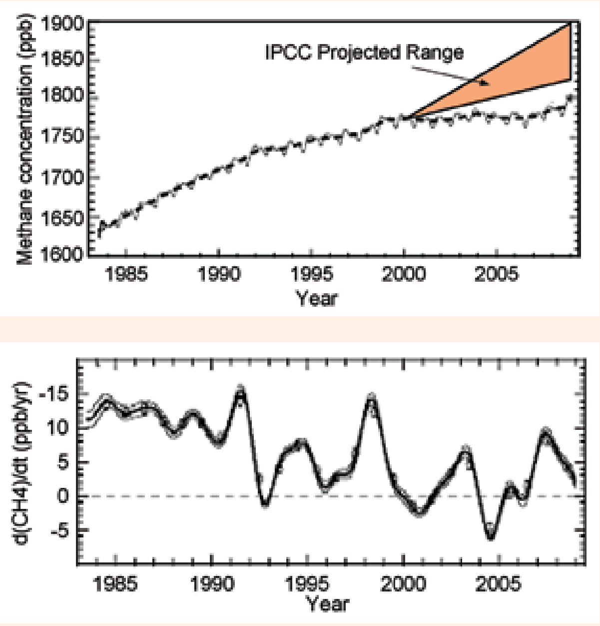
Before the industrial revolution, the concentration of atmospheric carbon dioxide was approximately 280 parts per million (ppm). When systematic measurements of its concentration began at Mauna Loa, Hawaii, in 1957, the concentration had risen to approximately 315 ppm, and now it is around 393.[2] The reason that it is difficult to precisely attribute the amount of late 20th century warming to carbon dioxide is because a warming of similar magnitude took place in early part of the century, when carbon dioxide concentrations were barely elevated above their background levels.

The primary source of this carbon dioxide is

Atmospheric Carbon Dioxide Concentration
(Observed and Projected)



Observed and projected atmospheric concentrations of carbon dioxide given by the UN's Intergovernmental Panel on Climate Change (IPCC). The observed value (red line) is very near the lower limit of the IPCC projections made in 2001.



Top: The rate of increase in atmospheric methane began to decline in the late 1980s and is now far beneath the range projected by the IPCC for the first decade of the 21st century. There is no clear scientific explanation for the cause of this change. Bottom: In recent decades, there are times when the atmospheric concentration change has been negative.[9]

the combustion of fossil fuels. Human activities have also increased the atmospheric concentration of the other greenhouse gases noted above. Water vapor is a very special case because it is already highly concentrated in the atmosphere, and a vigorous science debate rages on the nature of the interaction between water vapor, clouds, and greenhouse-effect warming.[3,4] The increase in greenhouse gases has resulted in a rise in surface temperature whose true value is unknown at this time because of conflicting studies "attributing" observed climate changes to changing greenhouse-gas concentrations.[5,6]

Greenhouse gases

Carbon dioxide concentration has increased because it is a by-product of the combustion of fossil fuels that are used in large part to power the developing and developed economies of the world. The world's forests are expanding concurrent with increasing carbon dioxide.[7]

Globally, the concentration of atmospheric carbon dioxide has grown by about 40 percent over its pre–industrial background. The observed increase in concentration is at the low end of the projection ranges given a decade ago by the United Nations' Intergovernmental Panel on Climate Change (IPCC).

Methane concentration has risen as a result of bovine flatulence, rice-paddy agriculture, mining, landfill decomposition, and infrastructural leaking of gas pipelines, particularly from collective societies with poor maintenance practices. Methane concentrations rose at a fairly constant 10 parts per trillion (ppt) per year for most of the 20th century. In the late 1980s, the rate of increase began to decline, and by the early 21st century, there were some instances in which atmospheric concentrations had lowered. The uniform consensus of scientists in the late 1980s was that methane would continue to increase at the rate established in the 20th century; there is no accepted explanation for its behavior in recent decades, which is clearly counter to what the IPCC still projects.[8]

As our figure shows, the IPCC clearly projects a continued linear increase in atmospheric methane through at least the middle of this century. Projections of warming that include this IPCC methane scenario must be adjusted downward because of this obvious error.

Industrial halocarbons do not occur naturally. These are largely chlorofluorocarbon (CFC) compounds that have effectively been banned by the United Nations' Montreal Protocol on Substances that Deplete the Ozone Layer, and atmospheric concentrations have begun to drop slightly.[10] Some of the replacement compounds, known as hydrochloroflourocarbons, also enhance the greenhouse effect, but their atmospheric concentrations are too low for them to exert any detectable effect on climate at this time.

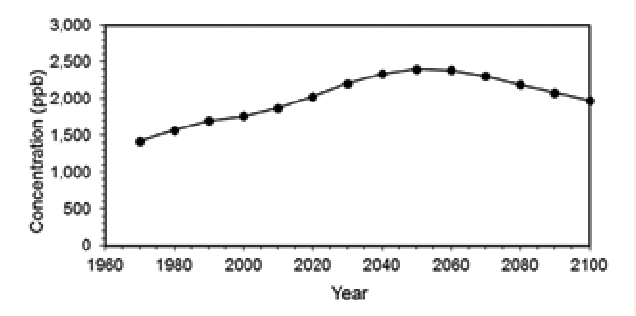
Ozone is a highly reactive and unstable oxygen molecule that contributes to warming by greenhouse activity in the troposphere and to cooling from its depletion in the stratosphere, which is caused in large part by the breakdown of industrial halocarbons. The IPCC estimates the net warming effect of ozone is about half that of methane. There is little doubt that stratospheric ozone had to undergo some very large natural changes when global volcanism was much greater than it is today. Any changes in Antarctic climate as a result of current ozone depletion are swamped by the fact that there is little if any net warming averaged over the continent for the last 35 years.[11]

Water Vapor is by far the most important and abundant greenhouse gas in the atmosphere. All computer models simulating large climate changes in the future are programmed to increase atmospheric water vapor concentrations as a result of an initial modest warming caused by changes in the other greenhouse gases listed above. There is evidence for some slight increase in atmospheric water vapor,[12] as well as evidence that its effect has been overspecified in global warming models,[13] or that the water-vapor–carbon dioxide feedback effect on temperature may actually be negative.[14]

Other human influences

In addition to enhancing the earth's natural greenhouse effect, other human activity also causes local and regional climate change. Clearly, our large cities are several degrees warmer than the surrounding countryside owing to their pavement, masonry, and the artificially rough surface that impedes the flow of ventilating winds. As such, they are interesting unintended experiments in which some of the effects of global warming can be devined. For example, while cities have clearly warmed, mortality from heat-related causes in North American cities has declined.[15]

Some human activities are hypothesized to offset greenhouse warming. As early as the mid-1980s, it was recognized that climate models driven only with greenhouse gases calculated about twice as much warming as was being observed.[16] The observed temperature history



Recent and projected methane concentrations from the "midrange" scenario in the 2007 IPCC report. The IPCC maintained the concentration increases from the 1970s and 1980s through the mid-21st century despite the fact that the rate of increase clearly declined to near zero by 2000.

of the 20th century was much more consistent with climate models if a competing, cooling compound, known as sulfate aerosol, was introduced. Because the effects of sulfates are complicated and unknown to the degree that NASA lobbied heavily for an expensive satellite (which failed on launch in 2011) to determine the effects, it is easy to select a value for this cooling that mimics global temperature histories. Science is replete with examples of *post hoc* parameterizations in order to preserve established syntheses;[17] it is hard to believe that climate science is immune from such a process.

Soot, or black carbon, is produced along with sulfate aerosol. A literature review by the acknowledged expert in this field concluded that fully one-quarter of observed surface warming since the mid-20th century is a result of this compound, which is not a greenhouse gas.[18]

The effects of various greenhouse gases and other compounds on Earth's climate depend in part on how long these gases and particles remain in the atmosphere. After emission, most of the atmospheric carbon dioxide is removed in the first 50–100 years. The smaller amounts that remain long thereafter will exert climate effects of similarly small magnitude (and that would have already been experienced). The effects of some aerosols last for only days, while others can linger for years. The climate effects of carbon dioxide emissions are detectable immediately in our urban areas,[19] while there is a longer lag-time in the ocean, with recent measurements indicating that the potential warming may in large part be spread through the tremendous depths and volume of the globe's seas.[20]

Human activities have also changed the land surface in ways that alter how much heat is absorbed by the surface. In general, a darker surface becomes warmer (which explains why people tend to wear white clothes where it is warm and dark ones where it is cold). Eminent scientists have resigned from the IPCC over perceived inattention to this effect.[21]

Natural influences

Several other natural factors influence climate. Some are purely external to the atmosphere and include changes in the sun's output and sporadic volcanic activity. Others are internal or may themselves be modulated by greenhouse gas and/or solar and volcanic changes, such as the periodic Pacific temperature oscillation known as El Niño, the North Atlantic Oscillation, and a host of other large-scale phenomena that were unknown prior to easy access to supercomputing. A very large El Niño in 1998 gave rise to a global average temperature record that, depending upon dataset used, has yet to be exceeded. Another large El Niño in the late 1980s was associated with the spike in temperature that first brought global warming to the political stage.

Climate scientists generally believe that the overall solar effect on climate change is small, while some theoretical physicists and astronomers believe it may be larger. Climate scientists generally conclude that solar changes might be responsible for 0.2–0.4°F of temperature variation since the industrial revolution, while others conclude that the majority of the warming of the early-20th century was caused by solar changes, as was a quarter of the 1975–98 warming.[22] A novel mechanism for amplification of small solar changes into larger climate changes has been proposed via cosmic rays.[23]

Both climate models and greenhouse-effect theory predict that stratospheric temperatures should decline smoothly, as more warming radiation is recycled in the lower atmosphere. While they indeed have gone down, the decline is one characterized by sharp drops associated with volcanoes, followed by periods of relatively constant temperature. Notably, there is no significant trend in any direction for the last 17 years,[24] which is concurrent with the well-known hiatus in surface warming.

There is less debate about the effects of major volcanoes on climate, which exert a short-term cooling of two to three years. The largest recent volcanoes were Agung (1963), El Chichon (1983), and Mt. Pinatubo (1991). A famous study of climate change used as the basis for the Kyoto Protocol on global warming suffered the effects of beginning with the cooling of Agung and ending with the late 1980's anomalous warmth.[25] When more comprehensive data was included, the result was invalidated but policymakers nonetheless went forward.[26]

Carbon release and uptake

Of the total amount of carbon dioxide that is emitted to the atmosphere annually, a significant fraction is absorbed by the oceans or taken up by vegetation. The remainder has accumulated in the air, increasing the global atmospheric CO_2 concentration. Given concerns over the potential for this trace gas to influence climate, it is important to understand the sources and sinks of carbon dioxide, how they vary across time and space, and how they might change in a warming (or cooling) climate. For example, it has been suggested that a thawing of permafrost might release carbon into the atmosphere, initiating a feedback loop in which the release of more carbon leads to more warming, which leads to a further release of carbon, a further warming, and so on. The notion of such a feedback loop, however, has been shown by researchers to likely be incorrect, as permafrost degradation is generally followed by rapid "terrestrialization," which often leads to more carbon being *stored* in the soils and vegetation than was initially lost during the thawing period.[27,28,29]

Over the past decade, atmospheric CO_2 has accumulated in the atmosphere at a rate of about 1.9 ppm per year, up from a rate of 1.6 ppm per year two decades earlier.[30] In spite of this increase, there is evidence that the terrestrial biosphere has become, in the mean, an *increasingly greater sink* for CO_2 carbon; and it has done so even in the face of massive global deforestation, for which it has more than compensated (see *The Increasing Vigor of Earth's Terrestrial Plants* in the Ecosystems chapter).[31]

Ocean acidification

Another perceived threat of increasing atmospheric CO_2 is ocean acidification, whereby higher atmospheric CO_2 concentrations lead to a greater absorption of CO_2 by the world's oceans and a decline in their pH values, which could to be detrimental to the calcification process that is so important to most marine life.

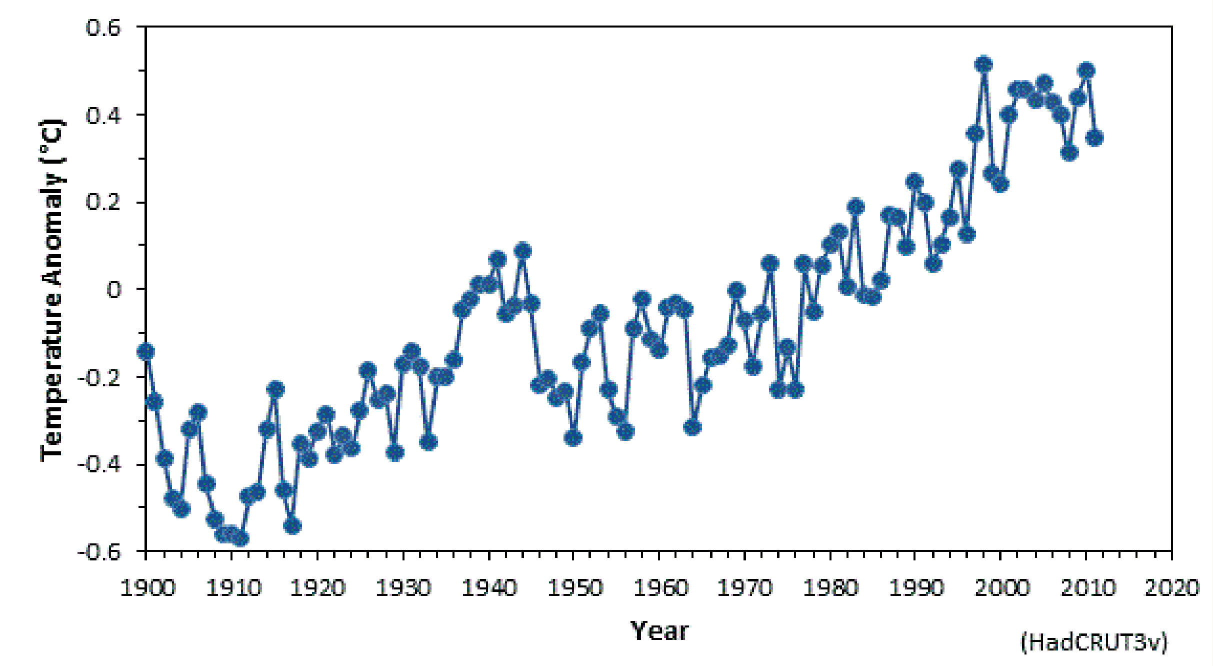
The scientific literature in this area has been expanding rapidly, and when evaluated in its entirety reveals a future that does not support alarming statements such as that we are in "the last decades of coral reefs on this planet for at least the next ... million plus years, unless we do something very soon to reduce CO_2 emissions,"[32] or that "reefs are starting to crumble and disappear," that "we may lose those ecosystems within 20 or 30 years," and that "we've got the last decade in which we can do something about this problem."[33]

This is dealt with in depth in the Ecosystems chapter.

Global average temperature has risen,sea levels have changed, and precipitation patterns show slight variation

Temperatures are rising from a combination of influences.

Global Temperature History, 1900–2011



There are two periods of warming in the 20th century of roughly equal magnitude, from 1910–45, and 1976–98. The first warming is not likely to be associated with greenhouse gas changes, and the lack of statistically significant warming since 1996, which is concurrent with the greatest increases in greenhouse gases, is of unknown importance at this time.

As measured by thermometric networks that were never designed to monitor globally, surface average air temperature has increased by 1.5°F since 1900.[34] This increase is the result of the combined influence of natural variability and human activities. Natural influences on the climate include changes in the output of the sun,[35] the timing of volcanic eruptions,[36] and variability internal to the climate system itself. Human activities with a potential to influence the climate include landscape changes,[37] emissions of tropospheric aerosols (or their precursors) that are hypothesized to counter greenhouse warming,[38] and the emissions of greenhouse gases.[39] The human influence on the Earth's climate is increasing.[40]

The variations in the average surface temperature of the earth (itself a combination of air temperatures over land and sea surface temperatures across the oceans) is based on measurements from thousands of weather stations, ships, and buoys unevenly scattered across the world, as well as from observations from instrumentation borne on Earth-orbiting satellites. These measurements are subject to a large array of influences that are not directly related to the temperature of interest. Such influences must be corrected. The analysis and processing of the raw observations into a compiled record of average global temperatures has been attempted by different research groups. There are a number of important steps in the data processing procedures. These include, but are not limited to, identifying and adjusting for the effects of changes in the instruments used to measure temperatures, the measurement times and locations, the local environment around the measuring site, and such factors as satellite orbital drift. The growth of cities causes a localized "urban heat island" effect, warming the urban environment relative to the surrounding countryside. There is evidence that these non-climatic influences have not been completely removed from the compiled temperature histories.[41,42]

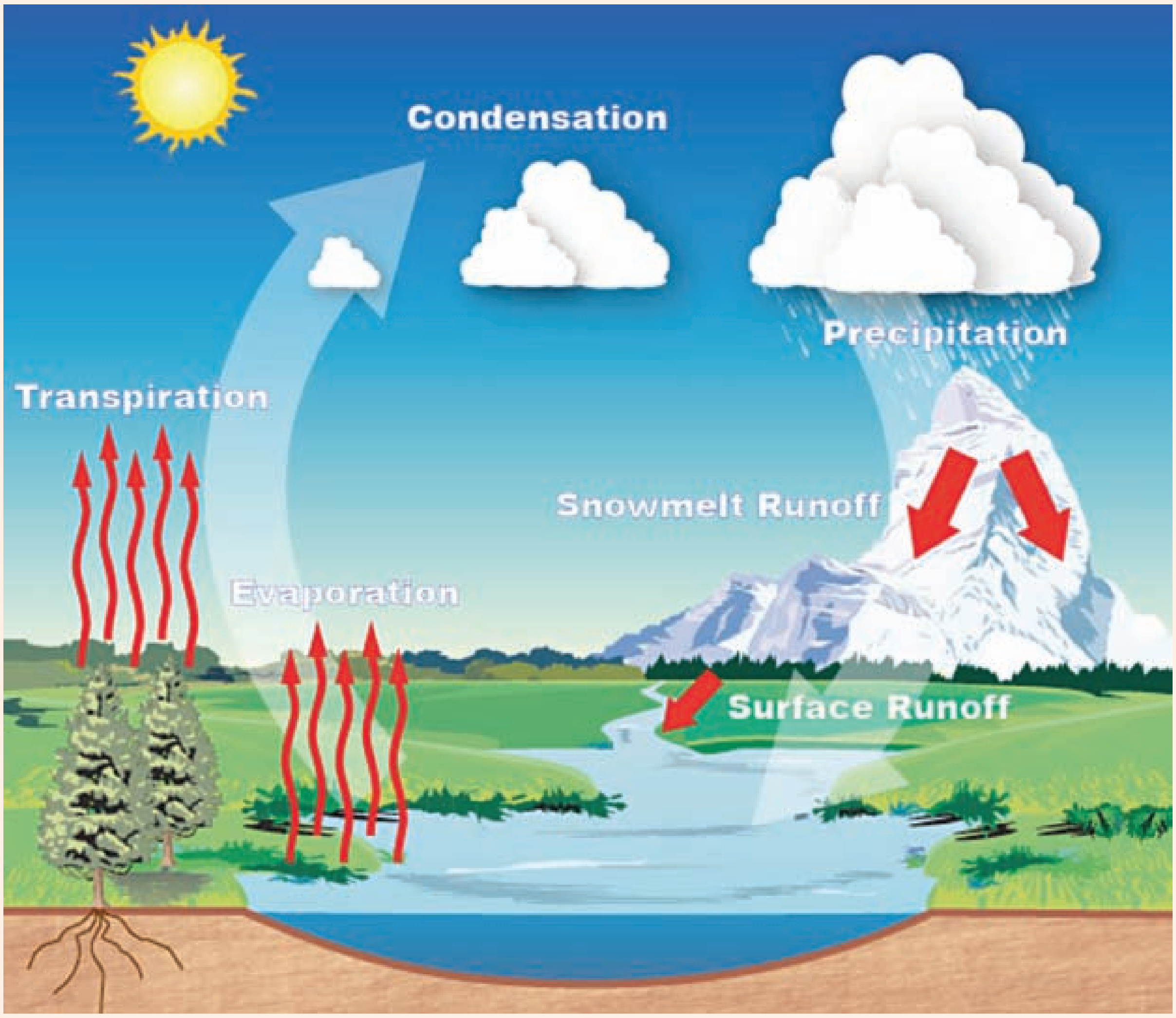
A number of research groups have produced estimates of the variations in global-scale surface temperature dating back into the late 19th century.[43,44,45] An overall warming trend is apparent in all of these compiled temperature histories. That the Earth's surface temperature during this time has warmed at a large-scale is additionally suggested by a collection of other, independent observations distributed around the world including the retreat of mountain glaciers, species range shifts, and rising sea levels.

Additionally, temperature measurements above the Earth's surface have been made by weather balloons since the late 1940s[46] and from satellites since the late 1970s.[47] These measurements show a global average warming of the troposphere and a cooling of the stratosphere. The rate of warming in the troposphere measured by satellites (0.25°F/decade) is less than that observed at the surface (0.28°F/decade) during the period of overlapping observations. This pattern of tropospheric and surface warming runs counter to our expectations of how the Earth's temperature should change in response to increasing greenhouse gas concentrations and thus challenges the current state of our understanding.[48]

Precipitation patterns have always been changing

There is no straightforward relationship between temperature, humidity, and precipitation because precipitation mechanisms, such as convection, orographic lift, and frontal uplift are all modulated by storm tracks and intensities that are potentially impacted by climate change in a complex (and not well-understood) manner.

Precipitation is not evenly distributed across the United States, and the location and intensity of storms depends upon factors such as the pattern of ocean temperatures in the Pacific, which exhibits a multidecadal cyclic behavior (the Pacific Decadal Oscillation, PDO) and shorter-term variability related to

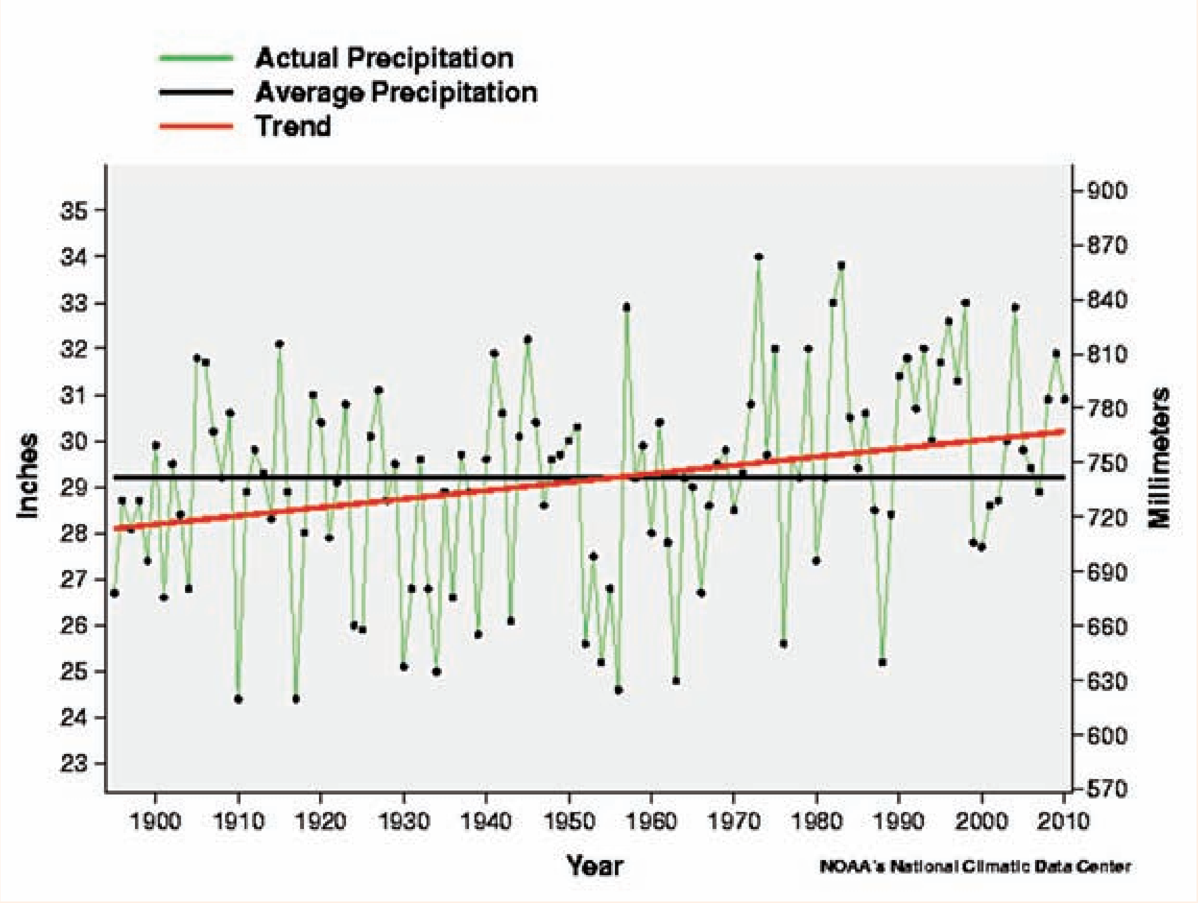


The hydrologic cycle is sufficiently complex to render relationships between global temperature, regional humidity, and local precipitation changes largely undecipherable.

the El Niño/La Niña pseudo-cycle.[49,50,51,52] There are no clear, predictable linkages between El Niño, PDO, and global warming.[53,54] Some climate models show changes in El Niño that are linked to increasing global temperatures, but the accuracy of these forecasts is low.

Earlier research reports a precipitation increase in the United States of about 10 percent,[55,56] but as noted below, recent data lowers this value to 7 percent, which is still statistically significant. While this is obviously beneficial from the standpoint of agriculture and water resources, it could prove detrimental if these increases are related to a marked increase in flooding.

Much of the focus on global warming impacts on precipitation have emphasized an increase in extreme precipitation events (and, by implication, more floods). However, more extreme precipitation is entirely consistent with increasing overall precipitation. Over any period of time, of the total precipitation observed at most locations, most will be delivered in a few events with heavy rain or snowfall. Thus, it is difficult to increase overall precipitation without increasing heavy precipitation. So the frequency of extreme events is perfectly commensurate with an overall increase in precipitation.[57]



Annual precipitation in the lower 48 states has risen approximately 2.1 inches, or 7 percent from 1895 through the present. While this number is quite small, the increase is statistically significant.

Sea level is rising slowly

Earth's sea levels rise and fall in step with changes in climate. During cooler times, colder temperatures contract or shrink ocean volume. Additional reductions take place as some of the water that evaporates from colder oceans is deposited on the surface as permanent snow and ice. In warmer times, the situation is reversed.

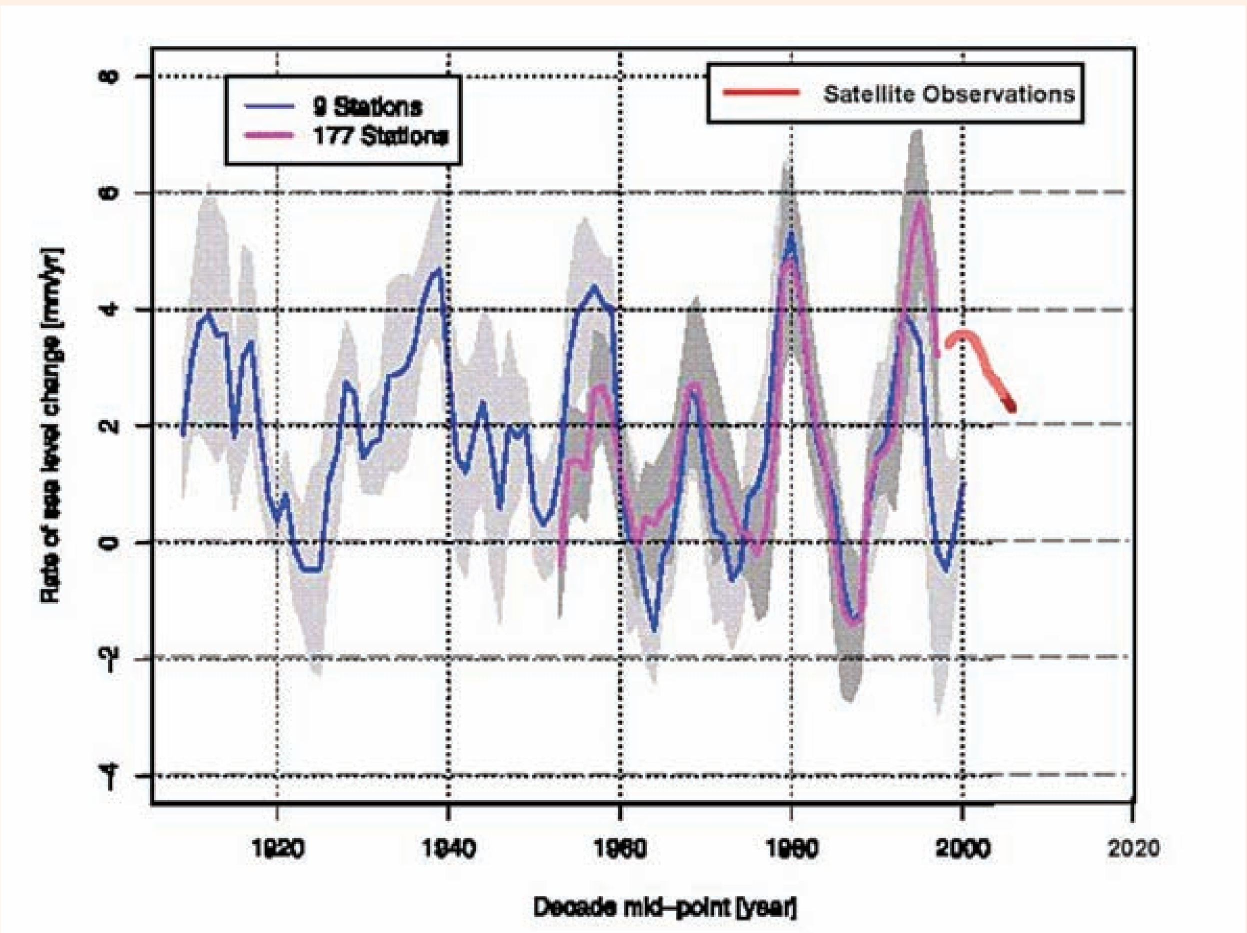
After at least 2,000 years of only a slight increase, sea level begin rising at a faster rate in the mid-19th century and rose by roughly seven inches during the 20th century. Based on a long-term study of tide gauge measurements, it has been determined that the rate of sea level rise undergoes decadal-scale variability.[58] Satellite data available over the past 20 years confirms that sea level undergoes variability at these timescales. The rate of sea level rise observed by satellites is currently on the decline and is approaching the 20th-century average established by the tide gauge network.

Warming has been observed in each of the world's major ocean basins. Globally, the rapid build-up of the heat content of the upper 700 meters of the ocean that characterized the period from the early 1980s through the early 2000s has abated somewhat, and consequently, the contribution to sea level rise from water expansion has slowed in recent years.[60]

Many non-polar glaciers have been retreating worldwide for over a century, pulling back from their advanced positions attained during a cold period known as the Little Ice Age. While a few glaciers continue to advance (in locations well below freezing, and where precipitation has increased), the retreat of most glaciers during the past few decades has continued, and consequently, the total volume of water stored in mountain glaciers worldwide has been in decline. However, in terms of sea level rise, the decline in global glacier volume has been slight, contributing perhaps one to two inches over the past century.

The major ice sheets covering Greenland and Antarctica are currently losing ice volume by increased melting and calving of icebergs, contributing to sea level rise. The Greenland Ice Sheet has experienced relatively high rates of melting in recent years, and is approaching an integrated melt that is similar to that experienced during a multi-decadal warm period there in the early mid-20th century.[61] If the entire Greenland Ice Sheet melted, it would raise sea level by about 20 feet. However, new research into the internal flow dynamics of the Greenland Ice Sheet concludes that a high rate of flow (and subsequent ice loss) is unlikely to occur over a sustained period of time.[62] Currently, ice loss from Greenland is contributing about 0.011 in/yr to the rate of global sea level rise.[63]

The Antarctic Ice Sheet consists of two portions, the more vulnerable West Antarctic Ice Sheet and the more stable East Antarctic Ice Sheet. The West Antarctic Ice Sheet contains enough water to raise global sea level by about 16 to 20 feet. If the East Antarctic Ice Sheet melted entirely, it would raise global sea level by about 200 feet. Complete melting of these ice sheets over this century or the next is impossible. In fact, computer models project that the Antarctic Ice Sheet will experience a net gain in

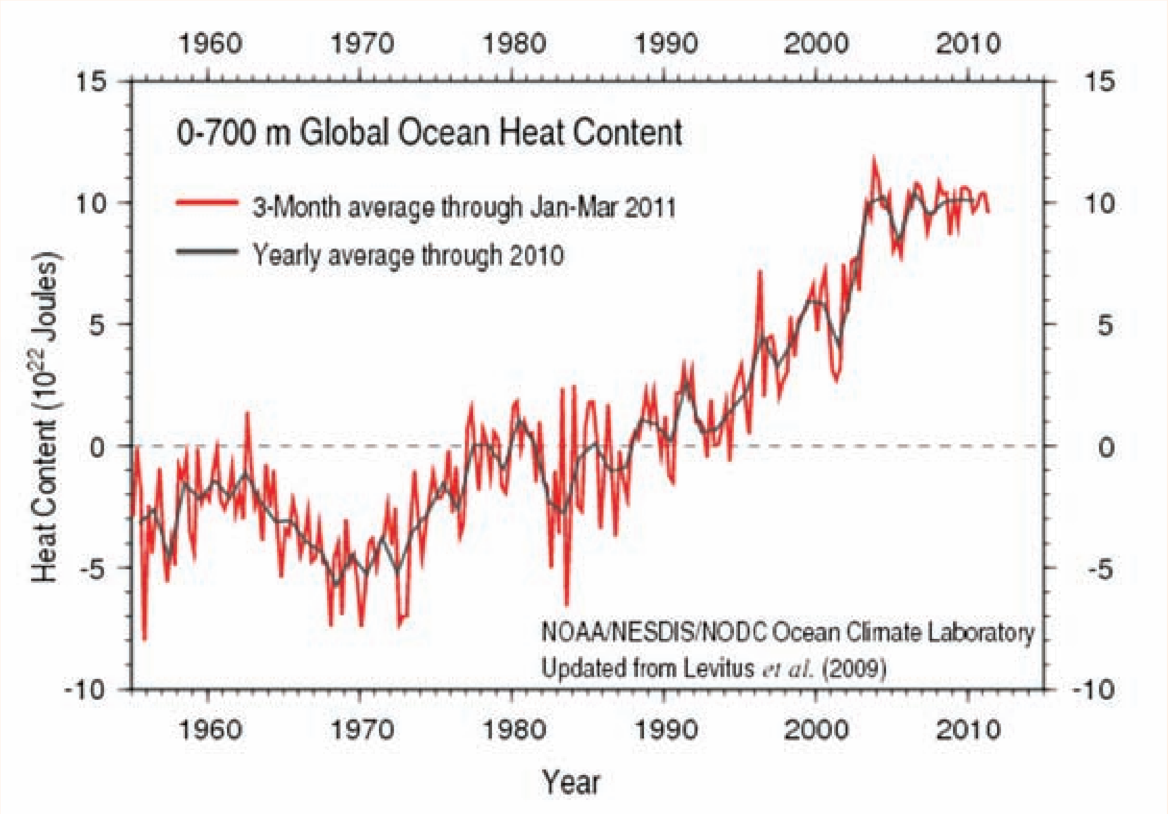


Decadal rate of sea level rise from satellites (red curve) appended to the decadal rate of global sea level rise as determined from a nine-station tide gauge network for the period 1904–2003 (blue curve) and from a 177-station tide gauge network for the period 1948–2002 (magenta) (modified from Holgate, 2007[59]).

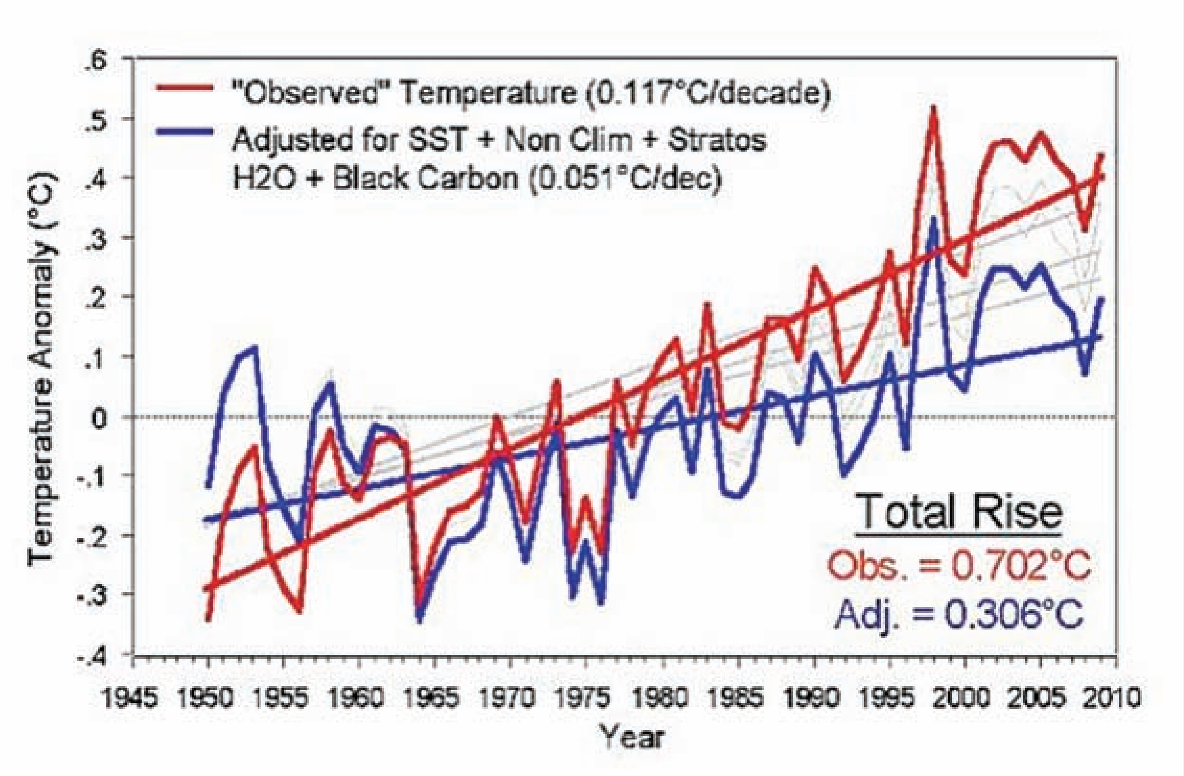
ice volume (leading to a reduction in global sea level) over the 21st century as increased precipitation in the form of snowfall outpaces ice loss through melting. Some satellite observations indicate that currently Antarctica is losing ice and contributing to sea level rise at a rate of 0.01 inches per year,[64] contrary to climate model projections. Other recent research contradicts these findings and indicates that snow accumulation across Antarctica is more than offsetting peripheral ice loss and leading to a net mass gain, consistent with model expectations.[65]

There is a third mechanism by which sea levels can rise. When water is extracted from the ground for purposes of irrigation and other human needs, much of it makes its way into the global oceans rather than back into the groundwater supply. Studies show that over the past century, groundwater extraction has increased global sea level by about 0.5 to 1.0 inches (~10 percent of the 20th-century rise)—and contributes to it at an ever-growing rate. Recent estimates are that groundwater extraction currently adds about 0.016 to 0.032 inches per year to sea level rise, an amount that is about15–30 percent of the current rate of rise[66] and an amount currently greater than the individual contributions from ice loss across Greenland or Antarctica.

The global warming of the past 50 years is due to combination of natural variability, human-induced increases in heat-trapping gases, and other human-altered changes to both the atmosphere and the surface. A large degree of uncertainty exists concerning the magnitude of the global temperature change that is associated with each of these various factors. The observed rise in global temperature



Oceanic heat content variability. Source: http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/.

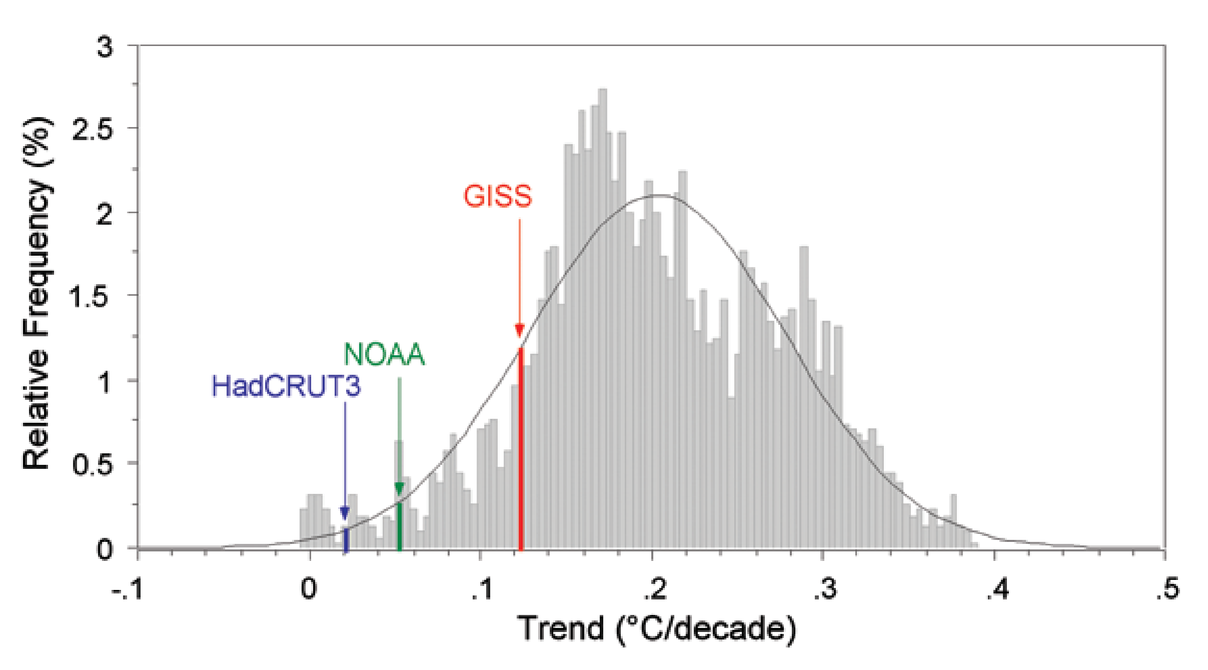


"Observed" global average temperature anomalies[74] from 1950–2010 (red) and "adjusted" global temperature anomalies after accounting for non-greenhouse gas influences from a cold bias in sea surface temperatures, a warm bias in land temperatures, increases in stratospheric water vapor, and revised estimates of the warming effect from black carbon aerosols (blue). The trend through the adjusted temperature anomalies is less than half the trend in the original "observed" data series.

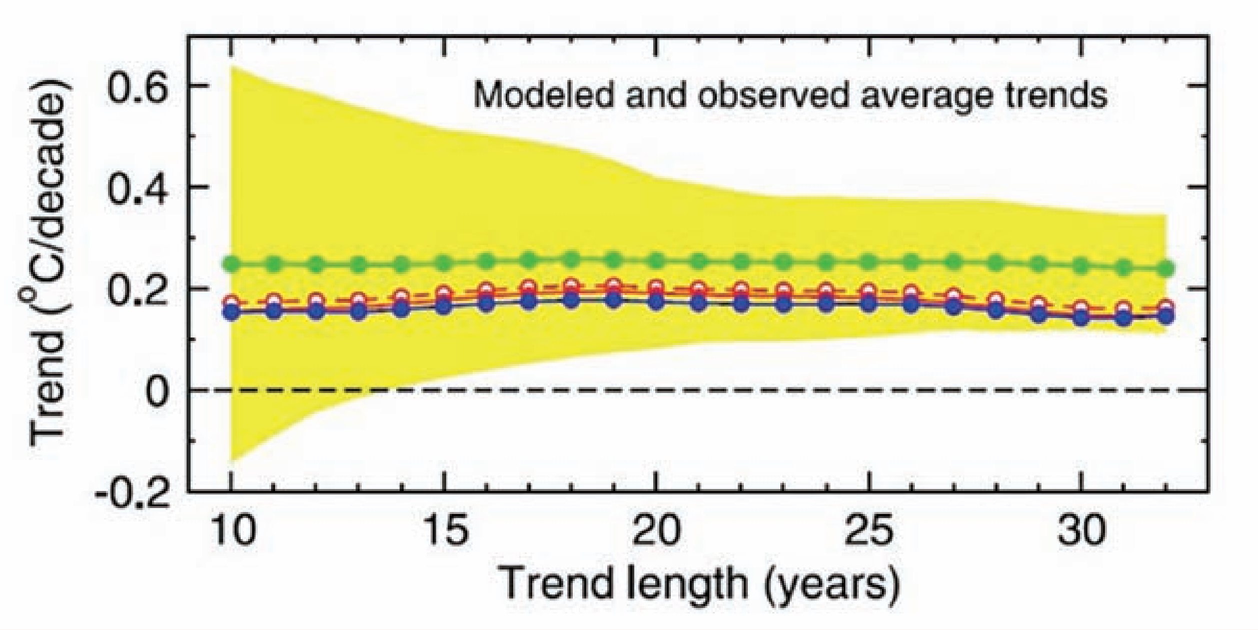
has been less than climate models have projected it to be

In 1996, the IPCC Second Assessment Report cautiously concluded that "the balance of evidence suggests a discernible human influence on global climate." Since then, a number of national and international assessments have come to much stronger conclusions about the reality of human effects on climate. The 2007 Fourth Assessment Report of the IPCC stated that "most of the observed increase in global average temperature since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." However, scientific findings published subsequently call into question the level of certainty associated with this conclusion. Accounting for the errors in measurements of sea surface temperatures,[67,68] a warm bias in the land surface temperature observations,[69,70] increases in stratospheric water vapor,[71] improved forcing estimates from black carbon aerosols,[72] and the timing of natural cycles[73] lower confidence in apportioning the observed warming between anthropogenic greenhouse enhancements and "other" influences.

Taken together, the results of these findings strongly suggest that there is a far greater degree of uncertainty as to the causes (and contributors) of the observed rise in global average temperature since the mid-20th century than indicated by the IPCC, and that the IPCC's statement is an inaccurate representation of the current state of scientific understanding. The hypothesis that the contribution from a rise of greenhouse gases to the observed warming trend since the mid-20th century is less than inferred by the IPCC is consistent with other lines of evidence that suggest that climate models inadequately and incompletely simulate



During the 15-year period from 1997–2011, the observed rate of global warming as derived from the five major compilations of global average surface temperatures (GISS (red), NOAA (green), Hadley Center (dark blue), MSU satellite—University of Alabama version (yellow), and MSU satellite–Remote Sensing Systems version (light blue))–falls out in the left-hand tail of the distribution of model projected trends of the same length (grey bars).

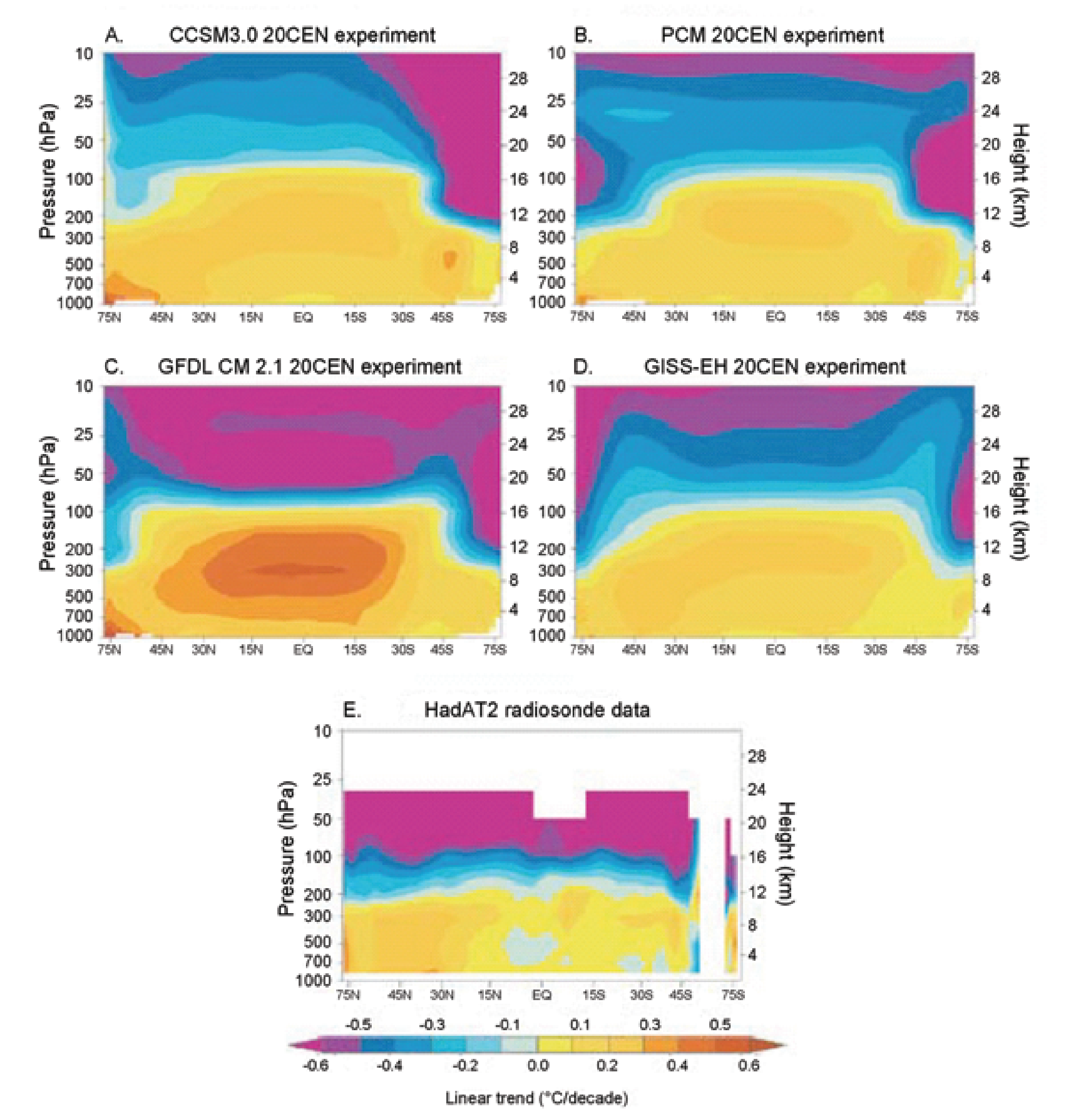


A comparison between modeled and observed trends in the average temperature of the lower atmosphere, for periods ranging from 10 to 32 years (during the period 1979 through 2010). The yellow is the 5–95 percentile range of individual model projections, the green is the model average, and the red and blue are from two sets of satellite-sensed temperatures.[84]

the complexities of the Earth's climate system. Model insufficiencies may lead to an overestimate of forecast global warming.

The warming both at the Earth's surface and the lower atmosphere that has been observed over the past several decades has been less than the average warming that has been projected by climate models to have taken place during the same period, although the observations are marginally within the noise defining the climate model range of projections.[75] The discrepancy between observed warming and climate model mean warming has been growing in recent years as the rate of global warming has slowed as natural influences which acted to enhance human-induced warming during the 1980s and 1990s[76] have now combined to retard it.[77,78] There is growing evidence that climate models do not adequately handle the strength and behavior of natural processes,[79,80,81] the timing and combination of which can influence the global average temperature from years to decades.[82,83]

Additionally, the vertical distribution of observed warming in the troposphere does not match with the model-projected patterns of



Patterns of atmospheric temperature change from 1979 to 1999 from four different climate models and in observational radiosonde (weather balloon) data. Model results are from the CCSM3.0 (National Center for Atmospheric Research (panel A), Lawrence Livermore Laboratory (panel B), Princeton/Geophysical Fluid Dynamics Laboratory (panel C), and NASA (panel D)). Observed changes (panel E) were estimated with weather balloon data. The modeled "hot spot" around a height of 300mb is largely absent from the observed data.[85]

the warming there. In the tropics, all models predict that the upper troposphere would be expected to warm more rapidly than the surface. Observations from weather balloons, satellites, and surface thermometers show the opposite behavior (more rapid warming of the surface than in the troposphere), or that the warming differential is not as large as projected.[85] This issue remains a stumbling block to both our understanding of the causes of climate change as well as its impacts,[86,87] as the vertical temperature structure of the atmosphere is a primary determinant of the patterns and character of regional weather.

In combination, the evidence shows that warming from rising greenhouse gases only contributes some fraction of the total observed warming, that the total observed warming is only some fraction of that projected to have taken place by climate models, and that climate models do not capture (or incorrectly simulate) important climate processes responsible for governing the pattern of temperature change in the lower atmosphere. This calls into question the level of scientific understanding, and the ability to capture that understanding in computer models, of the complex processes that govern the environmental responses, including the behavior of global temperature to changing levels of atmospheric greenhouse gases. Further, it greatly limits the utility of climate model projections of future climatic conditions.

Global temperatures are projected to rise over this century; by how much depends on a number of factors, including the amount of heat-trapping gas emissions and how sensitive the climate is to those emissions

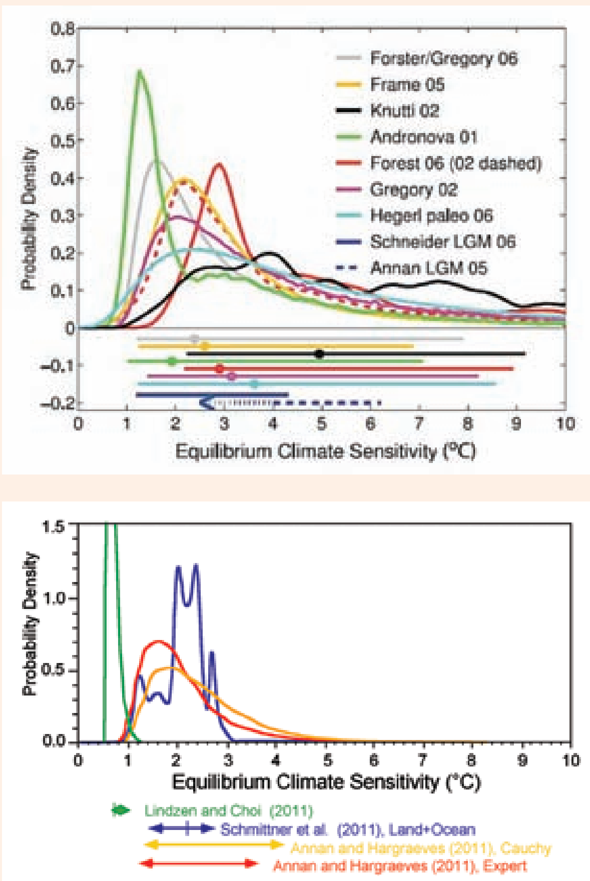
As discussed in the previous section, climate models are projecting a greater rise in the global average temperature than has actually been observed. The situation in 2012 has changed little from what existed at the time of the writing of the 1995 *Second Assessment Report* of the IPCC , which stated, "When increases in greenhouse gases only are taken into account… most [climate models…produce a greater warming than that observed to date, unless a lower climate sensitivity [to the greenhouse effect] than that found in most [climate models] is used…There is growing evidence that increases in sulfate aerosols are partially counteracting the [warming] due to increases in greenhouse gases."[88]

The IPCC was presenting two alternative hypotheses: Either the base warming was simply overestimated, or, aerosol emissions were preventing the warming from being observed. In the intervening decade and a half since that time, climate models have incorporated aerosol emissions in order to produce a better match between climate model reconstruction of the global temperature history of the past century and that which has been observed. However, that improvement largely comes in the form of "tuning" the climate models using aerosol emissions on a model by model basis, rather than from an improvement in the models' handling of greenhouse gas–induced climate warming.[89] Consequently, the climate models may still be overestimating the climate sensitivity—but with that overestimation being partially hidden by specifically devised aerosol cooling adjustments.

Evidence for this is growing.

In its *Fourth Assessment Report*, the IPCC said the climate sensitivity (amount of warming for an effective doubling of carbon dioxide) was in the likely range (with greater than 66 percent probability of occurrence) of between 2°C and 4.5°C, with a best estimate of 3.0°C.[90] The IPCC distribution of the possible value for the climate sensitivity is not a bell-shaped curve, but instead is characterized by a "fat tail" for higher sensitivities, (that is, a non-negligible possibility that the true climate sensitivity is greater than 6°C). However, recent research combined with newly available observations points to the climate sensitivity lying near or beneath the IPCC's low-end estimate of 2.0°C, and greatly suppresses the chances that the climate sensitivity lies above 3–4°C.[91]

Using satellite observations of cloud cover and temperature variability over the past decade, several analyses suggest that the short-term cloud response to changing temperatures indicates that the positive feedback present in climate models is not as strongly manifest in the real world.[92,93] An implication of these findings is that the climate sensitivity is lower than that produced by climate models. One estimate is that the mean value for the climate sensitivity estimates is 0.7°C, with a 5-95 percent range of 0.6 to 1.0°C.[94]



TOP: A collection of probability estimates of the climate sensitivity as presented in the IPCC AR4.[98] The horizontal bars represent the 5 to 95 percent ranges, and the dots are the median estimate. BOTTOM: A collection of post-IPCC AR4 probability estimates of the climate sensitivity showing a lower mean and more constrained estimates of the uncertainty. The arrows below the graphic indicate the 5 to 95 percent confidence bounds for each estimate along with the mean (vertical line) where available.[99,100,101]

Newly available reconstructions of both land and ocean temperatures during the Last Glacial Maximum (LGM)—a time when atmospheric carbon dioxide concentrations were thought to be about 100 ppm lower than pre-industrial values—have allowed researchers to make improved estimates of the climate sensitivity based on comparison of LGM conditions with current conditions. The results of such studies indicate generally lower and much more constrained estimates of the climate sensitivity than found in the IPCC AR4. One such study concludes, given methodological and data-based caveats, that the value of the equilibrium climate sensitivity likely (with a 66 percent probability) lies between 1.7 and 2.6°C (5–95 percent is 1.4 to 2.8°C), with a median value of 2.3°C, and that it is "implausible" that it lies above 6°C.[95]

An investigation into the statistical inferences which lie behind the IPCC AR4 "fat tail" determination finds that the assumptions underlying the IPCC's probability estimates of the climate sensitivity are faulty and unable to provide "meaningful and useable" results. Adopting a more "reasonable" set of assumptions produces a lower mean and much more constrained probability estimates which virtually eliminate the likelihood (less than 5 percent chance) that the climate sensitivity lies above 4.5°C.[96] Other research along these lines shows a similar tendency towards a lower median sensitivity and a flattening of the right-hand tail when a better set of prior assumptions are used in determining the climate sensitivity.[97]

If these new, lower, and more constrained estimates of the equilibrium climate sensitivity prove to be a better representation of the true climate sensitivity, they portend less overall global temperature rise and other associated climate changes than those currently projected by climate models (which contain greater climate sensitivity estimates). Additionally, the elimination of the "fat tail," allowing a significant possibility that the climate sensitivity is extremely high, helps better constrain the economic impacts of coming climate change and substantially lowers expected losses for any emissions scenario.[102]

Reducing emissions under any reasonable scenario will have no detectable effect on prospective warming for the policy-relevant future. For example, if every nation that has obligations under the failed Kyoto Protocol on global warming reduced emissions 83 percent, 37 years from now (as mandated by legislation passed by the House of Representatives), the amount of "saved" warming is approximately 0.14°F per half-century, an amount too small to measure.[103] This is in large part because of the dramatic increases in emissions from China (and other developing economies) that dwarf anything that we or our western allies can do. This is a major reason why companion legislation failed to gain passage in the Senate.

Abrupt climate change

The USGCRP report *Global Climate Change Impacts in the United States* asserts that "abrupt changes in climate become increasingly likely as the human disturbance of the climate system grows [and that such] changes could challenge the ability of human and natural systems to adapt."[104] Based upon a special report (USGCRP, 2008),[105] titled *Abrupt Climate Change*, it reports on a number of possible abrupt changes, specifically abrupt shifts in drought frequency and duration, rapid ice sheet collapse with related sea level rise, sudden release of methane, and changes in ocean circulation (such as a shutdown of the thermohaline circulation in the North Atlantic).[106]

The underlying report defines abrupt climate change as follows:

> A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, **and causes substantial disruptions in human and natural systems.**[107] [Emphasis added.]

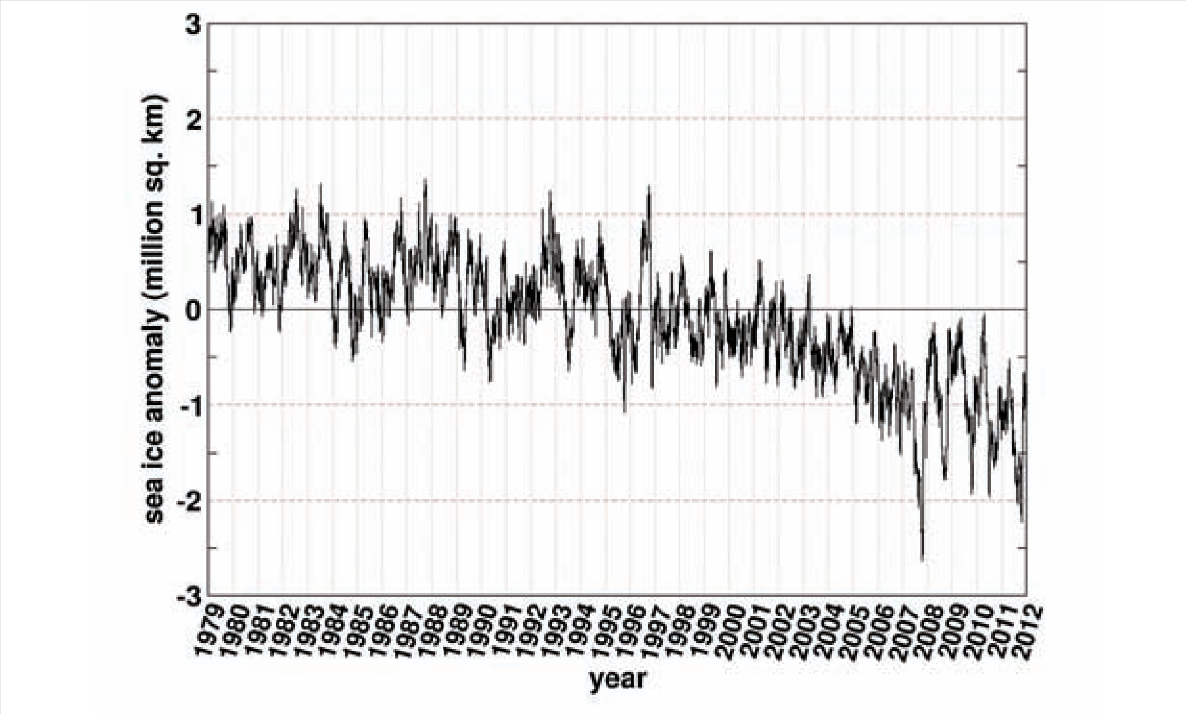
Note that there are at least two parts to this definition. One part deals with biophysical change, while another part requires knowledge of impacts on human and natural systems. Moreover, the term "disruptions" implies a very large adverse change to natural and/or human systems. But not all changes are necessarily adverse and large. That has to be shown, based on objective criteria, including criteria that distinguish "change" from "disruption." However, the USGCRP *Special Report* neither contains nor cites any such analyses or assessments—credible or otherwise—of the impacts of the abrupt biophysical changes enumerated above. Absent such analysis, it cannot be assumed that abrupt biophysical changes will necessarily lead to substantial disruption of human and natural systems or, for that matter, that the impacts will necessarily be adverse.

Arctic sea ice is declining; Antarctic sea ice is increasing

The most complete record of sea ice is provided by satellite observations that began in the 1970s. Prior to that, aircraft, ship, whaling records, and coastal observations make up the available data, and these become more sparse further back in time. There are more observations of ice conditions prior to the satellite era available from the Arctic regions than from the Antarctic. What records are available indicate that sea ice in both hemispheres has declined over the course of the past century.[108,109] Satellite observations show that in recent decades the Northern Hemisphere decline in sea ice extent has been hastened,[110] while in the Southern Hemisphere, the sea ice decline has reversed course and has been replaced by a statistically significant expansion.[111]

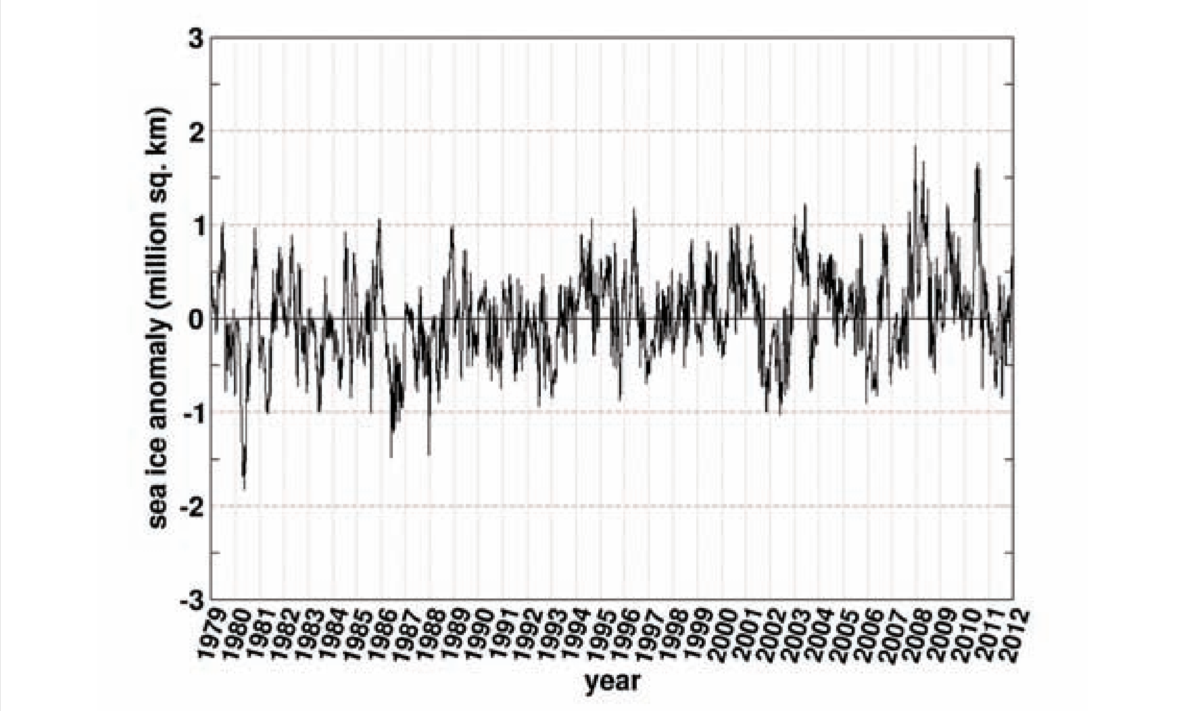
Proxy indicators of sea ice extent suggest that sea ice was greatly reduced and at times completely absent during the Northern Hemisphere summers during several extended warm periods during the last interglacial[113] and during the early Holocene from about 8,500 to 6,000 years ago.[114] Proxy data also indicate that oscillations

Northern Hemisphere Sea Ice Anomaly
Anomaly from 1979–2008 mean



Satellite-derived sea ice extent anomalies for the Northern Hemisphere from 1979–2011.[112]

Southern Hemisphere Sea Ice Anomaly
Anomaly from 1979–2008 mean



Satellite-derived sea ice extent anomalies for the Southern Hemisphere from 1979–2011.[112]

in Arctic sea ice extent driven by processes such as solar variability, volcanic eruptions, and changes in atmospheric and oceanic circulations can occur over periods from decades to centuries.[115] The overall loss of sea ice during the past century has been overlain by decadal-scale oscillations, but it has been driven by rising temperatures in the Arctic.[116] The increased rate of ice loss in recent decades has been most prominent in the summer season but is evident in the other seasons as well. One-third to one-half of the recent increased rate of ice extent decline has been linked to natural variations in wind flow patterns and oceanic circulation, the remaining to increases in temperature.[117,118]

The increase in the rate of decline in Arctic sea ice extent during the satellite era corresponds to a period of rapidly warming temperatures in the Arctic that began in the early 1970s—a period when Arctic temperatures were at their lowest values since the 1920s. Arctic temperature rose rapidly during the late 19th and early portion of the 20th centuries, rising from the cold conditions of the Little Ice Age—with expanded sea ice conditions[119]—and culminating in the regional warmth of the 1930s and 1940s, before declining through the 1970s. The high temperatures during the 1930s and 1940s have been associated with increased melting of surface ice in Greenland[120] and sea ice declines in some portions of Arctic.[121] These trends were slowed or reversed as temperatures in the Arctic cooled for the next several decades. Consequently, a portion of the subsequent rise in temperatures since the early 1970s and the accompanying decline in sea ice extent was a return to 20th-century mean conditions.

The decline in Arctic sea ice is expected to continue, although natural variability may act to slow the rate, or even reverse it for periods of up to a decade.[122] Estimates vary as to when and whether the end of Arctic summers will become ice-free. While the idea that the loss of late Arctic summer sea ice represents a condition from which recovery is impossible ("tipping point") has been refuted,[123,124] estimates suggest that conditions of greatly reduced late summer ice cover will become commonplace by the mid-to-late 21st century.[125]

Sea level rise due to melting of the Greenland and/or West Antarctic Ice Sheet

According to the IPCC Fourth Assessment Report, a negative surface mass balance would have to be "sustained for millennia" to eliminate the Greenland Ice Sheet (GIS), which would raise sea level by about 24 feet. The IPCC notes that during the Eemian (~125,000–130,000 years ago), when average global temperatures were 5–9°F higher and sea level was 5–9 feet higher than it is today, Greenland was much warmer but still not ice free.[126,127] But even if a tipping point is reached beyond which complete disintegration of the GIS is inevitable, it will take millennia for the full effects to be manifested on human and natural systems. The same thermodynamic considerations that apply to GIS also apply to the West Antarctic Ice Sheet (WAIS).

A modeling study that stabilized atmospheric carbon dioxide concentrations at four times pre-industrial levels estimated that a GIS collapse would raise sea level by 7.5 feet in the next thousand years (with a peak rate of 0.2 in/yr, or 20 inches per century).[128] If one were to arbitrarily double that to account for potential melting of the WAIS, that would result in total SLR of ~16 feet in 1,000 years with a peak rate (assuming the peaks coincide) of three feet per century. Over such time scales, human beings would certainly be able to cope. Natural systems should also be able to cope since a rise of 16 ft/millennium would also not be unprecedented.

Specifically, sea level has risen nearly 400 feet in the past 18,000 years, an average of 2.2 ft/century, or 22 feet per millennium. It may also have risen as much as 13 ft/century during meltwater pulse 1A episode 14,600 years ago.[129] Neither human nor natural systems, from the perspective of millennial time scales, seem the worse for it. Coral reefs, for example, evolved and their compositions changed over millennia as new reefs grew while older ones were submerged in deeper water.[130] So while there have been ecological changes, it is unknown whether the changes were for better or worse. For a melting of the GIS (or WAIS) to qualify as a catastrophe, one has to show, rather than assume, that the ecological (and human) consequences would also be catastrophic. However, no such showing is made explicitly. When it is generally assumed that an ecological change is necessarily worse for man and nature, that is theology, not reason.

If sea level were to rise 6.5 feet by 2100, then, "While the damages from sea-level rise are substantial, they are small compared to the total economy, provided that coastal protection is built."[131] Such a rise, however, seems unlikely since current measured rates of sea level increase are 1 ft/century (1993–2011 average).[132] In fact, some recent studies based on long-term tide gauge data not only found no significant acceleration in the rate of sea level rise during much of the 20th century but a slight deceleration since the 1930s for the United States[133] and 1940s for Australia.[134]

Methane

It is unlikely that there will be massive releases of methane from thawing of permafrost, clathrates on the seafloor, and wetlands this century, according to both the IPCC and the USGCRP. The IPCC's SRES scenarios and emissions inventory-based projections indicate that atmospheric methane concentrations should have been going up and should continue to increase relatively rapidly, but empirical data indicate annual increases have been very small over the past three decades.[135] From 1999–2006, the increase was less than 0.4 percent.[136]

Isotopic studies of a glacial ice core from West Greenland to determine the probable source of the large increase in methane during the abrupt warming of 18±7°F that occurred during the transition from the Younger Dryas to the Preboreal (~11,600 years ago)[137] indicate that "wetlands were the likely main driver of the [methane] increase and that clathrates did not play a large role," which is consistent with previous ice core CH_4 isotopic studies.[138,139] Thus, while methane emissions might increase if there is warming, there is no evidence of catastrophic releases from clathrates.

Thermohaline circulation

Both the IPCC, in its Fourth Assessment Report, and the USGCRP deem a shutdown of the thermohaline circulation to be unlikely. Nevertheless, if one assumes that it would occur, its socioeconomic impact is estimated at a few percent of GDP for some nations, "but the average global impact is much smaller."[140] A complete shutdown by 2150 would offset warming in Europe but not lead to net cooling.[141] It would increase sea level by 2.6 feet by 2150, render cod fisheries unprofitable, increase net terrestrial productivity, and perhaps decrease marine productivity. While regional socioeconomic impacts might be large, damages would be probably small compared to their gross national products.[142] This would, apparently, not qualify as a catastrophic "disruption."

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[1]Data are from the supplemental material in Shakun, J.D., et al., 2012: Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature,* **484**, 49-54. Data plotted by Willis Eschenbach at http://wattsupwiththat.com/2012/04/07/shakun-redux-mastertricksed-us-i-told-you-he-was-tricksy/#more-60932.

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National Climate Change

Key Messages:

- Coterminous U.S. temperatures have risen by 1.4°F since 1895, and precipitation has increased by 7 percent since then.
- There is no evidence for any systematic change in drought frequency and severity, or in extreme wetness, averaged across the coterminous United States, since 1895.
- There is no evidence for any systematic increase in tropical cyclone frequency or severity since accurate records began, and hemispheric activity is near its lowest value.
- There is no evidence for any increase in severe tornado frequency.
- U.S emissions of carbon dioxide per unit of economic output are typical of those of the most efficient nations.

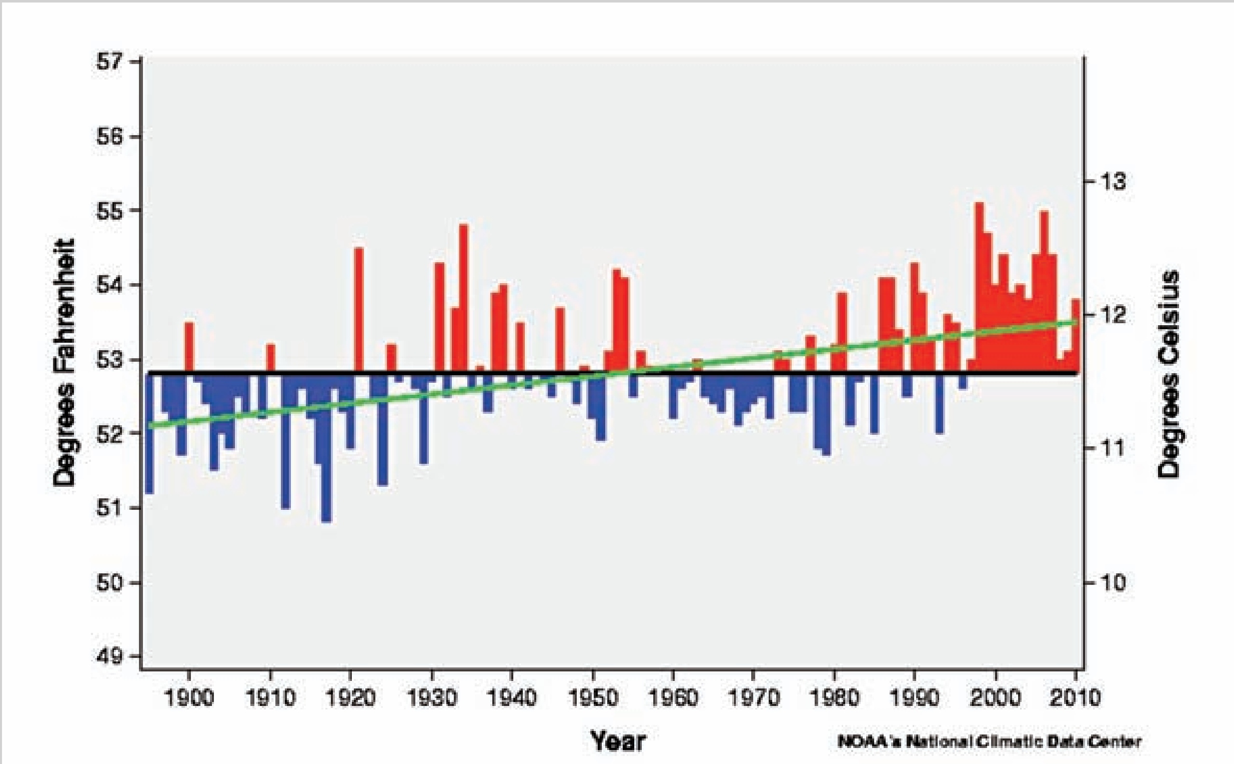
The U.S. average temperature has risen about 1.4°F since the late 19th century

The U.S. National Climatic Data Center (NCDC) has compiled a temperature history of the contiguous United States that begins in 1895. From 1895 through 2010, the U.S. annual average temperature, as fit with a linear trend, exhibits an increase of about 1.4°F (a rate of 0.12°F/decade). NCDC has attempted to account for elements that may have exerted a non-climatic influence on the temperature records of the individual stations that make up the compiled national temperature record.[1] Several recent analyses have concluded that the national temperature trend from the NCDC-compiled record well represents the character of the actual behavior (that is, in net, the trend is free from large non-climatic influences)[2,3] or has only very small nonclimatic bias.[4] Research on this important topic continues.

A notable feature of the U.S. temperature history is the multi-decadal variability—the 1890s-1910s were relatively cool, the 1930-1950s were relatively warm, the 1960s-1970s were relatively cool, and the 1980s-2000s were relatively warm again. Also of note is the sustained warm period from 1998-2007—a period of warmth unlike any other in the 116-year record. However, the national annual average temperature returned to near the level of the 20th century average in the years since 2007, which may be evidence that multi-decadal variability—acting in addition to slowly rising temperatures from anthropogenic climate change—is once again slowing the overall rise in temperatures. Similar behavior has been documented in global temperature patterns as well.[5,6]

The temperature does not change uniformly across the United States. Just as different regions of the country are subject to different climate influences and thus are in many ways climatologically dissimilar, so too are manifest the influences of climate variability and change. Since the turn of the 20th century, the western half of the United States has, in

U.S. Temperature History



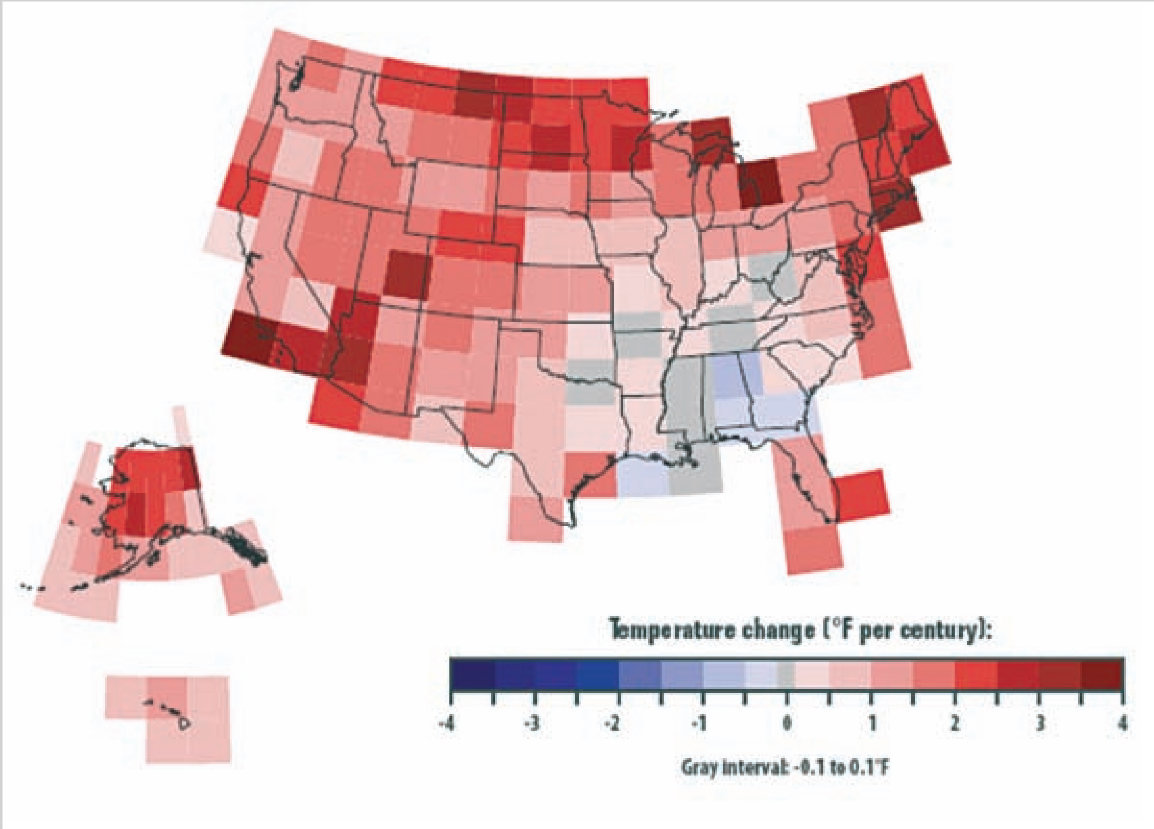
During the period when observations have been complied for the United States (1895–2010), the annual average temperature of the contiguous United States increased by about 1.4°F. The temperature change has not been uniform, but instead, annual and multidecadal variability are superimposed on a gradual underlying warming trend.

general, warmed more than the eastern half, and New England has warmed more than the Southeastern states, some of which have exhibited a very slight overall cooling. Also, during the same period, winter warming has dominated summer warming by a ratio of nearly 3:2.

It is expected that the U.S. annual average temperature will increase in the future as the human contribution to the Earth's greenhouse effect continues to expand along with the use of fossil fuels. It is not expected that the temperature increase will be smooth and monotonic, but instead will reflect the character of the temperature changes observed during the 20th century—that is, large annual and decadal/multidecadal temperature variability superimposed on a gradual underlying warming trend. Regional variations in the temperature trends are also expected but not well-projected, as natural variability plays a larger role in the local and regional trends.

Projections of the amount of warming in average U.S. temperatures over the course of the 21st century that may result from anthropogenerated greenhouse gases are complicated by an incomplete scientific understanding of the Earth's complex climate system, the unknowable course of greenhouse gas emissions from human activities around the world, and inadequate computer modeling.

Using a range of possible future emissions pathways, the climate models in the IPCC Fourth Assessment Report project that the U.S. annual temperature will increase between 3°F and 10°F between now and the end of the 21st century. But there are strong indications that the sensitivity of climate is overestimated in these projections (see previous chapter). If true, forecasts of future warming should be cut nearly in half, with a range of warming from 1.5 to 5°F, or as an average, a little more than twice what was observed during the 20th century.



The temperature change observed across the United States from 1901 to 2008 has not been uniform, as different regions of the country are subject to different climate influences. While on average, the annual average temperature of the United States has increased by about 1.4°F, more warming occurred in the western United States than in the eastern United States, where some portions of the Southeast actually cooled very slightly. (Image Source: U.S. EPA).[7]

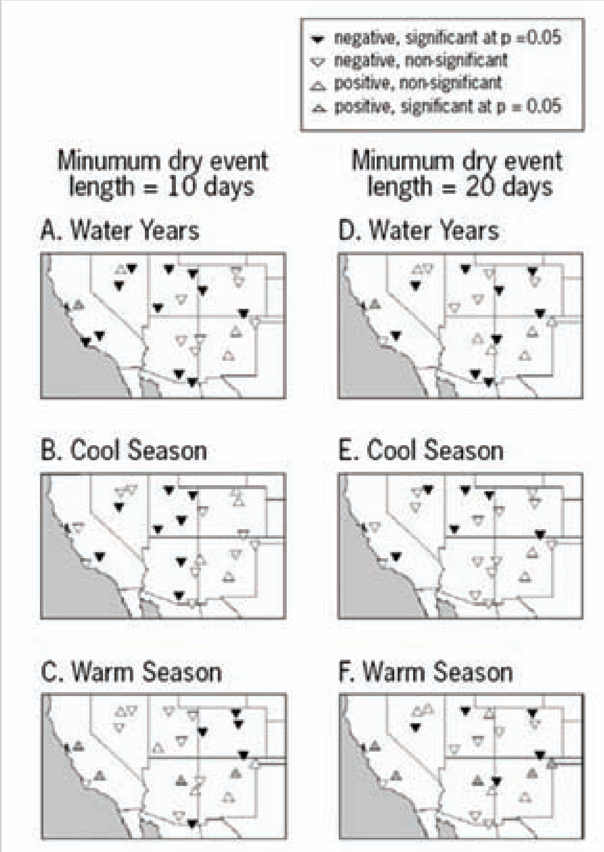
The ultimate course of climate change experienced across the United States will depend on the interplay between global anthropogenic greenhouse gas emissions, local/regional/global anthropogenic aerosol emissions, local/regional human alterations to the surface landscape, and natural variability of all scales.

Precipitation has increased an average of about 7 percent since 1895. Climate model projections for regional precipitation changes over the United States are of little if any utility

In the southwestern United States, where dry periods have been a concern since 2000, the difference between water use and supply is greater than in any other region of the United States.[8] Despite the recent dryness, a large majority of reporting stations in the region exhibit negative trends in dry event length, i.e., the time interval between precipitation events has generally been declining since 1951. Not surprisingly, much of the variability in dry event length is related to El Niño variability, which is strongly coupled to southwestern U.S. precipitation.[9]

There is no evidence for changes in droughts, and changes in heaviest rainfall are positive but small

Based upon the widely cited Palmer Drought Index, there has been no net change in nationwide drought frequency or severity since the instrumental record began in 1895. This lack of increasing dryness occurred despite warming of approximately 1.4°F during the period



In general, the length of dry events have been declining in the western United States (downward triangles).[10]

over the lower 48 states, because precipitation increased as temperatures rose. If the rainfall increase is a result of global warming, then there is no reason to believe that similar drought compensation will not continue.

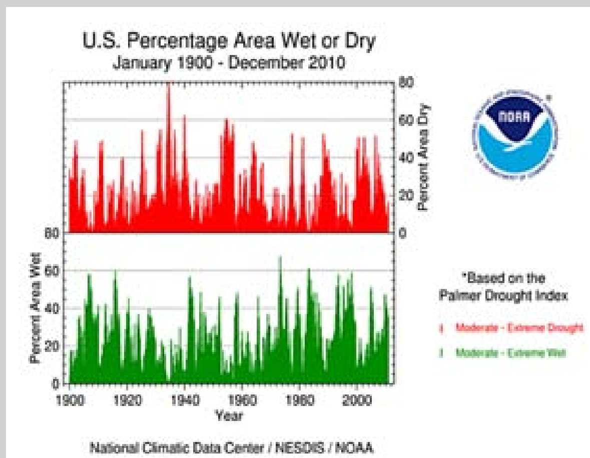
However, other studies show that from the early 20th century to the present, soil moisture has been increasing across almost all of the continental United States,[11] and that there has also been a tendency for droughts to be shorter, less severe, and cover a smaller total area.

In a larger context, these patterns are consistent with overall global trends. Based upon data starting in 1950, there is an overall tendency for most of the large-scale droughts to be concentrated in the 1950s–1960s—a period prior to the recent temperature rise. In North America, the longest drought occurred in the early 1950s, and the most areally extensive event was in 1956.[13] Since the late 1970s, North America has been mostly unimpacted by major droughts, a pattern consistent with increasing precipitation.

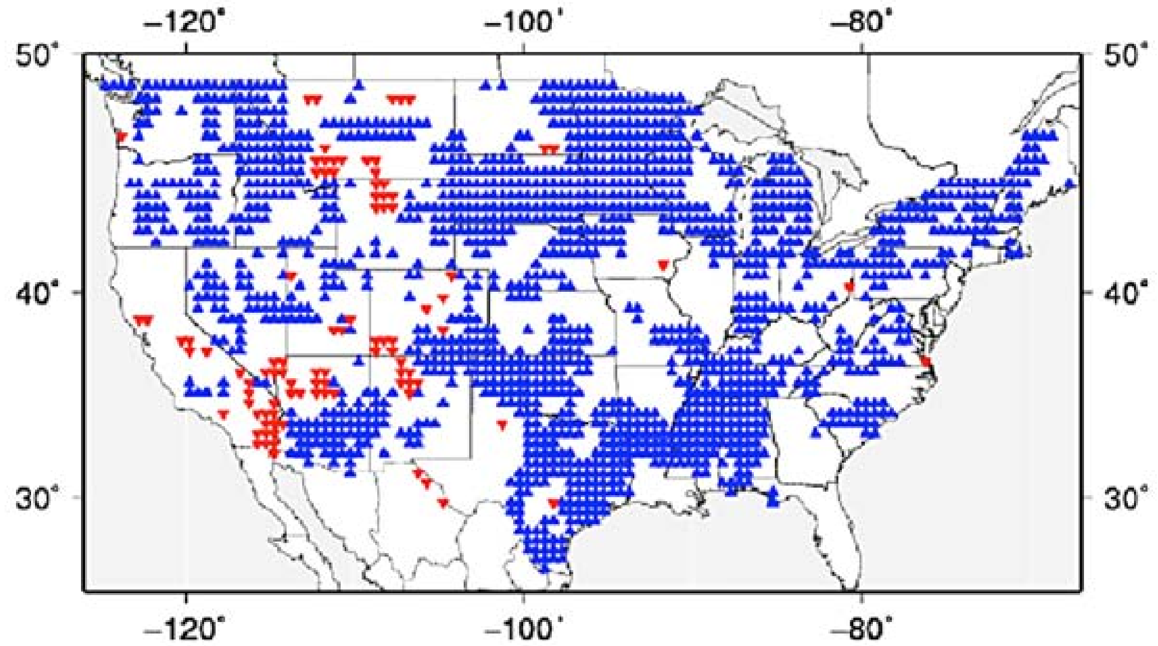
USGCRP 2009 shows projected precipitation changes for a high-emissions scenario for 2080-90. They included shaded areas which would normally connote statistical significance. In reality, the shaded areas are where 66 percent of the models give precipitation changes of the same sign. The probability of this by chance is 0.15, which is hardly a scientifically acceptable level of significance.

Given that these are high-emission, late-time-period (end of 21st century) projections, it is clear that the models' output for less constrained conditions is simply not distinguishable from random noise. Why this was not noted is evidence of an egregious attempt by the USGCRP to misinform policymakers.

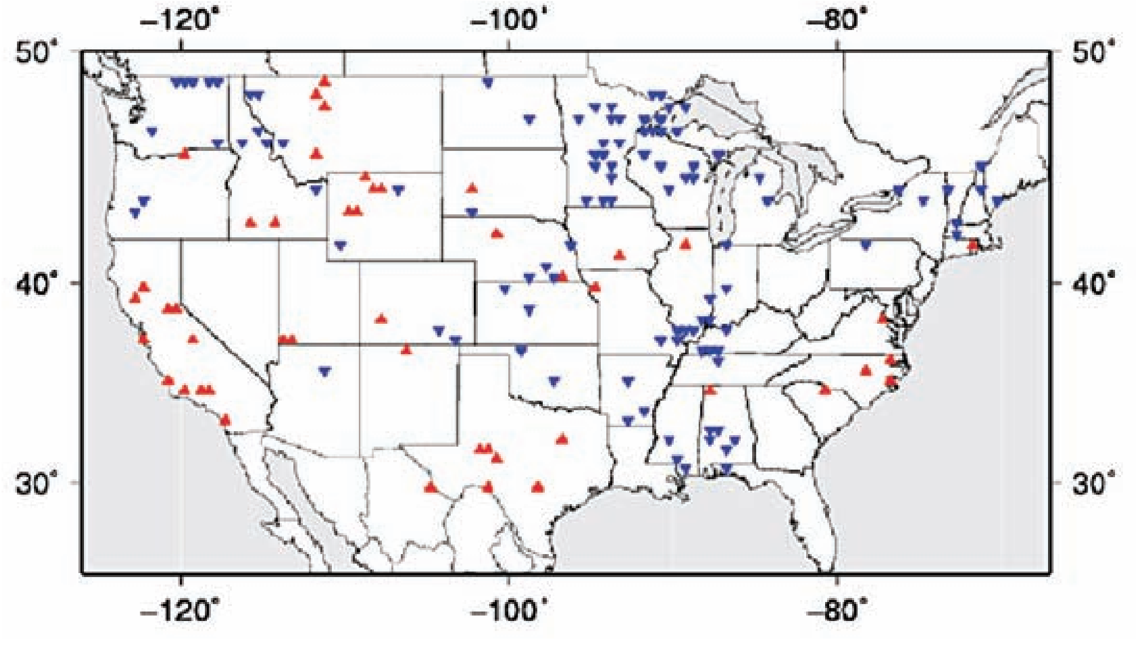
Nationally, there has been a significant increase in rainfall measured on the heaviest precipitation-day of the year, but the magnitude is very small—about 0.26 inches in a century. While this trend is statistically significant, it is so small as to likely be operationally unimportant.



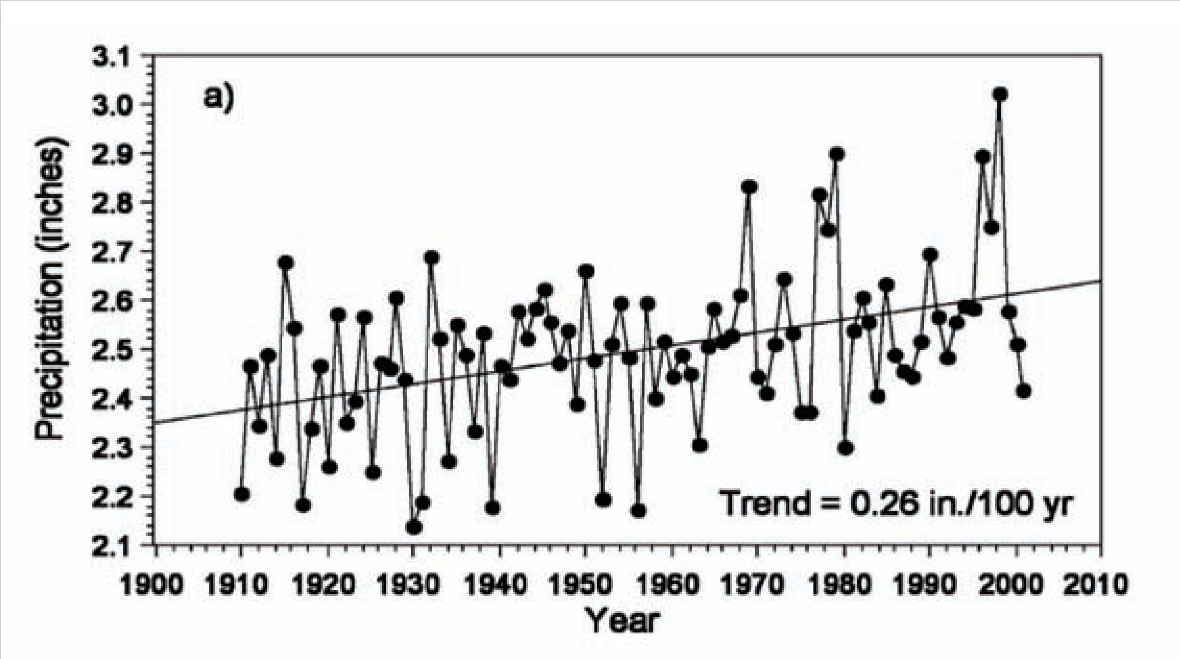
The Palmer Drought Severity index shows no trend in the area of the nation experiencing drought or excessive wetness over the period of record that begins in 1895.



Throughout the United States, soil moisture has been increasing through the 20th century (blue) much more than it has been decreasing (red).[12]



Throughout the 20th century, droughts have been getting shorter (blue triangles) in more locations than where they have been getting longer (red triangles).[14]



The trend in rainfall on the heaviest rain day of the year across the U.S. lower 48 states is positive and significant, but also very small—approximately a 10 percent increase in this daily amount over a century.[15]

Drought

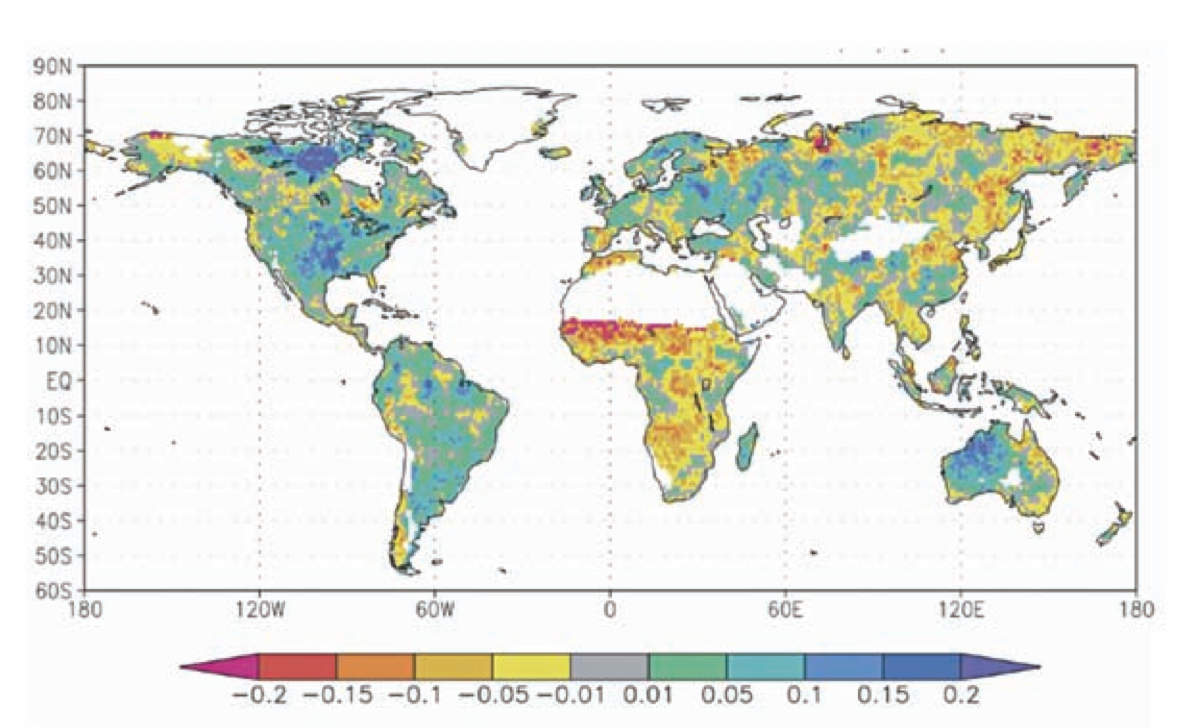
As shown above, there has been no change in the coverage or severity of drought or moisture excess over the continental United States. However, over shorter periods, such as the past three decades, the western United States, and particularly the Southwest, has trended toward increasing aridity, while there has been a reduction in drought frequency over the Midwest, Great Plains, and Northeast.[16]

In general, climate models predict that droughts in the United States should increase in frequency, magnitude, duration, and/or areal extent as the climate changes. There are many predictions for increasing drought in the scientific literature.[17,18,19,20] A 1990 paper[21] received considerable attention as a prestigious NASA research team predicted that drought frequency in the United States would increase from approximately 5 percent in 1990 to 50 percent by the middle of this century. Notably, the climate model used in this highly cited paper predicted almost twice as much warming as has been observed since the late 1980s, so it consequently overpredicted drought, too. In fact, there is not a statistically significant realtionship between global warming and drought across the United States.

Many studies have been published in the literature reconstructing drought from tree ring and other proxy records. These clearly show that droughts of the past 100 years are not exceptional compared to others that have occurred during the past 1,000 or even 10,000 years. Mega-droughts have occurred in warm periods of the past, but they seem to have occurred equally frequently during well-known cool periods in earth history.[23]

Heat waves

A heat wave is an extended period of unusually hot weather. In the United States, there was a high frequency of heat waves that were enhanced by large-scale drought conditions during the Dust Bowl; in fact, many all-time high temperature records from the 1930s remain to



Soil moisture changes since 1950. It is very clear that the United States has in general become increasingly moist.[22]

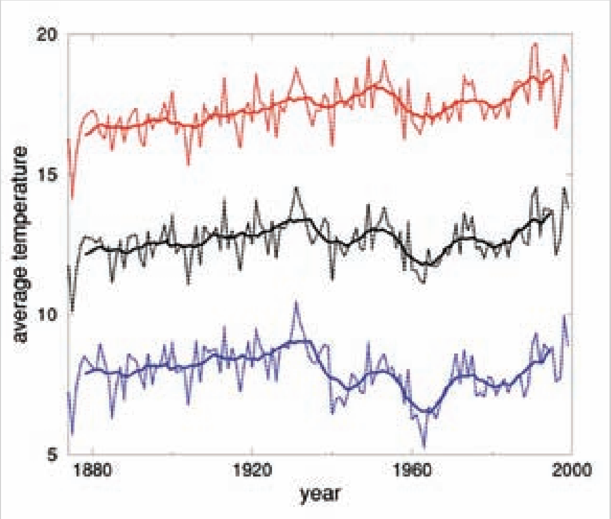
be broken. Mean summer temperatures in the first decade of the 21st century are similar to those of the 1930s, but there now appears to be more heat excursions under conditions of high humidity than there were then.

Nonetheless, detecting trends in heat wave outbreaks caused by global (rather than local) climate change is not easy using the empirical temperature record. Heat waves in cities are monitored by instruments that are badly contaminated with the urban heat island effect. As temperatures increase in cities, there is no question that an increase in heat waves will appear in the record. (In fact, cities are providing a "natural laboratory," without necessarily resorting to global warming, to determine the future trajectory of heat-related deaths; see the chapter on Human Health).

One way to remove the urban effect on thermometers is to measure temperature without them. Twice daily, weather balloons are launched simultaneously around the globe, and the height to which they must ascend in order to be above half of the atmosphere (by weight) is an excellent measure of lower atmospheric temperature, known as the 1,000 to 500 millibar "thickness."[24] A study of thickness measurements away from polar regions revealed no significant trends in extreme values above or below the mean from 1979 through 2003.[25]

Another interesting statistical approach to the issue of extreme urban heat and climate change appears in a study of the long-term temperature record from Philadelphia Even with the warming associated with urban growth, one cannot distinguish between the effects of random fluctuations and long-term systematic trends on the frequency of record-breaking temperatures with 126 years of data.[26]

While heat waves are likely to increase in frequency and intensity with planetary warming,



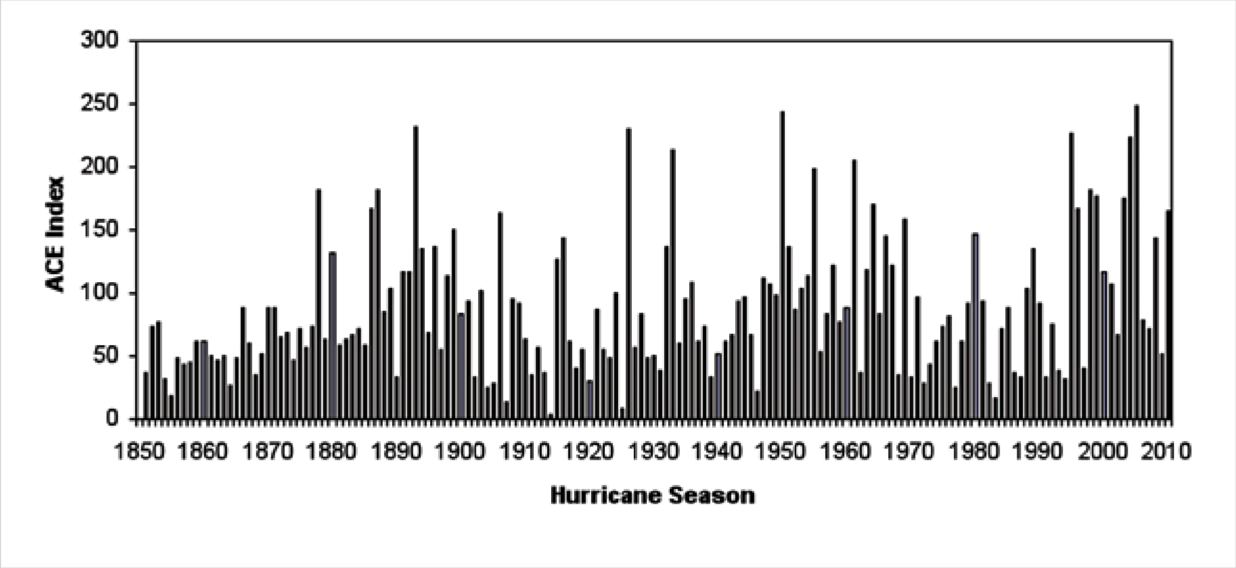
Average annual high, middle, and low temperature (in degrees Celsius) for each year between 1874 and 1999 in Philadelphia (dotted jagged lines). Also shown are the corresponding 10-year averages (solid curves). It is obvious that interannual variability in this long record is greater than any overall trend.

urban warming is already revealing the considerable adaptive capabilities that are built into our society, as heat-related mortality appears to decline as temperature excursions become more frequent and extreme.[27]

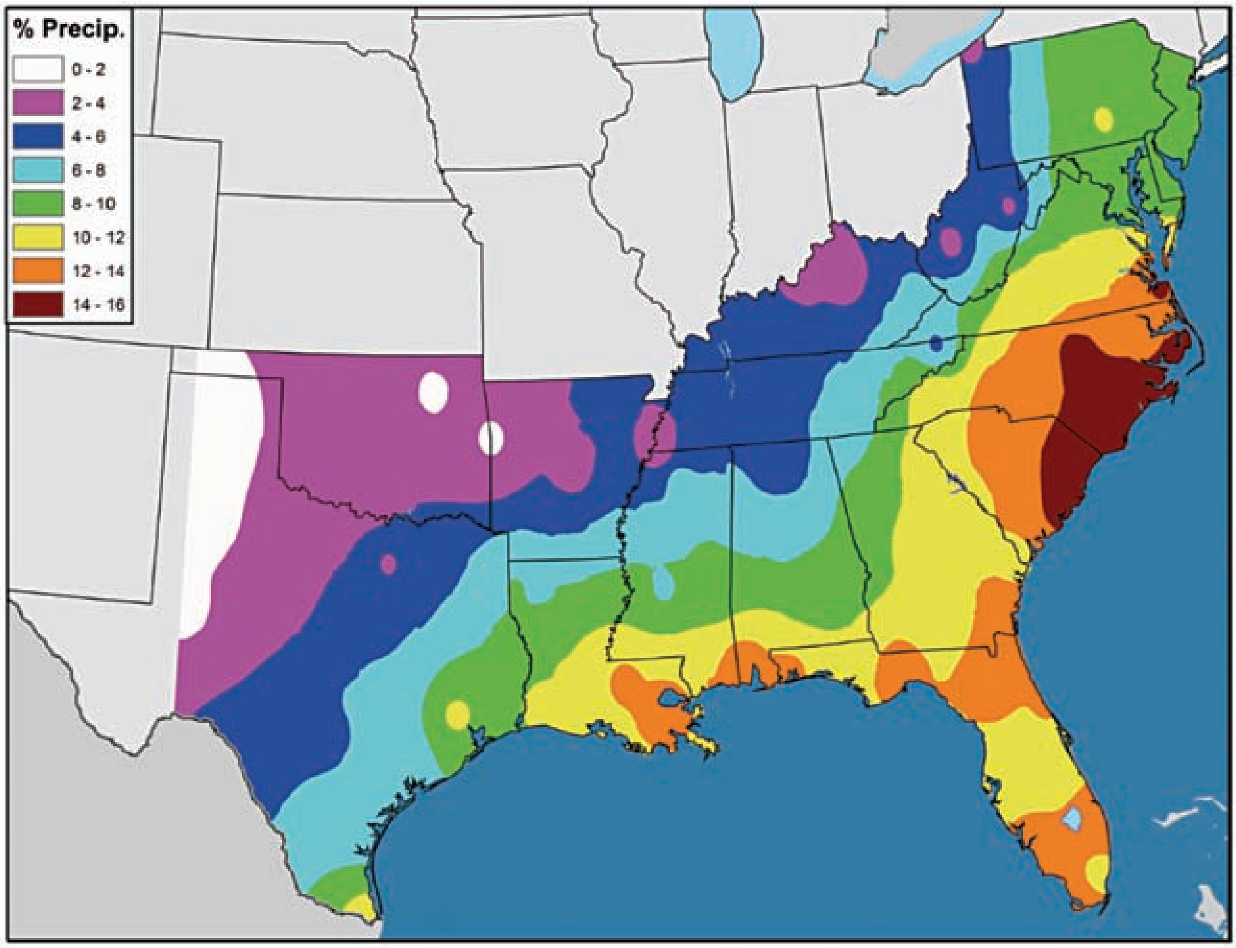
Tropical cyclone activity in the Atlantic basin exhibits strong decadal variability but little century-scale change

Of all the world's tropical storm and hurricane basins, the North Atlantic has been the most thoroughly monitored and studied. The advent of routine aircraft monitoring in the 1940s and the use of satellite observations since the 1960s have greatly improved our ability to detect storms. In addition, observations of tropical storm and hurricane strength made from island and mainland weather stations and from ships at sea began in the 1800s and continue today. Because of new and evolving observing techniques and technologies, scientists pay careful attention to ensuring consistency in tropical storm and hurricane records from the earliest manual observations to today's automated measurements.[28] This is accomplished by collecting, analyzing, and cross-referencing data from numerous sources and, where necessary, the application of adjustment techniques to account for differences in observing and reporting methodologies through time.[29,30,31,32]

The record over the past century and a half indicates that there are strong multi-decadal variations in the hurricane activity in the Atlantic Ocean basin (including the Gulf of Mexico) but little, if any, overall change when the multidecadal variations are taken into account. A



Accumulated Cyclone Energy (ACE) index for the Atlantic Basin from 1851 through 2010. There is obviously no relationship to the temperature rise shown in the last chapter. Data available at http://www.aoml.noaa.gov/hrd/tcfaq/E11.html.



Annual average percentage of hurricane-season (June through November) rainfall arising from tropical cyclones.[11]

comprehensive measure of year-to-year tropical cyclone activity is the Accumulated Cyclone Energy (ACE) index, which combines the intensity and duration of each storm into a seasonal total. The history of the ACE index shows the relatively high levels of activity in the 1880s–1890s, 1950s–1960s, and 1995–2005. Periods of low levels of Atlantic tropical cyclone activity include the 1850s, 1910s–1920s, 1970s–1980s and the present. There is simply no relationship between ACE and global mean temperature.

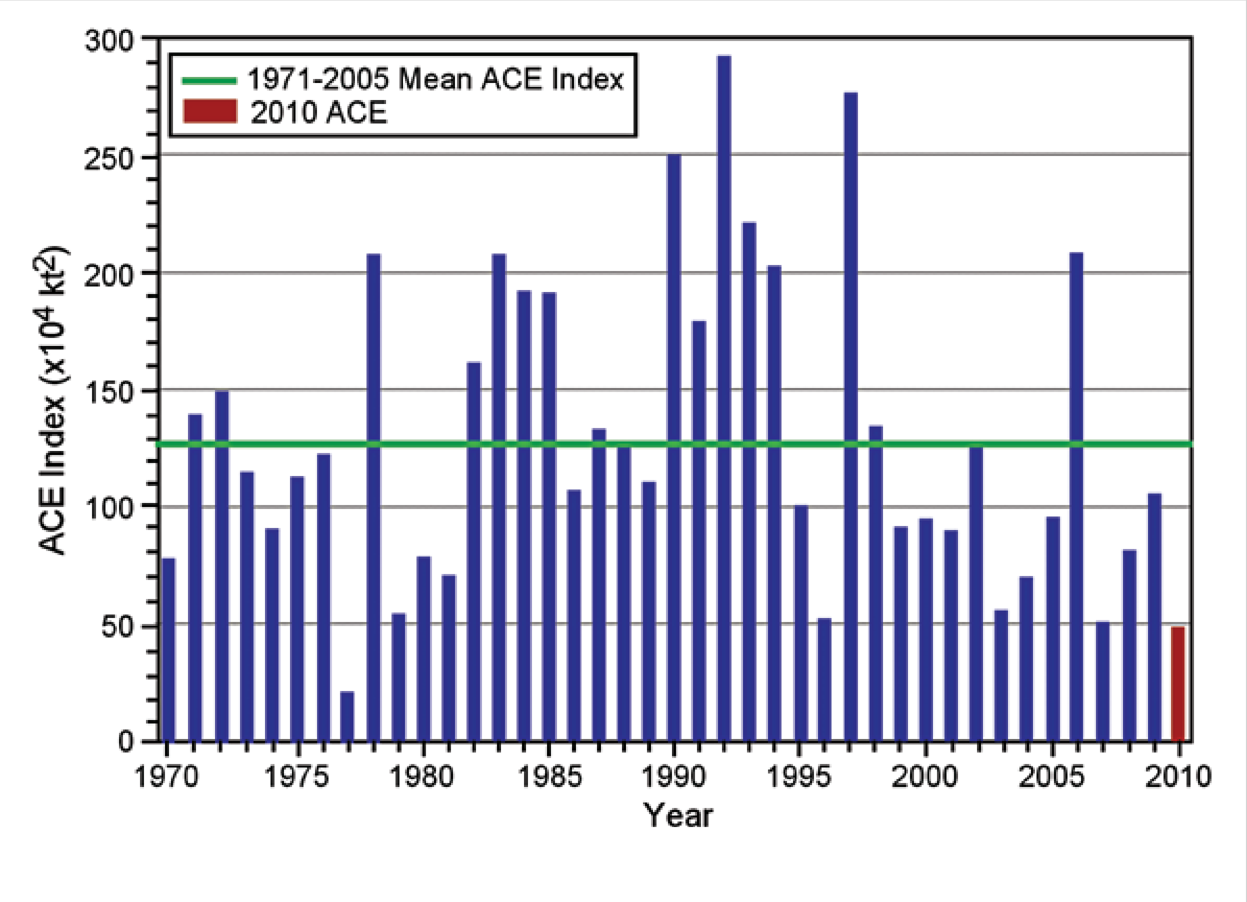
A variety of factors act together to influence tropical cyclone development, growth, track, and whether or not a storm makes landfall along the U.S. coast. These include large-scale steering winds, atmospheric stability, wind shear, sea surface temperature, and ocean heat content. Tropical storms and hurricanes develop and gain strength over warm ocean waters. However, it does not strictly follow that warmer waters lead to stronger hurricanes. New evidence has emerged that shows that the contrast in sea surface temperature between the main hurricane development region in the Atlantic and the broader tropical ocean plays an important role in hurricane development.[33,34,35] Additionally, other factors such as atmospheric stability and circulation can also influence hurricane frequency and intensity.[36] For these and other reasons, a confident assessment of the causes of tropical cyclone variability in the Atlantic Basin requires further study.

Projections are that sea surface temperatures in the main Atlantic hurricane development region will increase during this century under higher emissions scenarios. Other environmental factors are projected to change as well, complicating assessment of future tropical cyclone behavior. This highlights the need to better understand the relationship between hurricane frequency, intensity, climate, and climate change.[37]

The consensus is still evolving as to how anthropogenic climate change will alter the characteristics of Atlantic Basin tropical cyclones. There is growing evidence that the frequency of Atlantic Basin tropical cyclones will be little changed, but that some storms may become more intense, although the preferred tracks of storms may be altered in such a way as to reduce the threat of a U.S. landfall.[38] However, such changes are not anticipated to emerge above the level of natural noise until very late in this century.[39]

One important fact about the impact of tropical cyclones that is virtually certain is that further development of our coastlines, including growing population, increasing wealth, and expanding infrastructure, will increase the vulnerability to direct hurricane strikes regardless of any influence that a changing climate may impart.[41]

The eastern Pacific Ocean south of California averages more tropical cyclones per year than the more publicized North Atlantic, as cool water along the U.S. West Coast and atmospheric steering patterns make landfall in the continental United States a climatic rarity.[42] Direct strikes on the Hawaiian Islands are also rare,



In the eastern Pacific, hurricane activity has generally decreased during the past three decades.[44]

but elevated surf from decaying eastern Pacific storms is common.

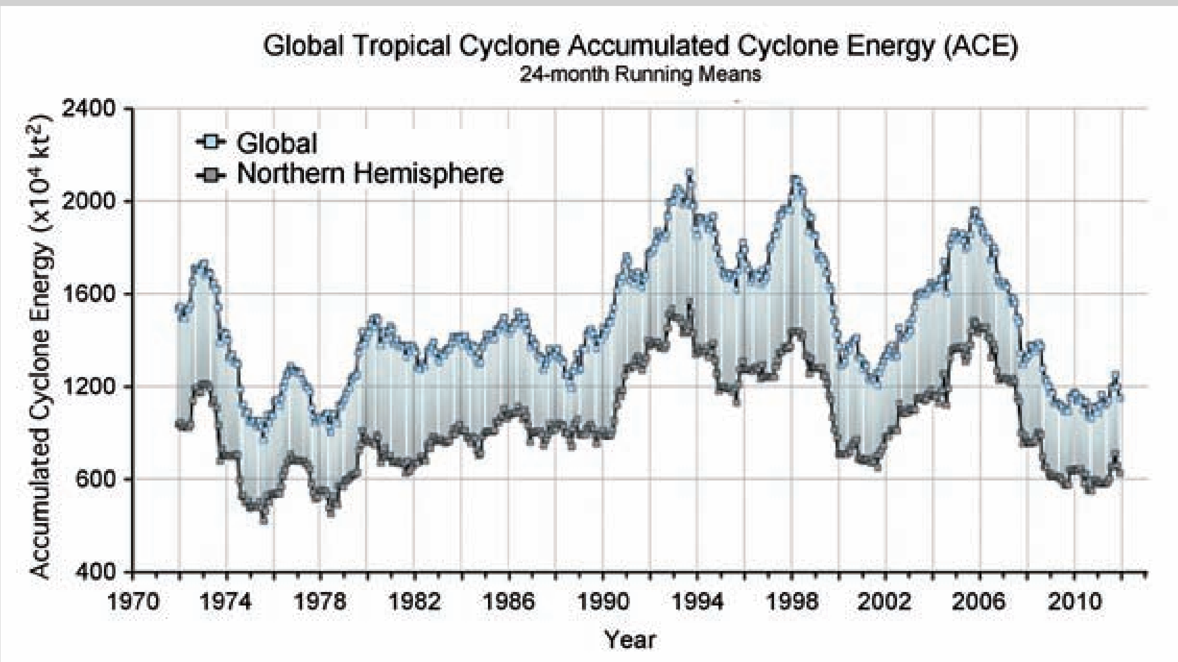
Although good records for tropical cyclones in the eastern Pacific only began with deployment of geostationary weather satellites in the early 1970s, it is clear that the total number of tropical storms and hurricanes in the eastern Pacific on seasonal to multi-decade time periods is generally opposite to that observed in the Atlantic. For example, during El Niño events it is common for hurricanes in the Atlantic to be suppressed while the eastern Pacific is more active. This reflects the large-scale atmospheric circulation patterns that extend across both the Atlantic and the Pacific Oceans.[43] During the past two decades, the tropical cyclone activity has decreased in the eastern Pacific.[44]

There has been no acceleration in sea level rise along the U.S. coast over the past 50 years, and projections of future sea level rise are likely overestimated

Sea level rise accelerated slightly during the 19th century, and rose by roughly seven inches during the 20th century. Long-term studies of tide gauge records reveal decadal variability,[46] and satellite data available over the past 20 years confirms this. The rate of sea level rise observed by satellites currently on the decline and is approaching the 20th century average established by the tide gauge network.

Mysteriously, U.S. sea level rise, as measured by tide gauges, has decelerated at many locations over the past several decades.[47,48,49] An analysis of 25 U.S. tide gauges, for example, revealed that since 1930, 16 stations experienced a deceleration of sea level rise while only nine experienced an acceleration.[50] Overall, the U.S. coast has recorded a mean deceleration rate of -0.0123 mm per year.

Sea levels are not rising at the increasing rates projected by climate models. While there should be some acceleration this century, sea level projections need to be adjusted for the consistent difference between modeled and observed temperature trends. Averaging results



Globally, hurricane activity as measured by the ACE index has been in general decline since the early 1990s and currently (as of 2011) is near its 40-year low.[45]

Station Location	Acceleration Since 1930
Annapolis, MD	-0.0218
Astoria, OR	-0.0108
Atlantic City, NJ	0.0254
Baltimore, MD	-0.0194
Boston, MA	-0.0150
Charleston, SC	-0.0286
Eastport, ME	-0.0504
Fernandina, FL	0.0086
Galveston, TX	-0.0384
Hampton, VA	0.0172
Honolulu, HI	-0.0018
Ketchikan, AK	0.0002
Key West, FL	0.0036
La Jolla, CA	-0.0096
Lewes, DE	0.0118
Los Angeles, CA	0.0134
Mayport, FL	0.0066
New York, NY	-0.0096
Pensacola, FL	-0.0132
Philadelphia, PA	0.0290
Portland, ME	-0.0514
San Diego, CA	-0.0102
San Francisco, CA	-0.0216
Seattle, WA	-0.0320
Seavey Island, ME	-0.0886

from a 2011 study from the Department of Energy[51] with another new analysis[52] suggests that the IPCC midrange emissions scenario projections should be adjusted to eight to 12 inches, which presents little to no cause for concern for coastal management.

Cold-season storm tracks are controlled by complex, interacting factors, and relating changes in them to global warming is highly uncertain

Cold-season storms—the typical "low pressure systems" that dominate the daily weather map—play a critical role in the global climate. Because there is always an excess of heat and humidity in the tropical latitudes, to maintain a long-term balance this heat and moisture must be exported into the higher latitudes. Storms (and associated frontal systems) are the effective mixing mechanisms. Therefore, storm tracks will naturally shift depending on the state of the global atmosphere at any given point in time.

Storms typically form along the boundary of warm, moist tropical air and cold, dry polar air (called the 'polar front'). With low latitude warming, a northward expansion of the tropics should shift the average storm track poleward.[53] Also, an increasing temperature gradient along coastlines (because land cools faster than water) could spin up more coastal storms.[54]

However, storms are influenced by a variety of other factors that make long-term storminess prediction difficult. Tracks are affected by the large-scale circulation state, and factors like ENSO (El Niño/Southern Oscillation) and the PDO (Pacific Decadal Oscillation) influence prevailing flow. Storm formation and sustenance requires a specific suite of atmospheric conditions (air that has the proper sense of spin ('vorticity') and upper air winds (jet stream 'divergence') that are dependent upon smaller scale features that are difficult to properly incorporate into climate models. As a result, future storm intensity is even more uncertain than future storm tracks.

Snowstorms

Large snowstorms require a unique mix of conditions to form: there must be a deep layer of cold (below freezing) air in residence, the humidity must be relatively high, and there must simultaneously be a growing storm large enough to produce snow.

It is difficult to predict how these various factors will interplay in future climates. As temperatures increase and the rain/snow boundary shifts poleward, locations near the southern reach of current snow events should see less snow and more rain. With more evaporation, a

A powerful cyclone centered over the Midwest clearly shows its linking of tropical warmth and polar cold.

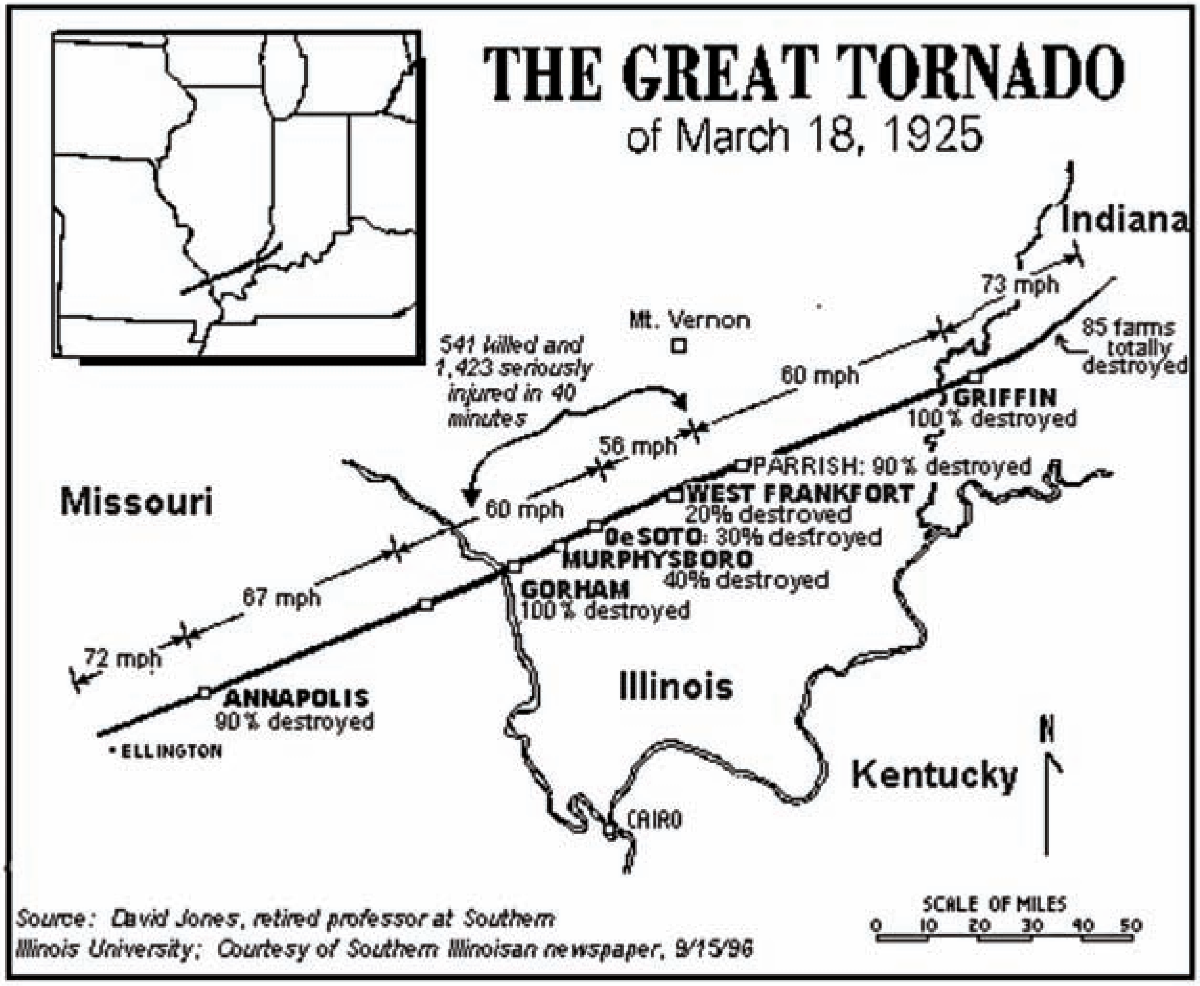
more humid atmosphere could increase snow amounts, but the likelihood of deep, cold air masses penetrating south will diminish. This is all coupled with a likely northward shift in winter storm tracks.

It is unclear how intense and concentrated "lake effect" snowstorms that fall in highly circumscribed regions in the lee of the Great Lakes would change with global warming. While warmer lakes would take longer to freeze, resulting in a longer snow season, the cold air that blows across the lakes from northern Canada should preferentially warm compared to other airmasses, reducing the temperature contrast that produces these intense snow squalls.

Tornadoes and severe thunderstorms

Reports of severe weather including tornadoes and severe thunderstorms have increased during the past 50 years. However, the increase in the number of reports is widely believed to be due to improvements in monitoring technologies such as Doppler radars combined with

"Lake-effect" snowstorms in the lee of the Great Lakes are small but extremely intense, as was this 10-footer in 2007.



The "Tri-State Tornado" of 1925 was probably similar in nature to the long-path system that caused great destruction in Alabama in 2011. But the 1925 death toll was almost 1400 greater because of the lack of modern infrastructure.

changes in population and increasing public awareness. When adjusted to account for these factors, there is no clear trend in the frequency or strength of tornadoes since the 1950s for the United States as a whole.[55]

The distribution by intensity for the strongest 10 percent of hail and wind reports is little changed, providing no evidence of an observed increase in the severity of events.

Severe thunderstorms and tornadoes are mesoscale and microscale phenomena (respectively) that only form in very unique environments; it is therefore impossible to predict how the interplay of relevant factors will change in the future. For example, fronts may become weaker, but low pressure systems could be stronger in some locations. Tornadoes often form in severe thunderstorms that require warm, moist surface conditions and cold, dry air about two to three miles aloft.

Current trends suggest that the surface environment would be more favorable for severe thunderstorms but that aloft, conditions would be less favorable. Furthermore, a weaker jet stream or one displaced northward from the southern Great Plains could lower the overall tornado risk for the United States. In reality, however, it is very difficult to accurately determine future changes in micro-scale features like tornadoes because climate models have no demonstrated utility at these levels.

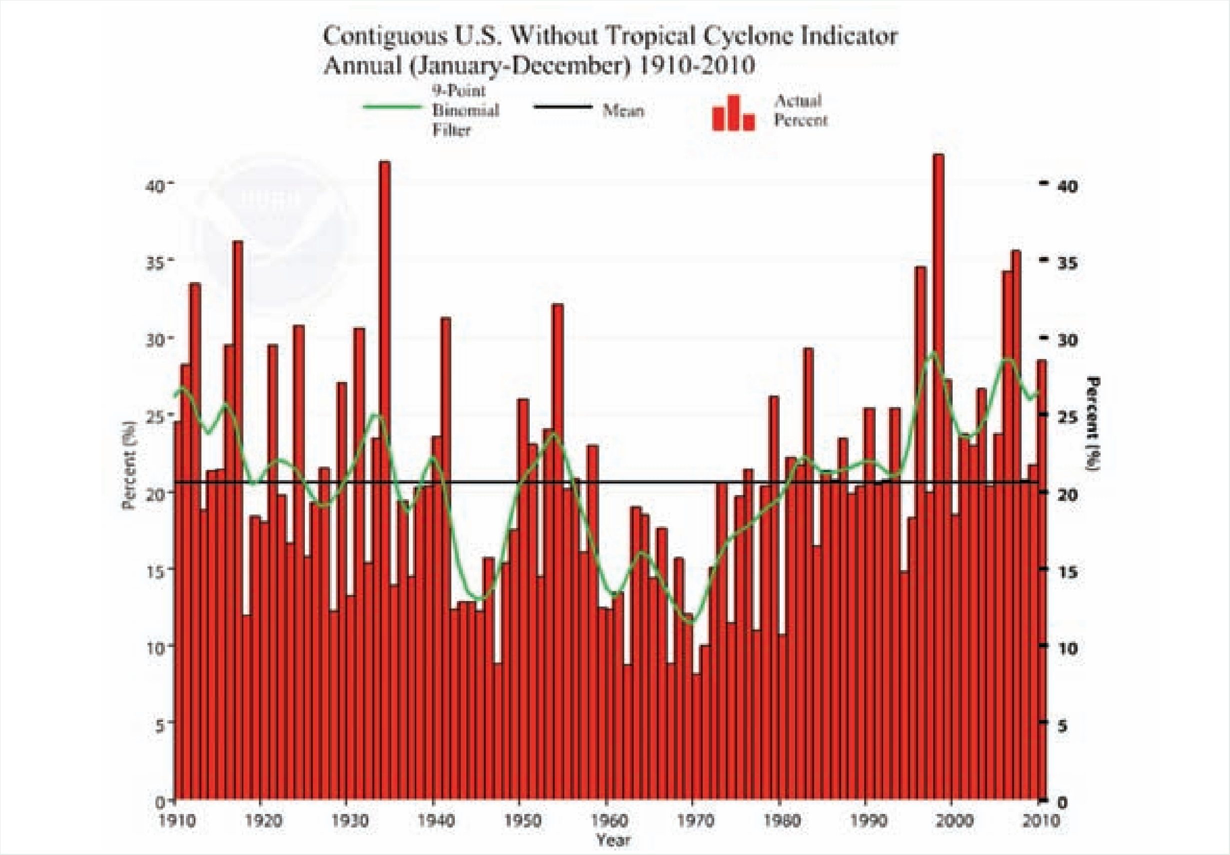
Index of extremes

A popular index that is available via the National Climate Data Center is the revised U.S. Climate Extremes Index (CEI)[56], which is the fraction of the area of the United States experiencing extremes in monthly mean surface temperature, daily precipitation, and drought (or moisture surplus). A plot of the index shows a substantial increase in 1970, and it is tempting to attribute the trend to global warming during the same time period. However, when one examines the plot over the period 1910 to near-present, it becomes apparent that the CEI decreased from 1910 to 1970 and then rebounded to levels seen in the beginning of the record.

In summary, the consistent behavior or various measures of weather extremes across the United States is that there have been increases in recent decades, but that the current regime clearly resembles that of the early 20th century, long before major greenhouse gas emissions.

U.S. carbon dioxide emissions in perspective

The United States historically has been the greatest emitter of carbon dioxide, contributing approximately 28 percent of the human fraction. However, since 2006, China has taken over the leadership for annual carbon dioxide emissions. U.S. emissions have been relatively constant for the last two decades, with a slight rise through the late 1990s followed by a slow decline.[57] The largest interannual decline in our emissions was 5.8 percent, between 2008 and 2009, associated with the economic consequences of the 2008 financial collapse as well as



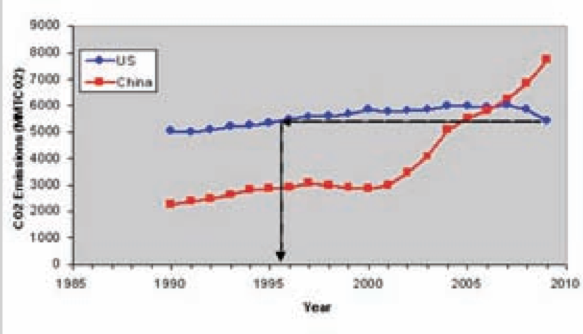
Climate Extremes Index, 1920–2010, not counting tropical storms and hurricanes.[57]

the substitution of natural gas for coal in electrical generation.[58] This latter cause occurred because of a dramatic increase in the supply of natural gas from shale formations.

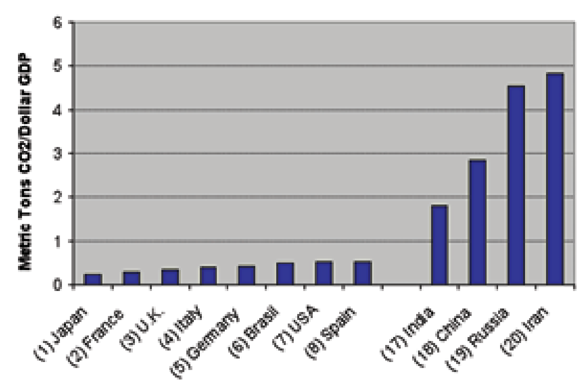
The efficiency of emissions is measured by the "carbon dioxide intensity," which is the amount of emissions (in metric tons), per unit of GDP (in this case, $1,000 in 2000 dollars). Iran, Russia, China, and India are by far the least efficient of the top 20 emitters, and would therefore benefit the most from the installation of a mix of power production technology similar to what is employed by the more efficient nations, although nuclear power—heavily used in the five most efficient economies—is certainly controversial in Iran.

The relatively similar emissions intensity figures for the eight most efficient nations (of the top 20 economies) indicate that, by far, the easiest targets for large emissions reductions are in fact the four most inefficient economies in this group.[59]

As U.S. emissions of carbon dioxide stabilized, evidence began to accrue that the "sink" of carbon dioxide in the world's vegetation was greatly underestimated. The first signs of this were published in 1992, when it was noted that terrestrial nitrogen increases from agriculture and industry were stimulating European forest growth,[60] effectively putting to rest the alarmist notion of European "waldenstrube," or forest death. Remote-sensing technologies document a global planetary greening first in 1997,[61] and soon a much larger than expected carbon dioxide sink was found in North American forests,[62] which is in part a result of direct stimulation of photosynthesis by carbon dioxide.[63] Additional research demonstrates that the "greening" of forests in recent decades is ubiquitous worldwide.[64] A recent comprehensive report shows that the forest sink for carbon dioxide removes nearly 20 percent of the historically high emissions of recent decades, and further, that this sink can expand dramatically with management and conversion of trees to long-term storage[65] known as "houses."



Annual carbon dioxide emissions from the United States (blue) and China (red). In the last year (2009), Chinese emissions were 142 percent of the U.S. total. In 1995, China emitted only half as much as the United States.[57]



Emissions intensity for the eight largest emitters, and India through Iran, (ranking number 17 through 20 ($ per metric ton carbon dioxide; Market Exchange Rates)).[57]

The net terrestrial forest carbon sink depends upon forest extent, growth, and loss. It is very clear that losses from deforestation caused by human activity, over time, reduce the potential global forest sink by as much as 75 percent,[66] which can be mitigated dramatically with long-term sequestering of wood rather than short-term combustion. Despite the occurrence of natural disasters, fire, and other negative influences on the sequestration of carbon dioxide by forests, there appears to be little net change over time.[67] Consequently, the overall outlook is that management and use of forests can result in even more sequestration than is occurring now; without deforestation, the world's vegetation can remove a remarkable 33 percent of carbon dioxide emissions per year.[68] Further, vegetation directly reduces warming, as much as 50 percent in the eastern United States in modeling studies.[69]

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Water Resources

Key Messages:

- Changing composition of the atmosphere will impact the water cycle by generally increasing atmospheric moisture at the global scale.
- Climate models generally predict that hydrological extremes (droughts and floods) may increase in the future, but at present, little empirical evidence supports the prediction.
- The greatest concern is for the Southwest, where demand for water may outstrip supplies, with or without climate change.
- The western United States is dependent upon snowpack for water supplies, but trends in snowpack are well within the limits of natural variation.
- Surface and groundwater quality may be influenced by climate change, but they will likely be far more influenced by non-climatic considerations.

There is little doubt that the globe and the United States have warmed over the past century and past half century, and any number of studies lead to the conclusions with respect to the hydrologic cycle that:

- the amount of moisture in the atmosphere over the United States has increased
- precipitation amounts have generally increased
- the amount of intense precipitation has increased
- runoff from rivers has increased
- extremes in runoff have not increased
- water temperatures have generally followed air temperature variations and trends, and
- reductions have occurred in lake and river ice.

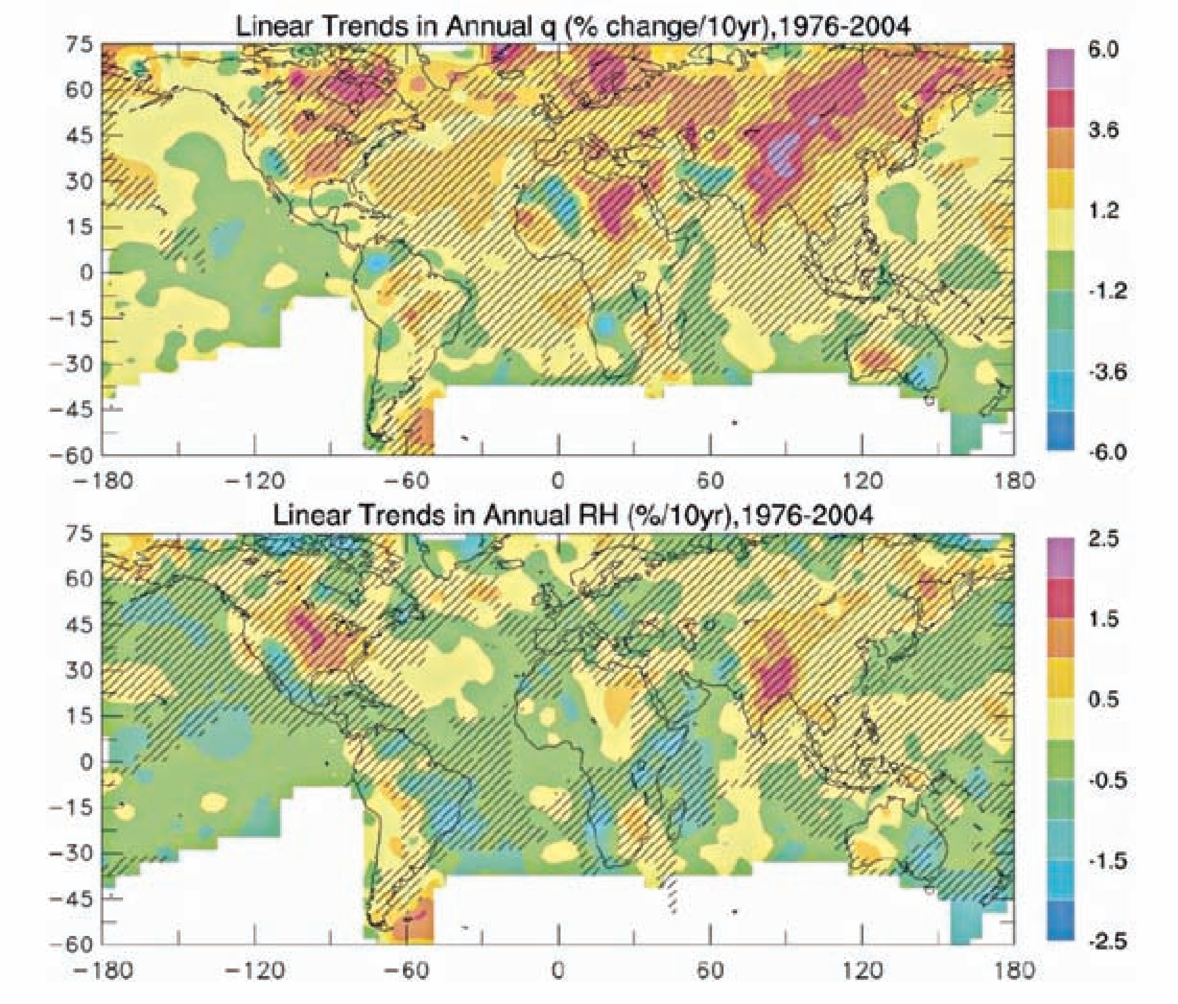
The conterminous United States covers 1.54 percent of the Earth's surface, and predicting regional variations in hydrological trends within such a small area may be well beyond the capabilities of current climate models.

The future will certainly brings floods and droughts to the United States that will undoubtedly affect energy production and use, human health, transportation, agriculture, and ecosystems. Climate change itself will have both positive and negative impacts. The extent to which climate changes can be attributed to human activities will continue to be debated for decades to come, but based on long-term climate reconstructions of the past, floods and droughts are in our future with or without anthropogenerated changes in climate.

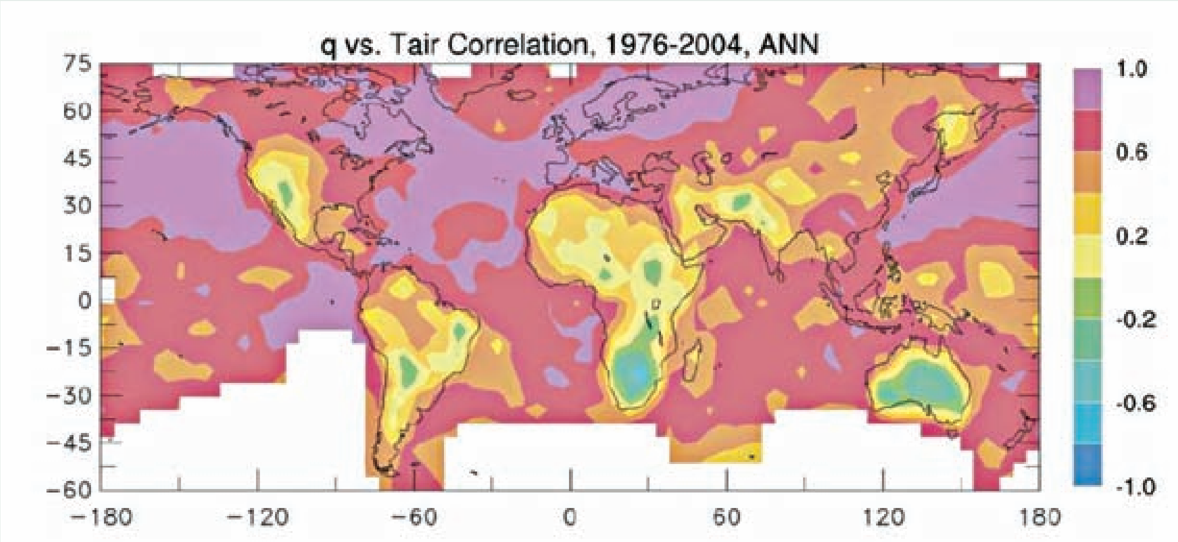
Variations in temperature alter the water cycle, and they have done so throughout the history of the Earth

There is absolutely no doubt that warming of the planet would, with all other things held constant, increase the moisture content of the atmosphere. For every 1°F increase in atmospheric temperature, the water holding capacity increases by approximately 4 percent.

The spatial pattern associated with changes in near-surface atmospheric moisture is surprisingly complex, with some areas showing an increase, some a decrease; the trends are also highly dependent on seasons as well.[1] A reason-



Spatial distributions of linear trends during 1976–2004 in (top) specific humidity [percent/dec.], and (bottom) relative humidity [percent/dec.]. Hatching indicates the approximate areas where trends are statistically significant at the 5 percent level.[3]



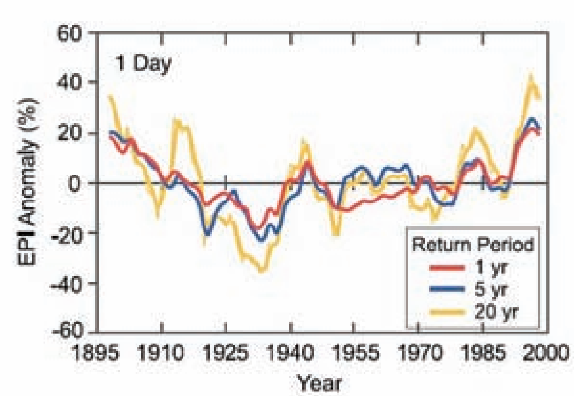
Map of correlation coefficients between observed annual mean surface specific humidity and temperature change 1976–2004. Absolute values above 0.4 are statistically significant.[3]

Linear trend in total annual precipitation as indicated by standardized regression coefficient (1975–2009).[4]

ably comprehensive study of trends in moisture levels shows that most of the Northern Hemisphere has seen an increase in atmospheric moisture (in terms of specific humidity), with most of the United States experiencing the increase over the 1976–2004 time period, except for the Southwest, where trends are not statistically significant and therefore cannot be differentiated from a constant value.[2] Over most of the United States, there is a high correlation between trends in air temperature and trends in atmospheric moisture, but this does not appear to be the case in the Southwest. This is different than what is occurring over other land areas around the planet, where correlations are much lower.

In general, climate models project an increase in precipitation for most areas of the United States, with the exception of the Southwest. The IPCC does show a small portion of the upper Midwest with a significant increase, but otherwise, total precipitation has been largely unchanged over the 1979–2005 time period. Scientists recently examined the trend in annual precipitation for the United States from 1975 to 2009, and they also found an increase in the upper Midwest and New England states and a decline in the West, particularly in the Southwest.[4] As with so many other climate variables, conclusions regarding trends in precipitation vary from study to study and depend on the datasets that are used, the time of study period, and the methods used to establish trends.

Will extreme precipitation increase because of the buildup of greenhouse gases?

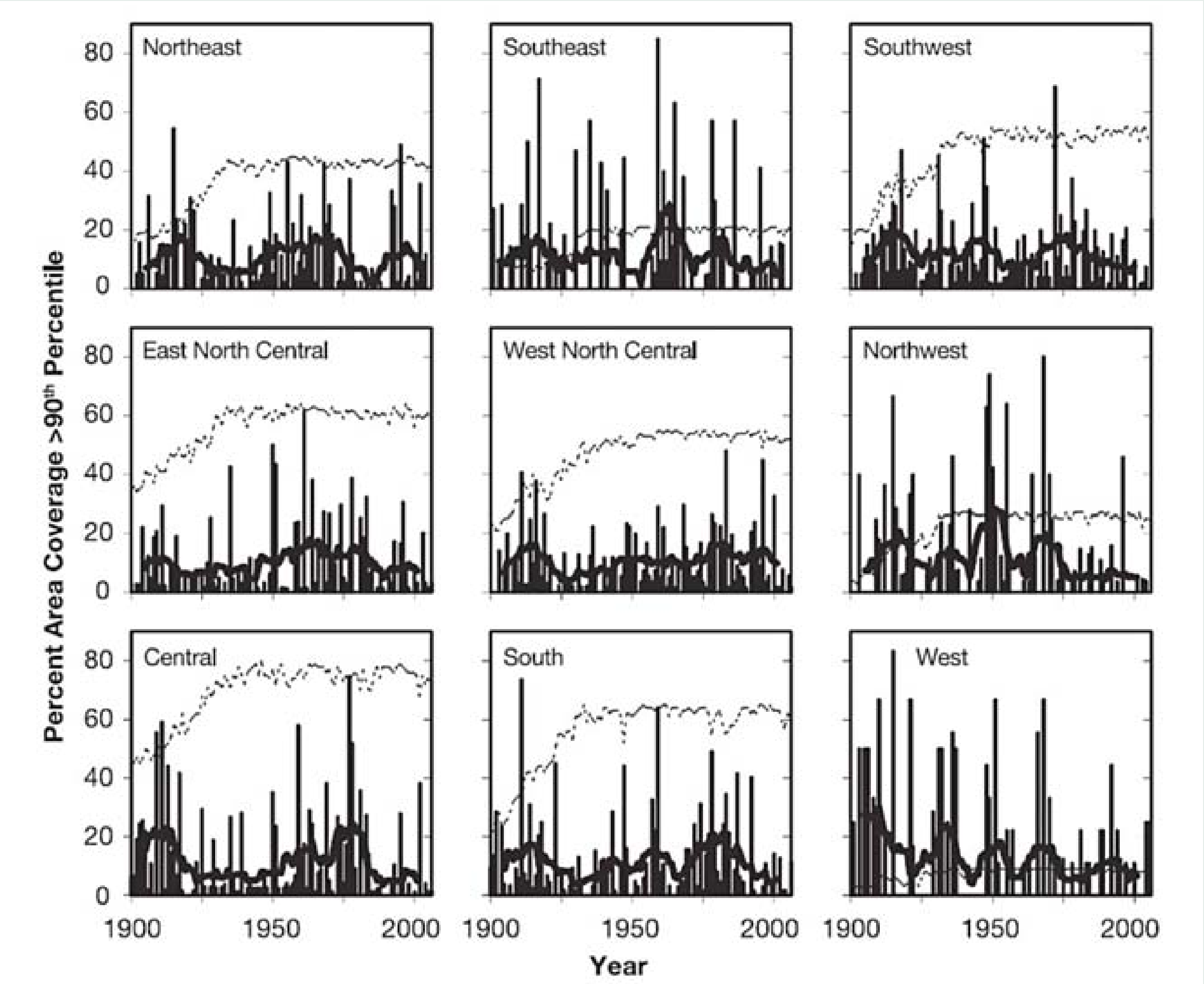


Time series of anomalies of the Extreme Precipitation Index of Kunkel et al.,[11] expressed in percent, for various combinations of duration and return period. The time series have been smoothed with a seven-yr moving average filter. Return periods of one year (red), five years (blue), and 20 years (yellow) are plotted. It is apparent that the recent regime of relatively "extreme" rainfall occurred previously in the late 19th and early 20th centuries.

The idea that heavy precipitation may increase due to warming is a simple concept—a warmer atmosphere with more moisture is inherently more unstable than a cooler and drier atmosphere. If all else remains constant, the warmer, wetter atmosphere should produce heavier precipitation events. Changes in storm tracks or the frequency, magnitude, duration, or intensity of mid-latitude or tropical cyclones could result in changed precipitation as well.

For more than two decades, scientists have analyzed various precipitation databases and found an upward trend in the largest precipitation events, and these conclusions have been reviewed by the IPCC and others.[5,6] However, the issue is not without its share of controversy. Several studies have shown that for the same area and for the same precipitation database, significant upward trends, no trends, and significant downward trends in extreme precipitation events can be identified depending on how one defines an extreme event.[7,8]

Scientists have noted another complication in any assessment of extreme precipitation events.[9,10] A climate record for the past 50 years may reveal a trend upward in some measure of precipitation intensity, and a claim could be made that the observed pattern is related to the



Regional average annual percentages of homogeneous snowfall stations exceeding the 90th percentile in snowfall, 1900–1901 to 2006–07. The thick black line is an 11-year running mean of the percentages, and the dashed line indicates the number of active stations each year. It is obvious that there are no systematic changes in this variable.[14]

buildup of greenhouse gases. But it has been found that longer-term records of a century or more reveal spatial and temporal patterns of extreme precipitation seen in the most recent decades appeared 100 years ago, confounding the attribution of recent heavy rain regimes to changes in greenhouse gas concentrations.

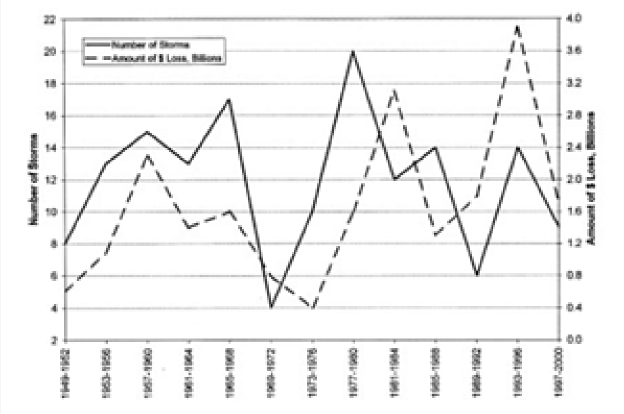
Extreme snowfall (blizzards)

One comprehensive assessment of the past century[12] found considerable interannual variability in large snowfall events, and most areas of the country in decline over recent decades. However, as with overall precipitation regimes, when the downward trends are seen in the context of the past 100+ years, it becomes apparent that they are within the natural variability observed over the longer time period. There is no significant trend in the occurrence of large snow events. Another study[13] focused on the frequency of "blizzards" in the United States, documenting an increase from 1959 to 2000; however, this study noted that the upward trend may be spurious and a result of changes in the definition of blizzards (we now document smaller blizzards). There is a strong possibility of this, given that no change was observed in the area impacted by blizzards over the same time period.

According to insurance data, the incidence of damaging snowstorms peaked in the 1976–85 period, with no significant upward or downward trends during their study period from 1949 through 2000.[15] The implication is that mid-latitude winter season cyclonic storms in the United States have not intensified over the past half century.

Is Western snowpack melting earlier in the year?

Are rising temperatures in the western United States associated with earlier snowmelt? This is an important question, as snow is a major source of agricultural and residential water in



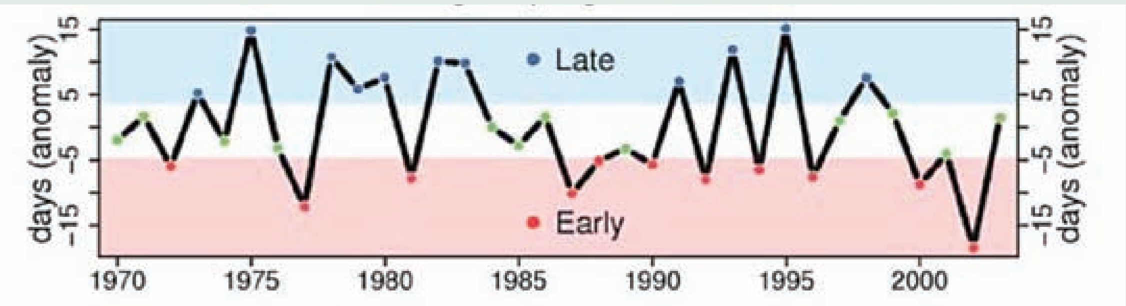
The number of severe snow storms causing >$35 million in losses (2000 dollars), and amount of their losses for four-year periods during 1949–2000.[16]

the West. A team of scientists[18] primarily interested in wildfires in the western United States gathered data on the time of snowmelt in the West, and although their results showed considerable year-to-year variability in the timing of snowmelt, they found no significant trend whatsoever over the past four decades.

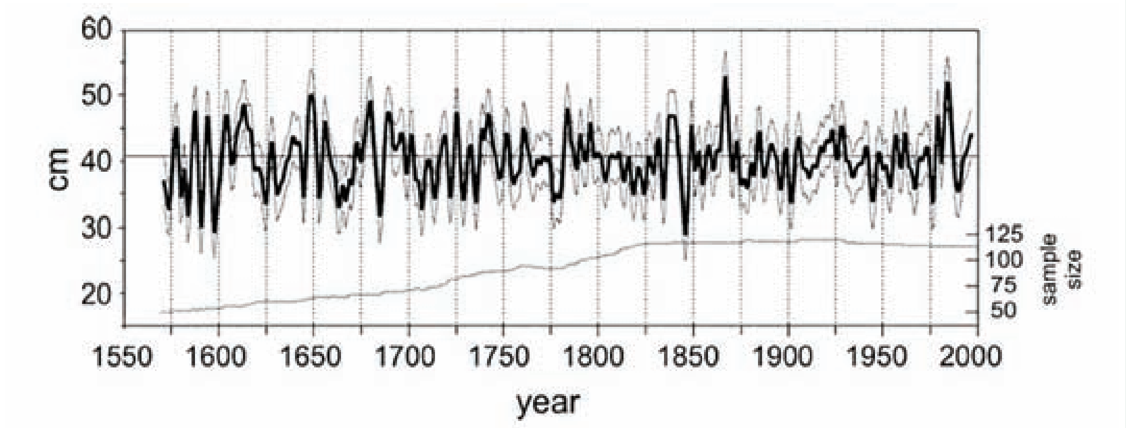
Irrespective of time period examined throughout the climate history of the earth, changes would be observed in any climate-related variable, including snowpack. In the West, selected tree ring records have been shown to be highly related to snow water equivalent in snowpack of the area. Given a long-term tree ring record, a proxy time series of water in the snowpack can be generated. One such record from the Gunnison River basin of western Colorado is well suited for such a reconstruction,[19] and the record does show a substantial decline in the most recent few decades. When viewed over the time frame of 430 years, the recent change appears to be well within the range of natural variability and does not seem exceptional at all.

For the United States as a whole, the amount of snow has not changed significantly, nor have characteristics of snowfall such as the onset or duration of snowfall.[21] Although the overall snowfall is largely unchanged, many investigators report an increase in snowfall in the Great Lakes area and a reduction in snowfall

Timing of Spring Snowmelt



Timing of spring snowmelt (the more negative the value, the earlier in the year the spring snowmelt occurred)[9]



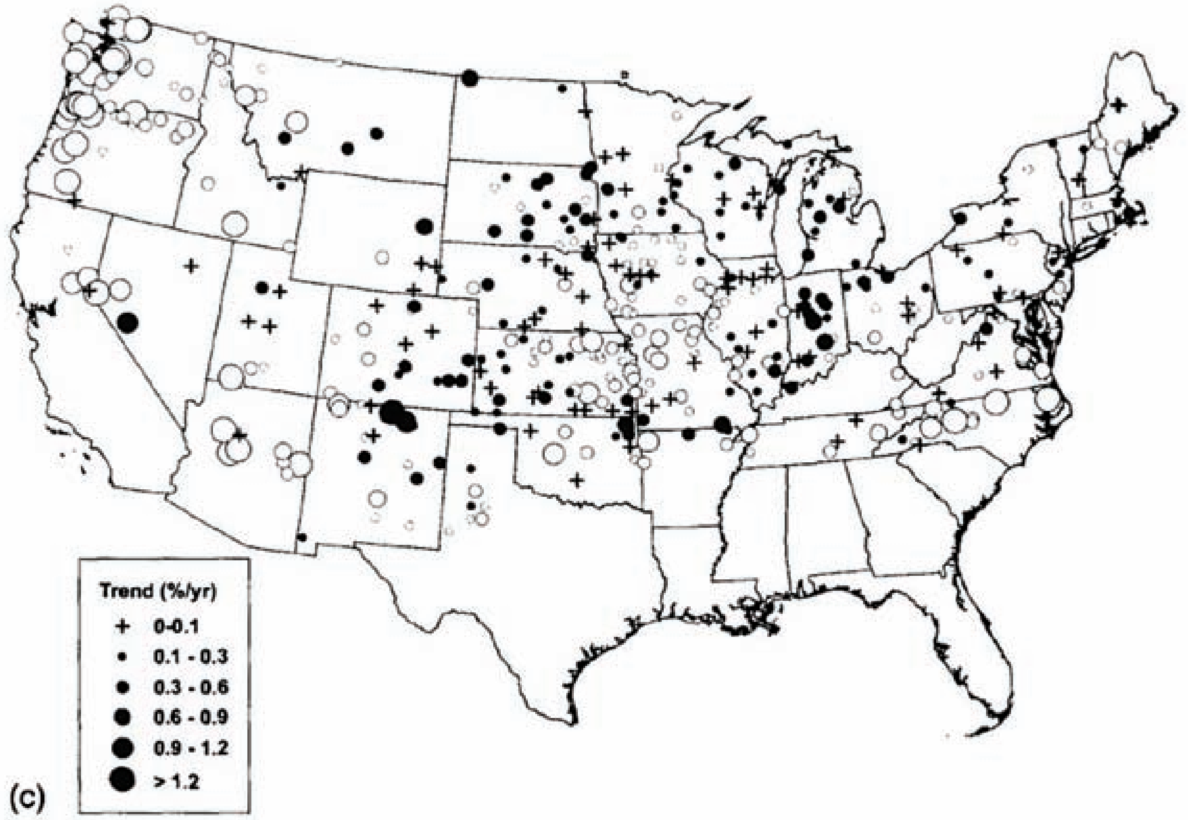
Full reconstruction of Gunnison, Colorado, snow water equivalent, smoothed with a 5-weight binomial filter (heavy line) and error bars (thin lines), 1571–1997. The thin line at the bottom of the graph indicates the change in total number of samples in the four chronologies used in the reconstruction over time (right-hand y axis).[20]

in the Northwest. The identification of trends in snowfall is difficult given many inconsistencies that badly contaminate long-term records. Furthermore, examples can be found of nearby stations having remarkably different trends in snowfall through time that point to problems with the records as opposed to any realistic change in climate.[22]

Is climate change a threat to groundwater resources?

Concern exists that groundwater resources in the United States will be negatively impacted by climate change because of increased drought and reduced recharge, increased pumping to keep up with increased potential evapotranspiration rates, and even the intrusion of brackish water related to ongoing sea level rise. There is no question that coherence exists between climate variables and groundwater resources with the interactions occurring at a variety of timescales.[25] Some scientists have found that climate change will be amplified in terms of groundwater response,[26] while others have found only small responses to climate change scenarios.[27] Most investigators agree that groundwater response will strongly depend on local soils, land cover, geology, topography, regional climate, and existing groundwater conditions. Furthermore, groundwater may also respond to a decrease in transpiration from plants associated with elevated atmospheric carbon dioxide concentrations.

There is little doubt that groundwater resources of the future will be far more related to human management strategies than to changes in climate. Given the natural variability in climate, the complex response of groundwater to



Snowfall trends from 1930–31 to 2006–07. Trends are given as a percentage of the 1937–38 to 2006–07 snowfall mean per year. Filled circles: positive trends; open circles and stippling: negative trends. [23]

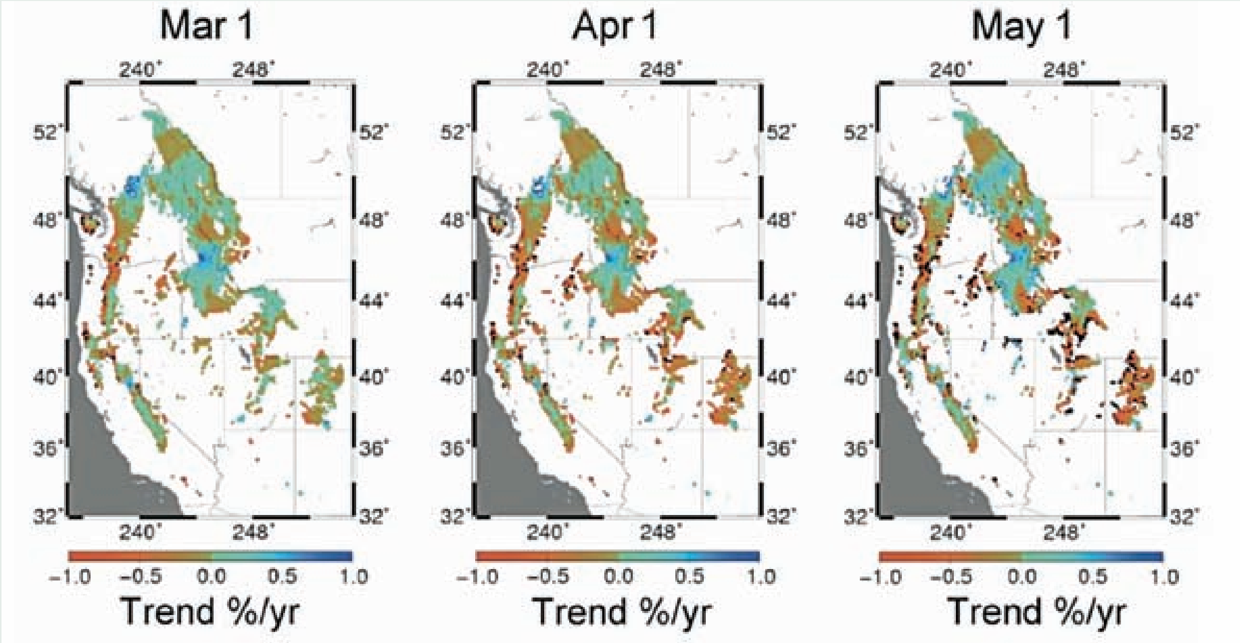
variations in climate, and the enormous impact on groundwater from pumping, groundwater impacts related to human-induced climate change will likely be undetectable for many decades to come.[28]

Streamflow and global warming in the United States

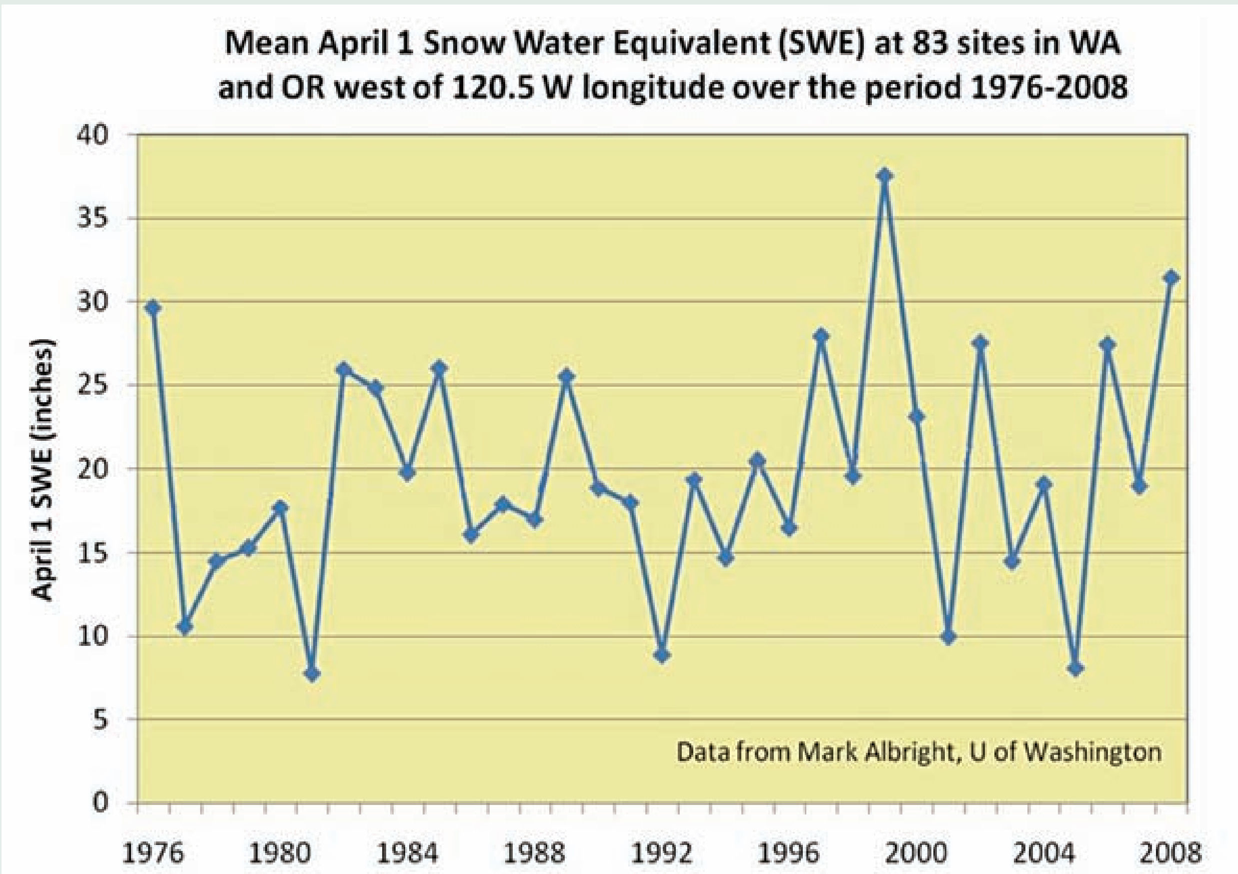
In North America, in a study of over 70 rivers, 26 show statistically significant changes (14 increases and 12 decreases) in maximum annual streamflow. Our map shows no strong regional signal in the results; many cases exist with streams close to one another showing opposite but significant trends.[30]

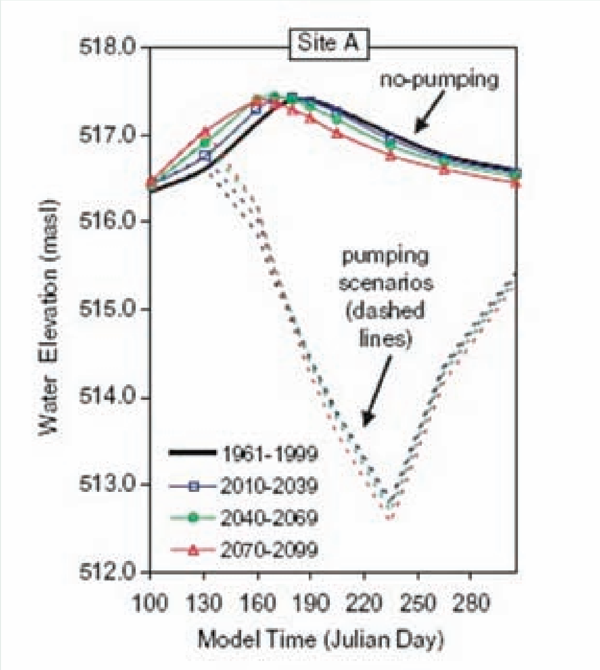
Over the United States, an analysis of 395 climate-sensitive stream gaging stations in the conterminous United States over the period 1944–93 showed that average streamflow was increasing but maximum (flooding) flows were not.[31,32] The studies indicate that the nation appears to be getting wetter, but with less extreme flow. Another study[33] analyzed 218 basins in the eastern half of the United States and found that the annual mean and low flow have increased during the period 1948 to 1997, but the annual high flow did not.

The literature is full of articles reporting the results from individual watersheds, and based on what is seen in the more comprehensive studies, some river systems show an increase in



Relative trends (percent/yr.) in simulated snow water equivalent for three calendar dates for the period from 1916 to 2003.[24]





There is little effect of climate change under pumping and non-pumping conditions on groundwater elevations: Site A (close to pumping wells), Site B (away from pumping wells).[29]

extreme discharges, some show a decrease, and many show no significant change whatsoever. Evidence can be found to support any prediction one makes about the future behavior of America's river systems. Furthermore, long-term reconstructions of different rivers typically show great variability over time, but rarely do they show evidence of any significant upward trend in extreme flows.

Spotlight on the Colorado River

Every watershed in the United States is vulnerable to climate change, but one area seems particularly at risk: the Desert Southwest, largely watered by the Colorado River and its tributaries.

Numerical models of climate all predict that warming will occur in the coming decades in the Southwest, and indeed, the Colorado Basin has warmed by 0.12 °F per decade over the past 100+ years. Precipitation during the recharge season, November to April, has shown no significant trend over either time period; the Palmer Hydrological Drought Index showed no significant trend over the 100+ year period, while it has trended toward increased drought since 1975.[34]

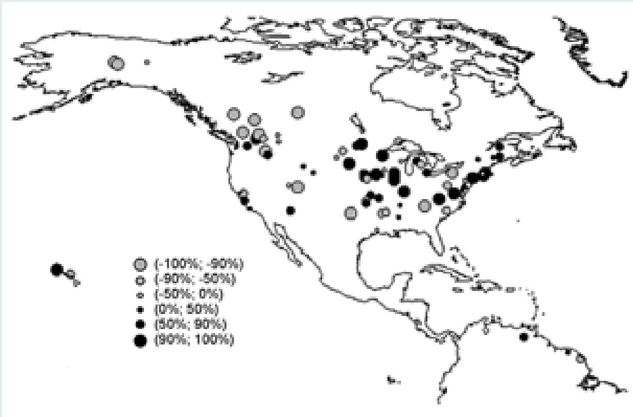
Observed and/or projected trends toward lower soil moisture levels and/or increased drought in this region have been noted in many articles in recent years.[36,37,38] These have caught the attention of the public and policymakers despite a much more complicated picture that is painted by a more comprehensive scientific literature.

For example, paleoclimatic reconstructions show that very large droughts have occurred in the past,[39] which means they will certainly occur in the future.

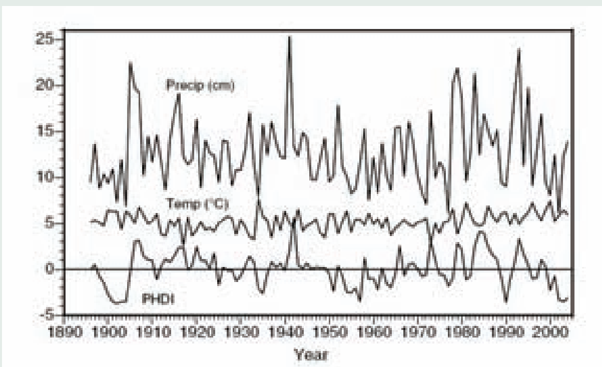
While all climate simulations predict warming in the region by the middle of this century, precipitation forecasts vary widely. Some models predict a large enough increase in precipitation to overcome evaporative losses associated with increased temperature, leading to increases in runoff in the future.[41] Other models predict less precipitation, leading to catastrophic declines in streamflow in the future.[42]

From the perspective of the last 500 years, it is obvious that current conditions are hardly unusual, and that the low flow in the Colorado River in the late 20th century occurred approximately seven times (with an anomaly of similar

Piscataquis River in Guilford, Maine (at/or near normal flow level).



Trends in annual maximum streamflow in 70 North American rivers. Positive trends (black circles) and negative trends (grey circles) are statistically significant at the 10 percent level in the largest circles.[30]

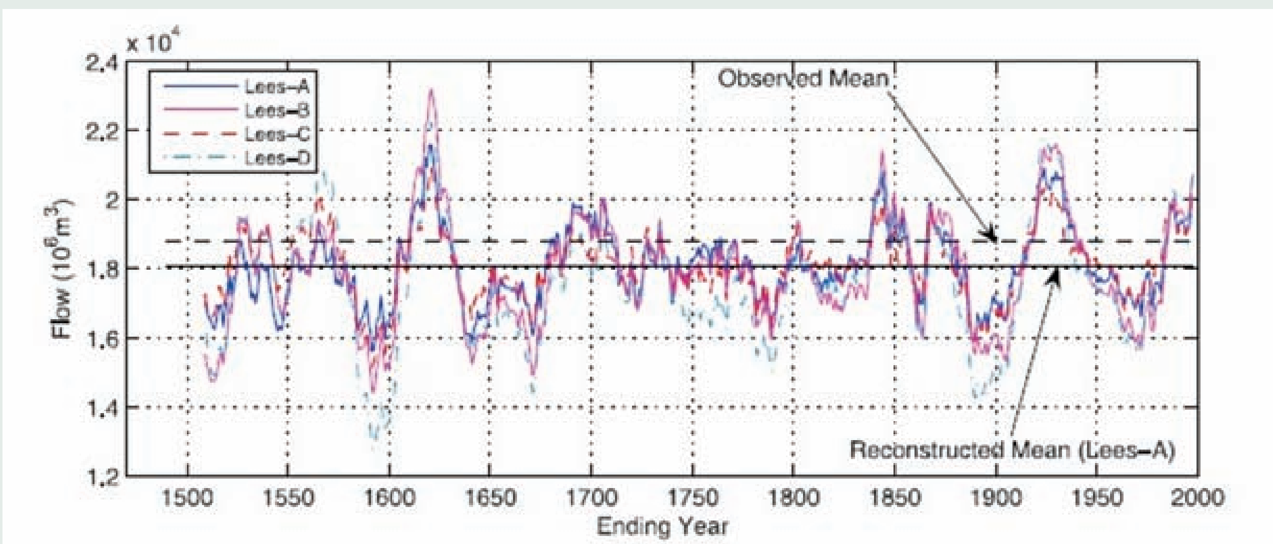


Time series plot of areally-averaged Colorado River Basin November–April total precipitation (cm), temperature (°C), and Palmer Hydrological Drought Index (PHDI) over the period November 1895 to April 2004.[35]

length) in the last 500 years.[43] There is strong evidence that the Colorado experienced persistently high discharges from near 1910 to 1940, a time when many agreements were reached regarding allocations for various users.

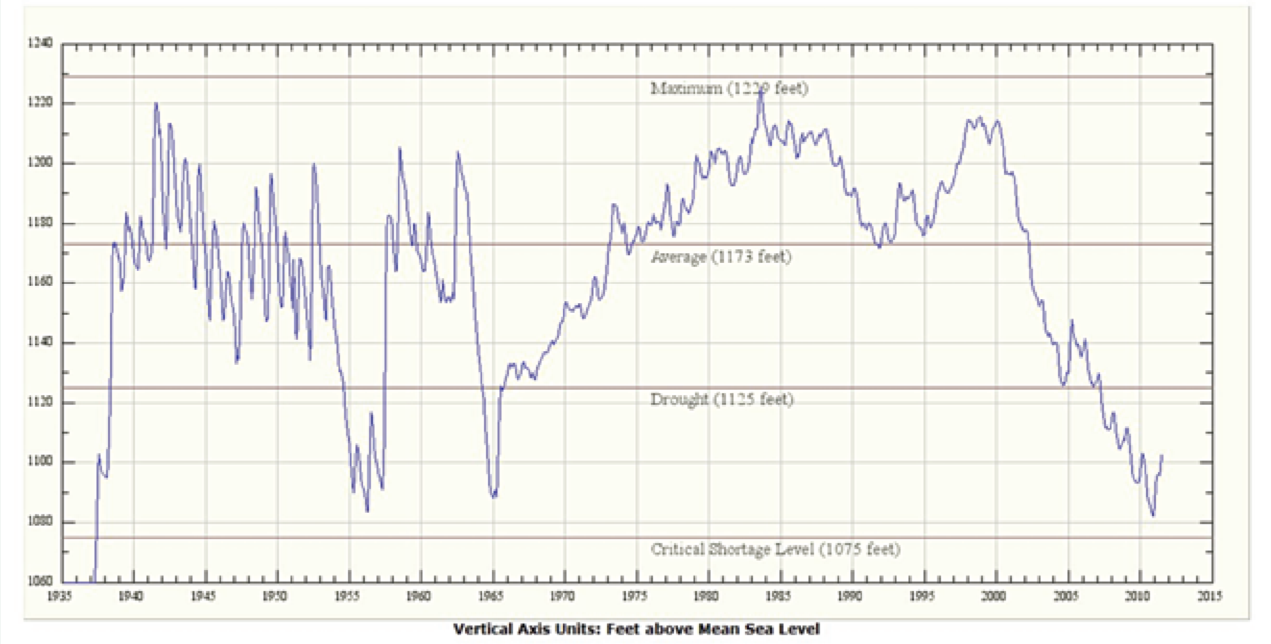
Levels at Lake Meade do not strongly resemble the upstream flow of the Colorado River—the Lake is highly managed behind the Hoover Dam and reflects decisions made by water managers much more than changes in climate.

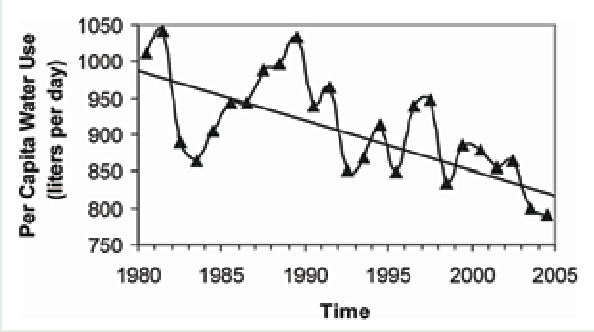
Water managers are well aware of the threat of a future drought, and adaptations are already underway. For example, most communities, including the city of Phoenix, have implemented water conservation policies, such as distributing water-saving devices, requiring low-flow devices for new and replacement fixtures, establishing educational programs, and creating pricing structures. Over the period 1980 through 2004, residential per capita water use in Phoenix decreased by 15 percent.[44] Other potential strategies include winter season cloud seeding in the headwaters of the basin to increase snowpack, genetic development of more water efficient crops and grasses, and improvements to engineering structures throughout the watershed. Nonetheless, if the human population expands in the Southwest as many are predicting, water managers will certainly be challenged, with or without climate change.



Reconstructed 20-year running means of Colorado River at Lees Ferry, Arizona, by various statistical models.[40]

Lake Mead Water Levels — Historical and Current





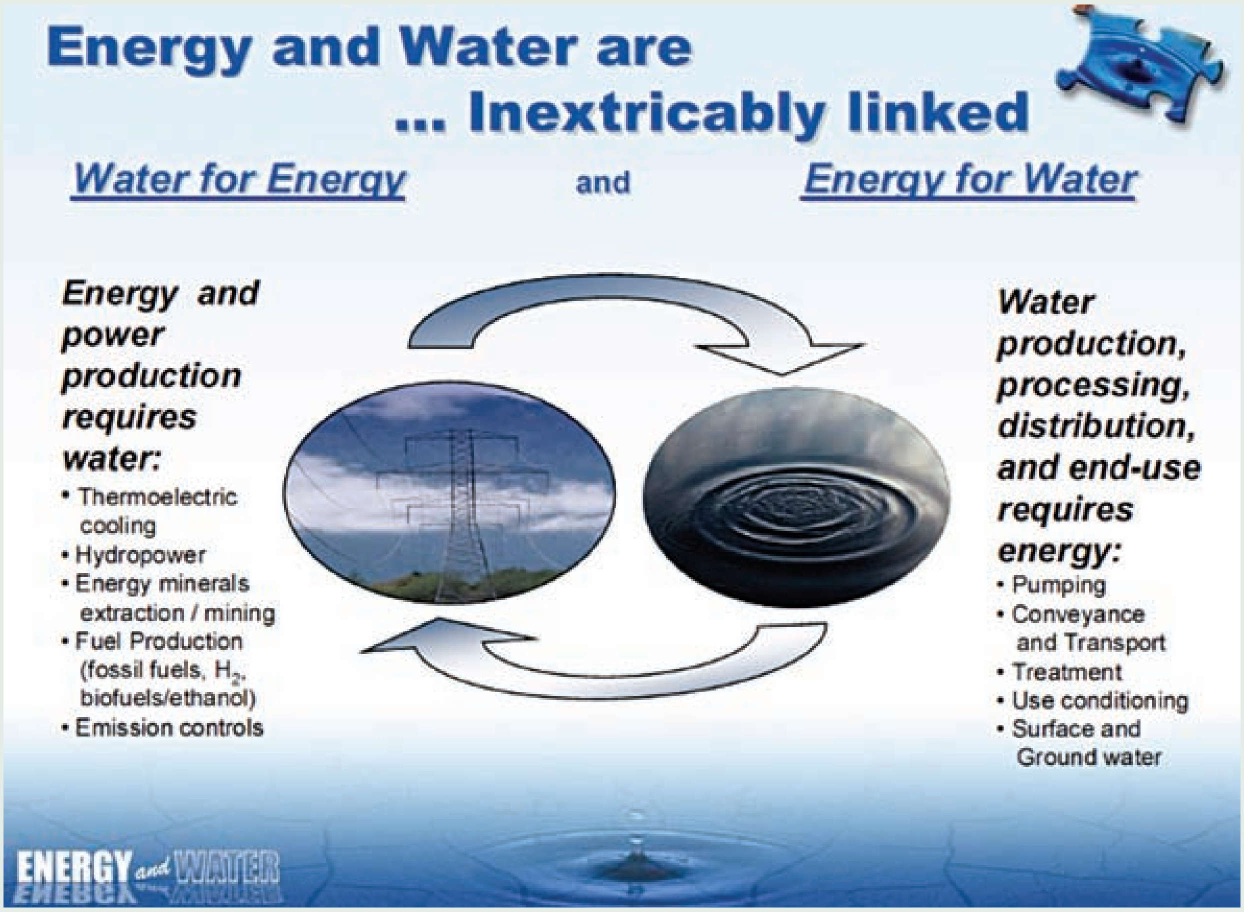
Phoenix per capita annual water use (liters per capita per day) from 1980 through 2004.[45]

Water and energy: complicating our ability to estimate the effects of climate change

Many studies linking water resources to changes in climate follow the well-established path of quantifying a statistical linkage between some water-related variable and actual weather or climate data and then using output from numerical climate models to estimate the change in the climate variables in years and decades to come given changes in atmospheric composition. While this approach is widely used and broadly accepted by the science community, one critical assumption is that all other interacting factors will in the future have the same approximate effect they had during the period used to generate the statistical linkage between observed climate and the water-related variable.

This is not a good assumption. Consider the strong and complex connection between water and energy. A huge amount of water is consumed in the production of energy throughout the United States. The U.S. Geological Survey reports that approximately 50 percent of fresh surface water withdrawals in 2000 in the United States were used in generating thermoelectric power.[46] For example, generating power requires far more water than irrigated agriculture, industrial water use, or residential water use. At the other end of this connection is the large amount of energy required to pump groundwater, treat source water as needed, deliver water, treat waste water and poor quality waters to augment the available sources of supply, and remediate polluted waters from a variety of sources, including energy production.

Policies aimed at combating climate change typically involve alterations in the energy mix



that can have implications on water use that far exceed changes in water demand that could come directly from any change in climate. Water use in the future may be far different from water use at present, but changes in our demand for energy, and changes in ways we generate energy, likely will far exceed changes in water use directly related to changes in climate.

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Energy Supply and Use

Key Messages:

- U.S. energy production and usage are affected not only by weather but also by climate change.
- On the supply side, energy producers anticipate and minimize the impact of severe weather events through best business practices and insurance policies.
- Responses to shifts in climate will not appreciably affect energy production as technological improvements are incorporated in daily operations over time.
- On the demand side, warming will lower demand for heating energy and increase demand for cooling energy.
- A reduced diurnal temperature range expected with greenhouse warming mitigates higher peaking demand for electricity capacity.
- Climate change is likely to affect hydropower production in regions subject to changing amounts of precipitation or snowmelt.

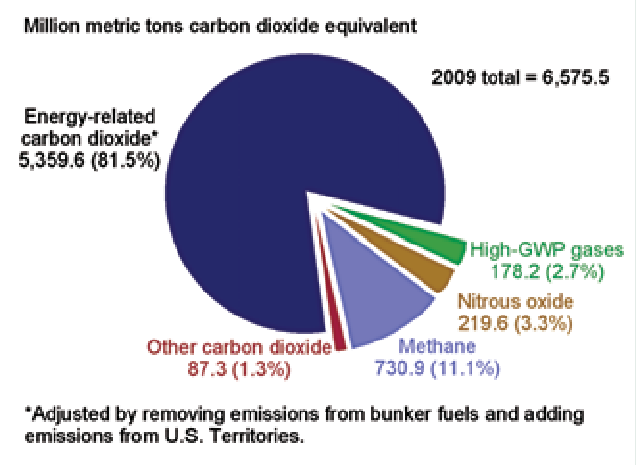
Energy is at the heart of the global warming challenge. Eighty-seven percent of U.S. greenhouse gas emissions are from energy production and use. Large scale mitigation—or reduction—of greenhouse gas emissions would reduce energy supply or increase cost, as "renewable" sources (which the exception of hydropower) are significantly more expensive and less dense. On the other hand, plentiful and reliable carbon-based energy facilitates societal resiliency to weather and climate changes at a lower cost. Adaptation rivals mitigation as a public policy strategy and, indeed, may be seen as its opportunity cost.

One would expect that the trend in the United States should be toward increased energy use per person. Population shifts to the South, especially the Southwest, where air conditioning use is high, an increase in the square footage built per person, increased electrification of the residential and commercial sectors, and increased market penetration of air conditioning would all lead to higher per capita use.

But the opposite has occurred. Energy consumption per person peaked in 1978 and 1979 and has fallen by 12 percent since then.[2]

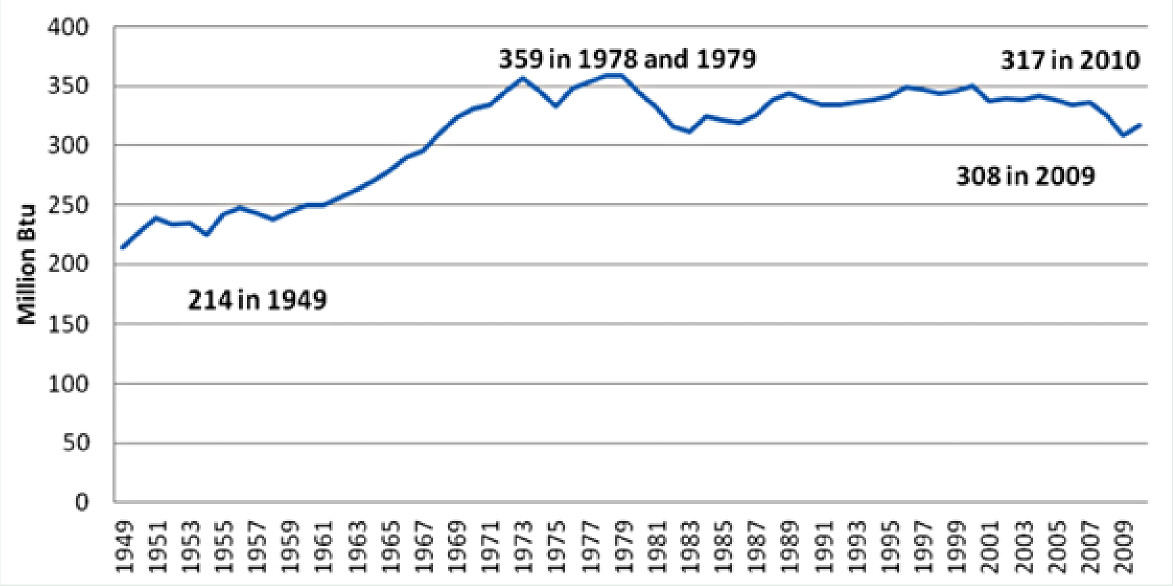
The decrease in energy use per person has partially occurred by increasing efficiencies of new electric and end-use technologies and a shift to more service-oriented industries resulting in decreased energy intensity (energy consumption per unit of Gross Domestic Product). Since 1973, energy intensity has fallen by 53

U.S. Greenhouse Emissions by Gas, 2009



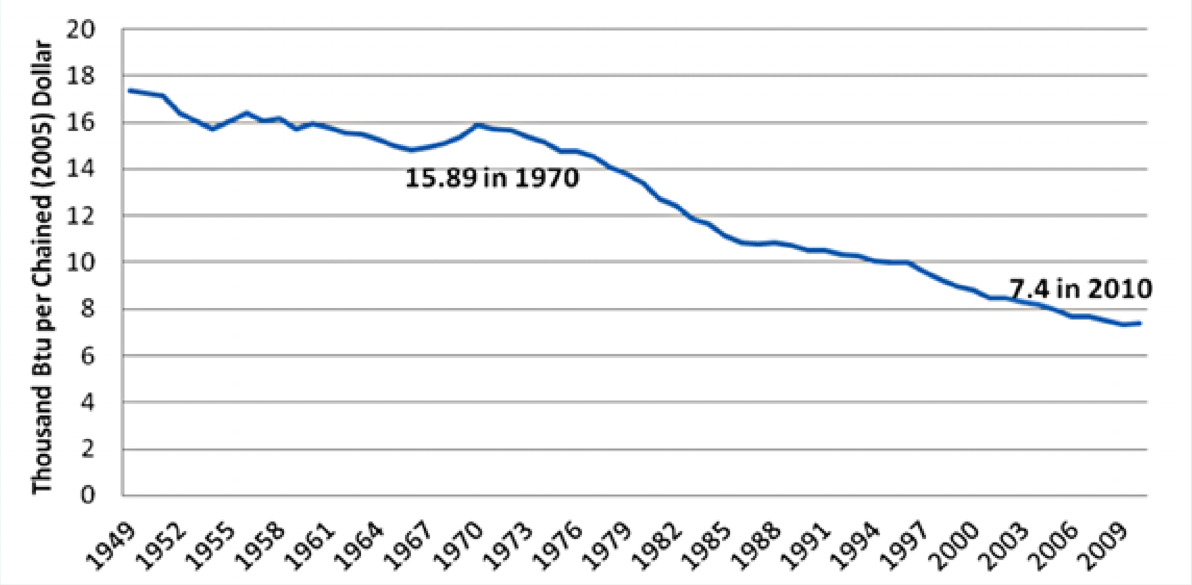
U.S. greenhouse gas emissions, 2009. [1]

Energy Consumption per Person



Per capita energy consumption has declined slightly in recent decades.[3]

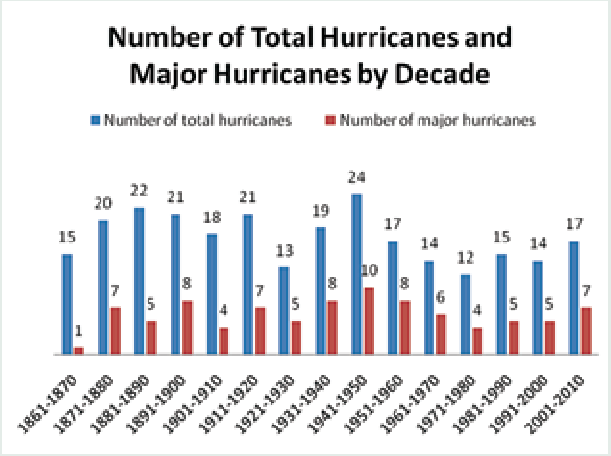
Energy Consumption per Real Dollar of Gross Domestic Product



"Energy Intensity," or the amount of consumption per unit economic output.[6]

percent,[4] and that declining trend is expected to continue. According to the Energy Information Administration, energy intensity is expected to be 42 percent less in 2035 than it was in 2010.[5]

Many of the effects of climate change on energy production and use in the United States are not known. Some of the effects of climate change, however, have clear implications for energy production and use. For instance, rising temperatures are expected to increase energy



U.S. landfalling decadal hurricane counts reached their maximum in the 1940s.[7]

requirements for cooling and reduce energy requirements for heating. Changes in precipitation have the potential to affect prospects for hydropower, positively or negatively.

One possible concern about global warming and its relation to energy is extreme weather such as hurricanes. Some believe that hurricane intensity is increasing and that the increase is due to warming, but that is not supported by the data, which shows that the largest number of total hurricanes and the largest number of major hurricanes (categories 3, 4, and 5) making landfall in the United States were in the 1940s. A more detailed analysis of hurricane climatology is in the section on National Climate Change.

Oil and natural gas disruptions from hurricanes in the Gulf of Mexico are a fact of business life. 2005's Hurricane Katrina was a memorable storm, a category 3 hurricane at landfall and a category 5 in Gulf of Mexico. It was the second-costliest hurricane (adjusted for constant dollars and normalized for population) in U.S. history, with catastrophic damages estimated at $108 billion to New Orleans and the Mississippi coast.[8]

Katrina was, in many ways, a worst-case hurricane for the oil-producing Outer Continental Shelf of the Gulf of Mexico, which is the source for 23 percent of crude oil production in the United States and 8 percent of natural gas production.[9] Refining operations in the Gulf were only shut-in for about a month.

Shortfalls were made up by refined product imports and crude purchases from the Strategic Petroleum Reserve.[10] Further, as a result of the hurricanes, older oil and gas drilling and production equipment that had to be replaced resulted in newer infrastructure that is more resilient and likely to withstand future storms.[11]

Future disruptions to natural gas supplies in the Gulf, if they were to occur regardless of cause, will most likely be countered by the economic production of shale gas onshore in the United States. The Energy Information Administration expects about 50 percent of total natural gas production to be from shale by 2035.[12]

Many weather-related energy deliverability problems result from regulations promulgated by the Environmental Protection Agency and other regulatory bodies; an example is the requirement for "boutique fuel" gasoline that meets the environmental needs of specific areas, but varies throughout the country. One part of the country cannot supply another without a wavier. In the case of Katrina, EPA's failure to provide a timely waiver extended the disruption of supply.[13] It is important to understand that the consequence of environmental regulation can indeed make adaptation to environmental extremes more difficult.

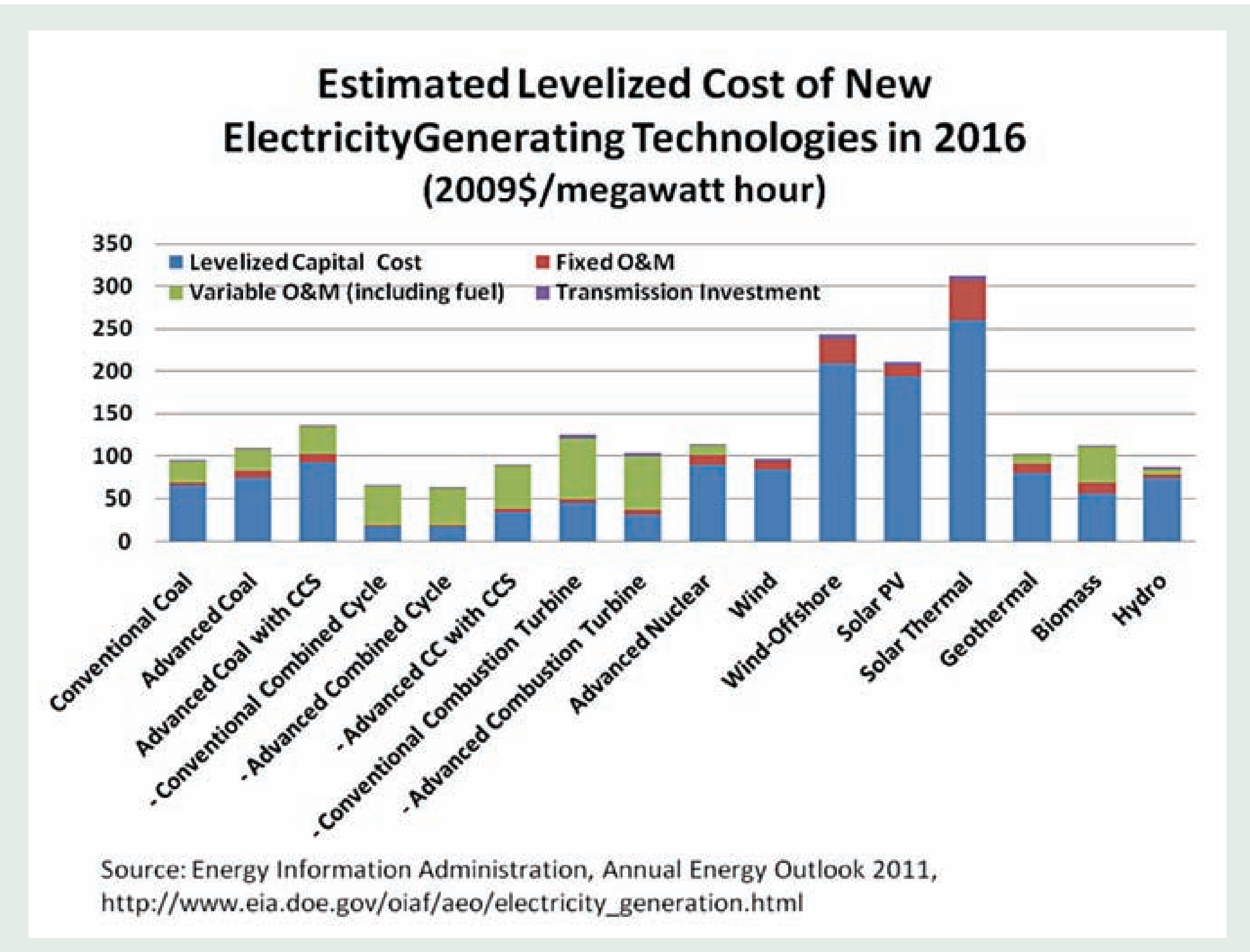
Another example is the requirement for corn-based ethanol mandated by the Energy Independence and Security Act of 2007. The required diversion of corn to ethanol increases prices, which escalate dramatically during weather extremes that affect the perception of corn supply, such as the Midwest floods of 2008 and the drought of 2012.

Concerns about climate change impacts will almost certainly alter perceptions and valuations of energy technology alternatives. For example, wind and solar generation facilities have very low load factors, do not perform at all during severe weather, and their ability to withstand interruption must be weighed against their higher costs and their intermittent power. The U.S. Energy Information Administration identifies offshore wind and solar as the most expensive power sources, and natural-gas combined-cycle as the lowest cost.

Wind power also requires additional transmission lines. Texas, which has the largest wind capacity in the United States at 10,468 megawatts,[14] is expected to need $6.79 billion in additional transmission lines to carry the wind power to demand centers. That estimate is 38 percent higher than initially projected in 2008. According to the Texas Public Utility Commission, the charge will be an additional $4 to $5 every month on every utility bill in Texas for years.[15]

Warming will likely be accompanied by decreases in demand for heating energy and increases in demand for cooling energy. The latter will result in increases in electricity use and higher peak demand

Research on the effects of climate change on energy production and use has largely been



limited to impacts on energy use in buildings. National studies project that the demand for cooling energy will increase from 5 to 20 percent per 1.8°F of warming,[16] and the demand for heating energy will drop by 3 to 15 percent for the same change. These ranges reflect different assumptions about factors such as the rate of market penetration of improved building equipment technologies.

An examination of population-weighted annual cooling degree days over the last 60 years show a marginally significant ($p=.047$) increase of 6 percent, and a marginally insignificant ($p=.064$) change in heating degree days (raw trend, -3.9 percent). [17] According to the Energy Information Administration, while the total number of households in the United States is expected to increase at a rate of 1.0 percent per year through 2035 and average house square footage is expected to increase at 0.2 percent per year, total energy consumed in BTUs per square foot is expected to decline by 1.1 percent per year.[18] The positive efficiencies resulting from new technologies will therefore have more of an effect on energy consumption than any increases that might be caused by warming.

Studies project that temperature increases due to global warming are very likely to increase peak demand for electricity. An increase in peak demand may lead to a disproportionate increase in energy infrastructure investment.

Because nearly all of the cooling of buildings is provided by electricity, warming will increase electrical consumption over much of the United States. The increase in electricity demand is likely to be accelerated by population movements to the South and Southwest, which are

Figure 1.9 Heating Degree-Days by Census Division

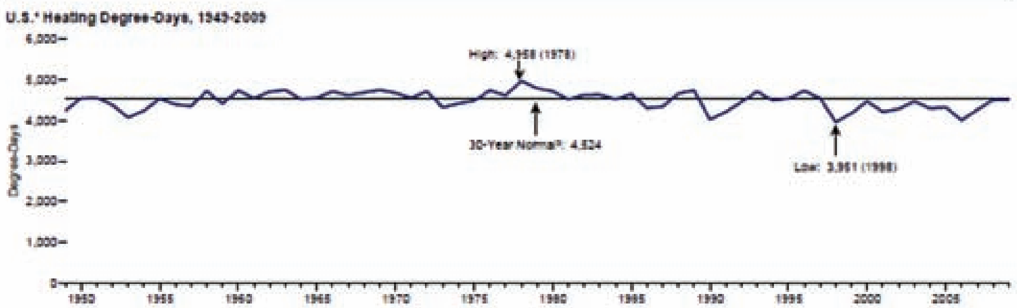
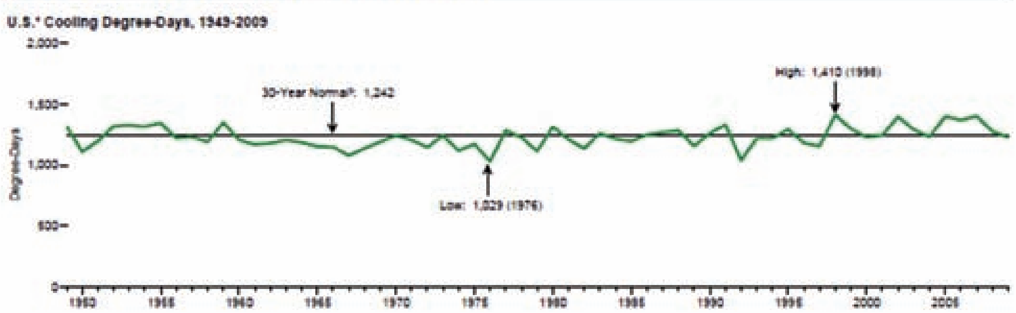
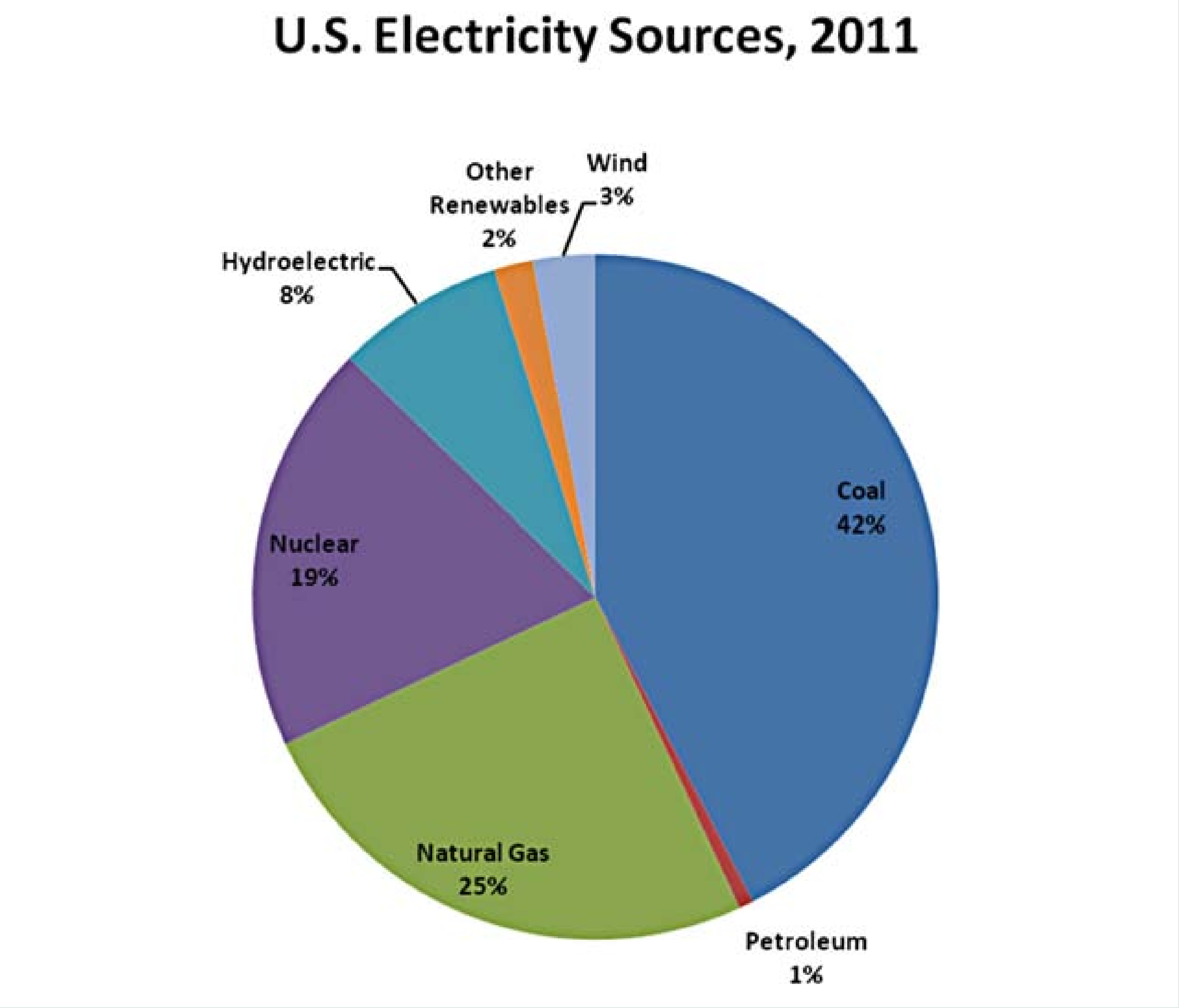


Figure 1.10 Cooling Degree-Days by Census Division



There is a marginally significant increase in cooling degree-days and a marginally insignificant decrease in heating degree-days over the period of record.[19]



Fossil fuels and nuclear make up almost 90 percent of U.S. generations.[20]

regions of especially high per capita electricity use, due to demands for cooling in commercial buildings and households.

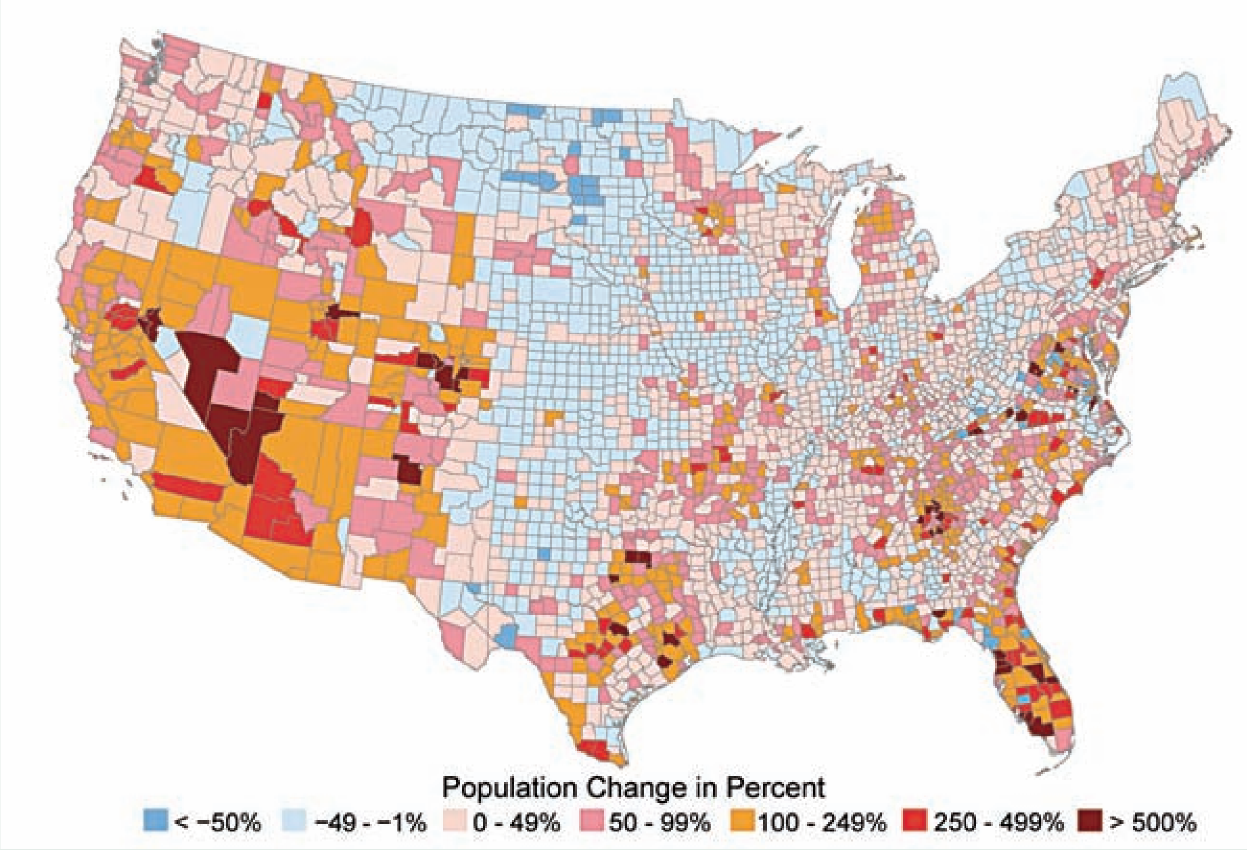
In 2011, while coal generated 42 percent of the electricity in the United States and is the largest fuel emitter of carbon dioxide, forecasters are projecting larger capacity growth for both gas-fired and renewable technologies. The Energy Information Administration projects that the capacity additions of natural gas combined cycle and renewable energy technologies will exceed that of coal by a factor of 4 (renewable technology) to 7 (combined cycle technology).[21]

Energy production may be constrained by rising temperatures and limited water supplies caused by drought conditions

One concern about global warming is that warming could lead to decreases in precipitation and/or water from melting snowpack. This could increase the competition for water among various sectors, including energy production (see Water Resources chapter). Readers should also consult our section on the Colorado River Basin in the Water Resources chapter.

Historic river flow data and centuries of tree ring data show that the drought conditions of the 1990s and the early 2000s were not

Change in Population from 1970 to 2008



U.S census data show that the largest percent increases in population are in the relatively dry and hot Pacific Southwest, the moist and hot southeast Texas, and the Florida peninsula.

unusual: longer and more severe drought conditions were a regular part of the climate in that part of the United States.[22]

Water availability is important to the production of energy from fossil fuels (coal, oil, and natural gas) as well as solar and biofuels. Generation of electricity in thermal power plants (coal, nuclear, gas, or oil) is water intensive. Power plants rank only slightly behind irrigation in terms of freshwater withdrawals in the United States. However, unlike other types of water withdrawals, thermal power plants return the majority of water they withdraw (53 percent). Further, only a small portion of power plant water withdrawals actually evaporates. When comparing total water consumption among uses, irrigation leads with an 85 percent share compared to thermoelectric power plants with a 3 percent share.[23] Solar thermal plants and biofuel plants use about the same amount of water as coal-fired power plants.[24]

Despite a major drought in the southern United States in 2011, there was not one report of thermal electrical generation being curtailed by water shortages. Given the extreme nature of this event, and the relatively small changes expected in overall precipitation, significant and damaging constraints on electricity production in thermal power plants in Arizona, Utah, Texas, Louisiana, Georgia, Alabama, Florida, California, Oregon, and Washington state that are forecast by 2025 by the U.S. Global Change Research Program (USGCRP), are likely to be gross exaggerations. Subsequent to 2009, the

USGCRP admitted that it had little real data upon which to base such speculation,writing "Because of the lack of research to date, prospects for adaptation to climate change effects by energy providers, energy users and society at large are speculative.... Given that the current knowledge base is so limited, this suggests that expanding the knowledge base is important to energy users and providers in the United States."[27]

The issue of competition among various water uses is dealt with in more detail in the Water Resources chapter. In connection with these issues and other regional water scarcity impacts, energy is likely to be needed to move and manage water. This is one of many examples of interactions among the impacts of climate change on various sectors that, in this case, could affect energy requirements.

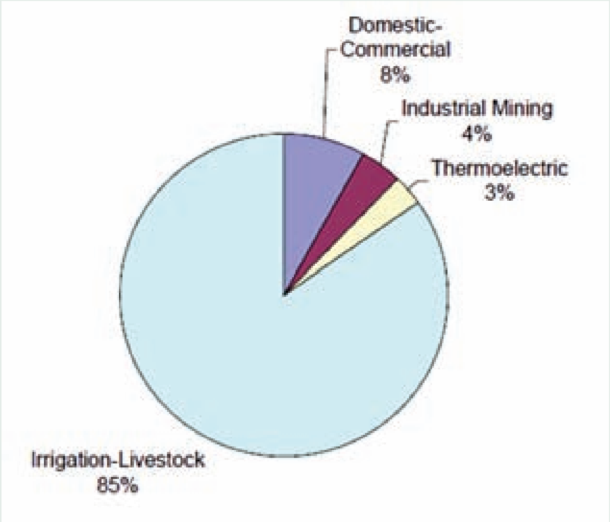
In addition to the problem of water availability, there are issues related to an increase in water temperature. Use of warmer water reduces the efficiency of thermal power plant cooling technologies. And, warmer water discharged from power plants can alter species composition in aquatic ecosystems. There was a 2004 news report in Missouri where large power plants were forced to shut down because of low water levels. This comes from an unrefereed source, and was the sole specific example of this, a climate-related shutdown, cited by the USGCRP (Bull et al., 2007) in its 2009 report.

The efficiency of thermal power plants, fossil or nuclear, is sensitive to ambient air and water temperatures; higher temperatures reduce power outputs by affecting the efficiency of cooling. However, this effect is generally small compared to the instability of wind and solar power. An average reduction of 1 percent in electricity generated by thermal power plants nationwide is smaller than the variability caused by intermittent wind and solar by an order of magnitude.

Energy production has not been impacted by sea level rise, and while extreme weather events can impact energy production and delivery, extreme weather events have not been increasing with warming

Because a significant fraction of America's energy infrastructure is located near the coasts, sea level rise could be a concern. The IPCC states that sea levels have risen approximately 7 inches since 1900, and that the rate of rise should increase. However, the rather brief satellite record only shows an increase when instrumentation changed, and the trends before and after that change are constant, with the exception of a slowing of the rise in recent years.[28] A global network of high-quality tide gauges shows that the rate of rise shows a modest decline in recent decades.[31] There is no evidence for any effect of sea level rise on the U.S. energy infrastructure.

Extreme weather is likely to be a misplaced concern vis-à-vis energy production, except on widely distributed and unsteady sources such as solar and wind. The U.S. dense energy industry has consistently shown resiliency, quickly resuming operations, as has been demonstrated after 2005 Hurricanes Katrina and Rita and other storms.[28] After most strong hurricanes, power is usually completely restored in less



Power generation is a minor consumer of water in the United States.[25] Note this is water consumption, rather than withdrawl, which is detailed in the previous chapter.

than ten days, with the majority of restorations in the first 48 hours.

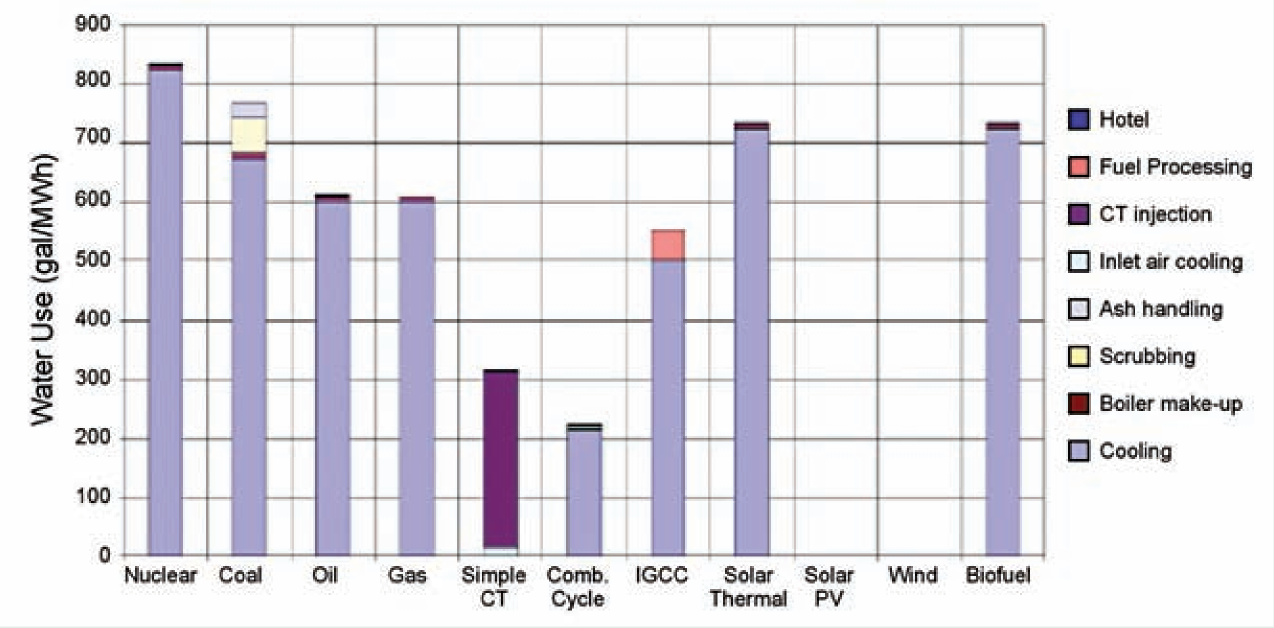
Hurricane Katrina is often cited as an example of energy infrastructure vulnerability, with a multimillion dollar cost for restoration and recovery. As one example, the Yscloskey Gas Processing Plant (located on the Louisiana coast) was forced to close for six months, resulting in lost revenues to the plant's owners and employees, and higher prices to consumers, as gas had to be procured from other sources.

However, this is far more the exception than the rule. Impacts of these events are lessened by the diversification of domestic natural gas production. As mentioned earlier, half of the natural gas production in the United States is expected to be from shale formations by 2035, which will put less pressure on offshore natural gas production.[30]

As noted earlier in this volume, there is no evidence for any increase in hurricane and tornado frequency and severity, but some evidence of a slight increase in rainfall on the heaviest day of the year. This could have some impact on rail transportation lines, which carry approximately two-thirds of the coal to the nation's power plants, as they often are placed near rivers, especially in the Appalachian region. While the economic and disruptive events of floods are usually local and sometimes severe, there is little evidence for any systematic disturbance of American productivity by severe weather, largely because of the adaptational capacity built in to a relatively free economy. Centralized energy planning, especially in response to a perceived increase in severe weather, is therefore likely to be counterproductive. Most major utilities are highly sophisticated with regard to their expectations of weather-related outages.

The electricity grid is generally marginally affected by severe weather. Familiar examples are the effects of severe weather events on power lines, such as from ice storms, thunderstorms, and hurricanes. In the summer heat wave of 2006, electric power transformers failed in several areas (including St. Louis, Missouri, and Queens, New York) due to high temperatures, causing interruptions of electric power supply.

Water Use by Plant Type



While Solar Photovoltaic and Wind use very little water, solar thermal electrical generation uses approximately the same amount of water as as fossil-fuel and nuclear plants.[26]

Utilities generally factor in climate extremes in their design specifications, and have been doing so for decades with or without the help of federal and state governments. There is no reason to expect this to change as our climate evolves.

It is noteworthy that the electric grid does not have storage, so production and sendout must simultaneously match. The relative rarity of multistate blackouts demonstrates that this load balancing, in general, is quite successful. However, intermittent production by wind and solar will make this problem more difficult, with or without climate change. Reliability issues are likely to increase because of renewable portfolio mandates, with or without climate change.

Climate change, hydropower, and other renewables

Renewable sources currently account for about 13 percent of electricity production in the United States. Hydroelectric power is by far the largest renewable contributor to electricity generation, accounting for over 8 percent of total U.S. electricity. Three percent is from wind, and the remaining 2 percent is from geothermal, biofuels, and solar.[32] While the dispersed nature of intermittent wind and solar makes them particularly vulnerable to the vagaries of North American weather, they are such minor sources of power that their influence on the national grid is nugatory. However, weather and climate can influence the more important hydropower.

Hydropower is a major source of electricity in the Northwest and an important source (originating in Quebec) for the Northeast. Precipitation is generally projected to increase in the Northeast, while the results are more seasonal in the Northwest, with a significant decline in (seasonally low) summer rain, and neutral or marginal increases in other seasons.

One important contributor to Northwest hy-

REGIONAL SPOTLIGHT
Gulf Coast Oil and Gas

The resiliency of the U.S. oil and gas industry has allowed energy production to continue even after large hurricanes. The Gulf Coast is home to a significant portion of the U.S. oil and gas industries, representing nearly 30 percent of the nation's crude oil production and approximately 13 percent of its natural gas production.[31] One-third of the national refining and processing capacity lies on coastal plains adjacent to the Gulf of Mexico. Several thousand offshore drilling platforms, dozens of refineries, and thousands of miles of pipelines are vulnerable to damage and disruption due to the high winds and storm surge associated with hurricanes and other tropical storms. Powerful Hurricanes Katrina and Rita in 2005 temporarily halted all oil and gas production from the Gulf, disrupted nearly 20 percent of the nation's refinery capacity, and closed many oil and gas pipelines. Such low-frequency extreme events will always cause disruptions, but the economic history of the United States shows that, in the large scope, they are inconsequential.

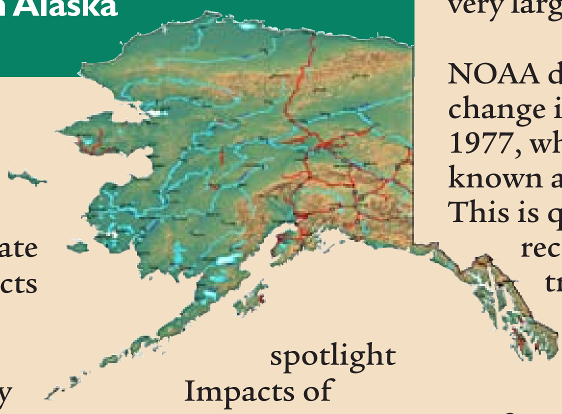
The diversification of supply points helps to cope with extreme events. As an example, in Katrina, most of the high-volume platforms that operate in deep waters and account for nearly half of the Gulf's offshore oil production escaped significant damage.

dropower is snowmelt. Are rising temperatures in the western United States making this occur sooner in the year? A study of western wildfires, which are caused in part by premature snowmelt, shows no significant trend whatsoever over the past four decades.[33]

Long tree-ring records in the West that are correlated with snowpack show no evidence of an unusual excursion from the warming of the last century.[34] Recent change appears to be well within the range of natural variability and does not seem at all exceptional.

Reports of a significant decline in snowpack in the Pacific Northwest are highly dependent upon the period of study. There is a significant decline in a study using data from 1947

REGIONAL SPOTLIGHT
Climate Change, global warming, and Energy in Alaska

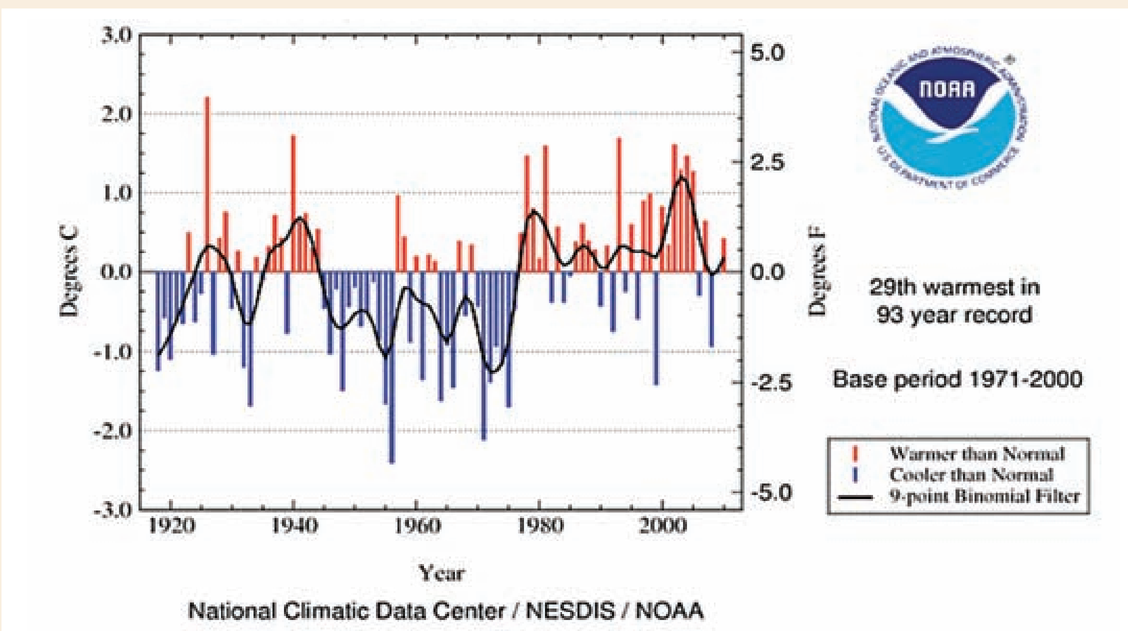


The Energy chapter of "Global Climate Change Impacts in the United States" has a spotlight called "Energy Impacts of Alaska's Rapid Warming." This title is extremely misleading, conflating global temperature trends with what would appear to be changes over the entire very large state of Alaska.

NOAA data show that there was a step-change in Alaska's temperature around 1977, which reflects a Pacific-wide incident known as "the great Pacific climate shift." This is quite different from the global record, which shows a clear warming trend from the initiation of the shift through the late 1990s.[38]

Rather, recent warming has been confined to the northernmost stations. In our illustration, the Big Delta (central

Alaska Statewide Temperature Anomalies
JANUARY – DECEMBER (1918 – 2010)

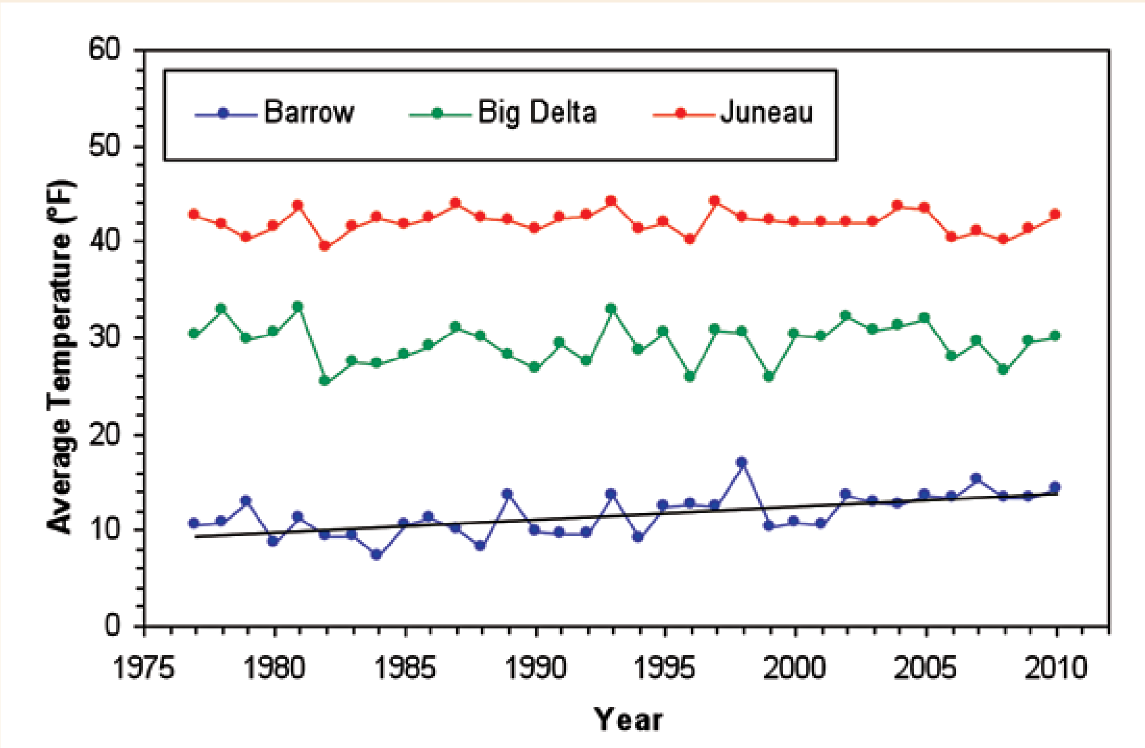


Alaska's statewide average temperature shows no trend since the great Pacific climate shift in 1977, at considerable variance with global records.

REGIONAL SPOTLIGHT (con't)

Alaska) and Juneau (southeast) records are typical, showing no net warming whatsoever since 1977. The outlier record, according to the Alaska Climate Research Center at the University of Alaska-Fairbanks, is Barrow, in the far north, where it is likely related to the recession of sea ice.[39] A similar recession of summer ice was likely to have been observed for millennia after the end of the last ice age.[40]

Any statewide trends in length of winter cannot be related to global temperatures as the local Alaskan trends are flat since 1977. Consequently, any changes in the transportation season on the Alaska ice roads are more likely a result of the Pacific climate shift than global warming, although the relationship between the shift and global warming is unclear at this time.



Temperature trends in Alaska away from the North Coast typically show no warming since 1977, such as the plots from Big Delta (central Alaska) and Juneau (southeast) shown here.

through 1997,[35] but a serious question has arisen concerning why this 2005 study stopped in 1997, because the snowpack subsequently returned to its previous average by the early 21st century.[36] In addition, a comprehensive study of Snow Water Equivalent on April 1 (which is approximately when the annual maximum occurs) showed no trend whatsoever.[37]

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Transportation

Key Messages:

- Carbon dioxide emissions from the U.S. transportation sector amounted to 6 percent of the total global carbon dioxide emissions in 2009. If they were completely eliminated, the amount of global warming that would be prevented is 0.11°F per half-century.
- Sea level rise is occurring at a rate of about one inch per decade. Adaptive responses protect the U.S. transportation infrastructure.
- The potential impacts on transportation infrastructure from storm surges will largely be determined by the rate of local sea level rise. Over much of the Atlantic and Gulf coasts, land is subsiding much more than sea level is rising.
- U.S. transportation infrastructure exists across the naturally extreme climate that characterizes North America.
- The magnitude of any future climate changes pales when compared to the magnitude of the naturally occurring range of climate extremes that exist across the United States.
- The impacts from increases in extreme precipitation are dependent on the magnitude and the timing of the changes and on the design and management of existing infrastructure.
- Natural variations in hurricane intensity, frequency, and preferred tracks pose variable risks to transportation infrastructure. Future projections of changes to hurricane characteristics do not clearly rise above the noise of natural variability.
- Arctic warming will continue to reduce sea ice, lengthening the ocean transport season, but also resulting in greater coastal erosion from ocean waves. Permafrost thaw will pose a threat to some existing transportation infrastructure and may require the adoption of highway engineering methods used in the lower 48 states.

The U.S. transportation sector produced 1,849 million metric tons of carbon dioxide in 2009, 34 percent of the total U.S. energy-related emissions of carbon dioxide.[1] The United States produced 18 percent of the global total carbon dioxide emissions from the consumption of energy in 2009.[2] The U.S. transportation sector was responsible for 6 percent of the global total. Emissions from the U.S. transportation section have been growing at an average rate of 24 million metric tons of CO_2 per year for the past two decades (although since peaking in 2007, they have been in decline[1]). The growth of emissions in China has been at a rate of 253 million metric tons of CO_2 per year during the same period, or more than 10 times greater than the growth of emissions from the U.S. transportation sector.[2] In fact, the average rate of emissions growth in China is so great that it adds new emissions equivalent to the total annual emissions from the U.S. transportation sector every five weeks.

Using the methodology of the United Nations' Intergovernmental Panel on Climate Change, a complete cessation of emissions from U.S. transportation would reduce mean projected global warming approximately 0.11°F per 50 years, an amount too small to reliably measure. Clearly, emissions from the U.S. transportation sector play a minor and rapidly diminishing role in total global greenhouse gas emissions.

It is not climate *change* but the vagaries of the climate itself that have the greatest impact on U.S. transportation. Climate change, to the degree that it is detectable and identifiable, contributes a mix of impacts, some positive and some negative, and the net impact has never been reliably quantified or monetized.

The impacts of climate and climate change are confused and thus used interchangeably; however, such usage is incorrect and misleading.

Major flooding in the Midwest in 1993 and 2008 caused large disruptions our nation's multimodal transportation system, restricting regional travel of all modes and disrupting freight and rail shipments across the country.

The Midwest drought of 1988 also caused disruption to the transportation system, stranding more than 4,000 barges on the Mississippi River and impairing freight movement up and down the river. However, these events have not been proven to be the result of climate change, but instead came about from a combination of the complex forces driving natural variability of the region's climate along with human re-engineering of the natural system of flood plains and river flow.[3,4,5,6]

Extreme events present major challenges for transportation. Such events are part of the naturally extreme climate of the United States, and separating out the influence of climate change from natural climate variability is both difficult and uncertain. Historical weather patterns reveal that extreme droughts, floods, hurricanes, heat waves, coastal storms, tornado outbreaks, and other types of extreme weather occur with alarming regularity across the United States, compared to most of the rest of the world. Whether or not climate change impacts the frequency of magnitude of any or all of these types of events will be the subject of intense scientific research for years to come.

The strategic examination of national, regional, state, and local transportation networks is an important step toward understanding the risks posed by climate and climate change. A range of adaptation responses can be employed to reduce risks through redesign or relocation of infrastructure, increased redundancy of critical services, and operational improvements. Adapting to climate and climate change is an evolutionary process. Through adoption of longer planning horizons, risk management, and adaptive responses, transportation infrastructure can becomes more resilient.

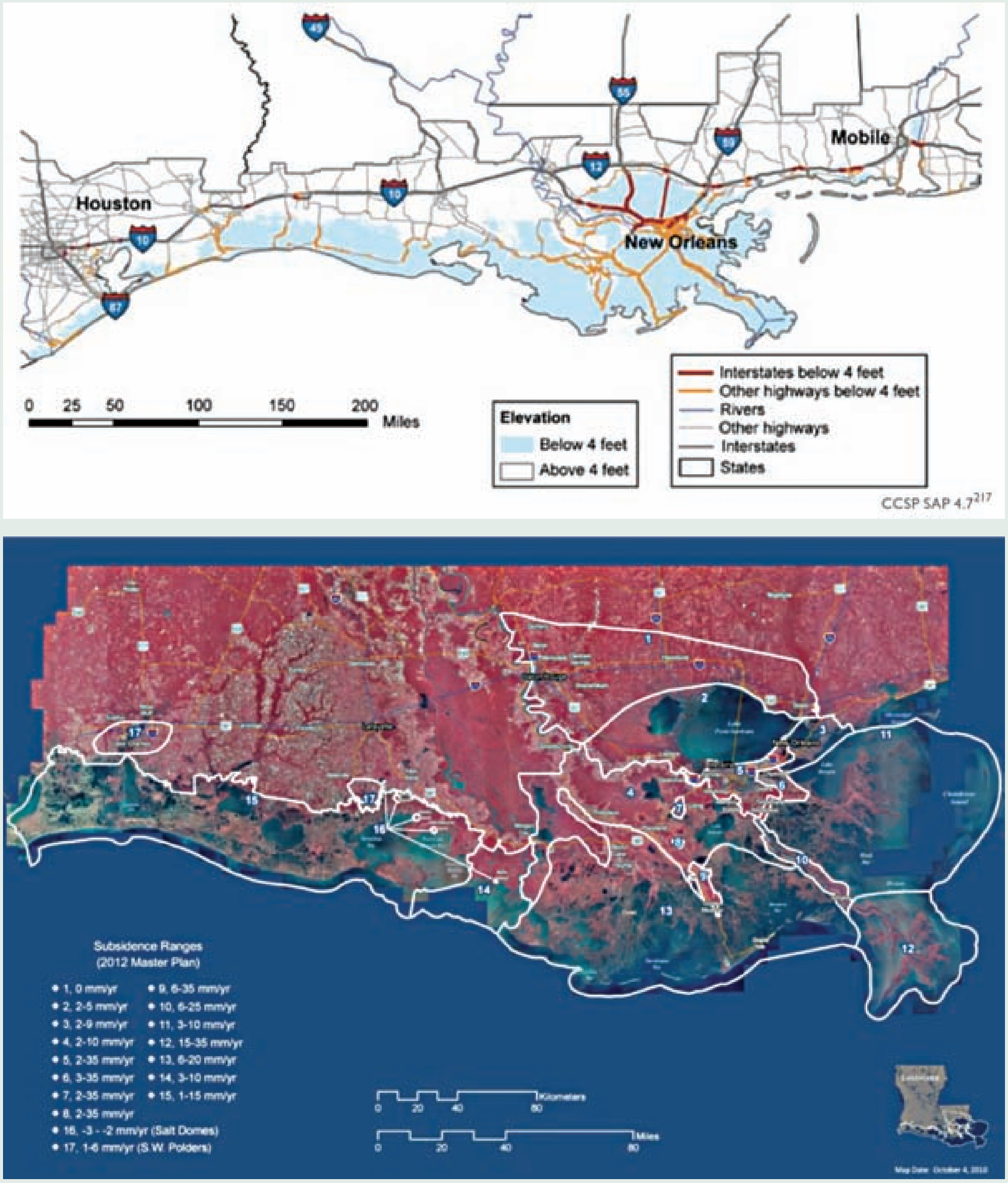
The average rate of sea level rise over the past several decades is about one inch per decade, a rate at which adaptive and protective responses have kept up with and protected the U.S. transportation infrastructure

Transportation infrastructure in the U.S. coastal regions in some areas and in some circumstances is vulnerable to sea level rise. The degree of vulnerability depends both on local geographical and site characteristics as well as the rate of relative sea level rise—a combination of land movement and ocean level changes.

According to the IPCC *Fourth Assessment Report*, "Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003. The rate was faster over 1993 to 2003: about 3.1 [2.4 to 3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear."[7] An update to the sea level rise record[8] through 2011 shows that the decadal rate of sea level rise has been slowing. From 2001 to 2011 the rate of sea level rise was 2.3 mm per year (0.09 inches per year). This slowdown in the rate of global sea level rise suggests that the faster rate of rise noted by the IPCC from 1993 to 2003 was dominated by short-term natural variability characteristic of the 20th-century sea level rise record, rather than an increase in the long-term rate of sea level rise.

The current rate of sea level rise is equivalent to approximately one inch per decade—a rate which adaptive and protective responses can keep up with and protect the U.S. transportation infrastructure. Evidence of this can readily be found in the vast and expanding influx of vacationers to coastal areas during summer months and the necessary infrastructure being established to service them. The popularity of coastal locations as tourist destinations remains high and has driven rapid expansion of development along both the U.S. Gulf and Atlantic Coasts during the past several decades—a period throughout which sea levels have been rising at rates similar to the current rate of sea level rise. Coastal developments including new housing, businesses, roadways, and the infrastructural components to support them have progressed along with sea level rise. Modifications, improvements, and additions to this infrastructure, including its transportation components, will take place in the future at such a pace as necessary to keep up with both the demand and the need—forces which include a large range of influences and interactions. The on-going and future rate of sea level

Gulf Coast Area Roads at Risk from Sea Level Rise

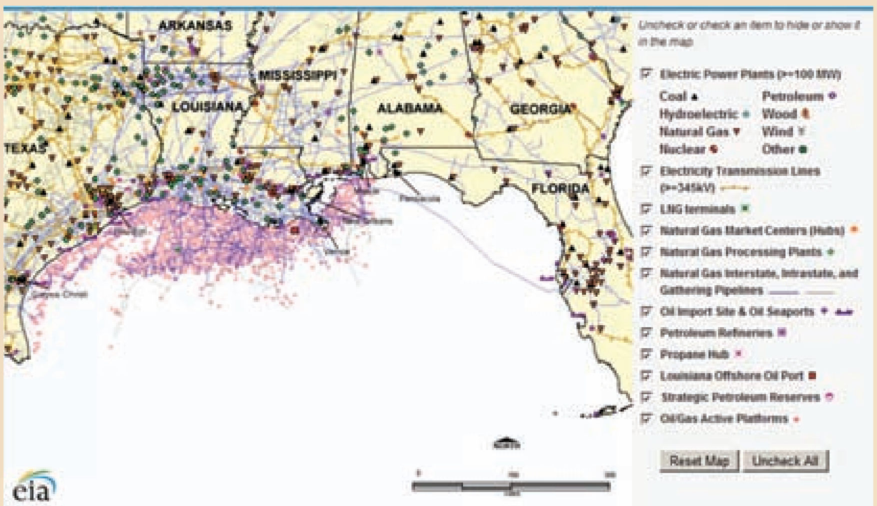


The upper map show the regions along the Louisiana Gulf Coast that would be inundated by a sea level rise of 4 feet, described by the USGCRP as "within the range of projections for this region in this century under medium- and high-emissions scenarios." The bottom map shows an estimate of the rate of land subsidence along the Louisiana coast—a sinking of the land not related to global sea level rise.[13] Although the subsidence rate varies by a large amount along the Louisiana coastline, on average it is occurring at a rate about 5 times greater than the actual sea level is rising. What this means, is that most areas along the Louisiana coast will experience sea level rise close to 4 feet from land sinking alone, irrespective of global warming–induced sea level rise. Therefore, actions to mitigate the impact of a large sea level rise will be required, where necessary, from ongoing changes in the geography of the region.

rise is but one component of the broader and complex set of considerations.

The same is true for the development and expansion of the nation's coastal freightways and ports. Coastal areas are major centers of economic activity. Seven of the ten largest ports (by tons of traffic) are located on the Gulf Coast.[9] The region is also home to much of the U.S. oil and gas industry, with its offshore drilling platforms, refineries, and pipelines. Roughly two-thirds of all U.S. oil imports move through this region.[10] Capacity has been steadily increasing for the past several decades,[11] and pipeline and refinery expansion is both underway and planned.[12] The expansion of the Gulf Coast oil refineries has occurred in a region which is experiencing the fastest rate of relative sea level rise in the country—where local land subsidence exceeds the rate at which the actual sea level is rising. These development trends are clear examples that economic interests are not being held back by rising sea levels, but instead adapt, modify, and expand to meet changing environmental conditions. There is no reason to expect that such trends will reverse in the future.

REGIONAL SPOTLIGHT Gulf Coast



The energy infrastructure of the U.S. Gulf Coast region including the locations of electric power plants, electric transmission lines, market centers, hubs, sea ports, refineries, pipelines, and oil/gas platforms. This infrastructure has been erected during a time of rapid relative sea level rise (source: Energy Information Administration[15]).

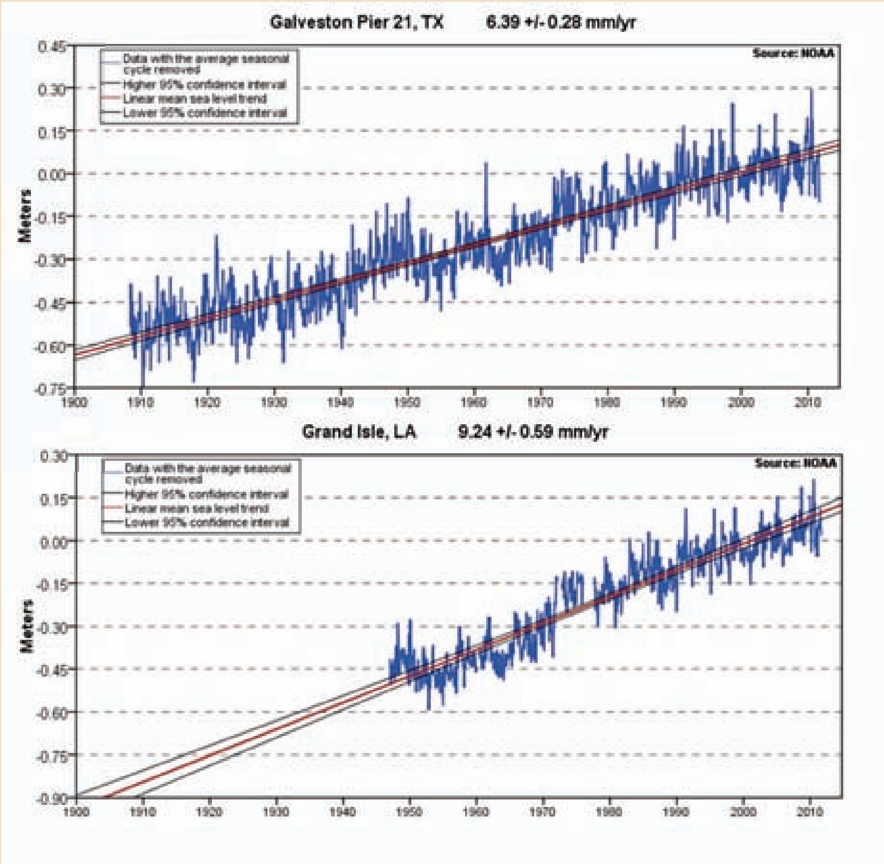
According to the U.S. Energy Information Administration (EIA)[14]:

> "The Gulf of Mexico area, both onshore and off shore, is one of the most important regions for energy resources and infrastructure. Gulf of Mexico offshore oil production accounts for 29 percent of total U.S. crude oil production and offshore natural gas production in the Gulf accounts for 12 percent of total U.S. production. Over 40 percent of total U.S. petroleum refining capacity is located along the Gulf coast, as well as almost 30 percent of total U.S. natural gas processing plant capacity."

The EIA has produced the map above that illustrates the complex interconnectivity of the region's energy infrastructure. All of this is in a region which has been experiencing a long-term relative sea level rise that is some 2 to 5 times greater than that of the global average rate. The rate of relative sea level rise recorded at Galveston, Texas, since 1908 has averaged 6.39 mm per year (2.1 feet per century). At Grand Isle, Louisiana, the relative level rise has averaged 9.24 mm per year (3.03 feet per century) since measurements began there in 1947. The global average sea level rise during the 20th century has averaged 1.8 mm per year (0.59 feet per century), indicating that the bulk of relative sea level rise in this region is from land subsidence. Regardless of the causes of sea level rise, the region's infrastructure was established during a time of rapidly rising water. That infrastructure, including transportation infra-

REGIONAL SPOTLIGHT
Gulf Coast (con't)

structure, supports the region's energy economy, indicating that rapid sea level rise does not stand in the way of widespread economic development.



Historical sea level data as recorded at tide gauges in Galveston, Texas, and Grand Isle, Louisiana (Source: U.S. National Oceanic and Atmospheric Administration[16]).

The potential impacts on transportation infrastructure from storm surges will largely be determined by the rate of local sea level rise. Large natural variability in the characteristics of the surge-producing storms themselves will dominate over any changes that can be related to the results of a changing climate

Storm surge—seawater that is driven ashore by the winds and low pressure of a storm system—is dependent on the strength, position, and speed of movement of a coastal or near-coastal tropical or extra-tropical storm system. Storm surge adds to the underlying rise of the ocean level as determined by the average height of the sea level and the lunar tidal cycle. If storm characteristics evolve under increasing greenhouse gas concentrations that produce larger storm surges, the U.S. transportation infrastructure would initially be vulnerable to disruption from the effects of periodic high water. However, observations show that few if any trends exist in the key storm characteristics for producing storm surge—instead, the observational record is marked by a high degree of natural variability characteristic of the underlying climate rather than climate change.

Storm surge is more of a threat to coastal transportation infrastructure in those regions where the coastal relief is low, such along the U.S. Gulf and East Coasts. Along the Gulf Coast, storm surges are most often associated with warm season tropical cyclones, while the East Coast is subject to storm surges produced both by tropical cyclones as well as by cold-season extratropical coastal storms, also known as nor'easters. Both Atlantic tropical cyclones and East Coast extratropical storms are affected by large scale atmosphere/ocean circulation patterns such as El Niño/La Niña (ENSO) and the Atlantic Multidecadal Oscillation. Extratropical storms are also influenced by the North Atlantic Oscillation. Natural variability has been documented in all of these patterns in both observations and climate models.

For nor'easters along the U.S. East Coast, storm surges and damage to coastal property, including transportation systems, are enhanced by slow-moving storm systems. Long-term studies indicate that there has been no overall change in the average speed of movement of these storms since at least the 1950s.[17] Nor have there been any increases in wave height associated with these storms since at least the mid-1970s.[18] The frequency of nor'easters has remained unchanged.[19] Consequently, there has been no change in in the number of storm surge events along the East Coast, once local sea level rise has been accounted for.[20,21] Multiple studies identify ENSO and the NAO as being a strong drivers in the natural variability of many characteristics of nor'easters.[17,19,21,22]

The picture is much the same for tropical cyclones. Natural variations in the track, intensity, and frequency characteristics dominate any long-term trend and can be related to natural climatological drivers.[23,24] Changing observational technologies can impart a false (i.e., non-climatological) trend in the tropical cyclone data sets that is often misinterpreted as being related to anthropogenic climate change.[25,26] Damage assessments from tropical cyclones, which include damage to transportation systems, often fail to account for changes in population and wealth when determining long-term trends.[27] When changing demographics and property values are properly accounted for, there is been no long-term residual trend in the magnitude of tropical cyclone damage.[28]

Damages to the U.S. transportation infrastructure from storm surge are on the rise, and that that will continue to grow. But that increase is not being driven by climate *change* but rather by elements of the natural climate coupled with large and growing coastal development.

Projections of potential changes to tropical and extratropical storm characteristics responsible for producing storm surge are neither large nor consistent enough to provide guidance for assessing potential impacts on U.S. transportation. The observed data indicate no trends over the period of rapid build-up of atmospheric greenhouse gases. Therefore, future impacts from storm surge resulting from climate change will likely be dictated by the magnitude of sea level rise, rather than by changes in storm characteristics.

Transportation modes and infrastructure exist across the climatic extremes that characterize the United States, providing evidence that our transportation technologies are adaptable to a wide range of conditions. The magnitude of any future climate changes pales in comparision to the naturally occurring range of conditions which exist across the United States

The United States experiences more tornadoes, more severe thunderstorms, more intense cold outbreaks, and more intense heat than most places on earth. The reason is simple: the most formidable barrier between polar cold and the warmth of a truly tropical ocean (the Gulf of Mexico) is a barbed wire fence. In most of the rest of the world, there is either an intervening ocean or a transverse mountain range separating air masses of remarkably different thermal characteristics. It is the redistribution of energy when they mix that makes our weather so violent. In addition, the Gulf Coast and the Outer Banks of North Carolina are among the most hurricane-prone lands on earth.

The upside to all this violence is that we have a remarkably resilient transportation infrastructure.

Temperature

The thermal climate of the United States is extremely varied. The July average high temperature in Phoenix, Arizona—whose MSA is home to more than 4 million people—is 106°F. On average, the maximum temperature there exceeds 110°F on 18 days per year. And the 3.3 million people who call the Minneapolis/St. Paul region home experience daily low temperatures in January which average 4.3°F—some 100°F lower the average July high temperature in Phoenix. Minneapolis/St. Paul average 30 days per year with nighttime low temperatures below 0°F.

Amtrak's Capitol Limited had no problem with the great "snowmageddon" storms of February, 2010. Barnesville, MD, where this photo was taken, received over 40 inches of snow in four days.

Both cities, and every region in between, are currently well served by transportation infrastructure supporting a wide range of transportation services, including state roads, interstate highways, passenger rail, freight rail, small airstrips, and major airports. While the climate of each city presents some different challenges to the local and regional transportation systems, those challenges have been overcome as the booming population in each city attests.

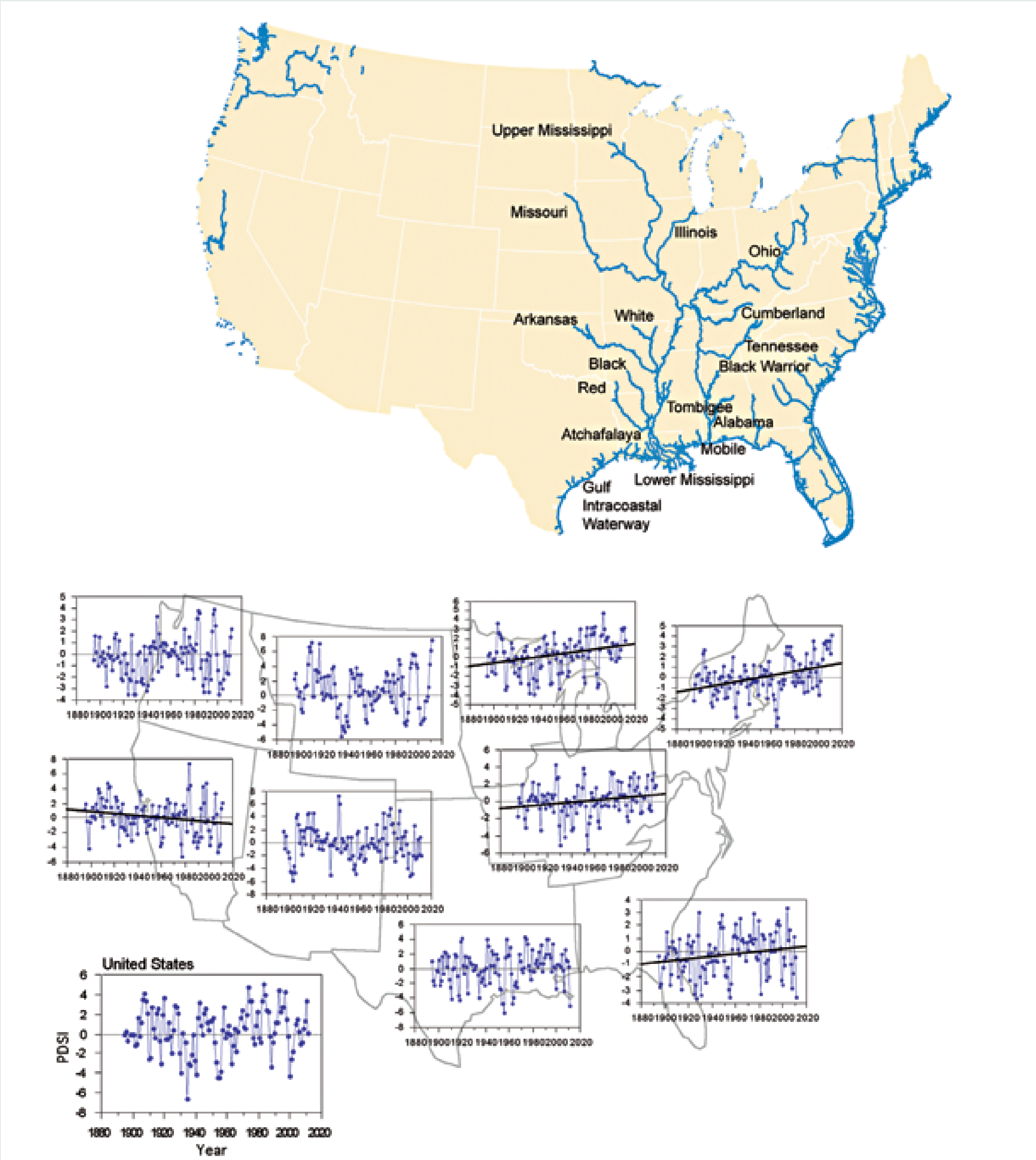
Worries that increased extreme heat as a result of climate change will damage roads, cause rutting from heavy traffic, produce deformities in rail tracks, overheat vehicles, etc., to such a degree as to lead to a decay in the quality of the local, regional, or national transportation networks are not founded in a survey of potential solutions and adaptations, but rather are based on a pessimistic view that techniques and technologies are unchanging in space and time. Such has never been the case.

Precipitation

The same is true for climate differences in precipitation type and amount across the country. The average annual precipitation in Phoenix is about eight inches, with rain falling on average about 36 days of the year. In Seattle, rain falls on about 154 days of the year, amounting to an annual average of about 37 inches. Mobile, Alabama, receives 66 inches of precipitation per year, and none of it from snowfall. Cleveland, Ohio, averages 36 inches of precipitation per year and 65 inches of snowfall. These major metropolitan areas are also well served by the local transportation network and infrastructure—which employ different methods for handling the types and amounts of precipitation produced by the local and regional climate. It is incorrect to suggest that change in the climate will not be met and overcome. The technologies to do so exist today, and are currently employed all across the various climate regimes of the United States.

Certainly, all across the United States, extreme weather events can and do cause damage and disruption to the transportation infrastructure. This is true in the past, present, and undoubtedly, the future. Such events are part of the natural climate of the country. To the degree possible, the local transportation infrastructure is designed to withstand the vagaries of the climate. Future climate change may act to alter the prevailing climate conditions and the incidence and types of extreme weather. In some cases, this will require alteration and adaptation of the transportation infrastructure; in other cases, it may require changes to the weather management plans. For example, if climate change results in winter warming and reduced snow and icy conditions, perhaps reducing the stockpile of salt, sand, and other chemicals may be in order, along with a reduction of the equipment used in snow removal. Associated cost savings from milder winter conditions could be used for modifications and maintenance of the roadways as necessary

Navigable Inland Waterways



Inland waterways are an important part of the transportation network in various parts of the United States. They provide 20 states with access to the Gulf of Mexico. Names of navigable rivers are shown in the top panel. In the bottom panel are the trends in the Palmer Drought Severity Index (PDSI) from 1895 through 2011 for climatological regions of the United States. The PDSI is a measure of the moisture status which integrates influences of precipitation as well as temperature. Notice that in most of the eastern half of the country—the region which most utilizes navigable waterways—there are significant upward trends in moisture. Fears that climate change will lead to drier conditions along these main transportation pathways and adverse effects of lower water levels are not borne out by actual observations.

to respond to climate change in other seasons, or for other infrastructural improvements. The natural climate of the United States presents challenges to transportation systems and infrastructure. As the existence of major cities in virtually all of the various climate regimes in the United States attests, these challenges are met and overcome. Climate change may require

Barge traffic on the Mississippi River can be impacted both by floods and droughts. Overall moisture levels have been increasing in the upper part of the basin, but have remained constant in the more heavily trafficked lower basin.

a change in the transportation infrastructural technologies currently employed at a specific location, but technologies change over time and space and will be available to meet any new challenges that rise.

Listing a string of negative impacts to the transportation infrastructure that *may* result from climate change is a pessimistic approach, because, such change *may not*, in fact, occur, and because in each and every case, similar impacts have already been addressed and overcome somewhere in America and its diverse natural climate.

The impacts from increases in extreme precipitation are dependent on the magnitude and the timing of the changes and on the design and management of existing infrastructure

Over many areas of the United States, an increase in total annual precipitation has been accompanied by an increase in heavy, or extreme, precipitation events.[29] This is a natural association, and not one unique to an enhancing greenhouse effect. Whether or not the increase in extreme precipitation is considered to be "disproportionate" or not is simply dependent on how the term is being applied[30] and bears little import when considering the potential impacts to the U.S. transportation systems from change in precipitation intensity.

Oftentimes, there is confusion when attributing or associating major flood events on major river systems—such as the Mississippi/Missouri river floods of 1993 and 2008—to increases in precipitation extremes.[6] These river systems are highly altered from there natural state by a variety of engineering schemes intended to "control" the rivers to enhance shipping commerce and protect riverfront communities from flooding. While the collection of levies, dykes, channel alterations, etc., largely achieve this goal on a day to day basis, they oftentimes exacerbate conditions of extremely high flow. Increases in impervious surfaces and the channelization of the river flow (which keeps the rivers from overflowing into their natural flood plains) leads to confined flow and increasing flow speeds, which can result in extremely high, erosive water levels, catastrophic flooding, and concomitant disruption of transportation services and damages to transportation infrastructure when the river level tops or breaks through existing protection structures. Certainly, heavy and persistent rainfall is the instigator of major flooding events, but human alterations to the waterways and management decisions can exacerbate the magnitude and destructive potential of the flood events.[31]

The role that climate change may play in negative impacts to the transportation infrastructure from flooding, over and above that of the natural climate, human changes to waterways and watersheds, and changes in the population living in flood plains and other at risk areas, is difficult to ascertain.[32] However, research studies that have investigated streamflow trends, rather than precipitation trends, have found increases in low to moderate streamflows and little overall changes in high streamflow[33,34,35,36]—the category associated with flooding events. This has been attributed to the seasonality of the observed increases in precipitation, which have been characterized by increases in autumn (the general time of low streamflow) and little change to spring precipitation (the general time of high streamflow).[37] Studies that have looked specifically at trends in annual peak streamflow find mixed results and inconsistent associations with atmospheric carbon dioxide levels or climate change.[38,39] Studies that examine trends in damage from flood events generally conclude that changes to population and wealth in vulnerable areas dominate over changes in the climate.[40,41]

Observed climate complexity makes it difficult to identify any changed climate signal in flood trends in the transportation sector. Such difficulties will persist into the future and likely worsen with increased development in flood prone regions. As such, focusing on methods to alleviate current and future vulnerability to the U.S. transportation sector with regard to natural climate and its variability, in addition to those vulnerabilities manifest by alterations to waterways and watersheds, should dominate over those geared towards mitigating the impacts of anthropogenic climate change—an unknown, uncertain, and likely unremarkable quantity.

Natural variations in hurricane intensity, frequency, and preferred tracks pose variable risks to transportation infrastructure. Future projections of changes in hurricane characteristics do not clearly rise above the noise of natural variability. Resilience and redundancy of the transportation infrastructure is an effective strategy to deal with this variable threat

Projections of future changes in tropical cyclone (tropical storm and hurricane) characteristics are neither overly large nor unambiguous. Globally, the frequency of tropical cyclones is expected to decline slightly with increasing atmospheric greenhouse gas concentration. Tropical cyclone intensity is expected to increase slightly. However, at the regional level, changes may depart from the global tendency. In the Atlantic basin, new research suggests that although there may be a tendency for a slight increase in both storm number and storm intensity, the preferred storm track may be shifted towards more storms out to sea in the central Atlantic and away from the continental United States.[42] As the greatest hurricane-related impact to coastal transportation infrastructure occurs when hurricanes make a direct strike to the United States, a future tendency for land-falling hurricanes (of any strength) to become less frequent would mitigate hurricane-related damages.

However, the projected changes to Atlantic tropical cyclone characteristics are neither certain nor large enough to warrant direct measures modifying the nation's transportation infrastructure. Instead, it should be recognized that there are large natural variations in hurricane characteristics that occur over timescales from years to decades. Tropical cyclones have and will continue to impose costs on coastal communities. Periods characterized by lulls in Atlantic hurricane activity—such as the late 1970s, 1980s, and early 1990s—underrepresent the true nature of the threat and encourage booms in coastal development and the accompanying transportation infrastructure. Active periods of Atlantic tropical cyclones, such as the 1940s and 1950s and 1995–2005 serve as reminders of existing vulnerabilities.

A collection of some of the world's leading hurricane researchers issued the following statement that reflects the current thinking on hurricanes and their potential impact:[43]

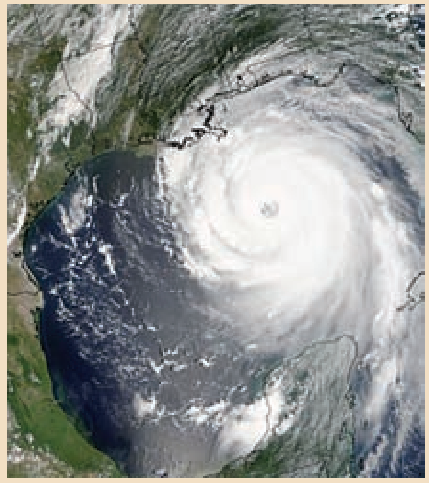
> ...the possible influence of climate change on hurricane activity is receiving renewed attention. While the debate on this issue is of considerable scientific and societal interest and concern, it should in no event detract from the main hurricane problem facing the United States: the ever-growing concentration of population and wealth in vulnerable coastal regions. These demographic trends are setting us up for rapidly increasing human and economic losses from hurricane disasters, especially in this era of heightened activity. Scores of scientists and engineers had warned of the threat to New Orleans long before climate change was seriously considered, and a Katrina-like storm or worse was (and is) inevitable even in a stable climate.
>
> Rapidly escalating hurricane damage in recent decades owes much to government policies that serve to subsidize risk. State regulation of insurance is captive to political pressures that hold down premiums in risky coastal areas at the expense of higher premiums in less risky places. Federal flood insurance programs likewise undercharge property owners in vulnerable areas. Federal disaster policies, while providing obvious humanitarian benefits, also serve to promote risky behavior in the long run.
>
> We are optimistic that continued research will eventually resolve much of the current controversy over the effect of climate change on hurricanes. But the more urgent problem of our lemming-like march to the sea requires immediate and sustained attention. We call upon leaders of government and industry to undertake a comprehensive evaluation of building practices, and insurance, land use, and disaster relief policies that currently serve to promote an ever-increasing vulnerability to hurricanes.

It is not climate *change* that demands our attention, but the vulnerability of existing and planned transportation infrastructure to the existing climate. The damage potential from on-going demographic changes in coastal locations far exceeds that from even the worst projections of climate change–induced alterations of the characteristics of tropical cyclones.

Arctic warming will continue to reduce summer sea ice, lengthening the ocean transport season but also resulting in greater coastal erosion from ocean waves. Permafrost thaw will result in damage to some existing transportation infrastructure and require the adoption of engineering used in the lower 48 states

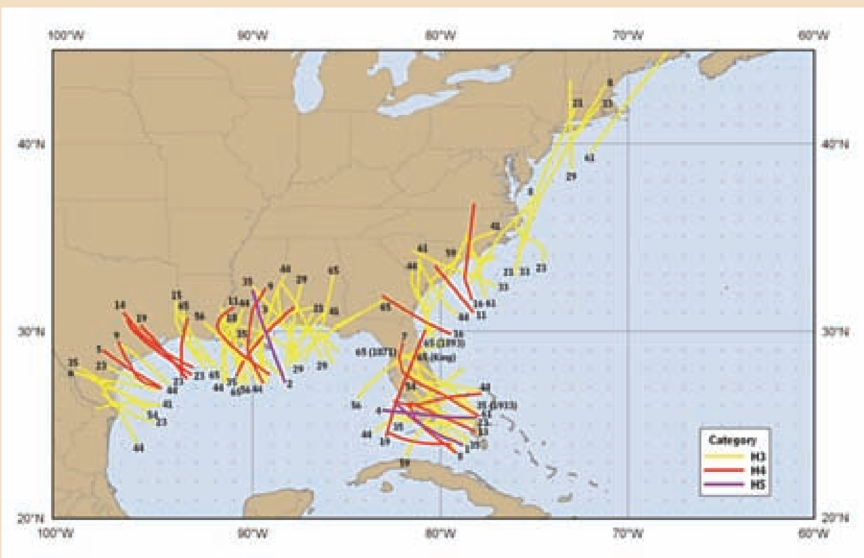
SPOTLIGHT ON Hurricane Katrina

Hurricane Katrina was one of the most destructive and expensive natural disasters in U.S. history, claiming about 1,200 lives and causing at least $108 billion in damage.[45] It also seriously disrupted transportation systems, as key highway and railroad bridges were heavily damaged or destroyed, necessitating rerouting of traffic and placing increased strain on other routes, particularly rail lines. Major hurricanes are a part of the Gulf and Atlantic Coast life, and have helped shape the region's history. The Galveston hurricane of 1900 was the deadliest of all U.S. weather disasters, claiming over 8,000 lives. When damages are adjusted for inflation, population, and wealth changes, the Great Miami hurricane of 1926 would have caused nearly 50 percent more damage than Katrina had it struck in 2010. Since 1851, 96 major hurricanes (category 3 or stronger; Katrina was a category 3 hurricane at landfall) have struck the U.S. mainland. And there have been at least 30 tropical cyclones which would have produced more than $10 billion dollars in damage (once properly adjusted for demographic changes over time).[45] Clearly, the U.S. Atlantic and Gulf Coasts are regions whose natural climate includes major impacts from tropical cyclones.



Massive Hurricane Katrina, a category 5 storm at the time this image was made, was a category 3 storm at landfall and a category 1 over New Orleans. However, its enormous size and the extensive time that it was a severe hurricane resulted in a category 5-type storm surge over Alabama and Mississippi. The damage in New Orleans was related both to corrupted infrastructure and Katrina's size.

In the aftermath of Hurricane Katrina, redundancies in the transportation system helped keep the storm from having a major, long-lasting impact on national-level freight flows. Truck traffic was diverted to alternative highways, trains were rerouted, and inland transportation hubs were not damaged. While a disaster of historic proportions, the effect of Katrina could have been much worse if not for the redundancy and resilience of the transportation network in the area. The Katrina experience shows that transportation infrastructure properly conceived serves well the needs of both the region and the nation, even in those places whose natural climate includes periodic direct strikes from major hurricanes. Wise planning and awareness of the natural climate will continue this resiliency into the future.



The most intense U.S. major hurricanes, ranked by pressure at landfall, 1851-2010. The black numbers are the ranks of a given storm (e.g., 1 has the lowest pressure all-time). The colors are the intensity of the tropical cyclone at its maximum impact on the United States. (source: National Hurricane Center[45])

Special issues in Alaska

Alaska's transportation infrastructure differs sharply from that of the lower 48 states. Although it is twice the size of Texas, its population and road mileage are more like Vermont's. Only 30 percent of Alaska's roads are paved. Alaska relies heavily on aviation and marine transportation to move people and goods. Many remote communities are connected to the rest of the world through either waterways or airports, and have no connecting roads. This makes Alaskans uniquely dependent on an efficient intermodal transportation system.[46] Climate change is likely to lead to warmer conditions in Alaska, bringing both opportunities and challenges to Alaska's existing and future transportation sector.

Sea ice decline

The summer and early fall sea ice in the Arctic Ocean has been declining for the past several decades from a likely combination of natural variability in atmosphere/ocean circulation regimes,[47] soot deposition,[48] and an increasing greenhouse effect. The declining ice concentration impacts transportation systems in Alaska in several ways.

The ice trend affords a considerable opportunity for the maritime transportation in Alaska, moving both people and goods. Continued reduction in sea ice should result in opening of additional ice-free ports, improved access to ports and natural resources in remote areas, and longer shipping seasons. Later this century and beyond, shippers are looking forward to new Arctic shipping routes, including the fabled Northwest passage, which could provide significant cost savings in shipping times and distances.

Declines in sea ice also have increased the vulnerability of north and west Alaska to coastal erosion and the threat of damages to coastal transportation infrastructure. The coasts of Alaska have historically been recognized to be subject to high rates of erosion[49,50,51,52,53] resulting in the loss of established infrastructure (both of indigenous peoples[49] as well as modern developments[51]). Warnings have been in place in the region for nearly a half a century against building too close to the ocean's edge.[50] Coastal erosion is exacerbated as the loss of land-fast sea ice increases the direct impact of ocean waves generated by the large storms that are characteristic of the region's climate. Coastal erosion is a natural part of the region's climate/ecology and will continue into the future, made even worse in some regions by declines in near-shore sea ice extent and thickness. The development of future transportation infrastructure should proceed with anticipation of very high erosion rates.

Thawing ground

Warming in Alaska presents challenges to some of the state's land-based transportation systems. Of the state's approximately 12,700 miles of roadways, less than 4,000 miles are paved. The majority of the state's roads are in the south or south-central portion of the state where permafrost is either sparse or discontinuous. Roads in the interior, particularly north of Fairbanks (i.e., the gravel Dalton Highway), traverse areas underlain by ice-rich permafrost and will require substantial rehabilitation or relocation if thaw occurs.[54]

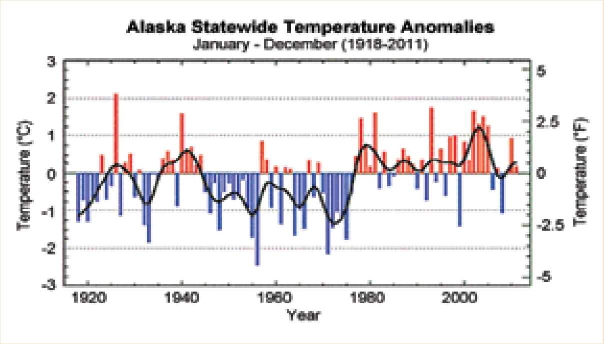
Rising temperature may also represent a threat to airstrips that are built on land underlain by permafrost. A significant number of airstrips in communities of southwest, northwest, and interior Alaska are built on permafrost and will require major repairs or complete relocation if their foundations thaw.[54]

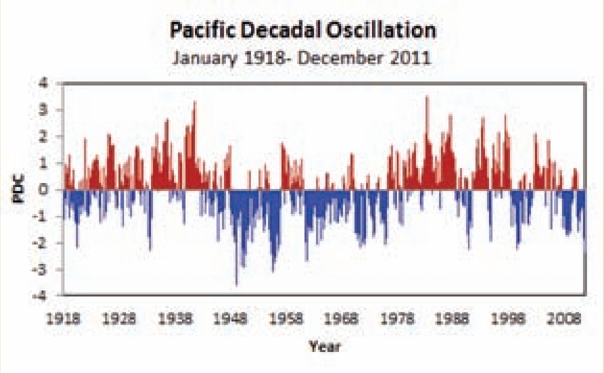
The vulnerability of Alaska's network of transportation infrastructure to thawing of permafrost should be assessed systematically. Roads, railways, and airstrips placed on ice-rich continuous permafrost will require relocation to well-drained natural foundations or replacement with substantially different construction methods. Roads through discontinuous permafrost will require this reinvestment for streches built on ice-rich permafrost. Roads and airstrips built on permafrost with a lower volume of ice will require rehabilitation, but perhaps not relocation, as the foundation thaws. Site-specific information is required.[54]

While thawing permafrost is a concern from rising temperatures—whether from the natural oscillations of the PDO, anthropogenic global warming, or some combination of these and other factors—the concern should not be overstated, in that the land-based transportation infrastructure of Alaska located in regions with potential thawing permafrost is sparse. Repairs and improvements can be made on a case by case basis and in association with other planned improvement and expansion projects. In the state of Alaska's long-range transportation policy plan adopted in 2008, concerns about thawing permafrost are rarely mentioned (except in association with planned improvement to the Dalton Highway) and concerns of climate change-related impacts to the state's transportation infrastructure play only a minor role in the overall long-range policy.[46]

SPOTLIGHT ON Temperatures in Alaska

Temperature trends in Alaska are dominated by a natural oscillation of atmosphere/ocean circulation patterns in the Pacific Ocean termed the Pacific Decadal Oscillation (PDO). Anthropogenic global warming, which is enhanced in the high latitudes, is expected to act on top of the natural oscillation of the PDO. Together with other forms of natural variability, the PDO and the increasing greenhouse effect should produce a general, but not monotonic, warming of Alaska and the nearby Arctic Ocean. This warming will have a variety of both positive and negative impacts on the transportation systems and infrastructure across Alaska.





The top panel shows the statewide average temperature in Alaska from 1918 through 2011. The bottom panel shows the PDO index over the same period. Notice that temperatures in Alaska largely reflect the PDO.

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Agriculture

Key Messages:

- Elevated carbon dioxide increases the productivity and water use efficiency of nearly all plants.
- Higher levels of atmospheric CO_2 ameliorate, and sometimes fully compensate for, the negative influences of various environmental stresses on plant growth, including the stress of high temperature.
- Health-promoting substances found in various food crops and medicinal plants have been shown to benefit from rising atmospheric CO_2.
- Elevated CO_2 reduces, and frequently completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth, and yield.
- Extreme weather events such as heavy downpours and droughts are not likely to impact future crop yields any more than they do now.
- On the whole, CO_2-enrichment does not increase the competitiveness of weeds over crops; higher atmospheric CO_2 will likely reduce crop damage from insects and pathogenic diseases.
- In addition to enhancing forage productivity, atmospheric CO_2-enrichment will likely not alter its digestibility by animals.

Agricultural productivity and yield have been increasing in the United States for many decades. Annual yields of the 19 crops that account for 95 percent of total U.S. food production have increased by an average of 17.4 percent over the period 1995-2009. Such an increase is good news for those concerned about feeding the ever-growing population of the United States and the world.

Percent change in yield between 1995 and 2009 (as derived from a linear trend through the data) for the 19 crops that account for 95 percent of all U.S. food production. Annual crop yield data were obtained from the Food and Agricultural Organization of the United Nations, available at http://faostat.fao.org/site/567/default.aspx#ancor.

Crop	Percent Change
Maize	32.8
Soybeans	17.3
Wheat	13.3
Sugar cane	-2.5
Sugar beet	37.3
Potatoes	22.2
Tomatoes	35.1
Sorghum	5.2
Oranges	-5.8
Seed cotton	31.5
Rice, paddy	26.3
Grapes	0.5
Barley	16.7
Apples	25.6
Lettuce and chicory	8.7
Maize, green	24.4
Onions, dry	28.9
Grapefruit	0.1
Oats	12.4
Average	*17.4*

Food security is one of the most pressing societal issues of our time. It is presently estimated that more than one billion people, or one out of every seven people on the planet, are hungry and/or malnourished. Even more troubling is the fact that thousands die daily as a result of diseases from which they likely would have survived had they received adequate food and nutrition. Yet the problem of feeding the planet's population is presently not one of insufficient food production, for the agriculturalists of the world currently produce more than enough food to feed the globe's entire population. Rather, the problem is one of inadequate distribution, with food insecurity arising simply because the world's supply of food is not evenly dispensed among the human population, due to ineffective world markets.[1]

As world population continues to grow, however, so too must our capacity to produce food continue to expand,[2,3,4] and our ability to fulfill this task has been challenged by claims that rising air temperatures and CO_2 concentrations will adversely impact future agricultural production. The remainder of this chapter evaluates that claim.

The CO_2-Temperature-Growth Interaction

The growth-enhancing effects of elevated CO_2 typically increase with rising temperature. This phenomenon is noted in experiments that exposed bigtooth aspen leaves to atmospheric CO_2 concentrations of 325 and 1935 ppm and measured their photosynthetic rates at a number of different temperatures. The figure below reproduces their results and slightly extends the two relationships defined by their data to both warmer and cooler conditions.

At 10°C, elevated CO_2 has essentially no effect on net photosynthesis in this particular species, as has been demonstrated is characteristic of plants in general. At 25°C, however, where the net photosynthetic rate of the leaves exposed to 325 ppm CO_2 is maximal, the extra CO_2 of this study boosts the net photosynthetic rate of the foliage by nearly 100%; and at 36°C, where the net photosynthetic rate of the leaves exposed to 1935 ppm CO_2 is maximal, the extra CO_2 boosts the net photosynthetic rate of the foliage by a whopping 450%. In addition, it is readily seen that the extra CO_2 increases the optimum temperature for net photosynthesis in this species by about 11°C: from 25°C in air of 325 ppm CO_2 to 36°C in air of 1935 ppm CO_2.

In viewing the warm-temperature projections of the two relationships, it can also be seen that the transition from positive to negative net photosynthesis - which denotes a change from life-sustaining to life-depleting conditions - likely occurs somewhere in the vicinity of 39°C in air of 325 ppm CO_2 but somewhere in the vicinity of 50°C in air of 1935 ppm CO_2. Hence, not only was the optimum temperature for the growth of bigtooth aspen greatly increased by the extra CO_2 of this experiment, so too was the temperature above which life cannot be sustained increased, and by about the same amount, i.e., 11°C.

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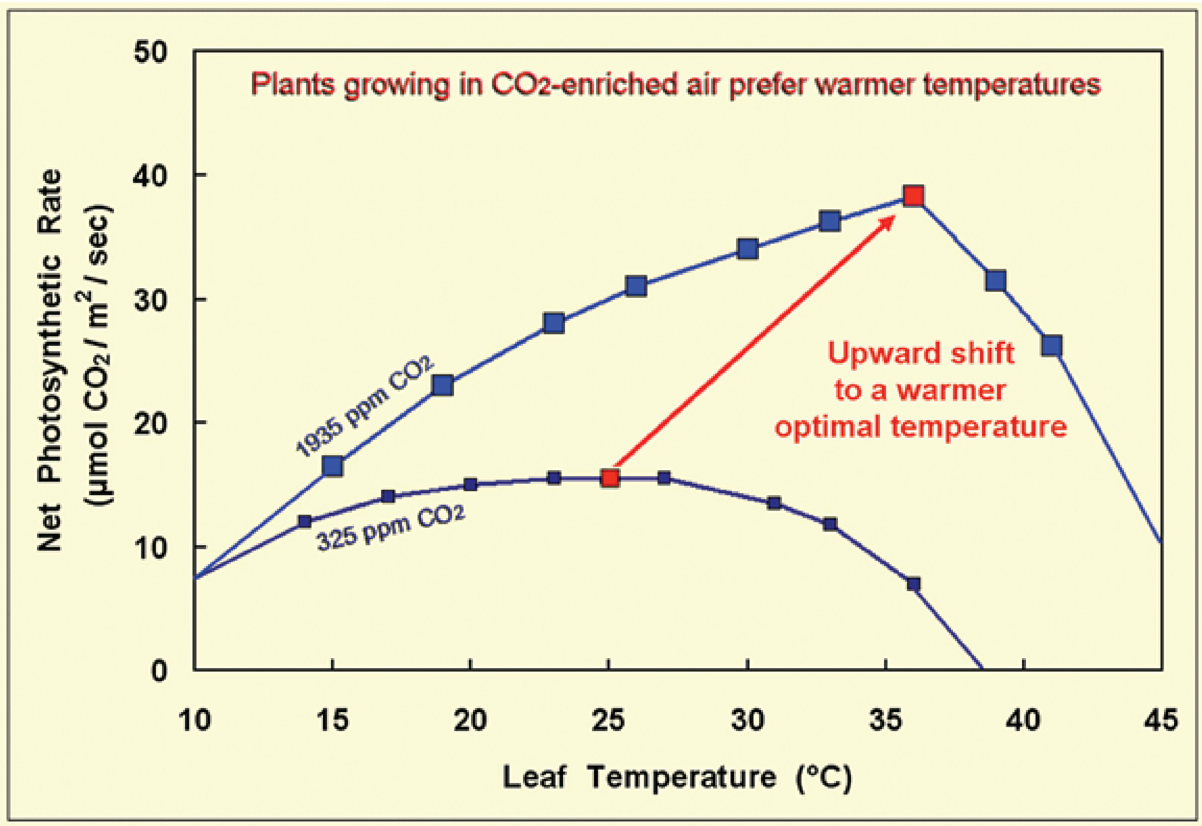
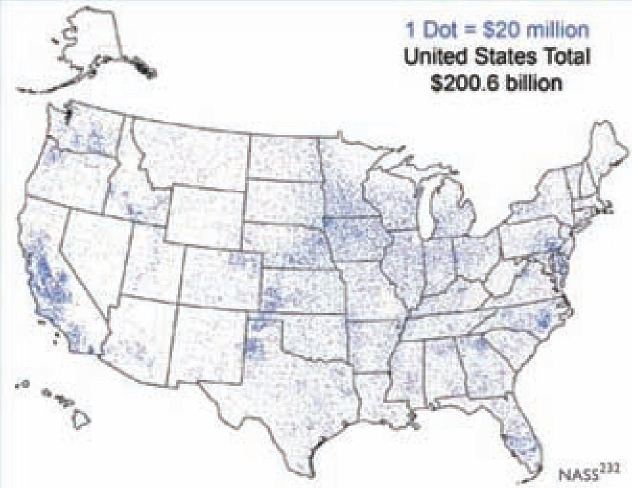


Elevated carbon dioxide increases the productivity and water use efficiency of nearly all plants, providing more food to sustain the biosphere

At a fundamental level, carbon dioxide is the basis of nearly all life on Earth, as it is the primary raw material or "food" that is utilized by plants to produce the organic matter out

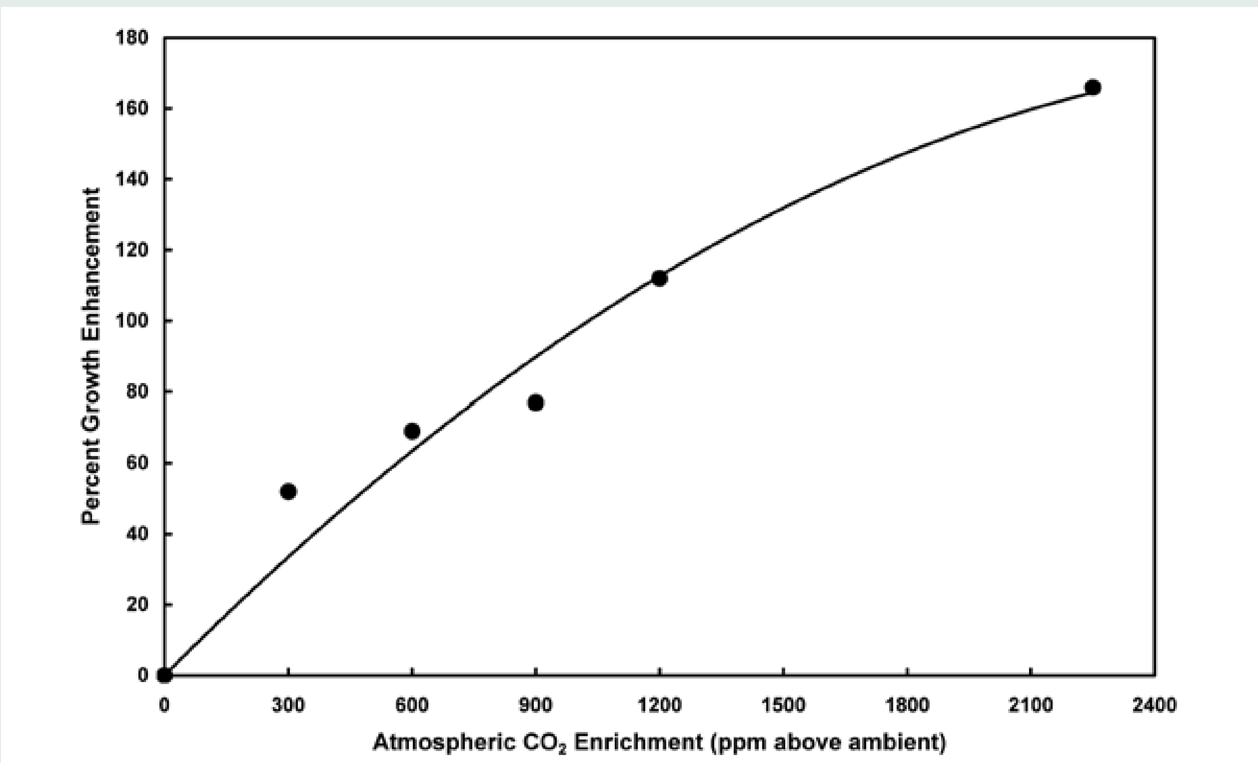
Market Value of Agricultural Products Sold, 2002



of which they construct their tissues, which subsequently become the ultimate source of food for all animals, including humans. Consequently, the more CO_2 there is in the air, the better plants grow, as has been demonstrated in literally *thousands* of laboratory and field experiments.[5,6]

Typically, a doubling of the air's CO_2 content above present-day concentrations raises the productivity of most herbaceous plants by about one-third; this positive response occurs in plants that utilize all three of the major biochemical pathways (C_3, C_4, CAM) of photosynthesis. On average, a 300-ppm increase in atmospheric CO_2 will result in yield increases of 15 percent for CAM crops, 49 percent for C_3 cereals, 20 percent for C_4 cereals, 24 percent for fruits and melons, 44 percent for legumes, 48 percent for roots and tubers, and 37 percent for vegetables.[8] Thus, with more CO_2 in the air, the growth and productivity of nearly all crops will increase, providing more food to sustain the biosphere.

In addition to increasing photosynthesis and biomass, another major benefit of rising atmospheric CO_2 is the enhancement of plant water use efficiency. Studies have shown that plants exposed to elevated levels of atmospheric CO_2



Percent growth enhancement as a function of atmospheric CO_2 enrichment in parts per million (ppm) above the normal or ambient atmospheric CO_2 concentration, showing that the growth benefits continue to accrue well beyond an atmospheric CO_2 concentration of 2000 ppm. These data, representing a wide mix of plant species, were derived from 1,087 individual experiments described in 342 peer-reviewed scientific journal articles written by 484 scientists residing in 28 countries and representing 142 different research institutions.[7]

The Agricultural Debt We Already Owe to Atmospheric CO_2 Enrichment

Writing as background for their study, Cunniff *et al.* (2008) note that "early agriculture was characterized by sets of primary domesticates or 'founder crops' that were adopted in several independent centers of origin," all at about the same time; and they say that "this synchronicity suggests the involvement of a global trigger." As they describe it, the *aerial fertilization effect* caused by the rise in CO_2 following the deglaciation of the last ice age, combined with its *transpiration-reducing effect*, led to a large increase in the *water use efficiencies* of the world's major C_4 founder crops; and they suggest that this development was the *global trigger* that launched the agricultural enterprise upon which civilizations were built.

As a test of this hypothesis, Cunniff *et al.* designed "a controlled environment experiment using five modern day representatives of wild C_4 crop progenitors, all 'founder crops' from a variety of independent centers." The five crops employed in their study were *Setaria viridis* (L.) P. *Beauv*, *Panicum miliaceum* var. *ruderale* (Kitag.), *Pennisetum violaceum* (Lam.) Rich., *Sorghum arundinaceum* (Desv.), and *Zea mays* subsp. *parviglumis* H.H. Iltis & Doebley. They were grown individually in 6-cm x 6-cm x 6-cm pots filled with a 1:1 mix of washed sand and vermiculite for 40-50 days in growth chambers maintained at atmospheric CO_2 concentrations of 180, 280 and 380 ppm, characteristic of glacial, post-glacial and modern times, respectively.

This work revealed that the "increase in CO_2 from glacial to postglacial levels [180 to 280 ppm] caused a significant gain in vegetative biomass of up to 40%," together with "a reduction in the transpiration rate via decreases in stomatal conductance of ~35%," which led to "a 70% increase in water use efficiency, and a much greater productivity potential in water-limited conditions."

In discussing their results, the five researchers concluded that "these key physiological changes could have greatly enhanced the productivity of wild crop progenitors after deglaciation ... improving the productivity and survival of these wild C_4 crop progenitors in early agricultural systems." And in this regard, they note that "the lowered water requirements of C_4 crop progenitors under increased CO_2 would have been particularly beneficial in the arid climatic regions where these plants were domesticated."

For comparative purposes, the researchers also included one C_3 species in their study -- *Hordeum spontaneum* K. Koch -- and they report that it "showed a near-doubling in biomass compared with [the] 40% increase in the C_4 species under growth treatments equivalent to the postglacial CO_2 rise."

In light of these several findings, it can be appreciated that the civilizations of the past, which could not have existed without agriculture, were largely made possible by the increase in the air's CO_2 content that accompanied deglaciation, and that the peoples of the Earth today are likewise indebted to this phenomenon, as well as the *additional* 100 ppm of CO_2 the atmosphere has subsequently acquired.

With an eye to the future, the ongoing rise in the air's CO_2 content will similarly play a pivotal role in enabling us to grow the food we will need to sustain our still-expanding global population in the year 2050 without usurping all of the planet's remaining freshwater resources and much of its untapped arable land.

Clearly, rising CO_2 has served both us and the rest of the biosphere well in the past; and it will do the same in the future.

Reference

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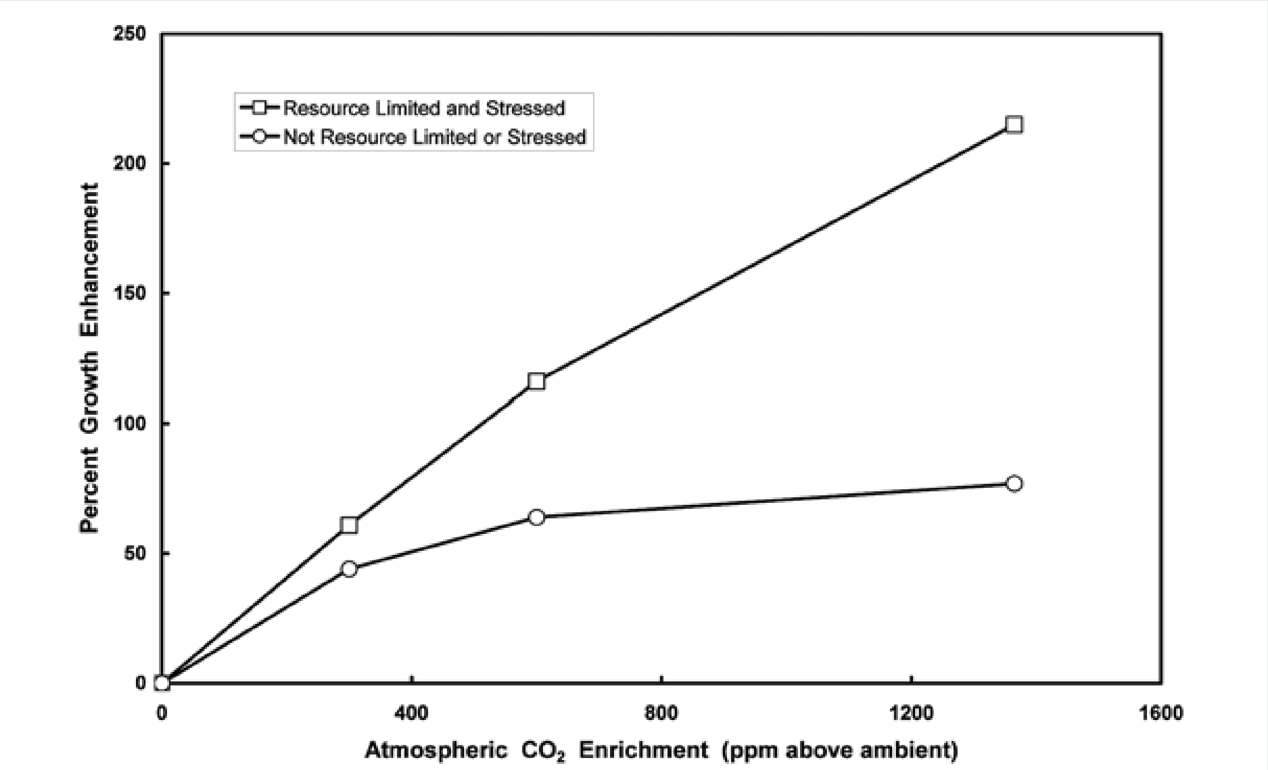
generally do not open their leaf stomatal pores (through which they take in carbon dioxide and give off water vapor) as widely as they do at lower CO_2 concentrations. In addition, they sometimes produce less of these pores per unit area of leaf surface.[9,10] Both of these changes tend to reduce most plants' rates of water loss by transpiration. As a result, the amount of carbon gained per unit of water lost per unit leaf area—or *water-use efficiency*—increases dramatically as the air's CO_2 content rises; and this phenomenon has been well documented in CO_2 enrichment experiments with agricultural crops.[11,12,13,14,15]

Higher levels of atmospheric CO_2 ameliorate, and sometimes fully compensate for, the negative influences of various environmental stresses on plant growth, including the stress of high temperature

Atmospheric CO_2 enrichment has also been shown to help ameliorate the detrimental effects of several environmental stresses on plant growth and development, including high soil salinity,[16,17,18,19] high air temperature,[20,21,22,23] low light intensity,[24,25,26] high light intensity,[27,28] UV-B radiation,[29,30,31] water stress,[32,33,34] and low levels of soil fertility.[35,36,37,38] Elevated levels of CO_2 have additionally been demonstrated to reduce the severity of low temperature stress,[39] oxidative stress,[40,41,42,43] and the stress of herbivory.[44,45,46] In fact, the percentage growth enhancement produced by an increase in the air's CO_2 concentration is generally even *greater* under stressful and resource-limited condi-



Percent growth enhancement as a function of atmospheric CO_2 enrichment in parts per million (ppm) above the normal or ambient atmospheric CO_2 concentration for plants growing under stressful and resource-limited conditions and for similar plants growing under ideal conditions. Each line is the mean result obtained from 298 separate experiments.[47]

tions than it is when growing conditions are ideal.

Among the list of environmental stresses with the potential to negatively impact agriculture, the one that elicits the most frequent concern is high air temperature. In this regard, there is a commonly-held belief that temperatures may rise so high as to significantly reduce crop yields, thereby diminishing our capacity to produce food, feed, and fuel products. It has also been suggested that warmer temperatures may cause a northward shift in the types of crops grown by latitude that could have additional adverse impacts on agricultural production. However, frequently left out of the debate on this topic is the fact that the growth-enhancing effects of elevated CO_2 typically increase with rising temperature. For example, a 300-ppm increase in the air's CO_2 content in 42 experiments has been shown to raise the mean CO_2 -induced growth enhancement from a value of zero at 10°C to a value of 100 percent at 38°C.[48]

This increase in CO_2-induced plant growth response with increasing air temperature arises from the negative influence of high CO_2 levels on the growth-retarding process of photorespiration, which can "cannibalize" 40 to 50 percent of the recently-produced photosynthetic products of C_3 plants. Since this phenomenon is more pronounced at high temperatures, and as it is ever-more-inhibited by increasingly higher atmospheric CO_2 concentrations, there is an increasingly greater potential for atmospheric CO_2 enrichment to benefit plants as air temperatures rise.

A major consequence of this phenomenon is that the optimum temperature for plant growth generally rises when the air is enriched with CO_2. For a 300-ppm increase in the air's CO_2 content, in fact, several experimental studies have shown that the optimum temperature for growth in C_3 plants typically rises by 5°C or more.[49,50,51,52,53,54,55,56,57,58,59]

Eldarica pines grown in increasing concentrations of carbon dioxide clearly show growth enhancement.

United States Department of Agriculture, Water Resources Lab, Phoenix, AZ.

These observations are very important; an increase of this magnitude in optimum plant growth temperature is equal to or greater than the air temperature rise predicted to result from a 300-ppm increase in atmospheric CO_2 concentration. Therefore, even global warming above the average envisioned by the Intergovernmental Panel on Climate Change will probably not adversely affect the vast majority of Earth's plants, for fully 95 percent of all plant species are of the C_3 variety. In addition, the C_4 and CAM plants that make up the rest of the planet's vegetation are already adapted to Earth's warmer environments, which are expected to warm much less than the other portions of the globe; yet even some of these plants experience elevated optimum growth temperatures in the face of atmospheric CO_2 enrichment.[60] Consequently, a CO_2-induced temperature increase will likely not result in crop yield reductions, nor produce a poleward migration of plants seeking cooler weather; the temperatures at which nearly all plants perform at their optimum is likely to rise at the same rate (or faster than) and to the same degree as (or higher than) the temperatures of their respective environments. And other research indicates that even in the absence of a concurrent increase in atmospheric CO_2, plants may still be able to boost their optimum temperature for photosynthesis as the temperature warms.[61]

Elevated CO_2 reduces, and frequently completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth, and yield

Tropospheric ozone is an air pollutant created by a chemical reaction between nitrogen oxides and volatile organic compounds in the presence of sunlight. Plants exposed to elevated concentrations of this pollutant typically display reductions in photosynthesis and growth in comparison to plants grown at current ozone concentrations. Because hot weather also helps to form ozone, there are concerns that CO_2-induced global warming will further increase the concentration of this pollutant, resulting in future crop yield reductions.[62] It is therefore important to determine how major crops respond to concomitant increases in the abundances of both of these important atmospheric trace gases. Several experiments have been conducted to determine just that, examining the interactive effects of elevated CO_2 and ozone on important agricultural commodities. These studies show that elevated CO_2 reduces, and frequently completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth and yield.[63,64,65,66,67,68] When explaining the mechanisms behind such responses, most scientists suggest that atmospheric CO_2 enrichment tends to reduce stomatal conductance, which causes less indiscriminate uptake of ozone into internal plant air spaces and reduces subsequent conveyance to tissues where damage often results to photosynthetic pigments and proteins, ultimately reducing plant growth and biomass production.

Analyses of long-term ozone measurements from around the world cast further doubt on the possibility that this pollutant will cause much of a problem for future crop production.[69] In western Europe, for example, several time series show a rise in ozone into the middle to late 1990s, followed by a leveling off, or in some cases declines, in the 2000s. And in North America, surface measurements show a pattern of mostly unchanged or declining ozone concentration over the past two decades that is broadly consistent with decreases in precursor emissions. The spatial and temporal distributions of these and other observations indicate that, whereas increasing industrialization originally tends to increase the emissions of precursor substances that lead to the creation of greater tropospheric ozone pollution, subsequent technological advances tend to ameliorate that phenomenon, as they appear to gradually lead to (1) a leveling off of the magnitude of precursor emissions and (2) an ultimately *decreasing* trend in tropospheric ozone pollution. In light of these observations, when atmospheric ozone and CO_2 concentrations both rise together, the plant-growth-*enhancing* effect of atmospheric CO_2 enrichment is significantly muted by the plant-growth-*retarding* effect of contemporaneous increases in ozone pollution, but as the troposphere's ozone concentration gradually levels off and declines—as it appears to be doing with the development of new and better anti-pollution technology in the planet's more economically advanced countries—the future could bring more-rapid-than-usual increases in earth's vegetative productivity, including crop yields.

Increasing atmospheric carbon dioxide will reduce agricultural sensitivity to drought

It has been suggested that the frequency and severity of drought across much of the United States will increase as greenhouse gases rise, causing crops to experience more frequent and more severe water deficits, thereby reducing crop yields.[70]

Recent droughts are not without historical precedent. Nonetheless, even if they were to increase in frequency and/or severity, agricultural crops become less susceptible to drought-induced water deficits as the air's CO_2 concentration rises. This is because water stress does not typically negate the CO_2-induced stimulation of plant productivity. In fact, the CO_2-induced percentage increase in plant biomass production is often greater under water-stressed conditions than it is when plants are well-watered.

During times of water stress, atmospheric CO_2 enrichment often stimulates plants to develop larger-than-usual and more robust root systems that invade greater volumes of soil for scarce and much-needed moisture. Elevated levels of atmospheric CO_2 also tend to reduce the openness of stomatal pores on leaves, thus decreasing plant stomatal conductance. This phenomenon, in turn, reduces the amount of water lost to the atmosphere by transpiration and, consequently, lowers overall plant water use. Atmospheric CO_2 enrichment thus increases plant water acquisition by stimulating root growth, while it reduces plant water loss by constricting stomatal apertures; these dual effects typically enhance plant water-use efficiency, even under conditions of less-than-optimal soil water content. These phenomena contribute to the maintenance of a more favorable plant water status during times of drought, as has been demonstrated in several studies.[71,72,73,74]

On the whole, CO_2-enrichment does not increase the competitiveness of weeds over crops; higher atmospheric CO_2 will likely reduce crop damage from insects and pathogenic diseases

Elevated CO_2 typically stimulates the growth of nearly all plant species in monoculture, including those deemed undesirable by humans, i.e., weeds, and concerns have been expressed that CO_2 enrichment may help weeds outcompete crops in the future. However, such worries are likely overstated. Out of the 18 weeds considered most harmful in the world, 14 are of the C_4 species type.[75] In contrast, of the 86 plant species that provide most of the world's food supply, only 14 are C_4 (the remainder are C_3 species),[76] and studies conducted on C_3 crops with C_4 weeds—the most common arrangement of all crop/weed mixed-species stands—typically demonstrate that elevated CO_2 favors the growth and development of C_3 over C_4 species.[77,78,79,80,81,82,83,84] Therefore, the ongoing rise in the air's CO_2 content should, on the whole, provide crops with greater protection against weed-induced decreases in their productivity and growth.

With respect to crop damage from insects, the majority of studies to date indicate that the fraction of plant production that is consumed by herbivores in a CO_2-enriched world will likely remain about the same as it is now or slightly decrease.[85,86,87,88,89,90] In one study, for example, offspring numbers of the destructive agricultural mite *Tetranychus urticae*, feeding on bean plants growing in 700-ppm CO_2 air, were 34 percent lower in the first generation and 49 percent lower in the second generation than the offspring produced in bean plants growing in air of 350-ppm CO_2.[91] This CO_2-induced reduction in the reproductive success of this invasive insect, which negatively affects more than 150 crop species worldwide, bodes well for society's ability to grow the food we will need to feed the population of the planet in the future.

In a somewhat different experiment, researchers fed foliage derived from plots of calcareous grasslands in Switzerland (maintained experimentally at 350 and 650 ppm CO_2) to terrestrial slugs and found they exhibited no preference with respect to the CO_2 treatment from which the foliage was derived.[92] And in a study that targeted no specific insect pest, it was observed that a doubling of the air's CO_2 content enhanced the total phenolic concentrations of two Mediterranean perennial grasses (*Dactylis glomerata* and *Bromus erectus*) by 15 percent and 87 percent, respectively. These compounds tend to enhance plant defensive and resistance mechanisms to attacks by both herbivores and pathogens.[93]

Notwithstanding such findings, another herbivore-related claim is that insects will increase their feeding damage on C_3 plants to a greater extent than on C_4 plants because increases in the air's CO_2 content sometimes lead to greater decreases in the concentrations of nitrogen and, therefore, protein in the foliage of C_3 plants as compared to C_4 plants. To make up for this lack of protein, it has been assumed that insects would consume a greater amount of vegetation from plants growing under higher CO_2 levels as opposed to lower CO_2 levels. However, contrary to such assertions, observations show little to no evidence in this regard. It has been suggested that the lack of increased consumption rates at higher CO_2 levels may be explained by post-ingestive mechanisms that provide a sufficient means of compensation for the lower nutritional quality of C_3 plants grown under elevated CO_2.[94,95]

When it comes to pathogenic diseases, researchers have noted a number of CO_2-induced changes in plant physiology, anatomy, and morphology that have been implicated in increased plant resistance to disease and that can enhance host resistance at elevated CO_2, among which are (1) increased net photosynthesis that allows the mobilization of resources into host resistance,[96,97] (2) a reduction in stomatal density and conductance,[98] 3) greater accumulation of carbohydrates in leaves, (4) an increase of waxes, extra layers of epidermal cells, and increased fiber content,[99] (5) production of papillae and accumulation of silicon at penetration sites,[100] (6) more mesophyll cells,[101] (7) increased biosynthesis of phenolics,[102] (8) increased root biomass and functionality,[103,104] (9) higher condensed tannin concentrations,[105,106] (10) increased root colonization by arbuscular mycorrhizal fungi,[107] (11) increased production of glyceollins,[108,109] (12) increased plant carbon gain,[110] and (13) changes in the allometric relation between below-ground and above-ground biomass.[111] Whatever the mechanism, the vast bulk of the available data suggests that elevated CO_2 has the ability to significantly ameliorate the deleterious effects of various stresses imposed upon plants by numerous pathogenic invaders. Consequently, as the atmosphere's CO_2 concentration continues its upward climb, earth's vegetation should be increasingly better equipped to successfully deal with pathogenic organisms and the damage they have traditionally done to society's crops, as well as to the plants that sustain the rest of the planet's animal life.

It is a well-established fact that atmospheric CO_2 enrichment not only boosts the productivity of both crops and natural vegetation but also enhances the *quality* of many important substances found within them by increasing the concentration of many important vitamins,[112,113,114,115,116] antioxidants,[117,118,119] and other phytonutrients[120,121,122,123,124,125] that are well-known for their nutritional and medicinal value. Experiments with bean sprouts, for example, have shown that a doubling of atmospheric CO_2 doubled the plant's vitamin C content.[126] Likewise, antioxidant concentrations have been found to increase by as much as 171 percent in a CO_2-enriched strawberry experiment.[127] Other studies show elevated atmospheric CO_2 increased the concentration of the heart-helping drug digoxin in woolly foxglove (*Digitalis lanata*) by 11 to 15 percent.[128,129] And in the tropical spider lily (*Hymenocallis littoralis*), in addition to increasing plant biomass by 56 percent, a 75 percent increase in the air's CO_2 content was shown to increase the concentrations of five different substances proven effective in treating a number of human cancers (melanoma, brain, colon, lung, and renal) and viral diseases (Japanese encephalitis and yellow, dengue, Punta Tora, and Rift Valley fevers) by 6 to 28 percent.[130]

Enhanced atmospheric CO_2 and food and forage quality

One concern that is frequently expressed with respect to the quality of CO_2-enriched food, however, is that large increases in the air's CO_2 content sometimes lead to small reductions in the protein concentrations of animal-sustaining forage and human-sustaining cereal grains when soil nitrogen concentrations are sub-optimal. Many crops, in contrast, do not show such reductions, or do so only in an ever so slight manner.[131] Nevertheless, for those that do, when they are supplied with *adequate* nitrogen, as is typical of modern farming techniques, no such protein reductions are observed.[132,133,134,135] It should also be noted that the rate of rise of the atmosphere's CO_2 concentration is only a couple parts per million per year, which is fully *two orders of magnitude less* than the CO_2 increases employed in most experiments that show small reductions in plant protein contents when soil nitrogen concentrations are less than adequate; there are many ways in which the tiny amount of extra

Atmospheric CO_2 Enrichment of a Pair of Medicinal Plants

According to Stutte *et al.* (2008), "many *Scutellaria* species are rich in physiologically active flavonoids that have a wide spectrum of pharmacological activity." Leaf extracts of *Scutellaria barbata*, as they describe it, "have been used in traditional Chinese medicine to treat liver and digestive disorders and cancers (Molony and Molony, 1998)," and they say that "recent research has shown extracts of *S. barbata* to be limiting to the growth of cell lines associated with lung, liver, prostate and brain tumors (Yin *et al.*, 2004)."

In an attempt to understand how these phytonutrients might respond under elevated CO_2 growing conditions, the three researchers studied both *S. barbata* and *S. lateriflora*, measuring effects of elevated atmospheric CO_2 concentrations (1200 and 3000 ppm vs. a control value of 400 ppm) on total plant biomass production and plant concentrations of six bioactive flavonoids -- apigenin, baicalin, baicalein, chrysin, scutellarein and wogonin -- all of which substances, in their words, "have been reported to have anticancer and antiviral properties," as described in the review papers of Joshee *et al.* (2002) and Cole *et al.* (2007). These experiments were conducted in a large step-in controlled-environment chamber that provided a consistent light quality, intensity and photoperiod to six smaller plant growth chambers that had "high-fidelity control of relative humidity, temperature, and CO_2 concentration." Each chamber also monitored nutrient solution uptake by plants that they grew from seed for a period of 49 days.

With respect to plant productivity, in the case of *S. barbata*, increasing the air's CO_2 concentration from 400 to 1200 ppm resulted in a 36% increase in shoot fresh weight and a 54% increase in shoot dry matter, with no further increases between 1200 and 3000 ppm CO_2. In the case of *S. lateriflora*, on the other hand, the corresponding increases in going from 400 to 1200 ppm CO_2 were 62% and 44%, while in going all the way to 3000 ppm CO_2, the total increases were 122% and 70%, respectively.

With respect to flavonoid concentrations in the plants' vegetative tissues, Stutte *et al.* report that in the case of *S. barbata*, "the combined concentration of the six flavonoids measured increased by 48% at 1200 and 81% at 3000 ppm CO_2," while in *S. lateriflora* they say "the total flavonoid content increased by over 2.4 times at 1200 and 4.9 times at 3000 ppm CO_2." Thus, in consequence of the compounding effect of increases in both plant biomass and flavonoid concentration, the total flavonoid content in *S. barbata* rose by 72% in going from 400 to 1200 ppm CO_2, and by 128% in going all the way to 3000 ppm CO_2, while in *S. lateriflora* the corresponding increases were 320% and 1,270%.

In the concluding sentence of their paper's abstract, Stutte *et al.* say their results indicate that "the yield and pharmaceutical quality of *Scutellaria* species can be enhanced with controlled environment production and CO_2 enrichment," and massively so. In addition, since they indicate that over 200 substances -- of which over 80% are flavonoids -- have been found in a total of 65 *Scutellaria* species, it would appear that the "increased concentration of flavonoids through CO_2 enrichment," as they describe it, "has the potential to enhance the production and quality of [many] medicinal plants."

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nitrogen needed to maintain current crop protein concentrations in the face of such a small yearly increase in the air's CO_2 concentration may be readily acquired.

Crops experiencing rising levels of atmospheric CO_2 produce larger and more-branching root systems (as they typically do in experiments when exposed to elevated CO_2 concentrations), which should allow them to more effectively explore ever larger volumes of soil for the extra nitrogen and other nutrients the larger CO_2-enriched crops will need as the air's CO_2 content continues to rise. Also, tiny bacteria and algae that remove nitrogen from the air and make it directly available to plants are found nearly everywhere, and elevated atmospheric CO_2 concentrations typically enhance their ability to perform this vital function.[136] As these phenomena are gradually enhanced by the slowly rising CO_2 content of the air, the slowly rising nutrient requirements of both crops and natural vegetation should be easily satisfied, and plant protein concentrations should therefore be maintained, at the very least, at their current levels.

Interrelated with the concern about CO_2-induced decreases in plant nutritive value is a hypothesis that lowered plant nitrogen will significantly reduce the nutritive value of grassland herbage and, therefore, affect the digestibility, forage intake, and productivity of ruminants. In fact, there are a number of observational studies that indications in atmospheric CO_2 enrichment will not have a negative impact on total herbage nitrogen concentration[137] or digestibility,[138,139,140] and even if it did, the impact would likely not be large enough to negatively impact the growth and wellbeing of ruminants feeding upon the forage,[141,142,143] as the nutritive value of grassland plants is often above the minimum range of crude protein necessary for efficient digestion by ruminants.[144]

Given the considerations noted above, it is likely that the ongoing rise in the air's CO_2 content will continue to increase food production around the world, while maintaining the digestibility and nutritive quality of that food and enhancing the production of certain disease-inhibiting plant compounds. The increase atmospheric CO_2 concentration is not only helping to meet the caloric requirements of the planet's burgeoning human and animal populations, it is also helping to meet their nutritional and medicinal requirements.

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Ecosystems

Key Messages:

- Earth's forests are becoming increasingly more productive and efficient in their use of water, primarily as a consequence of the ongoing rise in the atmosphere's CO_2 concentration.
- As air temperatures rise, plant and animal species tend to expand their ranges—both poleward in latitude and upward in altitude—in such a way that they overlap more, thereby increasing ecosystem biodiversity.
- Pest and pathogen damages to Earth's ecosystems have not been able to match the great "greening of the Earth" that has occurred over the past several decades and is readily detected by satellites.
- Coastal marine ecosystems have been able to withstand the challenges of both global warming and ocean acidification, due to the processes of adaptation, acclimatization, and evolution.

Near-surface air temperatures are predicted to increase as the atmosphere's concentration of CO_2 continues to rise. Will this devastate the world of nature and its many ecosystems? The Intergovernmental Panel on Climate Change, in its 2007 compendium, indicated that current surface temperatures are higher than they have been in the last millennium. Is this already driving a mass extinction? Further, alarm has been raised over CO_2-induced "ocean acidification," with major concern about a disruption of the calcification process that is involved in the construction of shells and bones, which could logically lead to the demise of many marine life forms, such as corals and shellfish.

But are these things really so? Although physical-chemical theory suggests that many of them *could* be true, the involvement of *life* in these matters adds a whole new dimension to them; in the sections that follow, these complex but intriguing subjects are briefly discussed, with extensive citation of the relevant scientific literature.

Earth's forests are becoming increasingly more productive and efficient in their use of water, primarily as a consequence of the ongoing rise in the atmosphere's CO_2 concentration

It has been claimed that rising temperatures and declining precipitation, i.e., heat and drought, will lead to decreased tree growth.[1] However, the increase in the atmosphere's CO_2 concentration ameliorates and can compensate for these two phenomena by simultaneously increasing the optimal temperature for photosynthesis[2,3,4] and the efficiency with which trees use water.[5,6,7] The beneficial impacts of the rise in the air's CO_2 content do indeed combine to lead to an ever-increasing productivity of Earth's trees, demonstrated by the results of several studies of many forest types from around the world, ranging from tropical trees[8,9,10] to temperate trees[11,12,13] to boreal trees.[14,15,16] This CO_2-induced productivity stimulation is experienced by trees that are also experiencing water insufficiency[17,18,19] and very old age.[20,21,22]

Old Trees Refusing to Retire

Using data obtained from the website of the International Tree-Ring Data Bank, as well as from cores that had been collected previously and stored in their laboratory at The Pennsylvania State University (USA), researchers S.E. Johnson and M.D. Abrams (2009) explored growth rate (basal area increment, BAI) relationships across age classes (from young to old) for eight tree species commonly found throughout the eastern United States, namely, bigtooth aspen (*Populus grandidentata* Michx.), blackgum (*Nyssa sylvatica* Marsh.), black oak (*Quercus velutina* Lam.), chestnut oak (*Quercus Montana* L.), hemlock (*Tsuga canadensis* L. Carr.), pitch pine (*Pinus rigida* Mill.), red oak (*Quercus rubra*) and white oak (*Quercus alba* L.).

According to Johnson and Abrams, "a remarkable finding of this study is that even the oldest trees of several species had slow but increasing BAI values, which continued throughout the life of most trees." The reason they characterize this finding as "remarkable," as they explain, is because it "contradicts the sigmoidal growth model that predicts growth rate should plateau and then decline, as middle age trees approach old age," citing the studies of Ryan and Yoder (1997) and Weiner and Thomas (2001). And they further report that "over the last 50-100 years, younger trees within a species grew faster than did the older trees when they were of the same respective age," which is what Knapp and Soule (2011) also found to be the case with ponderosa pine trees in the USA's northern Rocky Mountains.

In discussing their findings, the two researchers from Penn State's School of Forest Resources say "it seems reasonable to assume" that the greater growth rates of older trees of the current era compared to older trees of older times "may be due to a stimulatory effect of anthropogenic global change defined in the broadest sense," including "increased CO_2 levels, warming temperatures, increased precipitation, and changes in precipitation chemistry," while noting that "yearly average temperatures, atmospheric CO_2 and nitrogen levels have increased in the eastern US (as well as much of the rest of the world) over the last 50-100 years." And Knapp and Soule (2011) go even further, stating that "old-growth ponderosa pine forests of the northern Rockies have likely benefited from the effects of increased atmospheric CO_2 since the mid-20th century," additionally noting that "the benefits increase with tree age."

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As air temperatures rise, plant and animal species tend to expand their ranges—both poleward in latitude and upward in altitude—in such a way that they overlap more, thereby increasing local species richness and ecosystem biodiversity throughout the world

Eldarica pines grown in increasing concentrations of carbon dioxide clearly show growth enhancement.

It is feared that the rate of planetary warming will be so great that plants and animals will not be able to migrate towards cooler regions of the planet (poleward in latitude and/or upward in elevation) rapidly enough to avoid extinction, and that the process has already been set in motion. Consequently, might we be on the verge of a mass extinction of both plant and animal species, especially those species that already live near the upper extremes of latitude and altitude. In testimony to Congress, NASA astrophysicist James Hansen speculated that "polar species can be pushed off the planet, as they have no place else to go," while likewise opining that species in alpine regions are "similarly in danger of being pushed off the planet." [23]

Such dire hypotheses deserve investigation.

Latitudinal shifts in species ranges

It has been claimed that "the ranges of many butterfly species have expanded northward" but have "contracted at the southern edge," which, if true, could indeed suggest a possible reduction in range size and a push in the direction of extinction.[24] However, real-world field studies show that just the opposite is more commonly the case. In a study of changes in the ranges of close to three dozen non-migratory butterfly species whose northern boundaries were in northern Europe and whose southern boundaries were in southern Europe or northern Africa, for example, it was found that over the prior century of global warming, nearly all northward range shifts involved extensions at the northern boundary with the southern boundary remaining stable, which leads to range expansions.[25] Also, in a 2001 study concomitant with a modest regional warming of the British Isles over the preceding two decades, researchers documented a rapid expansion of the ranges of two butterfly species and two cricket species, wherein warming-induced increases in habitat breadth and dispersal tendencies resulted in 3- to 15-fold increases in range expansion rates.[26] Similar findings have been reported for butterflies in Canada.[27,28]

Things are much the same for birds. In a study of British birds over a 20-year period of global warming, it was found that the northern margins of southerly species' breeding ranges shifted northward by an average of 19 km from 1970 to 1990, while the mean southern margin of northerly species' breeding ranges shifted not at all.[29] This was also determined to be the case for European wading birds observed at 3,500 different sites in Belgium, Denmark, France, Germany, Ireland, the Netherlands, and the United Kingdom on at least an annual basis since the late 1970s.[30] Analogous results have been found for British and Irish seabirds,[31] birds in Finland,[32] and multiple species of birds throughout the portion of the United States located east of the Rocky Mountains.[33]

Another concern is the hypothetical potential for mismatches to occur between various species' life-cycle stages and the life-cycle stages of the plants and lower-trophic-level animal species they need to support themselves as the planet warms, with postulated temporal incongruities claimed to potentially lead to the demise of many higher-trophic-level species.[34] Fortunately, many real-world studies refute this contention.

A salient example is a study of 47 years of warming between 1961 and 2007 of: (1) the time of leafing-out of dominant English Oak trees at four different research sites in the Czech Republic located in full-grown, multi-aged floodplain forests that had been under no forestry management, (2) the time of appearance of the two most abundant species of caterpillars in the floodplain forests (those of the Winter and Tortrix Moths, which serve as food for new hatchlings) and (3) the first and mean laying dates of two of the ecosystem's most common birds: Great Tits and Collared Flycatchers.[35] Over this period, mean annual temperature showed a significant increase of 0.27-0.33°C per decade, with approximately the same magnitude of change during spring at all sites. In response to this warming, the researchers found that, on average (for all four sites), the bud burst date of English Oak advanced by 7.9 days and full foliage by 8.9 days, with approximately the same shifts being recorded for the beginning and end of the period of peak frass deposition by the herbivorous caterpillars, which was the observational variable they used to characterize the caterpillars' presence. In addition, they determined that the first laying date of Great Tits advanced by between 6.2 and 8.0 days, while the mean laying date advanced by 6.4 to 8.0 days. Likewise, they found that the Collared Flycatchers' first laying date advanced by 8.5 to 9.2 days over the past 47 years, and that its mean laying date advanced by 7.7 to 9.6 days. Because trends in the timing of the reproduction processes of both bird species were synchronized with trends in the leafing-out of the English Oak trees and with peak herbivorous caterpillar activity, it is clear that in this specific portion of this particular ecosystem, the common shifting of the different organisms' phenological stages toward the beginning of the year has not led to any mistiming in the critical activities of its trophic food chain.

A similar study focused on the breeding cycles of both Great Tits and Blue Tits in an oak-beech forest near Antwerp, Belgium, where researchers had collected data on the breeding of the two species from 1979 to 2007.[36] This study revealed that both bird species advanced their average first-egg dates by 11-12 days over the three-decade period, while the time from first egg to fledging was shortened by 2-3 days and the average time of fledging advanced by 15.4 and 18.6 days for Blue and Great Tits, respectively. Indirect estimates of the feeding peak suggested that both species had maintained synchrony with their food supply. Likewise, in a study of two populations of Blue Tits in the northern part of the French island of Corsica, it was determined that there was no mismatch between Blue Tit breeding dates and caterpillar peak abundance dates over any of the 14 and 21 years for which data from the two populations were available.[37]

Altitudinal shifts in species ranges

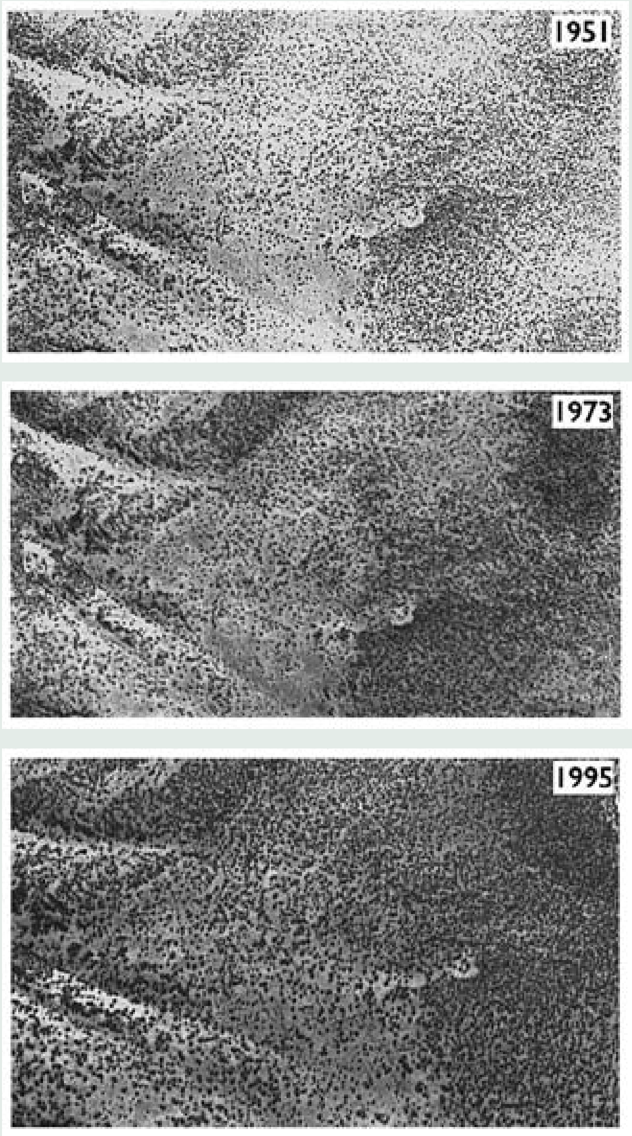
With respect to the contention that species in mountainous regions are in danger of being pushed off the planet into extinction as temperatures rise,[38] there are many studies based on real-world data that find otherwise. In one of them,[39] researchers visited 12 mountains having summits located between elevations of 2,844 and 3,006 meters in the canton of Grisons, Switzerland, where they made complete inventories of vascular plant species in 2004 that they compared with similar inventories made in the same locations by other researchers in 1885, 1898, 1912, 1913, and 1958, and where mean summer temperature increased by at least 0.6°C between the time of the first study and the one they conducted. This work revealed that the upward migration rates detected by the modern team were on the order of several meters per decade. Their data indicated that vascular plant species richness actually *increased*—by 11 percent per decade—over the last 120 years on the mountain summits (defined as the upper 15 meters of their peaks), because none of the original species were ever "pushed off the planet." Instead, they were merely joined by additional species arriving from lower elevations. This finding agrees well with other investigations from the Alps, where the same phenomenon has been detected.[40,41,42,43,44]

Another study documented and analyzed changes (from 2001 to 2006) in plant species number, frequency, and composition along an altitudinal gradient crossing four summits, from the treeline ecotone to the subnival zone in the South Alps (Dolomites, Italy), where minimum temperatures increased by 1.1-2.0°C during the past century, with a marked rise over the last decades.[45] These researchers determined, in their words, that "after five years, a re-visitation of the summit areas revealed a considerable increase of species richness at the upper alpine and subnival zone (10 percent and 9 percent, respectively) and relatively modest increases at the lower alpine zone and the treeline ecotone (3 percent and 1 percent, respectively)." In addition, with respect to threats of extinction, they reported that "during the last five years, the endemic species of the research area were hardly affected," while "at the highest summit, one endemic species was even among the newcomers." They concluded that "at least in short to medium time scales, the southern alpine endemics of the study area should not be seriously endangered," because "the three higher summits of the study area have a pronounced relief providing potential surrogate habitats for these species."

But what happens on mountains located at much higher and colder latitudes? Based on a survey of plant species diversity on 13 mountain summits in southern Norway[46]—in a reenactment of what another scientist had done more than three decades earlier[47]—as well as their assessment of regional warming over the intervening years, researchers investigated how plant species richness may have changed in response to what turned out to have been a significant increase, of 1.3°C, in local temperatures between the times of the two studies. Over that interval, plant taxa richness rose by an average of 90 percent, with two of the summits experiencing increases of fully 200 percent. Of these results, they say the average was in accordance with similar studies in both Scandinavia and southern Europe,[48,49,50]but they state that the 200 percent increase in taxa richness on two of the summits was "exceptional."

Reconstituted ecosystems

A number of studies of the Tertiary flora of what is now the western United States demonstrate that many montane taxa of that period regularly grew among mixed conifers and broadleaf schlerophylls,[51,52,53,54,55] whereas today these forest zones are separated from each other by fully 1,000 meters in elevation and 10-20 km or more in lateral distance.[56] In fact, during this many-million-year period—when the air's CO_2 content was generally much greater than it is today[57] —all three forest zones merged to form a "super ecosystem," with much richer species diversity than the ecosystems in the modern western cordilerra.[58] Studies of the *modern* world[59,60,61] indicates a strong correlation between biodiversity and ecosystem productivity, which suggests that the future world is also likely to have greater biological primary productivity.



Aerial photographs of the approximate 240-ha Horse Ridge Research Natural Area (HRRNA) in central Oregon. The HRRNA is located approximately 31 km southeast of Bend, Oregon, and ranges in elevation from 1,250 to 1,430 m. An increase in western juniper cover and density is obvious between 1951 and 1995.[106]

Pest and pathogen damages to Earth's ecosystems have not been able to match the increase in global vegetation that has occurred over the past several decades and is readily detected by satellites

Various pathogens and insect pests have been claimed to cause increasing damage to forests and other eosystems as the atmosphere's CO_2 content and temperature have risen over the past several decades.[62] This hypothesis is not supported by local and global vegetation data. In fact, the opposite, a planetary "greening," is occurring.[63]

The "greening" the planet's ecosystems is universal and consistent with the productivity-enhancing and transpiration-reducing effects of atmospheric CO_2 enrichment. It appears at every level of ecosystem complexity, from biological soil crusts in extremely arid lands to tropical rainforests at the other end of the moisture spectrum. In Africa, for example, both types of ecosystems have been responding, ranging from the greening of the Sahel[64,65,66] to the enhanced productivity experienced by old-growth closed-canopy tropical rain forrests.[67] In Asia, numerous studies also reveal a continent-wide greening,[68,69,70,71,72,73,74] as do others that have been conducted in Europe.[75,76,77,78,79,80,81] Ecosystems of North America are similarly greening up,[82,83,84,85,86,87,88,89,90] as are those of South America[91,92,93,94,95,96,97,98,99] and Australia.[100,101,102,103,104,105]

Coastal marine ecosystems have been able to withstand the challenges of both global warming and ocean acidification, due to the processes of adaptation, acclimatization, and evolution

Coral reefs and their associated ecosystems have long faced a number of challenges related to the activities of man, including increasing nutrient runoff from agriculture, invasive and destructive starfish, tourism, disruptive fishing and trawling techniques, overfishing, and disturbance by tourists.

Recently, the threat of CO_2-induced global warming has been added to the list, especially in light of some of the significant warming-induced episodes of coral bleaching that have occurred in recent decades. However, there are a number of compelling observational reasons indicating that global warming is not the threat that it is feared to be. There is substantial documentation of severely bleached corals not only surviving but thereafter exhibiting various degrees of phenotypical acclimation and/or genetic adaptation to subsequent episodes of equally severe or even stronger warming.[107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122]

Other marine organisms have also been observed to successfully adjust to rapid warming, including fish, macro-invertebrates, and macro-algae monitored at 136 sites around Australia's island of Tasmania,[123] consistent with an IPCC climate change scenario that "primary production will increase around Australia" with "overall positive linear responses of functional groups to primary production change," which "benefits fisheries catch and value and leads to increased biomass of threatened marine animals such as turtles and sharks."[124]

Antarctic fish appear to have the ability to acclimate to increases in water temperature of several degrees.[125] And in two other studies of the subject,[126,127] it was found that in spite of diverse independent origins across taxa, most fish species share a common suite of physiological adaptations allowing them to survive periodic exposure to high environmental temperature, and, therefore, that "exceptional thermal tolerance may be common throughout the biodiverse shallow waters of the Indo-Pacific," so that "tropical marine fishes inhabiting fringing nursery environments may have the upper thermal tolerance necessary to endure substantial increases in sea temperatures."[128] The economically important Alaskan King Crab also acclimates to a surprising temperature range,[129] and this work revealed that "growth increased as an exponential function of temperature" and provided "no evidence that culturing red king crab juveniles at elevated temperatures led to a decrease in condition or nutritional status."

Coastal marine ecosystems: succumbing to ocean acidification?

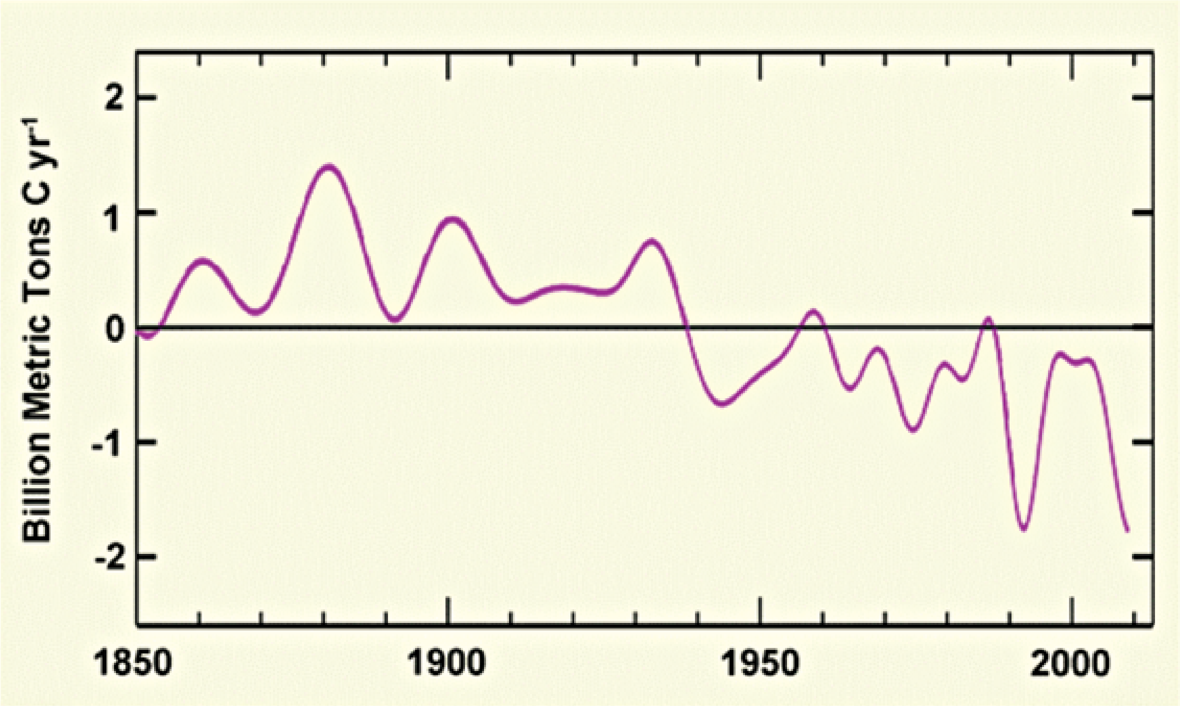
Another perceived threat of increasing atmospheric CO_2 to marine life is ocean acidification, whereby higher atmospheric CO_2 concentrations lead to a greater absorption of CO_2 by the world's oceans and a decline in their pH values. This is hypothesized to be detrimental to the calcification process that is so important to most marine life.

The scientific literature in this area has been expanding rapidly and, when evaluated in its entirety, reveals a future that does not support alarming statements such as that we are in "the last decades of coral reefs on this planet for at least the next ... million plus years, unless we

The Increasing Vigor of Earth's Terrestrial Plants

Are the natural sinks of Earth's carbon cycle are becoming ever less effective in removing from the atmosphere the newly added CO_2? While this has been proposed, (Canadell *et al*., 2007; LeQuere *et al*., 2007), recent data do not support this hypothesis.

Pieter Tans, from the National Oceanographic and Atmospheric Administration, calculated the residual fluxes of carbon (in the form of CO_2) from the terrestrial biosphere to the atmosphere (+) or from the atmosphere to the terrestrial biosphere (-), obtaining this result: depicted in the figure below.



Five-year smoothed rates of carbon transfer from land to air (+) or from air to land (-) vs. time. Adapted from Tans (2009).

As can be seen from this figure, Earth's land surfaces were a net *source* of CO_2-carbon to the atmosphere until about 1940, primarily due clearing of forests and the plowing of grasslands to expand agriculture. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an *increasingly greater* ***sink*** for CO_2-carbon; even in the face of substantial deforestation of tropical lowlands.

Tans notes that these findings do "not depend on models" but "only on the observed atmospheric increase and estimates of fossil fuel emissions," and he concluded that "suggestions that the carbon cycle is becoming less effective in removing CO_2 from the atmosphere (e.g., LeQuere *et al*., 2007; Canadell *et al*., 2007) can perhaps be true locally, but they do not apply globally, not over the 50-year atmospheric record, and not in recent years." In fact, he goes on to say that "to the contrary" and "despite global fossil fuel emissions increasing from 6.57 GtC in 1999 to 8.23 in 2006, the five-year smoothed global atmospheric growth rate has not increased during that time, which requires more effective uptake [of CO_2] either by the ocean or by the terrestrial biosphere, or both, to satisfy atmospheric observations." And the results portrayed in the figure above, which is adapted from Tans' paper, clearly indicate that this "more effective uptake" of CO_2-carbon has occurred primarily over land.

This observation-based analysis of real-world data pretty much verifies the substantial "greening" that has been noted in numerous independent studies conducted throughout the world. In addition, it refutes the unfounded arguments that various environmental stresses and resource limitations will not allow the full potential of the well-documented aerial fertilization effect of atmospheric CO_2 enrichment to be manifest in nature.

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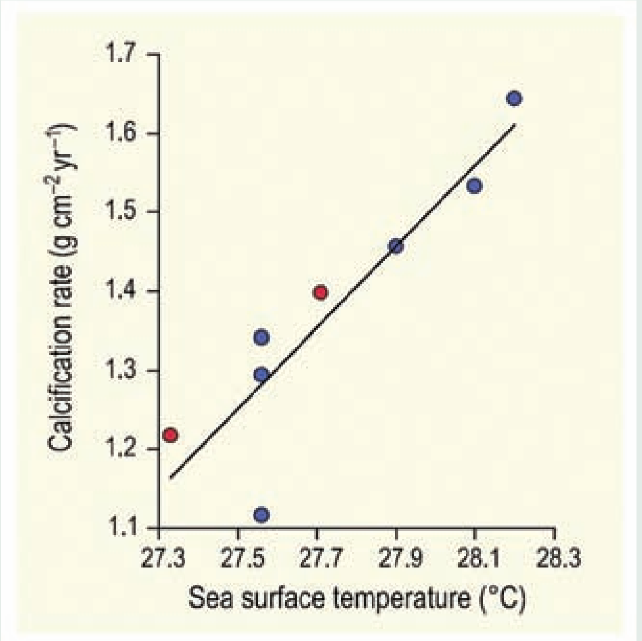
do something very soon to reduce CO_2 emissions,"[130] or that "reefs are starting to crumble and disappear," and that "we may lose those ecosystems within 20 or 30 years," and that "we've got the last decade in which we can do something about this problem."[131]

In reality, the pH decreases often invoked to reaching these conclusions[132] are much larger than those that can realistically be expected to occur, based on reasonable estimates of the size of the remaining recoverable fossil fuel deposits in the crust of the Earth.[133] Such conclusions are based primarily upon abiotic physical-chemical reactions that do not take account of the processes of life, which can greatly modify simple inorganic chemical processes.[134] Many of the experiments examining this issue that actually do deal with living creatures are often of very short duration and do not account for longer-term adaptation, acclimation, or evolution.[135]

A reconstruction of seawater pH spanning the period 1708–1988, based on the boron isotopic composition ($\delta^{11}B$) of a long-lived massive *Porites* coral from Flinders Reef in the western Coral Sea of the southwestern Pacific,[136] indicated that there has been no notable trend toward lower $\delta^{11}B$ values over the 280-year period. Instead, they say "the dominant feature of the coral $\delta^{11}B$ record is a clear interdecadal oscillation of pH, with $\delta^{11}B$ values ranging between 23 and 25 per mil (7.9 and 8.2 pH units)." In addition, they calculated changes in aragonite saturation state from the Flinders pH record that varied between 4.3 and 4.5, which values encompass, in their words, "the lower and upper limits of aragonite saturation state within which corals can survive." Yet in spite of this fact, they determined that "skeletal extension and calcification rates for the Flinders Reef coral fall within the normal range for *Porites* and are not correlated with aragonite saturation state or pH."



Mean yearly calcification rate of *Montastraea annularis* vs. mean annual sea surface temperature for the several sites.[140] The line that has been fit to the data is described by: Calcification Rate = 0.51 SST - 12.85 ($r^2 = 0.82$, $p < 0.002$). Adapted from Carricart-Ganivet and Gonzalez-Diaz.[137]

A study of historical calcification rates determined from coral cores retrieved from 35 sites on Australia's Great Barrier Reef, found that there was a statistically significant correlation between coral calcification rate and local water temperature, such that a 1°C increase in mean annual water temperature increased mean annual coral calcification rate by about 3.5 percent.[137] Nevertheless, it was reported that there were "declines in calcification in Porites on the Great Barrier Reef over recent decades." The researchers were quick to note, however, that their data depicted several extended periods of time when coral growth rates were either above or below the long-term mean, cautioning that "it would be unwise to rely on short-term values (say averages over less than 30 years) to assess mean conditions."

Notably, they reported that "a decline in calcification equivalent to the recent decline occurred earlier this century and much greater declines occurred in the 18th and 19th centuries," long before anthropogenic CO_2 emissions made a significant impact on the air's CO_2 concentration. In fact, the researchers report that "the 20th century has witnessed the second highest period of above average calcification in the past 237 years."

Similar findings were reported by another research team that reconstructed a history of coral calcification rates from a core extracted from a massive *Porites* coral on the French Polynesian island of Moorea that covered the period 1801–1990.[138] They performed this work, they wrote, because "recent coral-growth models highlight the enhanced greenhouse effect on the decrease of calcification rate," as well as the similarly projected negative effect of CO_2-induced ocean acidification on calcification rates. Rather than relying on theoretical calculations, they wanted to work with real-world data, stating that the records preserved in ancient corals "may provide information about long-term variability in the performance of coral reefs, allowing unnatural changes to be distinguished from natural variability." Similar to other studies, they found that a 1°C increase in water temperature increased coral calcification rate at the site they studied by 4.5 percent, which result stands in stark contrast to the 6-14 percent decline in calcification that had earlier been computed should have occurred over the past 100 years, based solely on physical-chemical considerations.[139] In addition, they observed patterns of "jumps or stages" in the record, which were characterized by an increase in the annual rate of calcification, particularly at the beginning of the past century "and in a more marked way around 1940, 1960 and 1976," stating once again that their results "do not confirm" those predicted by the purely physical-chemical model upon which the ocean acidification hypothesis is ultimately based.

In one final study devoted to corals that involves a much longer period of time, another research team determined the original growth rates of long-dead Quaternary corals found in limestone deposits of islands in the Wakatobi Marine National Park of Indonesia, after which they compared them to the growth rates of present-day corals of the same genera living in the same area.[142] This work revealed that the Quaternary corals grew in a comparable environment to modern reefs—except, of course, for the air's CO_2 concentration, which is currently higher than it has been at any other time throughout the entire Quaternary, which spans the past 1.8 million years. Most interestingly, therefore, their measurements indicated that the radial growth rates of the modern corals were 31 percent greater than those of their ancient predecessors in the case of *Porites* species, and 34 percent greater in the case of *Favites* species. Similar findings are ubiquitous, showing increasing rates of coral calcification in the face of rising temperatures and atmospheric CO_2 concentrations.[143,144,145,146,147,148]

Polar ecosystems may benefit from global warming

Polar ecosystems are often portrayed as being one of the most vulnerable of all communities due to CO_2-induced global warming.[149] Yet much empirical data exists to suggest that animals living in these ecosystems will survive and perhaps *thrive* if the world warms in the future. The polar bear is exemplary.

According to model projections, global warming will lead to the extinction of wild polar bears in Alaska by the end of the 21st century.[150] Yet, observational data indicate that, according virtually all scientists, polar bear populations have been *growing* since the 1970s.[151] Additionally, it has been shown that model-based forecasts of polar bear extinction often assume trends in sea ice and temperature that are unlikely to occur, rely on computer climate models that are known to be unreliable, and violate most of the principles of scientific forecasting.[152]

Remote Heard Island, 2,200 miles southwest of Perth, Australia, has seen a bloom in biomass and species diversity as it warmed approximately 1.8°F since 1950.

Another example of polar ecosystems thriving in the face of global warming can be seen from the results of a survey of the plants and animals on Australia's remote Heard Island, located 2,500 miles southwest of Perth. Over the past 50 years, this sub-Antarctic island experienced a local warming of approximately1.8°F that resulted in a modest (12 percent) retreat of its glaciers. In documenting the effects of such a warming and melting on the ecology of the island, scientists report that it led to rapid increases in both flora and fauna.[153] More specifically, researchers found that areas that were previously poorly vegetated were replaced with lush and large expanses of plants. In addition, populations of birds, fur seals, and insects also expanded rapidly. One of the real winners in this regard was the king penguin, which exploded from only three breeding pairs in 1947 to 25,000 five decades later. Similarly, the Heard Island cormorant staged a comeback from *vulnerable* status to a substantial 1,200 pairs, and fur seals emerged from *near extinction* to a population of 28,000 adults and 1,000 pups.

As is typical of nearly all places on Earth, when the temperature rises, when there is sufficient water, so too does ecosystem primary productivity and biodiversity; cold Antarctica is no exception. Historical observations and paleoecological records from the western Antarctic Peninsula, for example, reveal 200- to 300-year cyclical fluctuations in organic matter preservation that result from similar cycles in primary productivity, which researchers believe is due to increasing productivity during periods of warming.[154] In response to the dramatic warming of the past several decades on the Antarctic Peninsula, chinstrap penguins, followed by gentoo penguins, have begun to take up residence in the region around Palmer Station, joining Adelie penguins that have continuously inhabited the area over the past 500 years. A warmer climate has also been shown to benefit polar populations of southern elephant seals at various locations along Antarctica's Victoria Land Coast,[155] penguin species on the Ardley Peninsula,[156] and flowering plants, bryophytes, and terrestrial invertebrate communities along the Antarctic Peninsula and Scotia Arc (South Shetland, South Orkney, and South Sandwich Islands).[157]

Similar benefits have been reported among ecosystems in the high northerly latitudes, where regional rates of warming in the western North American Arctic have reached 0.1°C per year over the past 35 years. Such warming has been associated with marked benefits to terrestrial ecosystems, including increased microbial activity leading to increased plant nitrogen availability[158,159,160] and faster turnover of carbon in Arctic soils,[161,162] which has in turn led to an expansion of shrubs[163,164] and their invasion of tussock tundra.[165] Ectomycorrhizal fungi of the Arctic, which are known to positively respond to warming, have been shown to be important determinants of plant response to ecosystem change through their dual role as drivers of decomposition processes[166] and as the main nutrient harvesting structures of plants.[167]

Among oceanic ecosystems, a warmer climate might also prove providential by melting sea ice and increasing the number and size of open-water habitats known to benefit certain

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mammals. For example, scientists examining changes in the fraction of open water found within various pack-ice microhabitats of Baffin Bay-Davis Straight and northern Baffin Bay in the Arctic identified two types of vulnerability relative to *increasing* sea ice: (1) a direct physical impact where sea ice acts as a barrier for air-breathing foraging animals, and (2) cascading effects of changes in marine productivity.[168]

The first of these problems affects mostly cetaceans, including over 50,000 narwhal, 20,000 beluga, and many bowhead whales. In addition, 33,000,000 breeding pairs of little auks feed in the offshore open water of the North Water region in early May, when ice-free areas there are *declining* and less water is available for the little auks. Similar problems confront many of the more than 100,000 breeding pairs of king eiders and large numbers of thick-billed murres that come from lands as far away as Svalbard and eastern Russia. Considering reports of common eiders, little auks, and thick-billed murres succumbing in ice entrapments,[169] while hundreds of narwhals have periodically died during episodes of rapid sea ice formation caused by sudden cold periods[170,171] in this region, global warming could be welcome.

Coldwater fish

Several studies have documented the ability of fish to adapt and evolve to changes in climate over short time periods.

Adult sockeye salmon (*Oncorhynchus nerka* Walbaum) now migrate up the Columbia River 10.3 days earlier than they did in the 1940s. In an effort to determine why this is occurring, researchers from the Northwest Fisheries Science Center found it was because of an evolutionary response to thermal selection, noting that water temperature records in the lower river showed a rise of 2.6°C in mean July temperature since 1949.[172] This phenomenon explained approximately two-thirds of the phenotypic trend, while most all of the remaining one-third was accounted for in adaptive plastic responses to June river flow. As a result of such findings, the authors of this study concluded that directional environmental changes, such as global warming, "are very likely to induce more rapid evolution in the future."

In another study involving Pacific salmon (*Oncorhynchus* spp.), scientists report that growth of one-year-old chum salmon was less between 1940 and the mid-1970s compared with the mid-1980s to the present, and the change was a direct consequence of warmer sea surface temperatures during the latter period, which led to higher survival rates and larger population sizes of the fish species.[173] Warmer temperatures have also been shown to be responsible for above-average growth in largemouth bass collected and analyzed in the southeastern United States[174] and in golden perch found in the high southerly latitudes of Australia.[175] Furthermore, based on the temperature/growth relationship observed in the golden perch study from Australia, the mean annual growth of two-year-old perch will increase by approximately 15 percent under low CO_2 emission scenarios and by approximately 57 percent under high CO_2 emission scenarios, compared with 1990 CO_2 levels.

Lastly, in an examination of 11 of the fish species living in the extremely cold water around Antarctica, scientists learned that despite low critical thermal maxima (the temperature at which an animal loses the ability to escape from constant rapid warming), all species maintained the capacity to increase their heat tolerance through warm acclimation.[176] More surprising is the fact that they did so at such low temperatures, as cold-dwelling fish species have long been assumed to have a lower level of thermal flexibility.

Taken together, such findings suggest that the growth rates and numbers of many cold water fish species will likely increase under a warming climate. Even among the *coldest of the cold*, it would appear that fish species are capable of adapting (or evolving) to whatever challenges a warming world might present.

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Human Health

Key Messages:

- The health effects of climate change on the United States are negligible today, and likely to remain so in the future, unless the United States goes into precipitous economic and technological decline.
- Death certificate data indicate that 46 percent of all deaths from extreme weather events in the United States from 1993–2006 were from excessive cold, 28 percent from excessive heat, 10 percent from hurricanes, 7 percent from floods, and 4 percent from tornadoes.
- Over the long term, deaths from extreme weather events have declined in the United States
- Deaths in the United States peak in the colder months and are at a minimum in the warmer months.
- In U.S. cities, heat-related mortality declines as heat waves become stronger and/or more frequent.
- Census data indicate that the migration of Americans from the cold northern areas to the warmer southwest saves about 4,600 lives per year and is responsible for 3 to 7 per cent of the gains in life expectancy from 1970–2000.
- While the U.S. Global Change Research Program states that "Some diseases transmitted by food, water, and insects are likely to increase," incidence of these diseases have been reduced by orders of magnitude in the United States over the past century, and shows no sign of resurgence.

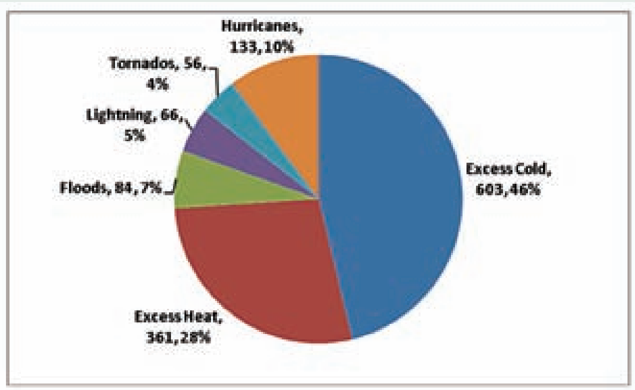
The USGCRP Synthesis Report[1] presents a pie chart showing deaths from various natural hazards, including various extreme weather events. The largest contributor to mortality is given as "heat/droughts." This is based on data from the publication *Storm Data*[2] from the U.S. National Climatic Data Center (NCDC).

However, epidemiological researchers use an alternative database, the CDC's Compressed Mortality Database, compiled from official death certificates filled out by attending physicians at the time of death.[3] The latter is, "in general, a more comprehensive database. As such, it would more likely include weather-related 'single kills' than would Storm Data."[4] Equally important, the judgment of trained physicians in attendance at time of death is to be preferred over that of non-physicians who are responsible for identifying deaths for NCDC, which are tabulated from journalistic rather than medical reports. The Compressed Mortality Database indicates that deaths from excessive cold far outnumber those from excessive heat.[5]

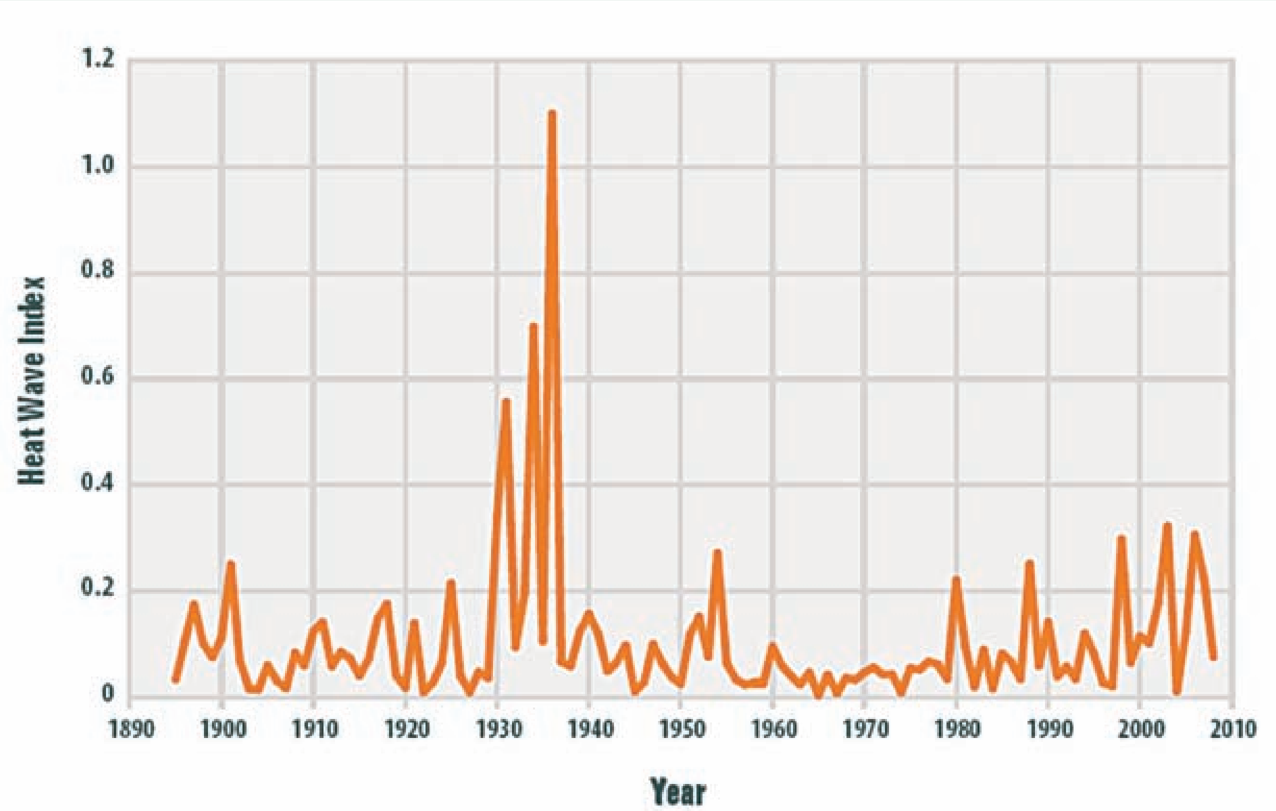
Indur Goklany contributed to this chapter.

Our figure shows annual deaths from weather extremes for 1993–2006. The largest component is the 46 percent from excess cold. There are roughly twice as many deaths per year from excess cold as there are from excess heat.[6] The average annual weather-related death figure of 1,301 is approximately 0.05 percent of the annual average of 2.37 million.

Annual Weather Hazard-Related Deaths in the U.S.



This pie chart shows the annual average number of deaths from six weather hazards as raw numbers and percents of total.[7,8,9,10,11]

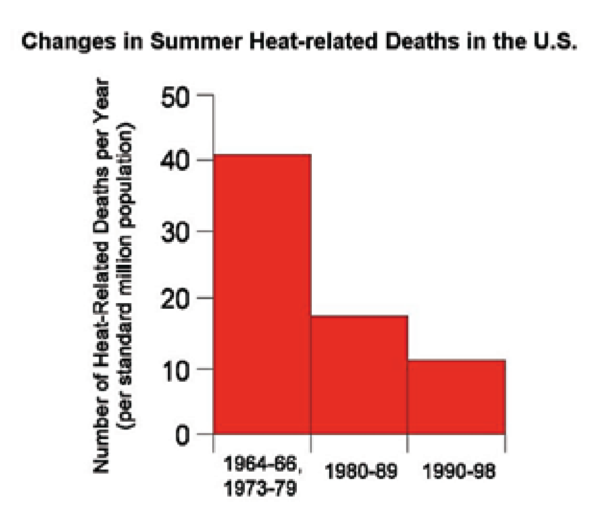


Annual Value of a U.S. national average "heat wave" index. Heat waves are defined as warm spells of four days in duration with mean temperature exceeding the threshold for a one in 10 year event. [15]

Mortality from heat waves declines as heat wave frequency increases, and deaths from extreme cold decline dramatically as cold air preferentially warms

The USGCRP Synthesis Report asserts that, "Temperatures are rising and the probability of severe heat waves is increasing."[12] The USGCRP also notes that from the 1970s to the 1990s, heat-related deaths declined (despite the great Chicago heat wave of 1995). Between 1979–1992 and 1993–2006, the average annual death rates for excessive cold and excessive heat declined by 31 percent and 17 percent, respectively.[13]

Based on data from 1895 onward, heat waves in the United States peaked in the 1930s, according to the U.S. Climate Change Science Program.[14] However, the latter notes that, "In contrast to the 1930s, the recent period of increasing heat wave index is distinguished by the dominant contribution of a rise in extremely high nighttime temperatures."

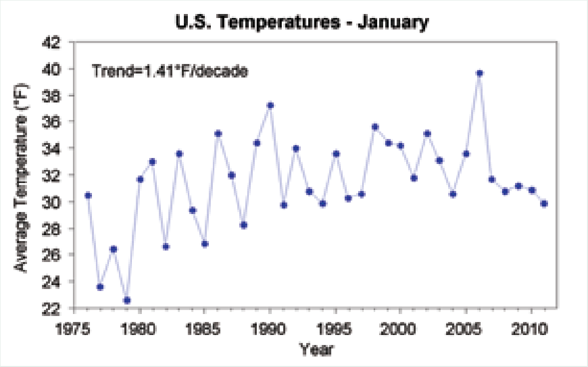


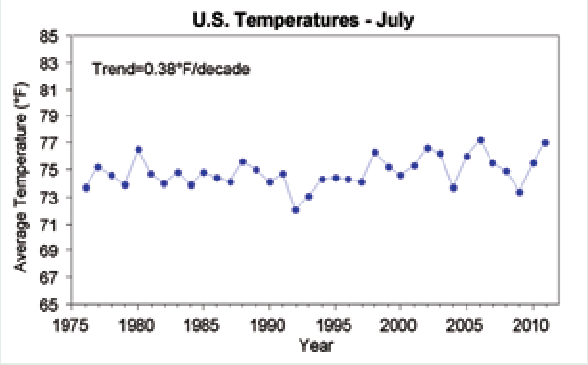
Average heat-related mortality in U.S. urban areas has declined nationwide;[18] subsequent research shows this trend continues into the 21st century.[19]

Consistent with this, several studies find that heat waves for the most part have become less deadly in urban areas. Davis et al. (2003) found that from 1964 to 1998, heat-related deaths declined significantly in 19 of 28 U.S. metropolitan areas, as well as for the 28-city average.[16] Kalkstein et al. found a reduction in mortality attributable to excessive heat events from 1996 to 2004 for 40 major U.S. metropolitan areas.[17]

The Davis et al. study also shows that base heat wave mortality is much lower in urban areas where they are more frequent. Notably, the two cities with the lowest mortality, Tampa and Phoenix, have some of the oldest age-distributions in the world. Thus, the USGCRP statement that "The elderly are also generally more sensitive to extreme heat," while physiologically correct , is profoundly misleading; it is quite clear that in affluent societies, adaptation

Greenhouse Warming Must Lower Thermal Mortality





January and July climatologically have the year's most extreme temperatures. These plots are coterminous U.S. average temperature beginning in 1976, which is the beginning year for the second ("global") warming of the 20th century. It is very clear from this data[20] that the extreme cold of winter has warmed approximately three times more than the extreme heat of summer.

As shown in the graphic at the beginning of this chapter, annual mortality from extreme cold is much greater than deaths from excessive heat.

Greenhouse physics demonstrates that the cold, dry air of the winter must warm more than the hot, moist air of the U.S. summer.

This is because the atmosphere's two main greenhouse gases, water and carbon dioxide, absorb some of the same infrared wavelengths emitted by the earth's surface. When both gases are in short supply (as they were in the necessarily dry winter air prior to the major emissions of carbon dioxide), an increment of either of them creates much more warming than a similar change in the moist warm air of summer. This logarithmic response of temperature to greenhouse gases at similar wavelengths has been known for over 100 years.

The reality of this can be demonstrated by comparing January and July temperatures over the United States that are concurrent with the global warming that began in the mid-1970s. These are the two months that see the most extreme cold and warm excursions of the calendar year.

As U.S. temperatures rose in the final decades of the 20th century, it is clear that the reduction in cold-related mortality has been greater than the reduction in heat-related mortality (notably, both are declining).

As the relative warming of extreme cold must be greater than the increase in extreme heat, greenhouse warming, coupled with greater use of air conditioning and other adapatations, has resulted in an overall decrease in temperature-related mortality.

to heat more than compensates for the relative inability of the elderly to tolerate very high temperatures.

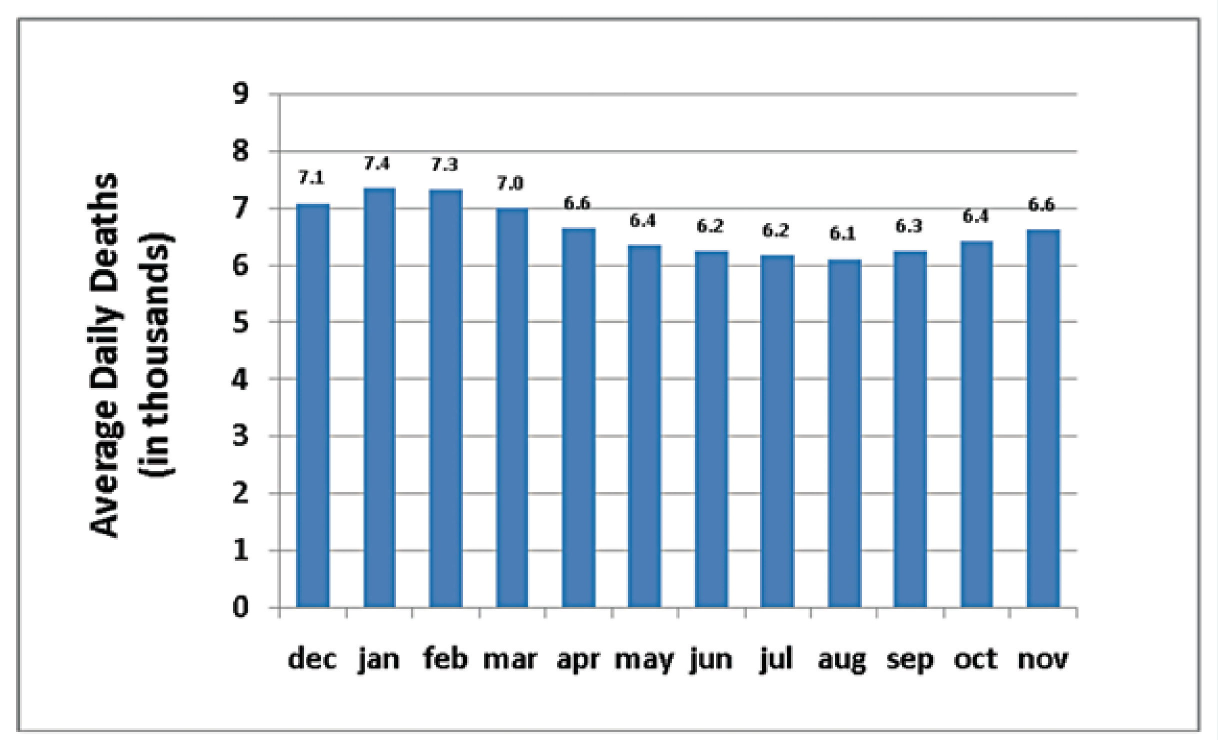
Reduced extreme cold

As noted above, death rates from extreme cold have dropped about twice as much as they have for extreme heat. Consequently, the net effect of greenhouse-induced climate change, where the integrated warming of cold temperatures must be greater than that of high temperatures (see sidebar), will be to reduce weather-related mortality, as is already occurring.

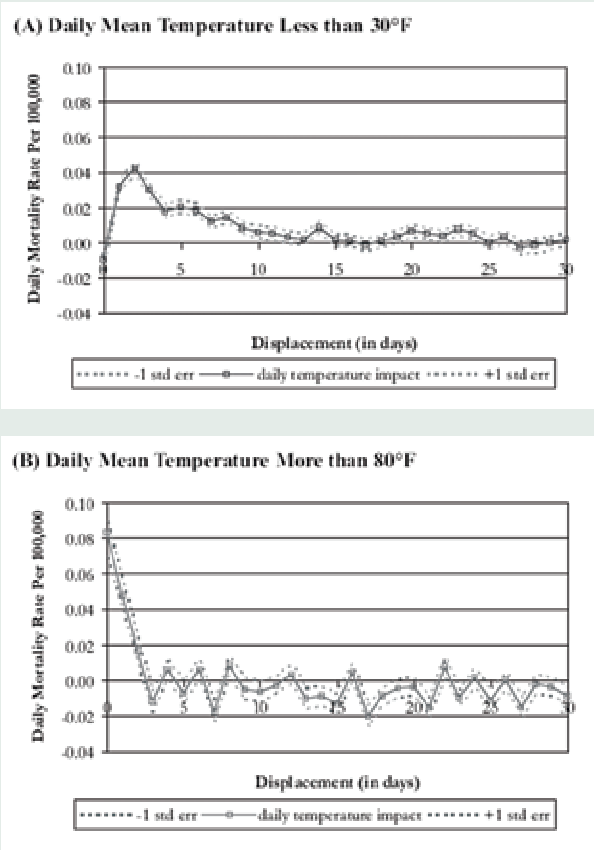
In the United States and many other countries outside the tropics, the daily death rate is higher in the colder months of the year than during the rest of the year.[21,22] This phenomenon of "excess winter mortality" was responsible for 108,500 excess U.S. deaths in January through March and December of 2008, almost two orders of magnitude higher than deaths from all extreme weather events.[23]

The USGCRP report leaves readers with the impression that global warming will add to the global mortality burden. Specifically, it claims that increases in deaths from extreme heat and heat waves are "very likely," whereas "Some reduction in the risk of death related to extreme cold is expected." However, in fact, additional warming should reduce deaths because of the disproportionate mortality from extreme cold.

U.S. data show that extreme cold–related mortality peaks about three days after the minimum temperatures (likely a result of transmissible viruses), while there is an immediate increase in mortality on days with extreme heat (likely a result of physiological stress). However, after hot events, net mortality is partially offset by a deficit of deaths on subsequent days (grimly called premature "mortality harvesting" of the infirm), whereas for cold events, mortality continues to rise and stay above the pre-event normal for the following 10–15 days.[24] Consequently, averaged over the following month, there is less of an increase in all-



Average daily deaths by month, United States, 1999–2008.[26]

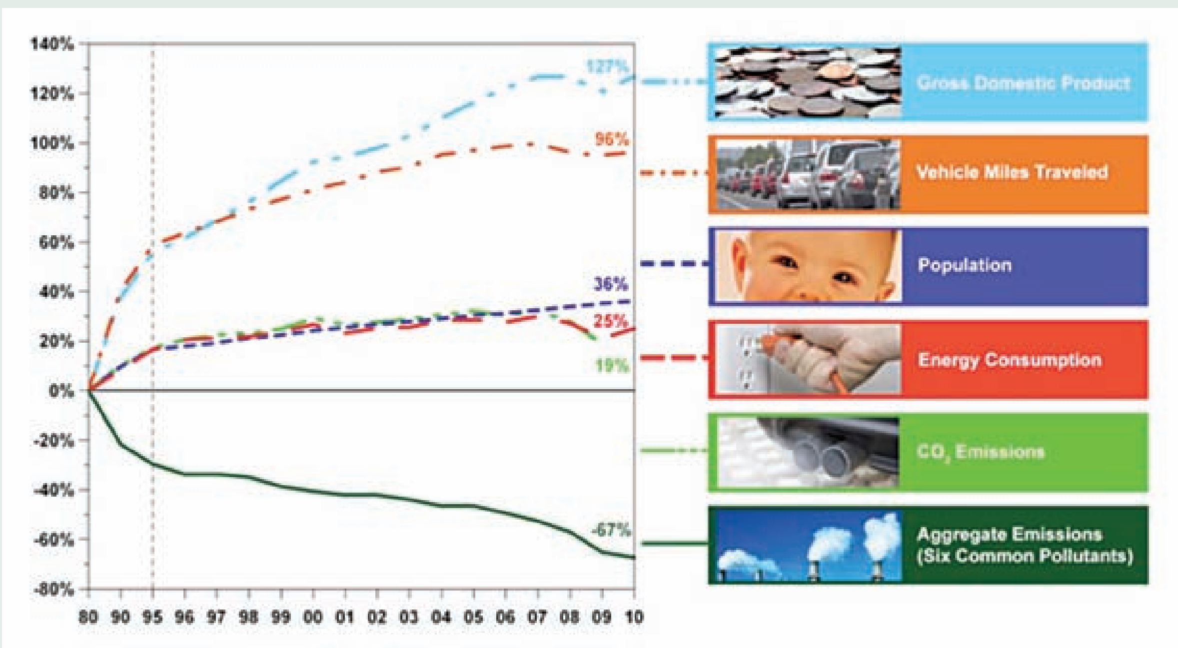


Estimated effect of cold and hot temperature exposure on daily female all-cause mortality rates for 30 days following exposure.[27] Note that the number of abnormal deaths from extreme winter cold persists to day 15, while the death rate actually drops below normal three days after extreme heat, and the average anomaly remains negative through 30 days.

cause mortality from a hot event than there is from a cold one. As a consequence, it has been estimated that the migration of Americans from the cold northern areas to the warmer Southwest saves approximately 4,600 lives per year (based on 2000 Census data) and is responsible for 3–7 percent of the gains in life expectancy from 1970–2000.[25]

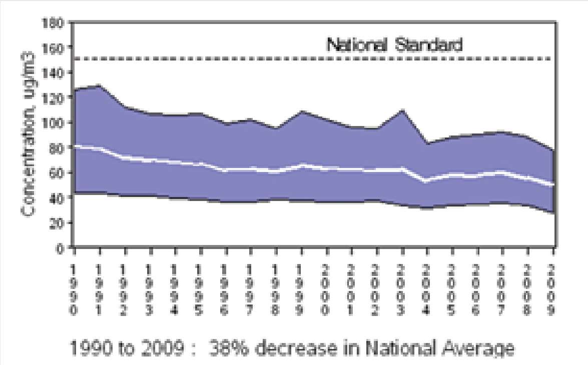
Air quality in the United States has been improving since 1970 and will likely continue to improve in coming decades

Higher temperatures increase most chemical reaction rates, and the resulting higher pollution levels can degrade air quality. Yet despite this fundamental fact of chemistry, air quality in the United States is better today than it has been at any time in the past 50 years, notwithstanding an observed warming. Since 1970, U.S. economic productivity has doubled and vehicular travel has increased dramatically, as has the population and energy consumption. Although these factors are typically linked to poor air quality, according to EPA estimates, total emissions of six major pollutants declined by almost 70 percent over that same time period.[28]



Despite an increasing population, energy consumption, and economic productivity, U.S. pollution emissions declined by 67 percent since 1980.[29]

PM10 Air Quality 1990–2009
(Based on Annual 2nd Maximum 24-Hour Average)
National Trend Based on 310 Sites

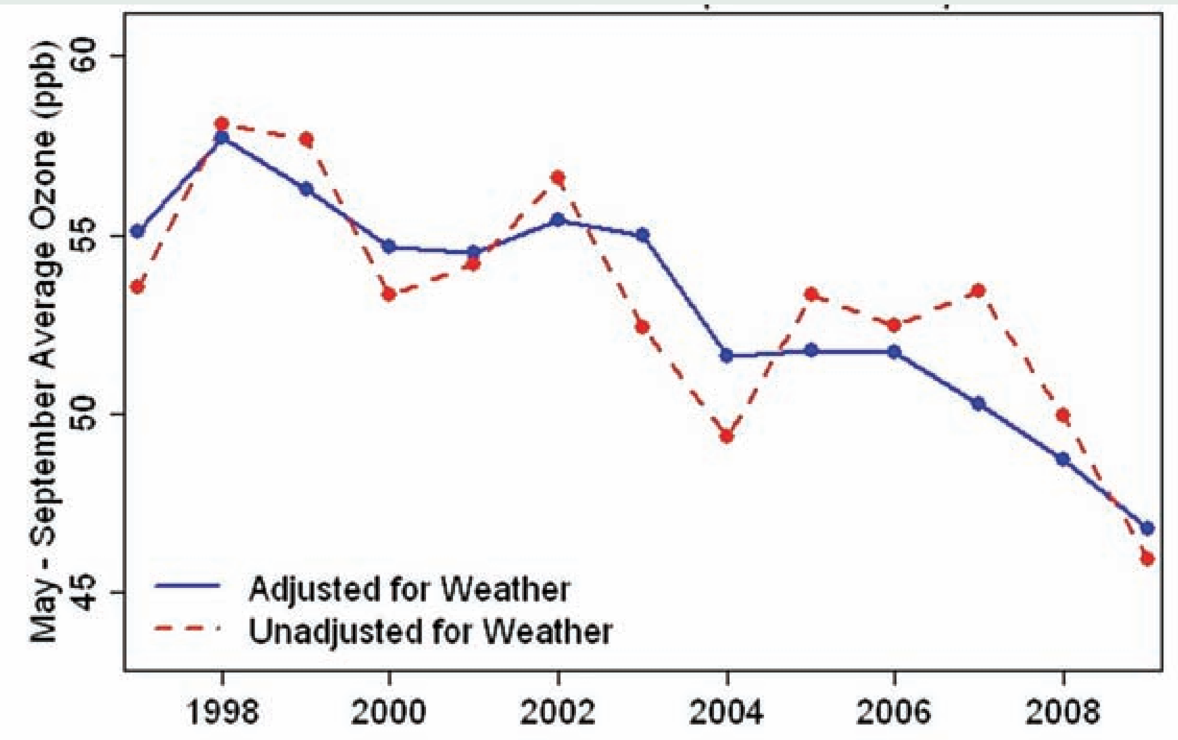


From 1990 through 2009, there was a 38 percent decrease in the concentration of large particulate matter in U.S. air.[33]

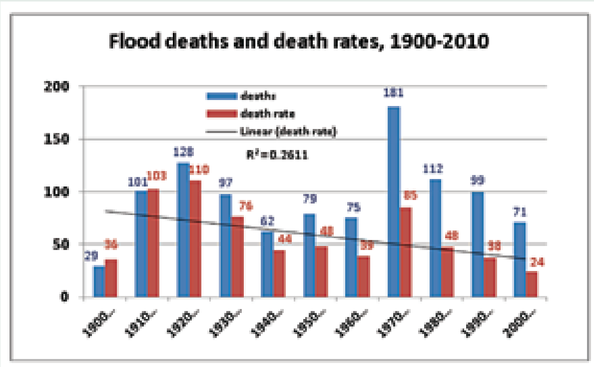
Much of the air quality improvement stems from technology that produces cleaner burning fuels, power plant scrubbers, more low emission vehicles, etc. Pollutants such as sulfur dioxide, nitrogen dioxide, and carbon monoxide have declined so dramatically since the 1970s and 1980s that they are no longer engender significant discussion. Because of their linkage to human respiratory health, the major pollutants of contemporary interest are particulate matter (both small (PM2.5) and large (PM10) diameter), and ozone. Like the other pollutants, PM levels have declined significantly since a consistent measurement program began around 1990.[30] Ozone, the main contributor to urban smog, has also declined.[31]

Pollution levels depend not only on emissions but on atmospheric conditions. Although rising temperatures should result in poorer air quality, temperature is not the only important factor in determining air quality, or even the most important one. Pollutants tend to concentrate in stable air masses in which temperature increases with height above the surface. However, because the surface has been warming relative to the overlying atmosphere, the long-term tendency has been to destabilize the atmosphere, resulting in more vertical mixing

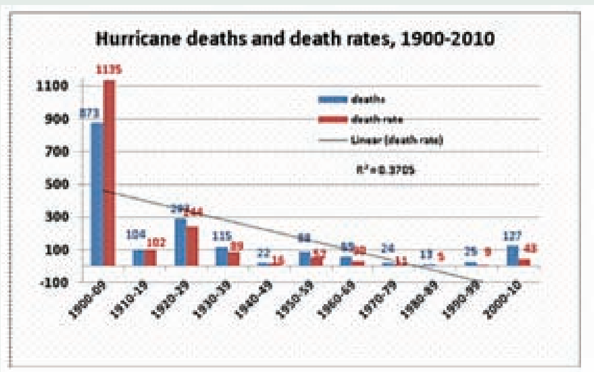
National Ozone Trend (166 Locations)



Both the observed trend in May–September ozone (red line) and the trend corrected for varying weather conditions (blue line) show a significant decline from 1997–2009.[34]



Annual U.S. flood deaths and death rates (fatalities per 100 million), by decade.[47]



Annual U.S. hurricane-related deaths and death rates (fatalities per 100 million), by decade. The 1900–09 data are largely skewed by one event, the 1900 Galveston hurricane, which killed approximately 8,000.[48]

and less concentrated pollutants. This trend is particularly true in cities (the areas of greatest pollution concern) because of the urban heat island effect in which cities are generally warmer than the surrounding rural areas. High humidity is also related to higher ozone levels, and increased temperatures have lead to a slight humidification over time. Furthermore, precipitation serves to wash pollutants out of the atmosphere, so the net effect of increasing precipitation across the United States over the past century has also played a role in air quality improvements. After accounting for the influence of the meteorological effects of air quality, the trend in ozone levels has declined markedly since 1997.[32]

Given the historic trends in air quality, technology, and climate, it is highly likely that U.S. air quality in future decades will be even better than it is today and that the populace will be healthier and have an even longer life expectancy.

Declining weather-related mortality

Deaths from virtually all categories of severe and extreme weather have declined impressively on longer time scales.[35] Specifically:

- Average annual flood deaths and death rates declined 60 percent and 72 percent, respectively, from 1970–79 to 2000–2010.[36,37,38]

- Average annual hurricane deaths and death rates declined 82 percent and 95 percent, respectively, from 1900–1909 to 2009–10.[39,40,41] Note, however, that this figure is biased by the 1900 Galveston hurricane that killed an estimated 8,000.

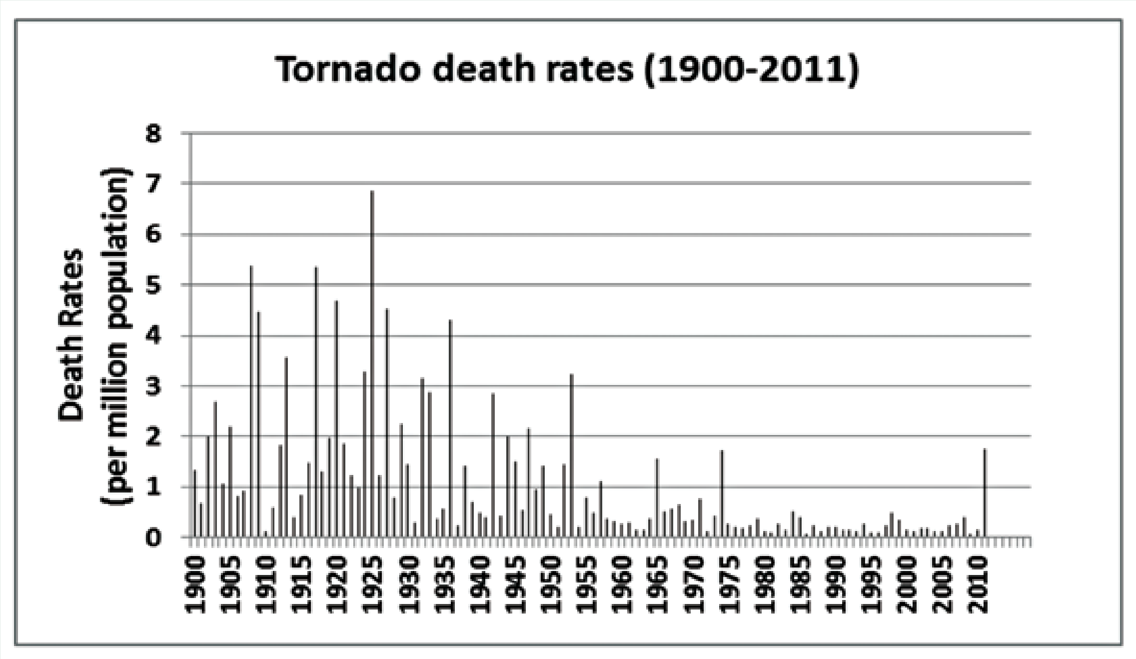
- Despite the active 2011 tornado season, deaths and death rates for tornadoes peaked in the 1920s.[42,43,44,45]

- Lightning deaths and death rates have been declining more or less steadily for as long as data are available.[46]

For the United States, the cumulative average annual deaths from extreme weather events declined by 6 percent from 1979–92 to 1993–2006 (despite a 17 percent increase in population), while all-cause deaths increased by 14 percent.[50] American society is mitigating the effects of weather-related events better than it is mitigating other causes of death. If there is any linkage between global warming and extreme weather events in the United States, the adaptational response of our society has rendered the change inconsequential.

Changes in extreme event frequency and magnitude

As noted above, the heat wave index peaked in the 1930s. Frequencies now resemble those in



U.S. tornado death rate, 1900–2011. Sources: Updated from Goklany (2009a), using USBC (2011); NWS, Hazard Statistics at http://www.weather.gov/os/hazstats.shtml, accessed May 11, 2012; NWS, Storm Prediction Center, Annual U.S. Killer Tornado Statistics, at http://www.spc.noaa.gov/climo/torn/fataltorn.html, accessed May 11, 2012.[49]

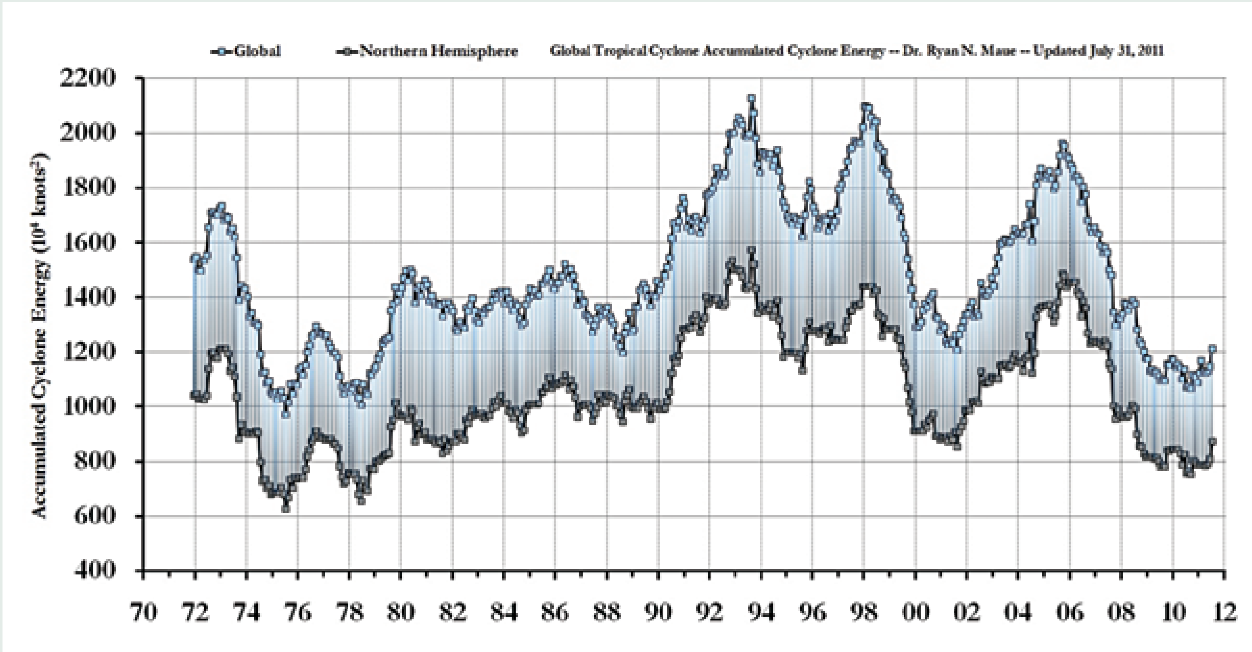
the early 20th century, rising from their historic low regime that occurred from the late 1950s through the mid-70s. Recent heat waves have been characterized by high night temperatures, which is consistent with both increasing urbanization and increasing greenhouse gas concentrations.

Precipitation has increased nationally by about 7 percent since 1900 with no clear relationship to global temperature anomalies. Rainfall on the heaviest day of the year has also increased since then, by about 0.30 inches, and the heaviest precipitation–days have become rainier, primarily in the Northeast.[51] However, analyses of 572 eastern U.S. stream gauge stations with at least 75 years of data prior to 2009 found "little evidence for increasing flood peak distributions associated with human-induced climate change."[52] Similar analysis using 196 stations for the Midwest also found no suggestion of increasing flood peaks.[53]

There is simply no trend for drought, averaged across the nation, although climate models and recent data suggest increasing aridity in the southwestern United States It is important to note that absence of an overall trend across the nation indicates that there is a compensatory decrease in drought elsewhere, mainly in the Midwest and the Northeast.

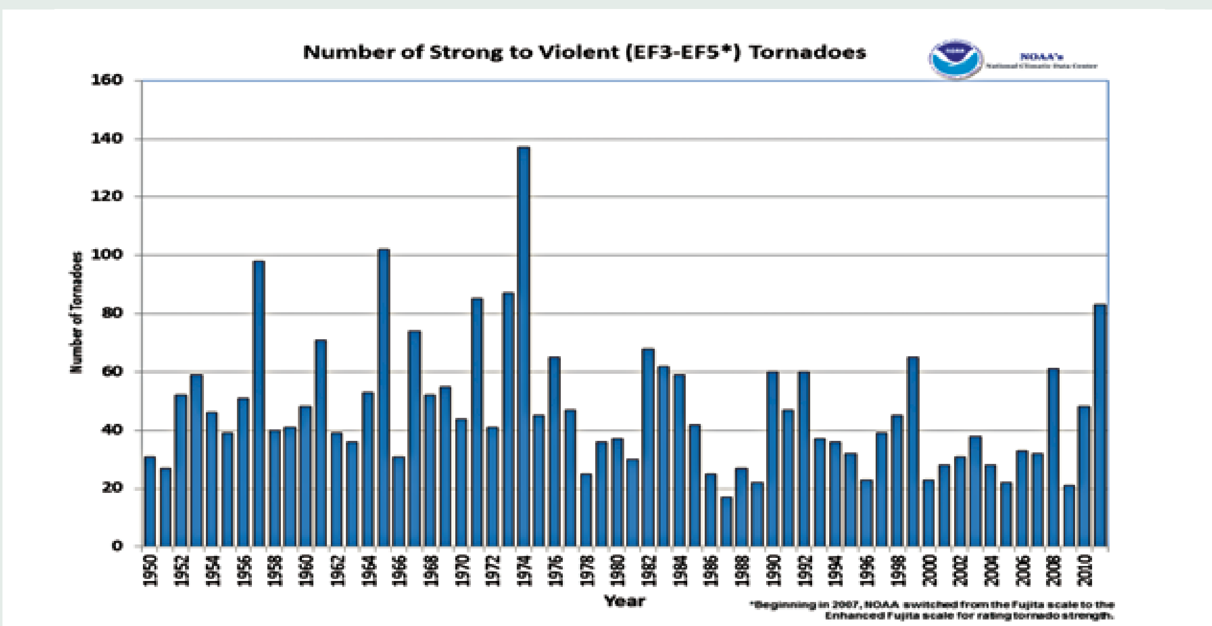
Nonetheless, recent analyses of empirical trends in the Southwest do not indicate any significant, monotonic trend in drought. Rather, "El Niño events have been more frequent, and this has resulted in increased precipitation in the southwestern United States, particularly during the cool season. The increased precipitation is associated with a decrease in the number of dry days and a decrease in dry event length."[54]

Recent droughts in the U.S. corn belt are modest in length and intensity compared to historical or millennial-scale paleo records.[55]



Global and Northern Hemisphere Accumulated Cyclone Energy: 24-month running sums through July 31, 2011. Note that the year indicated represents the value of ACE through the previous 24 months for the Northern Hemisphere (bottom line/gray boxes) and the entire globe (top line/blue boxes). The area in between represents the Southern Hemisphere total ACE.[61]

In a study that used tree ring data from 1591 through 2005, recent droughts in the Upper Snake River are "eclipsed by a sustained low-flow period lasting for over 30 years in the early to mid-1600s."[56] Longer term (millennium-scale) paleoclimatic studies for the United States confirm that 20th-century droughts, including the Dust Bowl, were unexceptional in length relative to droughts preceding the instrumental record,[57] regardless of global



Number of strong U.S. tornados, 1950–2011. Source: NCDC, U.S. Tornado Climatology, 7 March 2012, at http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html, accessed May 11, 2012.

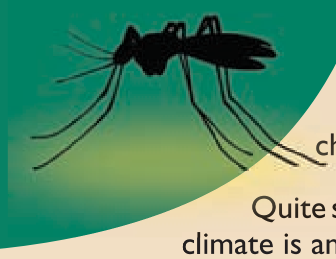
temperature. The continentality of the United States simply means that we are a drought-prone nation.

Atlantic hurricane frequency has not increased since the late 1800s despite any warming of sea surface temperatures.[58] Estimates of global and Northern Hemisphere Accumulated Cyclone Energy (ACE) from 1971 to the present (July 31, 2011) indicate that Northern Hemisphere and global tropical cyclone ACE are close to their lowest levels since the late 1970s.[59,60]

Additionally, the global frequency of tropical cyclones is also close to its lowest level in past decades. These patterns are inconsistent with any hypothesis that higher greenhouse gases lead to more extreme or more frequent hurricanes.

The history of strong (EF3–EF5) tornadoes from 1950 through 2010 does not indicate any monotonic increase in their frequency, again inconsistent with any hypothesis that carbon dioxide is a determinant of tornado numbers and/or intensity directly or indirectly via its temperature effect.[62]

SPOTLIGHT ON
West Nile Virus

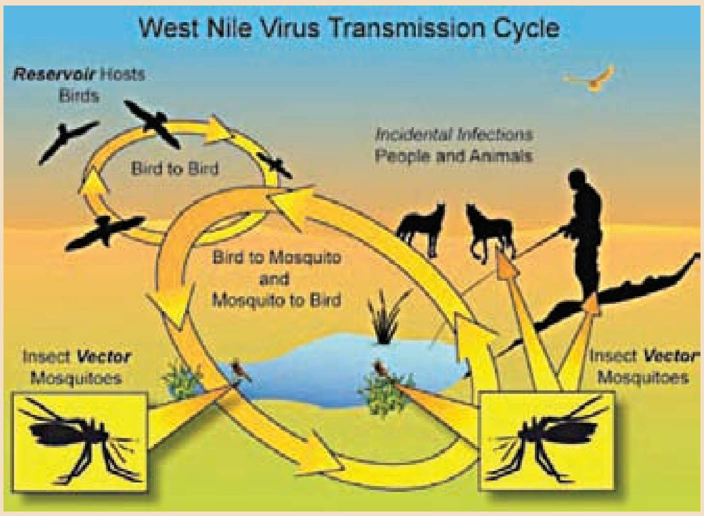


West Nile virus spread unrelated to climate change

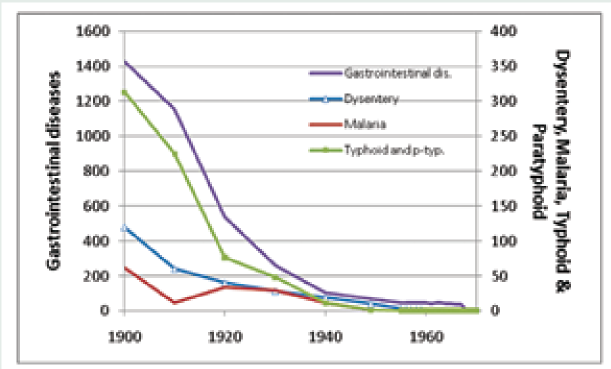
West Nile Virus was introduced to the United States in 1999, probably via an airline passenger in New York City. Over the subsequent decade, it spread throughout the lower 48 states. Although some claims have been made that the disease's spread was related to climate change, this theory is untenable based upon elementary observations.

Quite simply, West Nile spread throughout the United States because the U.S. climate is amenable to its survival. The virus has managed to survive in Boston, Minneapolis, Seattle, Phoenix, and Miami, making it obvious that that it thrives over a wide range of climate conditions.

Observations show that sometimes West Nile spread is more effective after wet winters, while at other times, it's greater after dry winters.[63] Clearly, the precipitation conditions favorable for viral spread are highly variable. Furthermore, when the observed spread of this disease is modeled based upon patterns of migratory birds, the resulting patterns fit observations better than patterns derived from the common mosquito-based hypothesis. [64] Therefore, climate change from 1999–present would also have to account for bird migration patterns. Other factors such as habitat suitability, competition, and predation have significant effects on the West Nile's survival. [65]



In short, it is extremely unlikely that the spread of the West Nile Virus across the United States in the early 21st century occurred because of very small changes in temperature, precipitation, winds, or other factors relative to the long-term trend. In reality, West Nile Virus would have spread though the United States if it were introduced in 1999, 1969, or 1909.



Death rates (deaths per million) for various water-related diseases, United States, 1900–1970. By 1950, these had become (and remain) inconsequential from a public health standpoint.

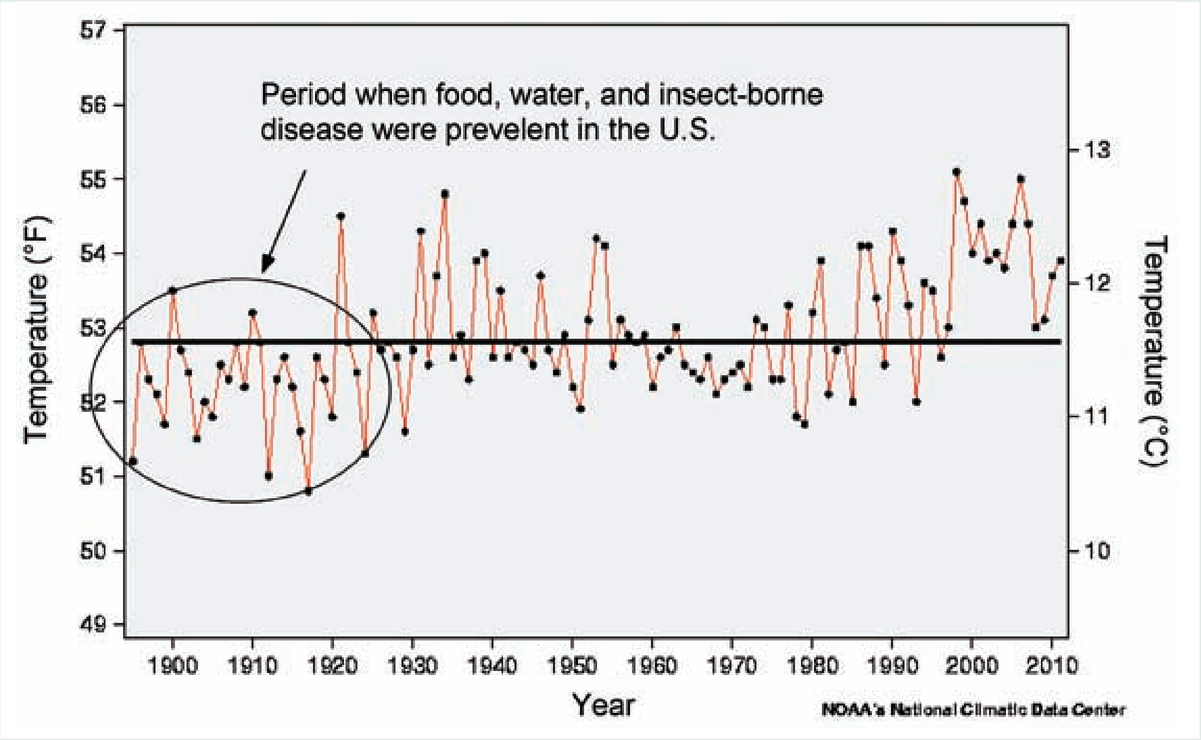
Food, water, and insect-borne diseases

Food, water, and insect-born disease were major killers in the early 20th century, the coldest period in the U.S. instrumental record. They were eradicated not by changing climate but by public health measures. Given the huge natural range of U.S. climate, the hypothesis that a few degrees of warming would suddenly bring back massive disease is risible (as is the notion that West Nile Virus spread across the United States because of climate change).

The cumulative death rate in 1900 from typhoid and paratyphoid, various GI diseases (gastritis, duodenitis, enteritis and colitis), and all forms of dysentery was 1,922 per million.[66] For a population the size of the United States today, that translates into over 600,000 deaths annually. Currently, however, deaths from all food-, water-, and insect-borne diseases are approximately 3,000, annually.[67,68] To put these numbers in context, the United States has 2,400,000 deaths annually. U.S. death rates from various water-related diseases—dysentery, typhoid, paratyphoid, other gastrointestinal diseases, and malaria—declined by 99.6–100 percent from 1900 to 1970.[69]

Malaria in the United States, 1882

Malaria was a national scourge in the United States in the late 19th century, when the average surface temperarture of the nation was about 1.5° lower than present.[70]



Food-, water-, and insect-borne diseases were at their peak during the coldest part of the 20th century.

In the late 19th century, when the coterminous United States was about 1.5° cooler than the present, malaria was endemic to the Canadian border. Public health measures, not climate change, are the major determinant of the disease.

Rising temperatures and carbon dioxide concentration increase and/or decrease pollen production and the pollen season in some plants and/or others

The syntax of the title of this section was used by the United Nations' Intergovernmental Panel on Climate Change, which it calls the "consensus of scientists," in an important report. Because increased levels of CO_2 enhance plant growth and higher temperatures lengthen the growing season, many plants and crops are blooming earlier and growing over a longer period of time. This is advantageous for certain commercial crops (e.g., grapes) that require a very long growing season to fully mature. This enhanced plant growth also affects pollen.

With an earlier onset of spring, this will shift the timing of the pollination of most plants. But the impact of higher temperatures and CO_2 on pollen is uncertain, as some species of plants seem to produce more pollen given the longer growing season[71,72,73,74] while others are negatively impacted.[75,76,77]

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Society

Key Messages:

- Society is much less sensitive to climate and, therefore, climate change, than it used to be.
- Death rates from climate-sensitive diseases and extreme weather events have declined substantially over the past several decades. There are no upward trends in economic losses from such events, once losses are corrected for growth in population and wealth.
- Whether global warming occurs or not, future populations should be wealthier than they are today and therefore have a wider range of technological options at their disposal. They should therefore be more resilient to adverse effects of climate and climate change.
- Future human well-being would be highest under the warmest IPCC scenario (A1FI) and lowest under the poorest (A2) scenario, even after considering the costs of global warming.
- As a result, fears that climate change will lead to societal breakdown, mass emigration, and security threats to the United States are inconsistent with the IPCC scenarios of climate change.
- Climate change policies could reduce economic and technological development, which would reduce society's resources and options.
- Agriculture and recreation will adapt to the slow evolution of climate change in this century.
- Increasing development of global markets will mitigate the international effects of climate change on the United States.

Diverse and developed societies, such as that of the United States, have demonstrated only marginal sensitivities to observed climate changes, while poor and underdeveloped ones, such as in sub-Saharan Africa, have been more effected.

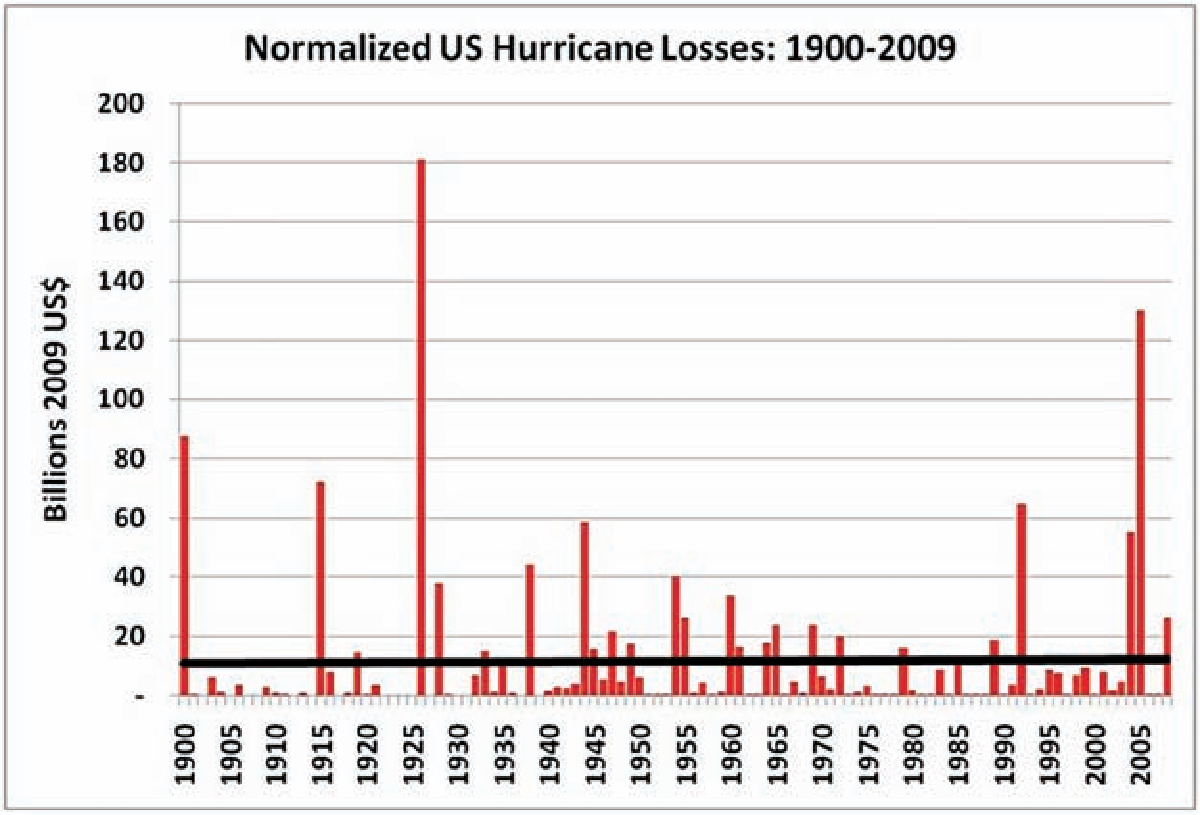
The world's civilizations have developed under a wide range of climates, with humans living comfortably in seasonal temperatures from -40° to 120°F. U.S. society is particularly adapted to a very broad range of climates, from the extreme cold of central Alaska to teeming desert cities like Las Vegas, where temperatures regularly exceed 110°F, and on to the tropical climate of southeastern Florida.

As noted in the last chapter, our society has serially *reduced* its sensitivity to climate extremes. There is no reason to expect, as the rest of the world continues to develop, that the same will not be repeated around the globe. To believe otherwise is to maintain a pejorative view of humanity that does not comport with the American experience.

Indur Goklany contributed to this chapter.

The notion that poorer countries' vulnerability to climate change imposes major problems because of the interconnectedness of the world indeed eschews the market nature of those connections. Nowhere on earth forever experiences salutary weather and climates. Nations that are not agriculturally productive purchase from those that are, and those in variable environments can alternatively export or import food. Since the advent of modern technological agriculture, there has never been a systematic and worldwide food shortage caused by weather and climate. In fact, it is the diversity and variability of climate that ensures such interwoven security.

Hi-tech agriculture ensures a world market supply of food.



U.S. tropical cyclone damage (in 2009 dollars) when adjusted for inflation, population growth, and wealth, 1900–2009.[3]

Population shifts are prolonging and enriching lives, but increasing exposure to hurricane damage

Shifting populations from cold-to-warm winter environments saves approximately 4,600 lives per year.[1] Despite massive growth of the desert and dry cities of Phoenix, San Diego, and Las Vegas (whose MSA has a population of approximately 2,000,000 and historically has doubled in ten years) and considerable political ferment over water rights and distribution, water continues to flow with no major or systematic emergencies.

Paleoclimate records cited earlier in this volume indicate that the Colorado River drainage, which provides water to much of the Southwest, is subject to major and prolonged droughts that are far beyond those experienced since the rapid development of the region.

With or without climate change, there will at some point be major and persistent drought that regional planners should take into account.

Hurricane damages have escalated dramatically in recent decades with the advent of virtually complete development of the Atlantic and Gulf coasts. However, the rise in costs is not related to any secular change in tropical cyclones, as none has occurred. Actual damage costs adjusted for population, inflation, and real estate valuation changes show no significant escalation.[2]

Vulnerability of society to climate variation has declined over time

Until the Industrial Revolution, mankind's well-being was intimately tied to climate and weather. Since then, the importance of these two related factors has declined dramatically.

Consider that no other major economic activity can be as sensitive to climate and weather as agriculture. But because of economic and technological development, driven in large part by greater fossil fuel–powered energy use, weather sensitivity of global agriculture has monotically decreased. In 1800, about 80–90 percent of the U.S. working population was engaged in agriculture. This dropped to 41 percent by 1900, 16 percent by 1945, and today it is 1.5 percent.[4,5] Although agricultural production increased spectacularly, its contribution to the country's economic output also shrank because of massive gains in other sectors. In 1900, agriculture accounted for 23 percent of GDP,[6] today it is 0.7 percent.[7] The same dynamic is operating in other countries, and agriculture's share of gross global product is declining worldwide.[8]

Also, as was shown in the chapter on Human Health, U.S. deaths from climate-sensitive water-borne diseases (including malaria, typhoid, paratyphoid, and various gastrointestinal diseases) have declined by over an order of magnitude since 1900. Water-borne diseases, for example, were responsible for 600,000 deaths in 1900. Today, they contribute to fewer than 5,000 deaths annually despite a quadrupling of the population. Deaths from extreme weather events have also been reduced, but by a lesser amount.

The decline in the importance of climate and weather for human and economic well-being means that over the long term, the United States has become much less dependent on the climate and weather for its well-being. By the same token, climate change is itself of lesser importance. This is true not only for the United States but around the world.

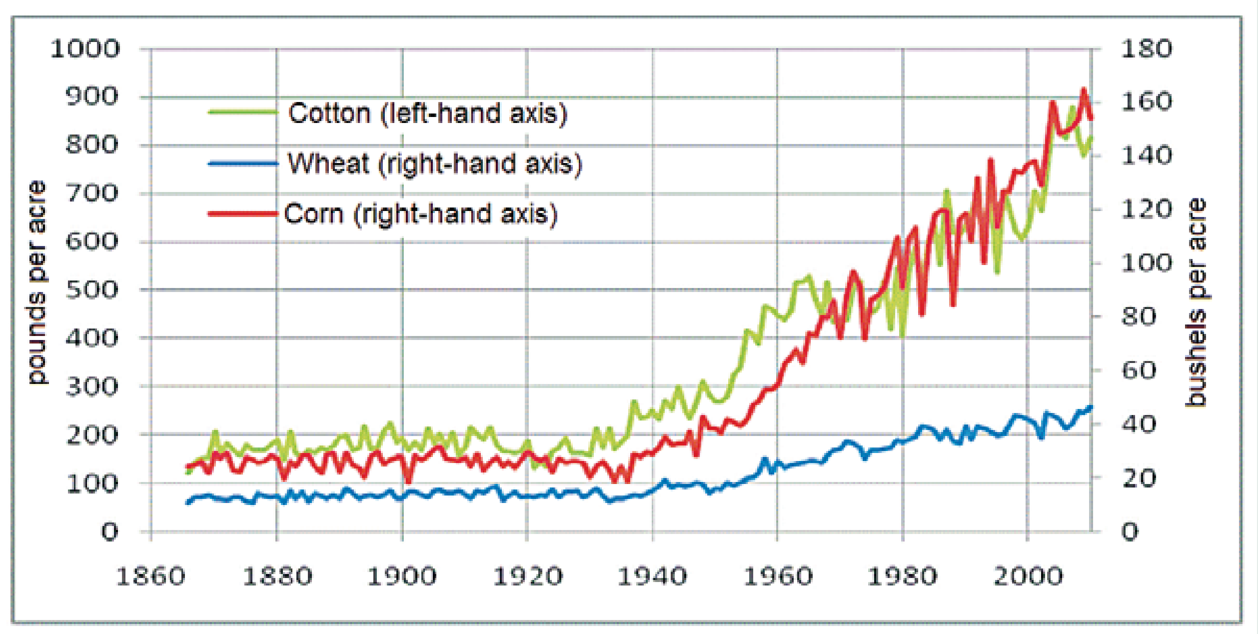
Other factors have accelerated these trends. In particular, the increase in trade in agricultural and forestry products means that if an area experiences a shortfall of food either because its productivity has always been low or it has been depressed because of weather (or man-made events such as poor agricultural policies or conflict), food shortfalls can be made up via trade.[9]

Vulnerability declines as resources and options expand

Greater economic development allows societies to better afford the technologies needed to cope with problems in general and climate change in particular.[10] It is also associated with higher levels of human capital, which is a critical factor for adaptive capacity. From 1820 to 1900, U.S. GDP per capita (adjusted for purchasing power) had more than tripled from $1,257 to $4,100 (in 1990 International dollars).[11] By 2009, it had grown another sevenfold to $30,550.[12] These increases in economic development, coupled with secular technological change, have expanded both resources and options for coping with or taking advantage of climate, climate variability, and climate change.[13] Consequently,

- Agricultural yields have increased several-fold. Since the end of the Civil War, U.S. wheat yields have quadrupled while corn and cotton yields have grown six-fold. This occurred in an era of global and national warming, which clearly could only be a minor contributor to yield increases. More noteworthy is the fact that warming certainly was *not* associated with reductions in yield, and that the agent of warming—carbon dioxide—increased yield.[14] Notably, many of the technologies that enabled the growth in agricultural yields depend on fossil fuels. These include fertilizers, pesticides, irrigation, and agricultural machinery, all of which depend on fossil fuels for their manufacture or operation.

- Death rates from climate-sensitive water-borne diseases declined 99.6 percent–100 percent between 1900 and 1970.[17]



U.S. cotton, corn, and wheat yields, 1866–2010.[15]

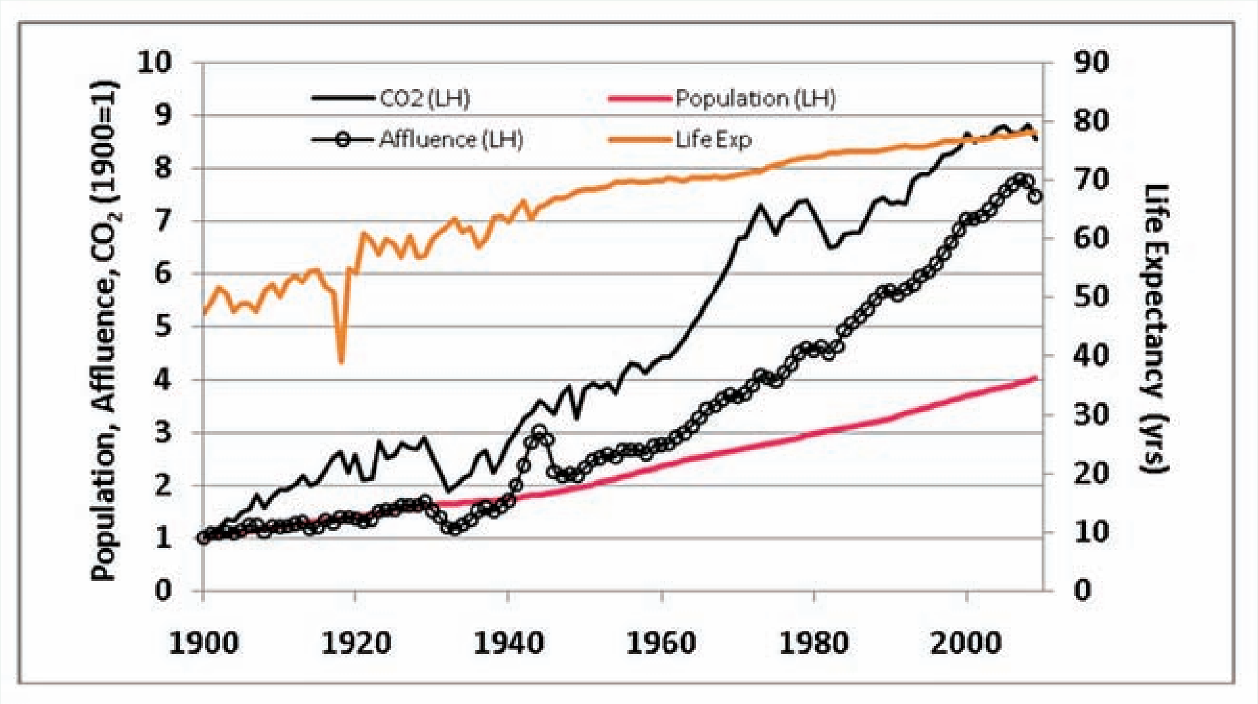
- Cumulative death rates from hurricanes, floods, tornadoes, and lightning declined by 80 percent since the early 1900s.[16]

Similarly, deaths and death rates from excessive heat events have also declined.[18] These reductions can be attributed, in substantial part, to energy-intensive technologies such as air conditioning to ward off excessive heat, transportation to move people out of areas threatened by extreme weather (while moving in emergency responders, food, medical, and other emergency supplies), and reliable communication systems. This has been aided by improved meteorological forecasts, which rely mainly on electricity-powered communications systems for dissemination.

Furthermore, analysis of property losses from various extreme weather events—floods,[19] hurricanes,[20] tornadoes[21]—indicate no upward trend in economic losses if losses are normalized to account for inflation and increases in property-at-risk.

All these findings reinforce the conclusion that vulnerability to climate and climate change has declined.

More importantly, the benefits of economic and technological change, underpinned to a large extent by fossil fuel energy use, are not limited to reducing vulnerability to climate and climate change but to many other sources of adversity.[22,23] Consequently, we see that compared to prior decades, after solving or managing one problem after another, people are now, for example, living longer and healthier.[24] U.S. life expectancy—the best single measure of human well-being—increased from 47 years in 1900 to 78 years in 2009, even as carbon dioxide emissions grew eight-and-a-half fold and population quadrupled. Yet, Americans now have more creature comforts, they work fewer hours in their lifetime, their work is physically less demanding, they devote more time to acquiring a better education, they have more options to select a livelihood and live a more fulfilling life, they have greater economic and social freedom, and they have more leisure time and greater ability to enjoy it.[25] These trends are evident not just in the United States



U.S. carbon dioxide emissions, population, GDP per capita (affluence), and life expectancy at birth, 1900-2009.[27]

but, with some notable exceptions caused largely by repressive dictatorships, elsewhere as well.[26]

If future populations are wealthier than current ones and technological advances continue, as has been the case since the Industrial Revolution, they should be more resilient and less vulnerable than current populations to the adverse effects of climate change.[28]

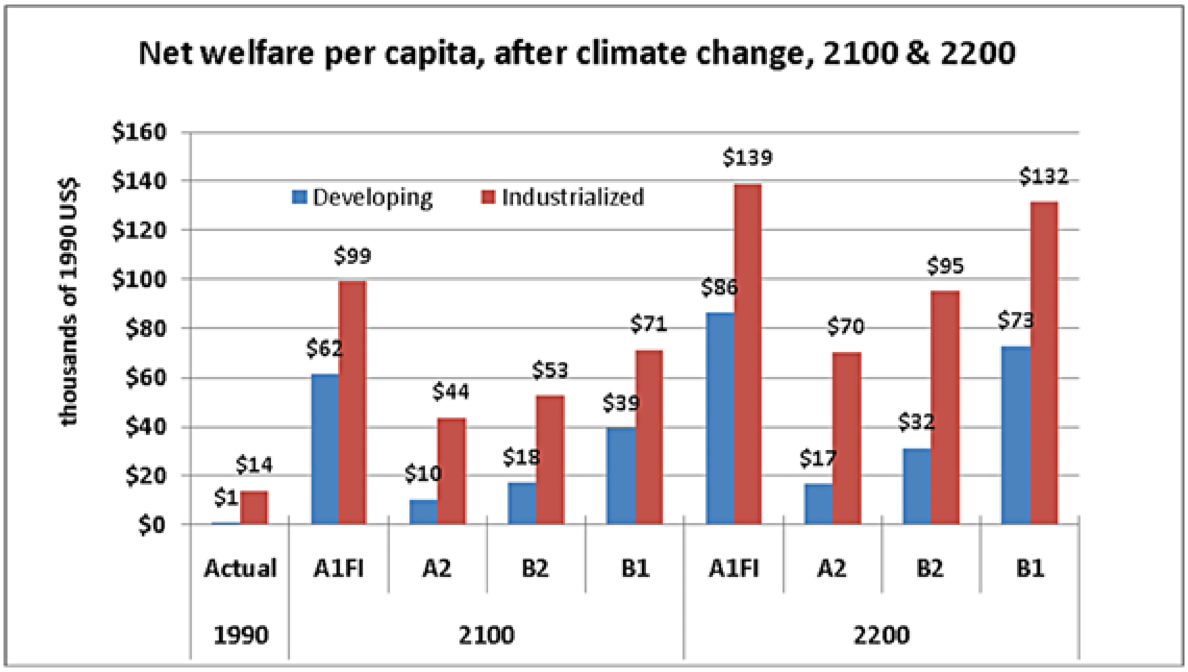
Vulnerability should decline further in the future

Projections based upon status-quo economics are likely to be gross errors. This may be relevant to an important statement made on page 99 of the USGCRP report:

> Unequal adaptive capacity in the world as a whole also will pose challenges to the United States. Poorer countries are projected to be disproportionately affected by the impacts of climate change and the United States is strongly connected to the world beyond its borders through markets, trade, investments, shared resources, migrating species, health, travel and tourism, environmental refugees (those fleeing deteriorating environmental conditions), and security.

Based on such considerations, some analysts contend that climate change is a national security concern for the United States.[29]

Countries that are relatively poor today are not necessarily poor in the future. Our figure provides *lower-bound* estimates of net GDP per capita—a key determinant of adaptive capacity—for 1990 (the base year used by the IPCC's emissions scenarios), 2100, and 2200 for four IPCC reference scenarios for today's developing and industrialized countries.[30] The net GDP per capita is calculated by subtracting the equivalent costs (or damages) per capita of global warming from the GDP per capita in the absence of any warming (i.e., unadjusted GDP per capita).[31]



Net GDP per capita, 1990–2200, after accounting for losses due to global warming for four major IPCC emission and climate scenarios. For 2100 and 2200, the scenarios are arranged from the warmest (A1FI) on the left to the coolest (B1) on the right.[37,38]

To derive a conservative estimate of the net GDP per capita, the figure uses the Stern Review's estimates for the damages from global warming. Unlike most other studies, the Stern Review accounts for losses due to market impacts, non-market impacts (i.e., environmental and public health impacts), plus the risk of catastrophe. In addition, although many researchers argue that the Stern Review's central estimate overstates losses,[33,34] the figure above uses its 95th percentile (upper bound) estimate of GDP losses under the "high climate change" scenario. The latter is equivalent to the IPCC's warmest scenario (A1FI), which projects a global temperature increase of 4°C from 1990–2085. These losses are adjusted downward for the cooler scenarios.[35,36] Each of these overstate the cost of global warming.

After accounting for warming:

- In today's developing countries, net GDP per capita (after accounting for global warming) will be more than 10–62 times higher in 2100 than it was in the base year. It will be even higher (more than 17–86 times) in 2200.
- Industrialized countries will have net GDP per capita three to seven times higher in 2100 than in 1990. In 2200, it will be five to ten times higher.
- Net GDP per capita in today's developing countries will be higher in 2200 than it was in industrialized countries in the base year (1990) under all scenarios, despite global warming.

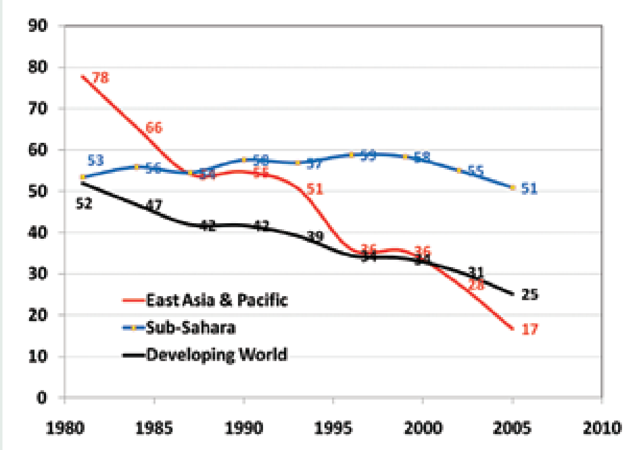
That is, regardless of any global warming, by 2200, populations living in today's developing countries will be much better off in the future than people currently inhabiting the developed nations. This is also true for 2100 for all but the "poorest" (A2) scenario.

In other words, everywhere—even in developing countries—people will be wealthy by today's standards, and their adaptive capacity should be correspondingly higher. Therefore, even if one assumes there will be no secular technological change—that no new or improved technologies will become available, nor that the price of technology drops between the 1990s and 2100—developing countries' adaptive capacity should on average far exceed that of the United States today. While the USGCRP claims that developing countries will be unable to cope with climate change might have been true for the world of 1990 (the base year), that simply will not hold for the world of 2100 under the assumptions built into the IPCC scenarios and the Stern Review's analysis.

Malaria is functionally eliminated in societies whose annual per capita income reaches $3,100.[39] Therefore, even under the poorest scenario (A2), the average developing country should be free of the disease well before 2100, even assuming no technological change in the interim. Similarly, if the average net GDP per capita in 2100 for developing countries is $10,000–$62,000 and technologies become more cost-effective as they have been doing over the past several centuries, then their farmers would be able to afford technologies that are unaffordable today (such as precision agriculture), as well as new technologies that should come on line soon (such as drought-resistant seeds formulated for specific locations).[40]

Since impact assessments generally fail to account fully for increases in economic development and technological change, they substantially overestimate future damages while underestimating the benefits from global warming.[41,42] The notion that global warming will lead to societal disruption in the future in today's developing countries, which will then lead to environmental refugees seeking to migrate to the United States—and otherwise create security problems—for the United States is fatuous.

The opportunity costs of climate change policies could increase vulnerability and slow progress towards poverty reduction



Poverty rates in the developing world, 1981–2005. [44]

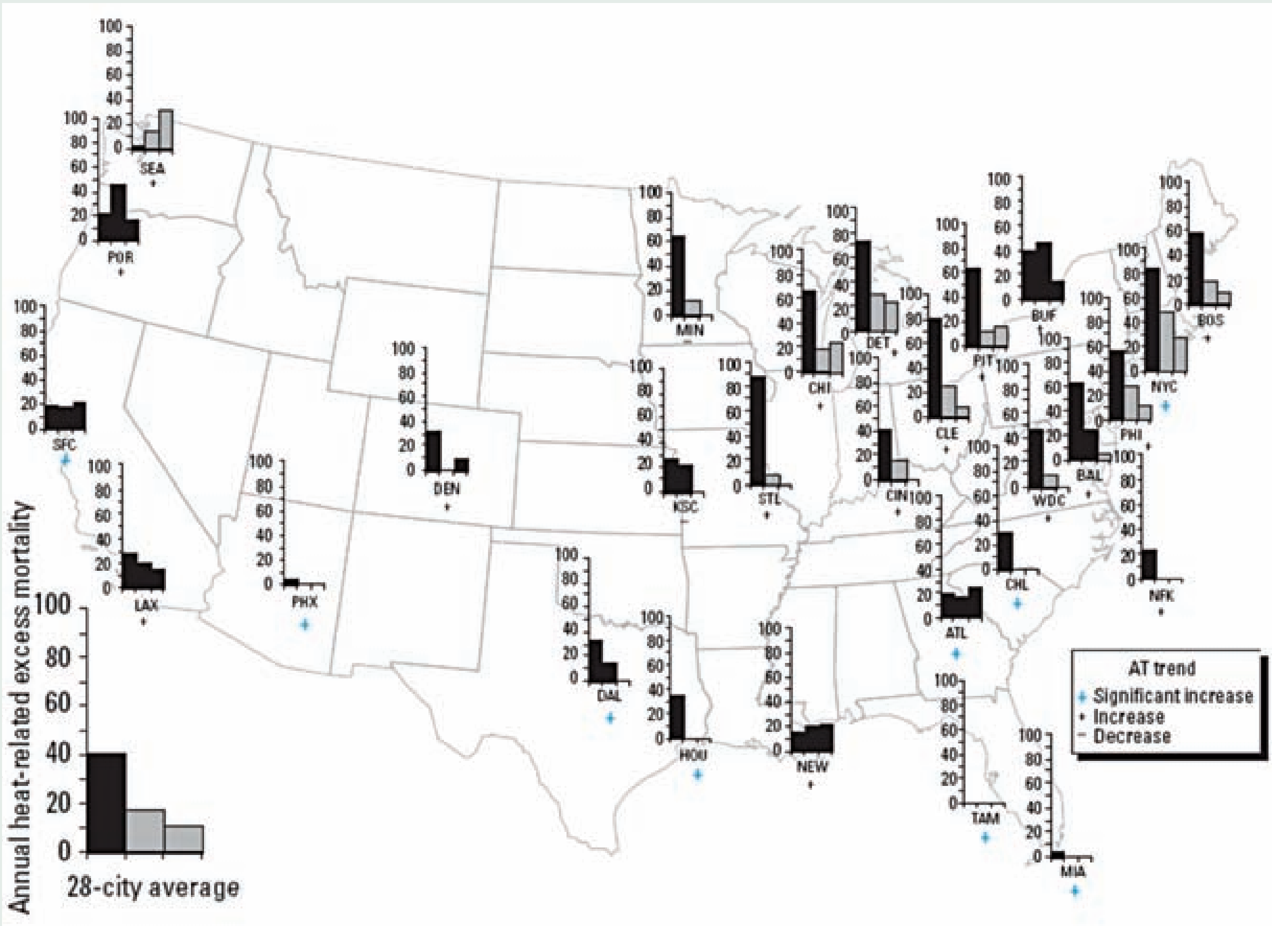
Since society's vulnerability increases if resources and options are reduced, climate change policies, by directly or indirectly reducing economic development and access to technological options, increase vulnerability not only to weather but to virtually any other problem that society might face in the future.

This is presently evident in the United Kingdom, where aggressive global warming policies have dramatically increased the number of "fuel poverty" cases, resulting in a substantially increased sensitivity to the normal winter climate of the British Isles.[43] There is no reason that similarly unwise domestic policies would not affect the United States.

Poverty reductions have been greatest in areas with the most rapid economic development. Therefore, slower economic growth could exacerbate poverty and its attendant problems.

America's cities predict the adaptation of society to prospective global warming

The urban heat island effect has raised average urban air temperatures by 2 to 5°F over the surrounding countryside, and as much as 20° at night.[45] This warming takes place gradually and is similar in magnitude to non-urban warming rates predicted for the 21st century



Excess mortality per million age-standardized population for three successive periods spanning the mid-1960s through the late 1990s for each of 28 major metropolitan areas.[47]

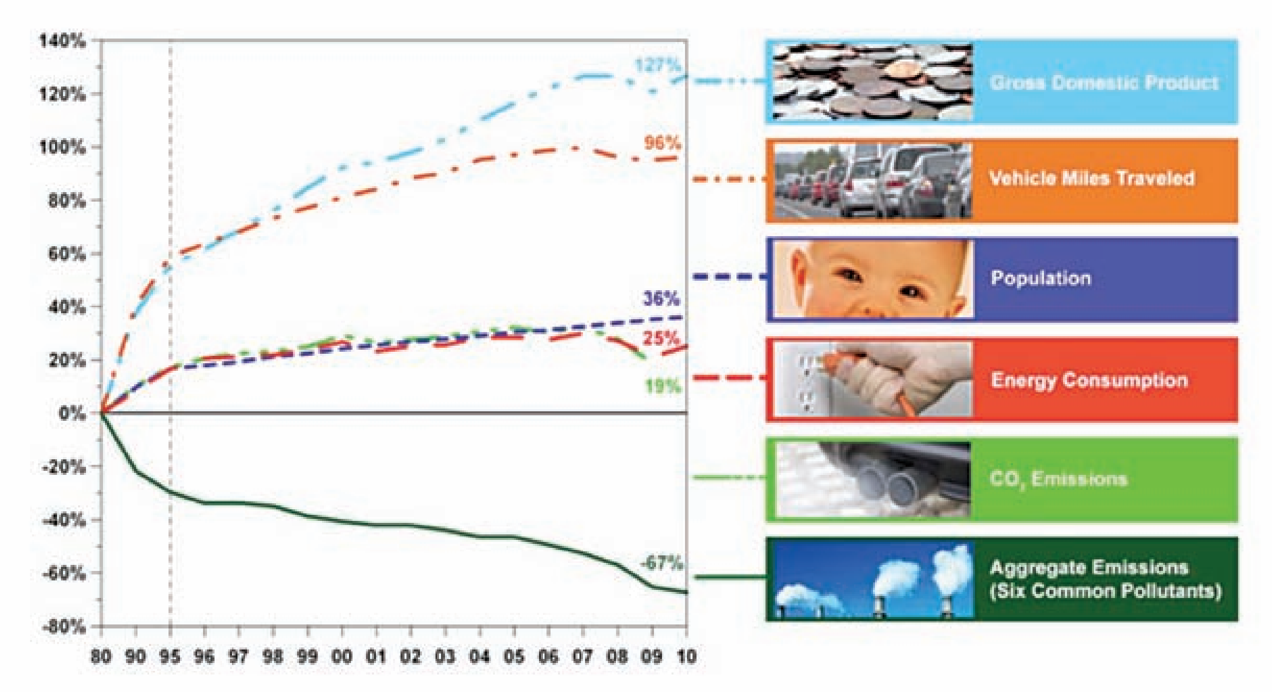
from increasing atmospheric greenhouse gases. Cities and their residents are indeed testing the hypothesis that global warming increases heat-related mortality.

Heat waves for the most part have become less deadly in urban areas. From 1964 to 1998, heat-related deaths declined significantly for 19 of 28 U.S. metropolitan areas, as well as for the 28-city average.[47] Since then, another study found a reduction in mortality attributable to excessive heat events from 1996 to 2004 for 33 out of 40 major U.S. metropolitan areas.[48]

Baseline heat wave mortality is much lower in urban areas where it is more frequent.[49] Notably, the two cities with the lowest such mortality, Tampa and Phoenix, have some of the oldest age-distributions in the world. A USGCRP statement that "The elderly are also generally more sensitive to extreme heat," while physiologically correct, is profoundly misleading; it is quite clear that in affluent societies that adaptation to heat more than compensates for the relative inability of the elderly to tolerate very high temperatures.

Air quality improves despite urban warming

In general, warming temperatures should increase the rates of the chemical reactions that create urban smog, ozone, and other noxious compounds, including NO_x. Nonetheless, as cities have warmed, air quality has improved. This has occurred despite major increases in economic activity and vehicular traffic in most cities. According to EPA estimates, total emis-



Despite an increasing population, energy consumption, and economic productivity, U.S. pollution emissions declined by 67 percent since 1980.[51]

sions of six major pollutants declined by more than 60 percent over that same time period.[50] There are several reasons for this. Regulations regarding pollutants are certainly a major factor, and, despite increasing the rates of associated chemical reactions, climate change also plays a role. Pollutants tend to concentrate in stable air masses in which temperature increases with height above the surface. However, because the surface has been warming relative to the overlying atmosphere, the long-term tendency has been to destabilize the atmosphere, resulting in more vertical mixing and less concentrated pollutants. This trend is particularly true in cities (the areas of greatest pollution concern) because of the urban heat island effect in which cities are generally warmer than the surrounding rural areas. Furthermore, precipitation serves to wash pollutants out of the atmosphere. While nationally-averaged rainfall has increased, there is another increment that is strictly related to urban warming itself.[52]

Given the historic trends in air quality, technology, and climate, it is highly likely that U.S. air quality in future decades will be even better than it is today and that the populace will be healthier and have an even longer life expectancy.

Climate change is mitigated by markets, while climate change policies can create major inefficiencies

Human communities are economically connected by markets, which adjust prices based upon perceived scarcity and demand.

Communities that are dependent upon regional agriculture will change their modes of service depending upon the crops that are grown or the policies that are promulgated.

As an example, many small towns in the upper Midwest have flourished because of climate change–related policies to produce ethanol from corn, with local distilleries reducing the costs of relatively inefficient transport of corn versus the more concentrated form of the grain as ethanol. Communities that become dependent upon policies then lobby for their continuation, even as corn ethanol is now known to result in more global warming emissions than using the energy equivalent from gasoline to power automobiles.[53]

Some types of agricultural production must adjust for changes in seasonality. For example, farmers who take advantage of earlier dates of last spring frost[54] and earlier warming of the soil, both of which are consequences of greenhouse warming, are competitively advantaged because corn varieties requiring longer growing seasons in general are more productive than shorter season cultivars.

Warming will likely move the seasonality of maple syrup production earlier, although it appears that this simple adaptation (which will be fostered by competition) should maintain syrup volumes from the 20th century through the 21st.[55]

Climate change will also impact recreational activities. Sparsely visited ski resorts in marginal environments located at relatively low elevations, such as those in the southern Midwest, are likely exit the business if warming is sufficient to render dependable snowmaking impossible. However, conversion of these facilities to golf courses is likely to increase usage as winters become shorter and less cold. High-elevation, high-traffic resorts in the West are likely to see an increase in snow and snow quality, as they are located far above current mean freezing levels or those anticipated this century. Increased atmospheric moisture will translate into more snow, similarly to what is forecast for Antarctica.[56]

Insurance claim trends show no evidence of increasingly severe weather

Trends in insurance claims are often used as a marker of integrated climate change impacts. People often assume that global warming produces more severe and extreme weather. While in most cases the evidence for a physical connection between climate extremes and climate change is lacking, it is nevertheless useful to examine insurance trends to assess the long-term tendencies in weather events that produce damage to property or livelihood.

Clearly all of these trends cannot be ascribed to weather—we must also consider the number of people who are vulnerable to damaging weather. Changes in human migration patterns and population demographics often place more people in danger of natural hazards, and it is

Examples of Impacts on Recreation

Activity	Climate Change Impact	Estimated Economic Impact
Skiing, Southern Midwest	Inability to make snow	Changeover to golf
Skiing, Lake Tahoe Region	More and deeper snow	Increased revenue
Beaches, North Carolina	Expanded warm season	Increased revenue
	More beach maintenance	Higher maintenance costs
Softball	Longer seasons	More injuries to elderly

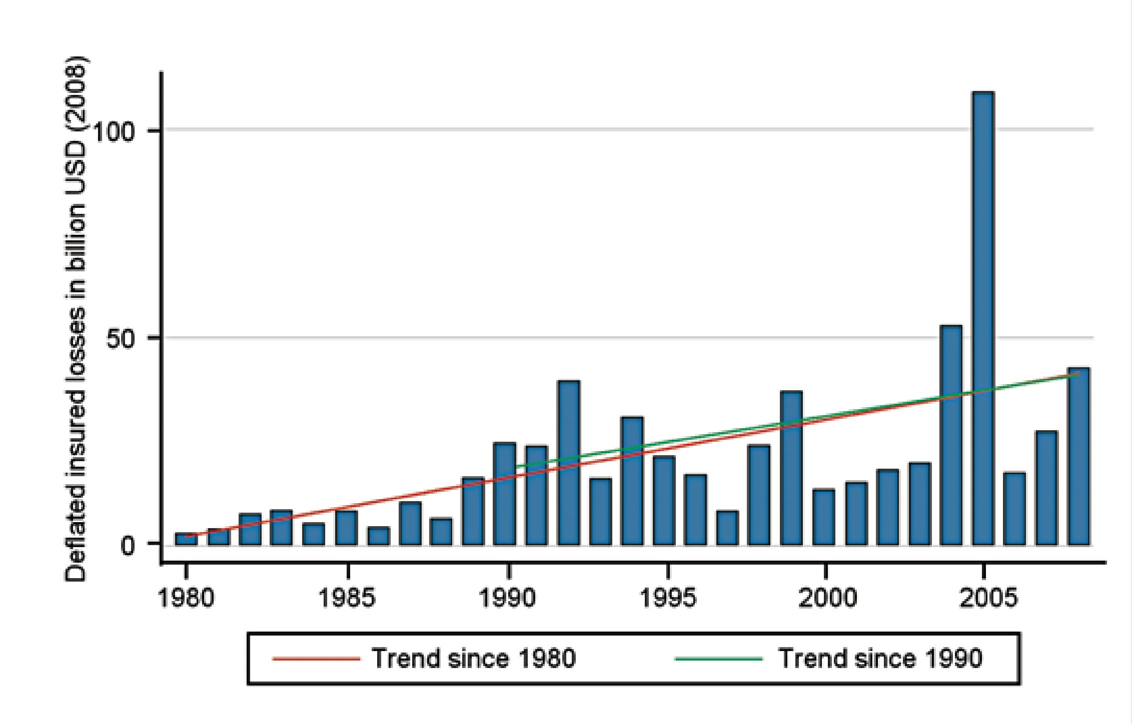
a simple mathematical fact that as the population increases, so too does the risk of people being affected by natural disasters. Therefore, all examinations of trend must be normalized or standardized for these demographic changes.

Over the period 1980–2008, based on data from Munich Re insurance, there is a significant upward trend in global insurance losses after accounting for inflation,[58] as shown in our accompanying figure. However, upon adjustment for the fact that a given disaster today will impact more people, there is no trend. This analysis suggests that all of the upward trend is a result of more people with more wealth living in harm's way. Even after removing factors that are clearly non-climatic (e.g., tsunamis, volcanoes...) there is no global trend, nor is there a trend in developed countries (where more people are insured and the data are more reliable). For damage specifically related to convective storms (hail, lightning, tornadoes, etc.), there is no significant trend, nor is there a trend for insured losses from tropical cyclones or from damage related to precipitation.

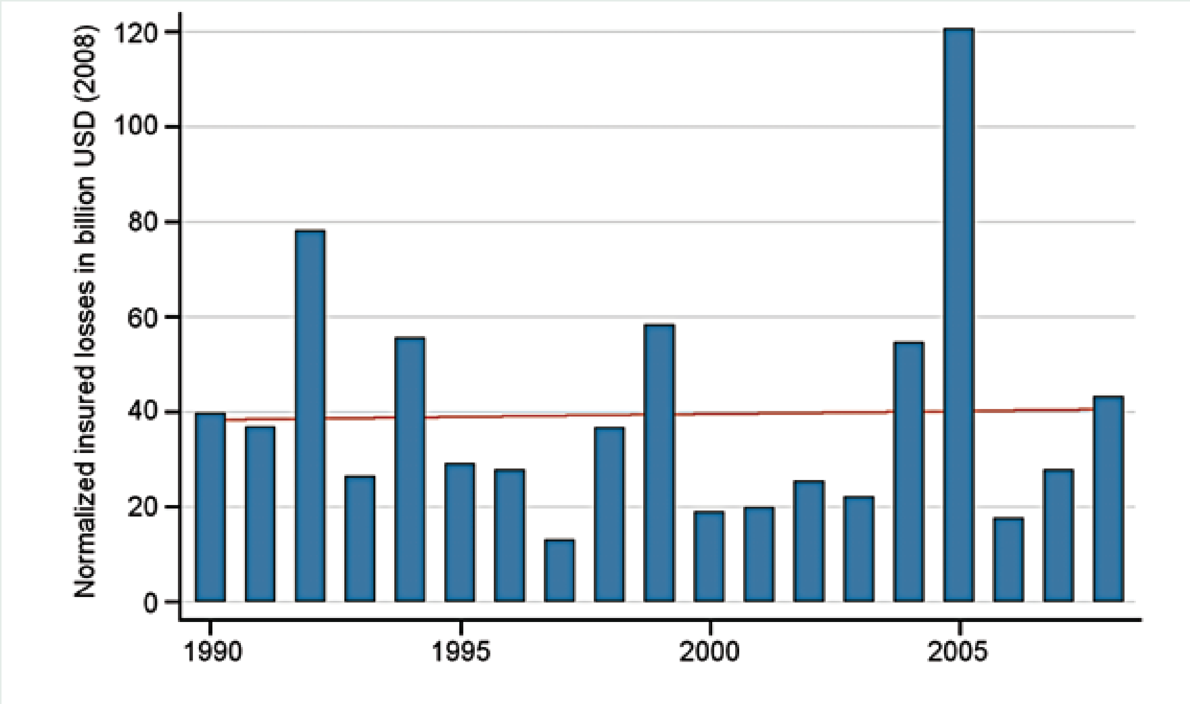
U.S. trends in insurance losses arising from seven major weather-related categories over a 48-year period ending in 1997 have been investigated, adjusting for inflation and societal conditions. In six of the seven cases (hail, tornadoes, severe thunderstorms, winter storms, wind storms, and hurricanes), there was either no trend or a downward trend in either the weather event or the associated losses. Overall, there is no national trend in (normalized) insurance losses from these weather events.[59]

As the population increases, so does the population density, with more people living in cities and along coastlines. As income and wealth have increased over time, so, too, have individual's holdings that are subject to storm-related damage.

This is especially evident along beaches where development has grown substantially over time. After accounting for inflation, population growth, and growth in real wealth (inflation-adjusted), there is no residual trend in insurance losses.[60]



Inflation-adjusted global insurance claims have been increasing significantly since both 1980 and 1990. [57]



Using the same data as in the previous figure, there is no global trend in insurance claims after adjusting for population demographics and income.[61]

The United States is connected to a world of increasingly globalized trade, which reduces overall vulnerability to climate change

American society will experience climate change in a world of increasingly interdependent markets and trade freedom. It is the nature of markets to provide exchange between nations that are advantaged to produce different products. A prime example is agriculture, where the normal variability of year-to-year rainfall moves several nations from net export to net import, and vice-versa.

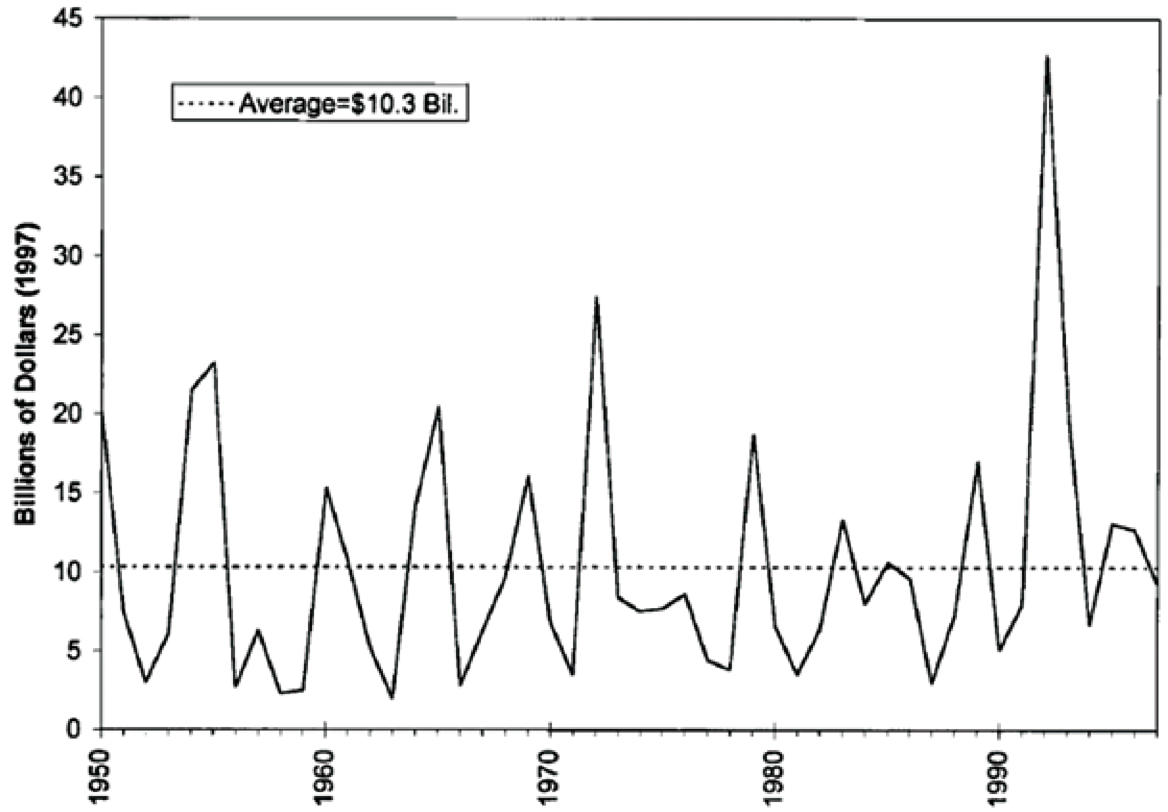
Climate change policies that result in massive allocation of U.S. corn to ethanol production create a diversion of food and feedstock that, in general, greatly exceeds worldwide shortfalls from bad weather. Civil unrest over corn prices in recent years is largely due to climate change policies, rather than climate change.

Developed societies generally display reduced sensitivity to weather and climate fluctuations. Global trends in development strongly indicate that a continuation of the process of becoming more "weather-independent" is highly likely. The reduction of international conflict as a consequence of trade and an increase in market-based commodity security argues that development will create more stability even as climate changes. Rapidly expanding economies, such as in India and China, contribute to global stability even as they emit increasingly large fractions of carbon dioxide.

Condition	Weather extreme trend	Losses trend
Hail	Down*	Down*
Tornadoes	None	Down*
Severe thunderstorms	Down*	Down*
Winter storms	None	Up*
Heavy rains	Up*	Up*
Wind storms	None	None
Hurricanes	Down*	Down*

*Indicates a trend is statistically significant at the 10% or lower level.

Trends in weather event occurrences and insurances losses from seven major storm types in the United States from 1950–97. Most of the trends are either downward or non-significant.[62]



There is no trend in annual (inflation-adjusted) losses from U.S. weather events from 1950–97.[63]

Over half of the world's population, including many major cities, depend upon snow or glacial melt for consumptive water supply. The largest such ice field, in the Himalayas, will continue to yield large amounts of water in the coming century, and its gradual reduction in magnitude can easily be countered by technological improvements such as impoundments. If a warmer world is, in general, one with more precipitation (which should be the case as ocean evaporation increases with temperature), then water supplies will in general increase if flow is properly husbanded.

Because of increasing development, societies will become successively less impacted by climate change. Climate-related migrations, a hallmark of colder periods prior to widespread development,[64] should generally be minimized or disappear as per capita wealth increases.

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Northeast

Because of its complex topography and its proximity to an ocean with fairly constant annual temperature, the Northeast has significant climatic and topographic diversity over small areas. These features, known as "mesoscale" and "microscale" climates, contribute to a biotic diversity that shelters many of the living inhabitants from the vagaries of climate change. For example, the Dolly Sods and Cranberry Glade regions of northern West Virginia have a flora much more reminiscent of Alaska and the northern edge of the Canadian forest (which borders on the tundra) than what one would normally associate with a climate at latitude 39°N.

This is one reason why it is so inappropriate to simply "move" the summer climate of a state like New Hampshire to North Carolina, as was done in the USGCRP report on the Northeast.

The statewide Northeast record is digitized back to 1895 and is available from the National Climatic Data Center (NCDC). NCDC does not include West Virginia in the "Northeast," while the USGCRP does. The USGCRP defines Northeast as the region stretching from southwest Maine through West Virginia.

Using the NCDC data, overall trends since the beginning of the record in 1895 show

- A mean temperature increase of 0.09° per decade, or 1.0 degrees over the period of record
- An annual precipitation increase of 0.52 inches per decade, or 6.0 inches over the period of record (see note on this data in the sidebar).

Regional Climate Data

The data used by the USGCRP consist of records from the U.S. National Climatic Data Center (NCDC). The long-term regional temperature and precipitation records are from a reporting network known as the "Cooperative Observer Network," largely volunteers from around the nation. They are available at the "Climate at a Glance" NCDC website: http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html.

NCDC states that this data is "primarily intended for the study of climate variability and change."

NCDC makes this claim in their "Climate at a Glance" website:

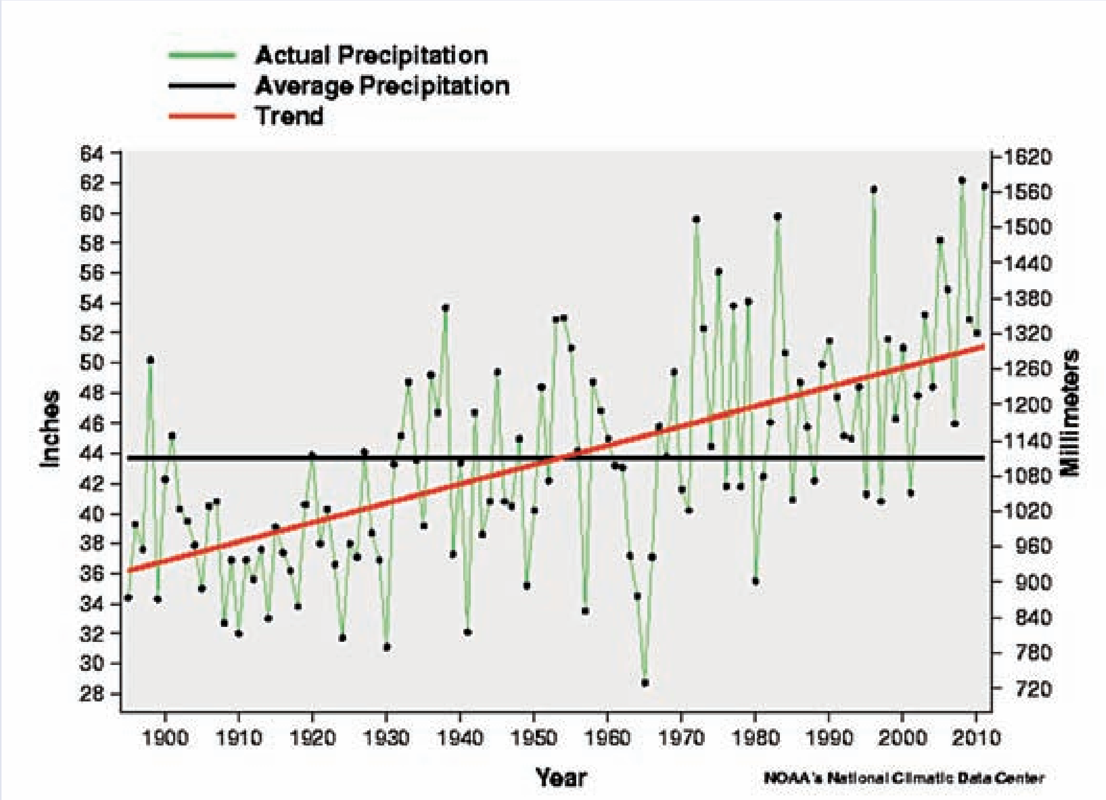
> Whenever possible, observations have been adjusted to account for the artificial effects introduced into the climate record by factors such as instrument changes, station relocations, observer practice changes and urbanization. As a result, some values available on this site differ from the official observations.

This is untrue and only applies to their National product. Regional and statewide data at "Climate at a Glance" are only adjusted for time-of-observation bias. While we use this data for comparisons between our document and the original USGCRP report, the data used in that report are not readily available. In the data we use, some clear errors in rainfall have been identified by researchers at Texas A&M University[1] and in temperature data by Barry Keim of Louisiana State University.[3]

Maximum and minimum statewide values for climate trends are:

- The largest temperature change is .21°F/decade (2.4° from 1895–2011) in Rhode Island.

Annual 1895–2011 Average = 43.68 Inches
Annual 1895–2011 Trend = 1.28 Inches / Decade



Data in NCDC's "Climate at a Glance" indicates a remarkable 41 percent rise in Massachusetts statewide average precipitation since 1895.

- The smallest is no net change in both Maine and West Virginia, 1895–2011.
- The largest change in statewide average rainfall is an increase of 1.28 in./decade (14.8 in. from 1895–2011) in Massachusetts.
- The smallest change in statewide average rainfall is a decline of -0.21 in./decade (-2.4 in. from 1895–2011) in Maine.

There are problems with some of the trends found in the "Climate at a Glance" precipitation data in the Northeast. Based upon shifts in the distribution of stations used to form the statewide average, the apparent rise in Massachusetts precipitation of a remarkable 41 percent should be questioned. Accounting for these changes reduces the trend to approximately 10 percent, a major difference.[3] Changes

The massive urban "heat islands" of the Northeast warmed more in the last century than has been predicted for many rural areas around the world in this century. As the warming took place, levels of pollutants dropped dramatically as a result of air quality regulations.

REGIONAL SPOTLIGHT: "Sugaring" in the Northeast

The 2009 USGCRP report states that warming will adversely affect the maple syrup industry in the Northeast. In fact, the future may be even better for this sweet treat.

Maple syrup is a sweetener made from the sap of sugar maple or black maple trees. In cold climates, trees store starch in their stems and roots before the winter, which is then converted to sugar, rising as sap in the spring, when the trees are tapped.

Vermont is the biggest U.S. producer, with nearly a million gallons of syrup produced annually, and Maine produces about a third of that amount. While U.S. production of maple syrup is significant, Canada produces 80 percent of the world's total, mainly in Quebec.

Production occurs from February through April, depending on local weather conditions. Freezing nights and warm days are needed to induce sap flows. The change in temperature from below to above freezing causes water uptake from the soil, and also creates a stem pressure, that, along with gravity, causes sap to flow out of tapholes or other wounds in the stem or branches.

Sap flow is therefore dependent upon weather conditions, and predicted changes in local and regional climate can be linked to the production of maple syrup. According to the USGCRP, climate change will surely be bad for syrup production in the Northeast.

Perhaps they cried wolf too soon. Christopher Skinner and two Cornell University colleagues found that the scientific literature was quite conflicted about the future state of maple syrup production, so they developed a computer model to relate high-resolution daily high and low temperatures and maple syrup.[5]

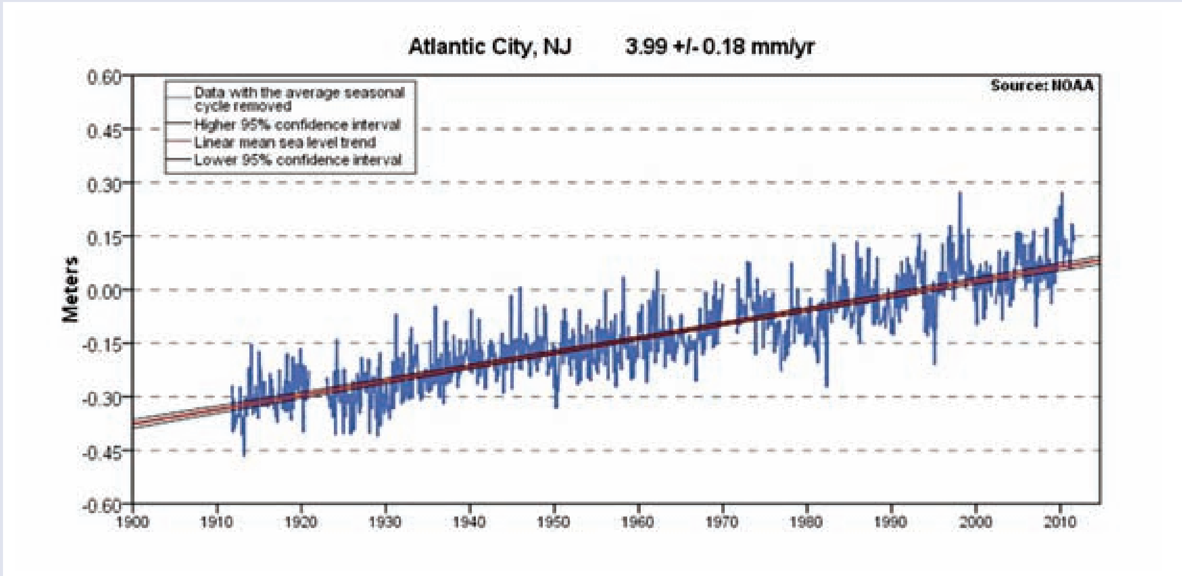
They concluded that

> The major finding is that sap collectors will need to get busy earlier in the late winter and spring to adapt to the expected warming winters in the New England states. Through the twenty-first century, the optimal time to maximize sapflow days will advance to an earlier date in the year. By 2100 this change will be nearly 30 days.

Further,

> Provided the change in the beginning of the sapflow window can be anticipated, the number of sapflow days will change very little through 2100 in the heart of the Northeast U.S. maple syrup production region. In fact, across Maine, the simulations show an increase in the number of sapflow days provided the 8-week window is moved to early February.

They concluded that a minor change in the schedule of sugaring operations will maintain current production levels throughout this century.



The sea level rise at Atlantic City is characteristic of what has occurred for the last 100 years along much of the Northeast coast. This rise, of approximately 16 inches per century, is slightly larger than the IPCC midrange emission scenario midpoint of a global average rise of 14 inches for the 21st century induced by climate change.

in population patterns have changed the sign of the trend in Maine precipitation from negative (-0.2 inches per decade) to slightly positive.

Despite rising temperature in an increasingly urbanized environment, air quality in the Northeast continues to improve

As noted in the previous chapter, warming temperatures should increase the rates of the chemical reactions that create urban smog, ozone, and other noxious compounds, including NO_x. Nonetheless, as cities have warmed, air quality has improved, despite major increases in economic activity and vehicular traffic.

It is important to note that urban "heat island" effects in the quasi-continuous urban corridor from Northern Virginia to Boston equal or exceed the net global warming projected for the summer in most 21st-century climate models. So, even if these forecasts are correct (despite the fact that temperatures are rising slower than the mean rise in the midrange emissions scenario models), simple regulation seems to bring about "adaptation as usual" to changing climate.

Air quality improved because of regulation and because there is more vertical motion induced by the heating of the ground, which is reflected in an increase in precipitation, which cleanses the air.[4]

Sea level has risen in the last century over much of the Northeast at a rate faster than the UN projects (in its midrange emissions scenarios) for the coming century worldwide from global warming. Legend: Green arrows, 0 to 8 inches per century; Yellow, 8 to 16; orange, 16 to 24. Data from the National Oceanic and Atmospheric Administration.[6]

Given the historic trends in air quality, technology, and climate, it is highly likely that urban air quality in the northeast megalopolis in the future will be even better than it is today.

Northeasterners have adapted to sea-level changes larger than those projected by the United Nations

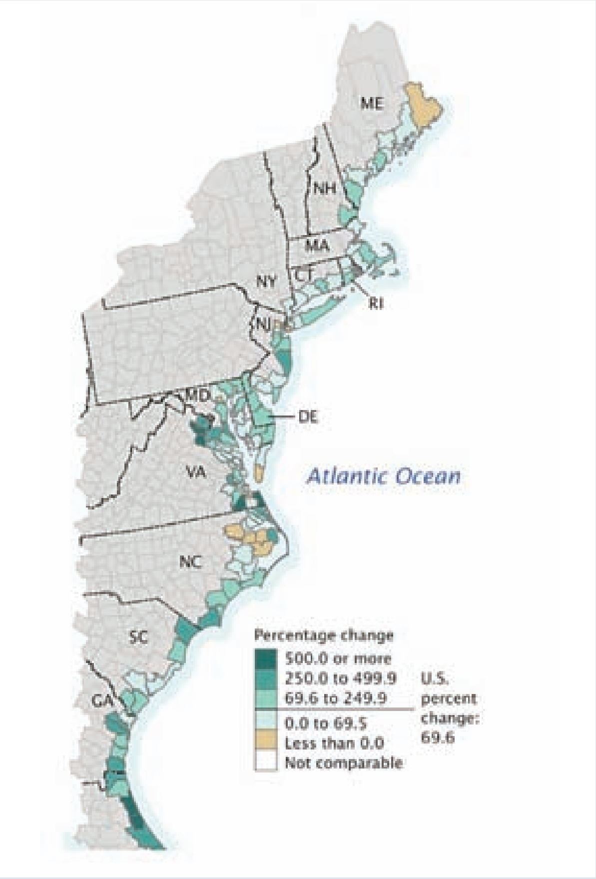
Human adaptation to climate change often occurs simply as a result of business-as-usual. Thanks to a number of geological processes, including continued recovery from a major extraterresterial impact, sea level at many densely populated locations in the Northeast rose in the last century at a rate greater than that projected from climate change in the 21st century.

At the same time, real estate prices rose dramatically, in spite of the fact that when your beachfront property washes away, it is gone and therefore cannot be sold at any price. If this were such a great risk, it is doubtful that these parcels (and the homes built on them) could command such high prices.

There is no reason to expect that adaptation-as-usual will suddenly stop in this century, if the past—when sea levels rose faster than they may from climate change in this century—is any guide to the future.

The perceived threat from sea level rise can be indirectly measured by the demand to live near the ocean. As shown in the accompanying figure, historical population levels clearly indicate that this figures very little in people's choice of a place to live.

Change in Coastline Population by County
1960 to 2008



Population growth in oceanfront counties has been much greater than that of the nation as a whole, indicating little perception of sea level rise as a threat. Along most of the East Coast, sea levels rose approximately one foot in the last century, or twice the worldwide estimated average. The lifestyle in this region is "adaptation-as-usual."

Ski Resorts Likely to Increase Golf Revenue
(Higher Emissions Scenario from USGCRP)

In the Northeast, many ski resorts have diversified into "four season" operations featuring high-end golf courses and other outdoor sports. The formula has proven very successful further south in the Appalachian mountain ski areas of Virginia and North Carolina. As the climate of the Northeast gradually becomes more like that in the Mid-Atlantic, one can expect increasing revenue from golf operations and higher property values for course-side residences. Our chart shows the resorts with the highest enhanced golf potential under a clearly overstated emissions scenario (called "even higher") in the USGCRP report.

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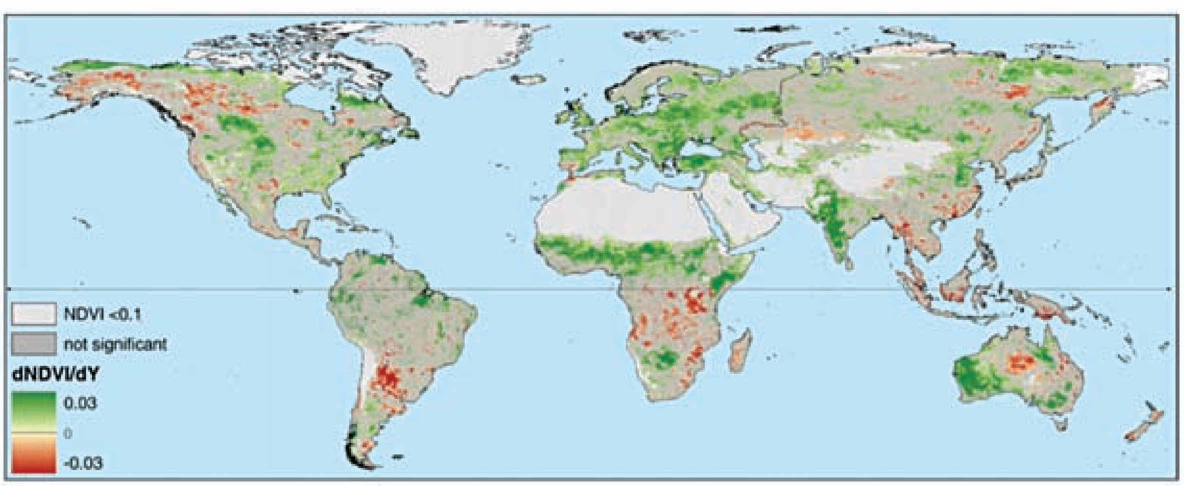
Southeast

The climate of the U.S. Southeast is typical of lower midlatitude locations on the western shores of oceans in the Northern Hemisphere. Within the normal limits of statistical confidence, both the average annual temperature and total annual precipitation in the Southeast are unchanged since the beginning of the NCDC record in 1895. Note that NCDC does not include Kentucky, Tennesee, Louisiana, Arkansas, or southeast Texas in its "Southeast."

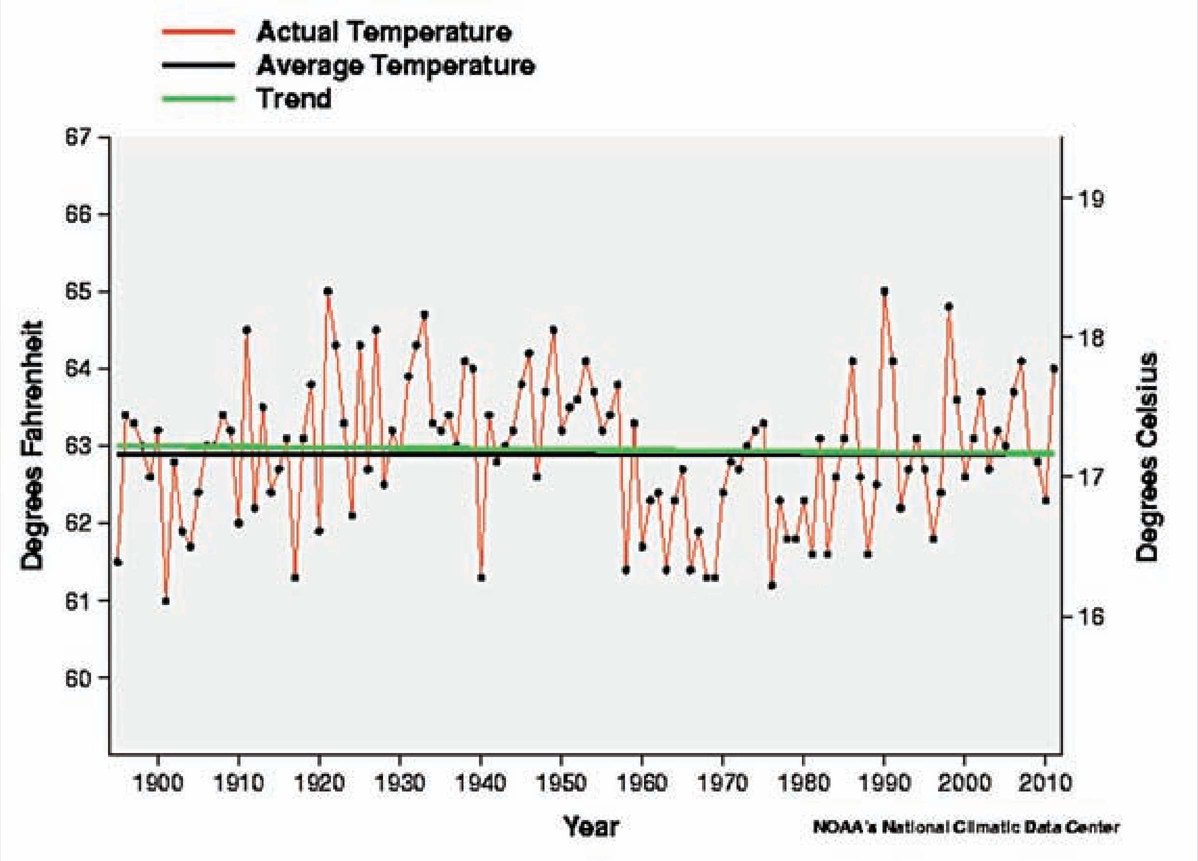
Maximum and minimum values for statewide trends are:

- The largest temperature change is - .07°F/decade (-0.8° from 1895–2011) in Alabama.
- The smallest is no significant net change in temperature in Arkansas, Florida, Kentucky, Mississippi, North Carolina, and Tennessee.
- The largest change in statewide average rainfall is an increase of 0.99 in./decade (11.5 in. from 1895–2011) in Alabama.
- There is no significant net change in annual rainfall in Florida, Georgia, North Carolina, South Carolina, or Virginia.

The Southeast temperature history in general shows no change or slight declines, while there are large and significant increases in annual rainfall in Alabama and Mississippi, and increases of marginal significance in Arkansas, Louisiana, and Tennessee. Given the combination of increased rainfall, constant temperatures, and rapidly increasing carbon dioxide concentrations, it is quite clear that events are conspiring to produce a greener Southeast, which is evident from satellite imagery.



Spatial trends in net primary plant productivity, 1981–2006 The combination of small climate changes with large changes in atmospheric carbon dioxide concentration has "greened" virtually all of the United States.[1]



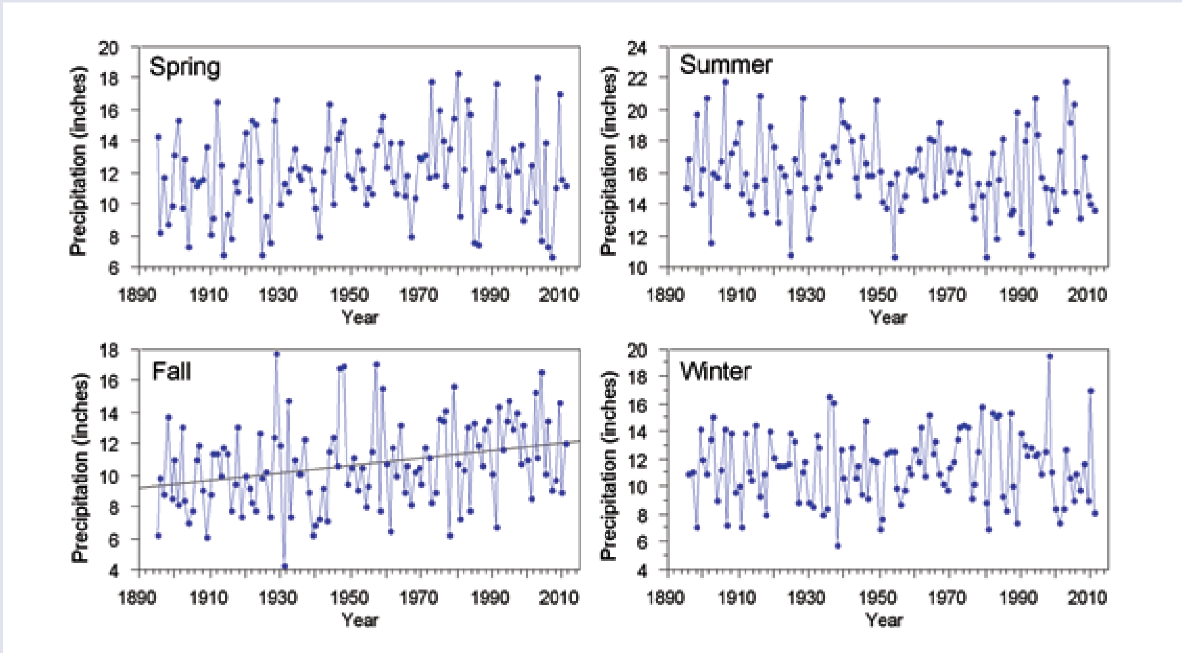
The trend in Southeast temperature as given by NCDC is virtually zero and of no statistical significance.

Data mining can select subperiods of any length to "find" significant trends. For example, one could arbitrarily pick on spring precipitation since 1970 over the Southeast, as did the USGCRP. Inspection of our accompanying graphic in fact shows a decline. The decline is statistically significant. The year 1970 is of no particular importance in climate science. Even a cursory inspection of the seasonal charts here (which show *all* of the data, rather than a selection by the USGCRP) shows that there is nothing remarkable in the southeastern precipitation history. While the title of the USGCRP report is "Global Climate Change Impacts in the United States," it is ludicrous to claim that one trend, beginning in 1970, in one season, is somehow related to "global climate change."

The destructive potential of Northern Hemisphere tropical cyclones, which is at or near historical lows, was addressed earlier in this report, as well as the fact that there is no trend in storm-related damages in the United States after allowing for the very large increase in beachfront population, which results in dramatic rises in property values. The vast majority of hurricane-related damages occur in the Southeast.

Projected increases in air and water temperatures will cause adaptation and innovation

As noted earlier in this report, heat-related deaths in urban areas are inversely related to summer mean temperature; the warmer it is, the *fewer* people die from the heat. Tampa, for example, is one of the hottest cities in the United States, and yet its heat-related death rate is near zero.[2]



Only the fall season shows a statistically significant trend in total precipitation amount in the Southeast. The trends in precipitation during the winter, spring, and summer seasons are statistically insignificant, which means they cannot be distinguished from a flat (zero) trend. These four charts should be compared to the figure on page 111 of the USGCRP report.

The distribution of major crops in the United States indicates a likely shift from soybeans to grain sorghum in the eventuality of significant regional drying in a hot environment like the Southeast. At any rate, the slow evolution of climate change over the course of a century will certainly be outpaced by the revolution in genetic engineering in crop science. With regard to animals raised for meat, the Southeast has led the nation in the development of air-conditioned intensive agriculture to supply the region's (and the nation's) insatiable appetite for barbecued pork. There is no reason that these trends will not continue.

Under any climate scenario, the Southeast has abundant rainfall. Problems with water supply are political and social, not climatic

According to the National Climatic Data Center, the Southeast experiences more precipitation, almost exclusively in the form of rain, than any other coterminous U.S. region, with an average of slightly more than four feet (50.2 inches) per year. There is simply no climatic excuse for this region to experience significant water shortages.

Even using unrealistic emissions scenarios, the USGCRP cannot project changes in annual rainfall in the Southeast that are at all significantly different than today's totals. While evaporation from reservoirs could increase a few inches a year, the percent change in available water would be probably be less than 10 percent.

While U.S. population is projected to increase by nearly 50 percent between 2005 and 2050,[3] that increase is likely to be larger in the South. Even if it were not, raising population by 50 percent surely impacts a constant water supply much more than a 10 percent change in available water.

Rolling topography characterizes much of the Southeast, with the exception of the Florida peninsula and the Mississippi River delta. Catchment basins for the four feet of water that falls from the sky in an average year are plentiful. Opposition to them is a classic "NIMBY" (not in my back yard) problem, but that is certainly not insurmountable (as our highway systems demonstrate). If regions in the Southeast choose to experience economic losses because of decreased water availability, as forecast by the USGCRP, that is a social choice and not a climate-change-induced *fait accompli*.

Land subsidence is raising water levels in the northern Gulf Coast by an order of magnitude more than is sea level

For a variety of non-climatic reasons, onshore areas of the northern Gulf Coast are subsiding (dropping) at a rate that can average ten times or more the current global average sea level rise. In some parts of Louisiana, near the mouth of the Mississippi and the Chenier Plain, water is rising at an inch per year,[4] compared to a global average of 0.07 inches/year from melting land ice and the thermal expansion of the ocean given by the IPCC in its latest climate compendium.

The median mid-range forecast for global sea level rise from 1990 to 2100 from the IPCC is 19 inches, which is around 20 percent of the apparent rise that will occur in the northern Gulf Coast if historic subsidence rates persist. Consequently, global warming will be a minor contributor to the large inundations that subsidence has caused and will cause.

As noted in the chapter on national climate change, the last 150 years of hurricane history indicates that there are strong multi-decadal variations in the hurricane activity in the Atlantic Ocean basin (including the Gulf of Mexico) but little, if any, overall change when the multidecadal variations are taken into account. A comprehensive measure of year-to-year tropical cyclone activity in the Atlantic Basin is the Accumulated Cyclone Energy (ACE) index, which combines the intensity and duration of each storm into a seasonal total. The history of the ACE index shows the relatively high levels of activity in the 1880s–1890s, 1950s–1960s, and 1995–2005. Periods of low levels of Atlantic tropical cyclone activity include the 1850s, 1910s–1920s, the 1970s–1980s, and from 2006 to the present. There is simply no relationship between ACE and global mean temperature.

Large-scale subsidence is contributing to ecosystem disruption, impacting the regional economy

High subsidence rates have and will contribute much more than global warming to

- The sudden loss of coastal landforms that serve as a storm-surge barrier for natural resources and as a homeland for coastal ecological communities,[5]
- An increase in sea level that has allowed widespread, rapid salt-water intrusion into coastal forests and freshwater aquifers, and
- A precipitous decline of wetland-dependent coastal fish and shellfish populations due to the rapid loss of coastal marsh.[6]

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[1]Jong, R., et al., 2011: Analysis of monotonic greening and browning trends from global NDVI time-series. *Journal of Remote Sensing*, **115**, 692-702.

[2]Davis, R.E., et al., 2003: Changing heat-related mortality in the United States. *Environmental Health Perspectives,* **111**, 1712-1718.

[3]Pew Research Center, 2007: U.S. Population Projections, 2005-2050. Pew Research Center at http://www.pewhispanic.org/2008/02/11/us-population-projections-2005-2050/.

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[5]Burkett, V.R., et al., 2005: Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. *Ecological Complexity,* **2**, 357-394.

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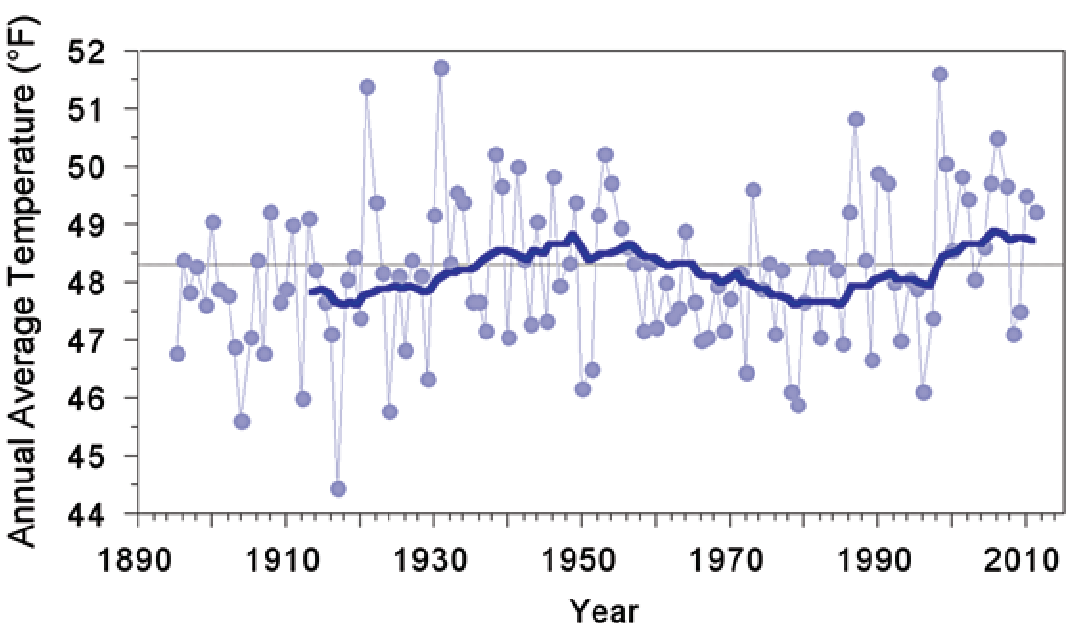
Midwest

NCDC data beginning in 1895 show statistically significant increases in annual temperature in Ohio, Iowa, Minnesota, and Wisconsin, and no significant trend in the remaining states. Precipitation increases are significant everywhere except in Missouri.

Greenhouse effect theory predicts that winter should warm more than summer, that land areas should warm more than the oceans, and that areas most removed from oceanic influence (so-called "continental" climates) should show the strongest winter warming. Indeed, this is exemplified by Minnesota, with a winter warming trend of 2.6°F since 1895. (Whether or not this is viewed as bad by the citizenry there has not been determined.) The summer warming trend, which should be less, is 0.7.°

Maximum and minimum values for annual statewide trends since 1895:

- The largest annual temperature change is .14°F/decade (1.6° from 1895 to 2011) in Minnesota.
- The smallest is no significant net change in temperature in Illinois, Indiana, Michigan, and Missouri.
- The largest change in statewide average precipitation is an increase of 0.49 in./decade (5.7 in. from 1895–2011) in Indiana.
- There is no significant net change in annual rainfall in Missouri.



NCDC average annual temperature 1895–2011 for the USGCRP's "Midwest" region. The line is the 20-year running mean; at the endpoint, it is the mean of the 1992–2011 data. It is very clear that temperatures in the 20-year periods ending in the late 1940s are, within any reasonable statistical bound, the same as for periods ending in recent years.

USGCRP's statement that "In recent decades a noticeable increase in average temperatures in the Midwest has been observed" in the volume entitled "Global Climate Change Impacts in the United States" implies that the recent warm decades observed there are related to global warming. In fact, a regional plot of the area-weighted statewide averages shows that temperatures since 1990 do not look dissimilar to those observed between 1930 and 1950, before there was very much influence of anthropogenerated carbon dioxide on global temperatures.

Increasing frequency of urban summer heat waves will lead to adaptational responses and reduced mortality

Data from across the United States show that cities with relatively warm summer temperatures—and those which therefore experience more very hot temperatures during heat waves—tend to show the lowest rates of heat-related mortality. Further, heat-related mortality is declining in most coterminous U.S. cities (there are very few heat-related deaths in Alaska or Hawaii), with the exception of Seattle (our coolest major metropolitan area in the summer), where heat-related mortality is rising.[1]

Consequently, as Midwestern cities warm, heat waves in fact become more common, and adaptation is accelerated. A substantial portion of the adaptive process is rooted in local politics, for which Chicago is famous.

In 1995, as massive heatwave struck between July 12 and 16. Heat index values were officially measured as high as 125°F at Midway Airport, and no doubt there were higher ones elsewhere in the city. Death estimates vary, but 700 seems reasonable.[2] A similar heat wave occurred four years later, and only 114 died.[3] Because of the 1995 tragedy, Chicago improved its heat-emergency infrastructure, including cooling shelters, community outreach, and increased public awareness to the threat of extreme heat. A similar adaptation in France occurred between the great 2003 heat wave and one of similar magnitude in 2006.[4]

Climate scientists writing in 2001 in the *Bulletin of the American Meteorological Society* noted that Midwestern urban areas clearly had adapted between these two heat waves:

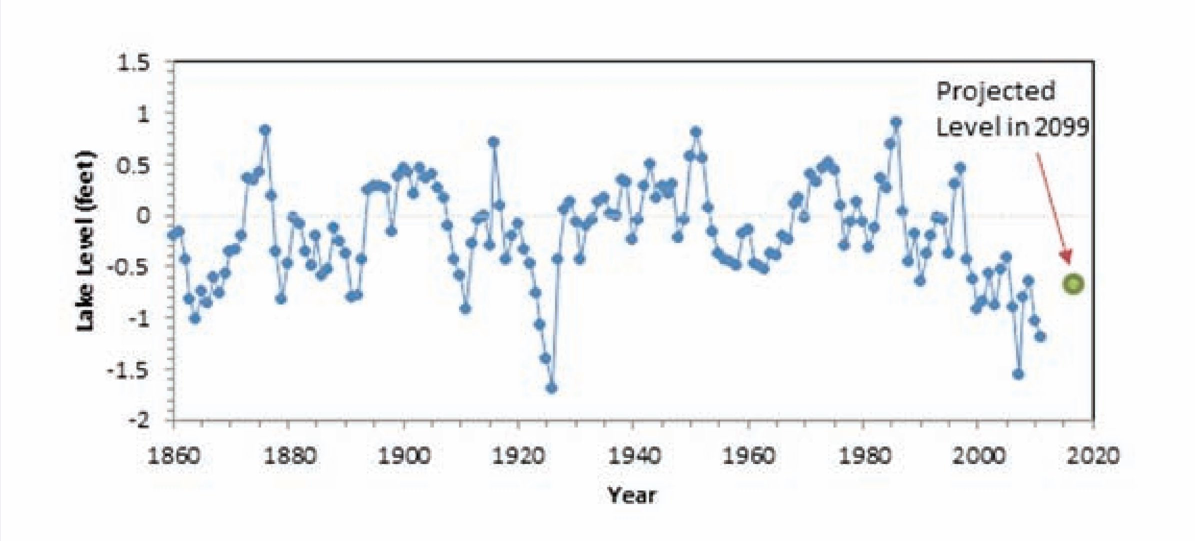
> In conclusion, since the heat-related death rates in both metropolitan areas were similar, this suggests that St. Louis and Chicago had similarly effective heat emergency response systems in place for the 1999 heat wave. These and other cities in the Midwest appear to have learned their lessons from the 1995 heat wave. This analysis has also shown that there may be new lessons to be learned after this and other future events. It is quite possible that some future increases in heat wave frequency, intensity, and duration may occur due to natural climate variations, such as happened during the 1930s, or due to a broader global climate change.[5]

The natural variability of Great Lakes water levels will obscure any effects of climate change for the policy-forseeable future

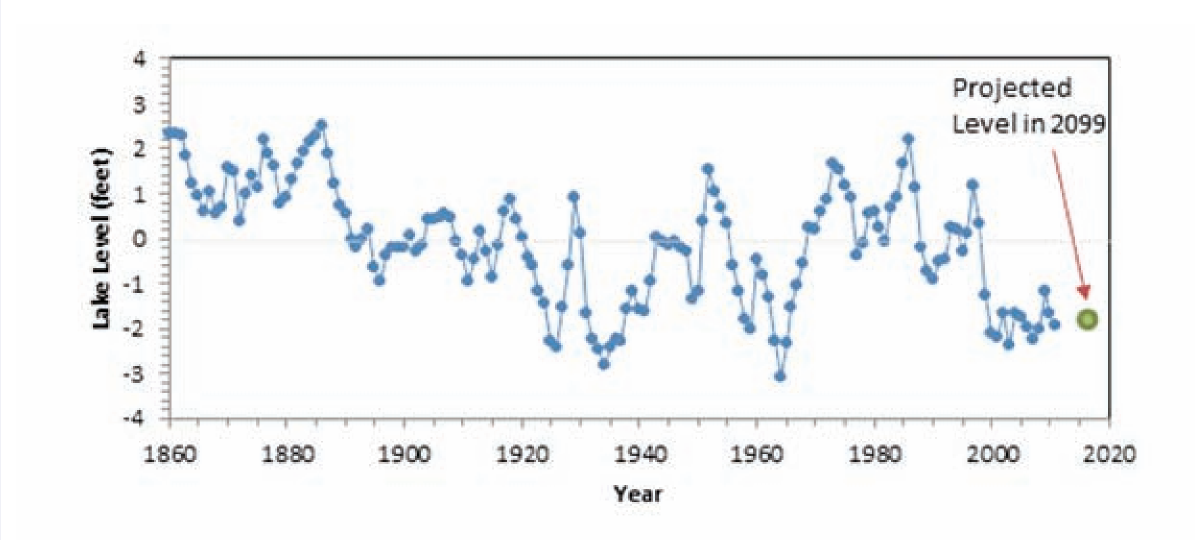
Scientists writing in the *Journal of Great Lakes Research* in 2009 noted that "Competing effects of shifting precipitation and warmer temperatures suggest little change in Great Lake levels over much of the century until the end of the century, when net decreases are expected under higher emissions."[6]

In this case, "higher emissions" means an concentration pathway that our atmosphere is not on. Given the large (multi-century) reserves of exploitable natural gas now known to exist, the higher emissions scenario is not likely to develop.

As shown below, lake levels forecast for 2099 for Superior and Michigan-Huron (which, Lake Superior Water Level



Lake Michigan/Huron Water Level



Projections of water levels in Lakes Superior and Michigan/Huron based upon an unrealistically high emissions scenario in 2099[7] are clearly within the range observed in the last 150 years.

respectively, have the lowest and highest historical variability of the Great Lakes) are clearly within the range of observations over the last century.

Indeed, under a lower emissions scenario fueled in part by increased shifting of coal to natural gas for electrical generation (which is taking place very rapidly in the United States), any declines in Great Lakes water level will be well within one standard deviation of 20th-century observations.

One interesting aspect of Great Lakes warming is that localized "lake effect" snow can increase in the early winter and persist longer if freezing is delayed and/or reduced. As the snow plumes from Lakes Michigan-Huron and Erie largely feed high-elevation ski resorts in West Virginia, it is quite possible that snowfall will be enhanced there.

It is irresponsible to use precipitation changes forecast by computer models in the USGCRP report for any future planning

As noted in our chapter on National Climatic Change, precipitation changes cited by the USGCRP as having more "confidence" over the conterminous United States in fact generally do not meet normal scientific criterion of .05 probability for statistical significance. Areas of the precipitation projection map are cross-hatched, indicating confidence, when a mere 66 percent of the computer models predict a change of the same *sign* by 2080–99.

Further, these projections are based upon a "higher" emissions scenario, noted above, that is not likely to be realized. It is doubtful that a Master's Degree committee at a reputable research university would ever allow such results to be published as a mere thesis, and it is a tribute to the internal bias of the USGCRP that it allowed publication in a document that it knew would serve as the basis for sweeping environmental regulation.

Also in our chapter National Climatic Change is a quantitative analysis of the increase in precipitation on the heaviest precipitation day of the year. Nationally, the value works out to approximately 0.25 inches per century. It is somewhat insulting to citizens to claim that there is difficulty in adapting, at the 100-year timeframe, to such minuscule changes.

Projections of increased winter and spring precipitation are so unreliable that one could not likely detect any significant influence on the timing of spring planting in the Midwest. However, increases in spring and fall temperature will certainly lengthen the growing season, allowing for more productive cultivars of major crops and increased cutting in pasturelands.

Plant hardiness zones are likely to shift northward, allowing for more diverse and colorful southern species, such as coneflowers, dogwoods, redbuds, and azaleas to flourish where appropriate soil types exist or can be modified from existing ones.

Impacts on forests are likely to be positive, as noted in our chapter on Ecosystems. The increase in the atmosphere's CO_2 concentration results in increased water-use efficiency[8,9,10] and increases the optimal temperature for photosynthesis.[11,12,13] The beneficial impacts of the rise in the air's CO_2 content do indeed combine to lead to an increasing forest productivity by temperate trees.[14,15,16] CO_2-induced productivity stimulation is experienced by trees that are also experiencing water insufficiency[17,18,19] and very old age.[20,21,22]

Plants exposed to elevated concentrations of ozone typically display reductions in photosynthesis and growth in comparison to plants grown at current ozone concentrations. Because hot weather helps to form ozone, there are concerns that CO_2-induced global warming will further increase the concentration of this pollutant, resulting in forest damage. Elevated CO_2 reduces, and frequently completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth and yield.[23,24,25,26,27,28] When explaining the mechanisms behind such responses, most scientists suggest that atmospheric CO_2 enrichment tends to reduce stomatal conductance, which causes less indiscriminate uptake of ozone into internal plant air spaces and reduces subsequent conveyance to tissues where damage often results to photosynthetic pigments and proteins, ultimately reducing plant growth and biomass production.

Analyses of long-term ozone measurements are encouraging. In North America, surface measurements show a pattern of mostly unchanged or declining ozone concentration over the past two decades that is broadly consistent with decreases in precursor emissions. The spatial and temporal distributions of these and other observations indicate that, whereas increasing industrialization originally tends to increase the emissions of precursor substances that lead to the creation of greater tropospheric ozone pollution, subsequent technological advances tend to ameliorate that phenomenon, as they appear to gradually lead to (1) a leveling off of the magnitude of precursor emissions and (2) an ultimately *decreasing* trend in tropospheric ozone pollution. The result is that the growth-enhancing effects of CO_2 are increasingly dominant.

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[3]Palecki, M.A., S.A. Changnon, and K.E. Kunkel, 2001: The Nature and impacts of the July 1999 heat wave in the midwestern United States: Learning from the lessons of 1995. *Bulletin of the American Meteorological Society,* **82**, 1353-1367. doi:http://dx.doi.org/10.1175/1520-0477(2001)082<1353:TNAIOT>2.3.CO;2.

[4]See http://www.worldclimatereport.com/index.php/2008/02/14/few-french-fried-in-2006/.

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Great Plains

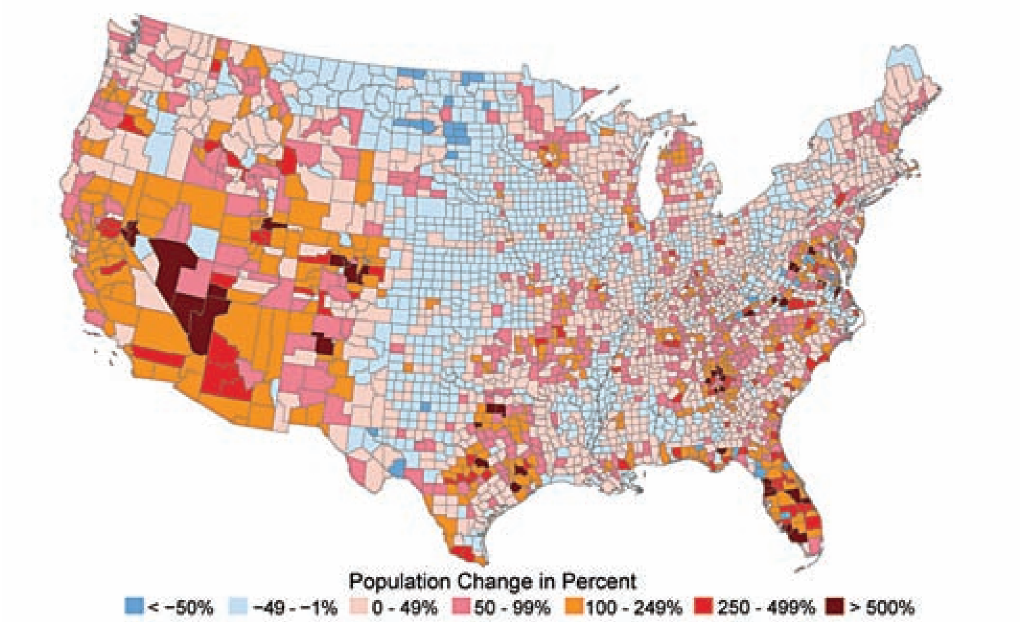
The climate of the Great Plains region is characterized by strong seasonal climatic variations. Over thousands of years, records preserved in tree rings, sediments, and sand deposits provide evidence of recurring periods of extended drought (such as the Dust Bowl of the 1930s) alternating with wetter conditions.[1] This variability is likely to continue with or without exogenously forced climate change.

In the future, semi-arid conditions in the western Great Plains will gradually transition to the moister climate found in the eastern parts of the region today. In the 21st century, winter days in North Dakota will average a bit less than 50° colder than those in west Texas.

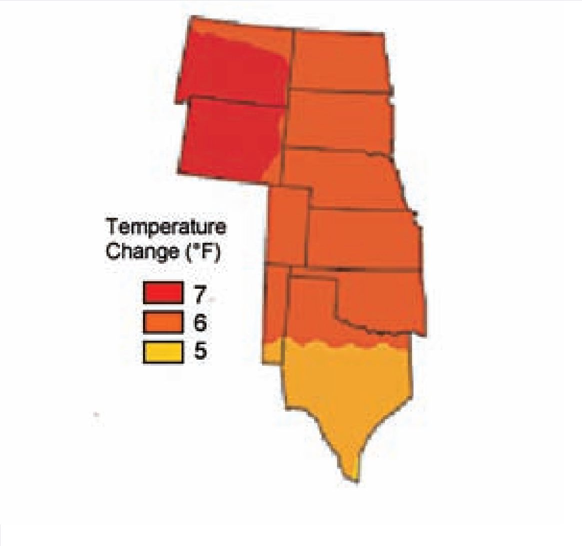
Maximum and minimum values for annual statewide trends since 1895:

- The largest annual temperature change is .26°F/decade (3.0° from 1895 to 2011) in North Dakota.
- There is no significant net change in temperature in Montana, Nebraska, Oklahoma, South Dakota, and Texas.
- The largest change in statewide average rainfall is an increase of 0.48 in./decade (5.6 in. from 1895–2011) in South Dakota.
- There is no significant net change in annual precipitation in Montana, Nebraska, North Dakota, and Texas.

The largest seasonal temperature changes are in North Dakota in the winter, a decadal trend



The depopulation of the Great Plains has been quite striking and is multifactoral. There is very little understanding of what role future climate change would have in altering established social trends (Source: U.S. Census; data from 1970 to 2008).



Summer temperature changes between now and 2080–2099 in the Great Plains projected by a model whose net global warming most comports with what has been observed.

of 0.44°F, or a trended change since 1895 of 5.1.° This is consistent with the large trend in Minnesota winter temperatures noted in the last section.

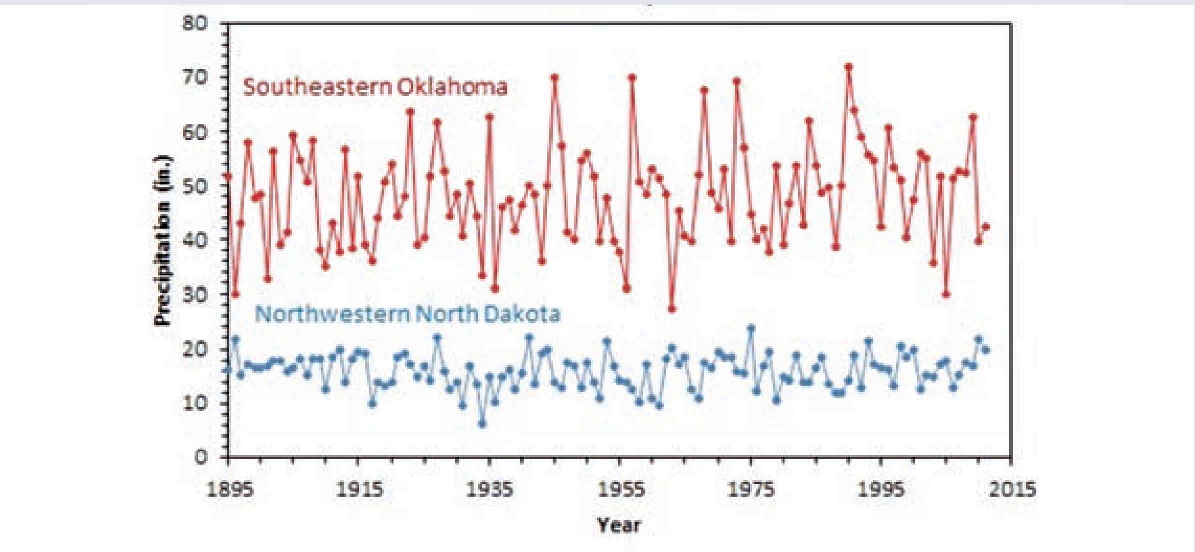
Greenhouse warming tends to be amplified in cold airmasses, which, by their very nature, are dry, as the dewpoint cannot exceed the ambient temperature. In fact, the deeper the cold dry winter airmass, the more it warms.[2] As a result, a signature of the warming of winters in mid-continental regions has been a substantial reduction in the number and frequency of severe cold outbreaks of Canadian or polar origin. In North Dakota, these airmasses are associated with the coldest observed temperatures below 2,000 feet in the coterminous United States (-60°F, also recorded in Minnesota).

As shown in our map, the Great Plains generally have been depopulating, with emigration mostly to the region's cities and to warmer climates. While the reasons for depopulation are complex, involving changes in agricultural economics and sociology, it is unclear whether warming will counter or enhance this trend.

Projected increases in temperature and uncertainty about changes in future precipitation suggest an increase in regional dryness

While it is very likely that the Great Plains will experience an increase in mean temperature,

Annual Precipitation



Precipitation histories in the wettest part of the Great Plains (specifically, the Ouachita Mountain region of southeastern Oklahoma) and from very dry northwestern North Dakota certainly show no trend related to regional temperature change. A plot (not shown) of summer rainfall in southeastern Oklahoma shows record-low rainfall in 2011, but there is no obvious trend.

primarily in the winter, precipitation forecasts do not meet the normal criteria for statistical significance. Absent a significant forecast, one usually assumes that the long-term average in rainfall will continue. This temperature-precipitation combination means that there should be increased evaporation of the same amount of surface moisture, so the probability of dryness increases, compared to the current era.

It is noteworthy that Great Plains precipitation changes forecast on page 31 of the USGCRP report are not occurring. Our plot shows the histories from the wettest climatological division in the Great Plains (which is actually the very hilly Ouachita Mountain region of southeast Oklahoma), and from the arid northwestern corner of North Dakota.

Agriculture is likely to adapt to increased dryness by changing crops

Agriculture, range, and croplands cover more than 70 percent of the Great Plains, with wheat being the principal crop. Heat and water stress obviously reduce yields, particularly during the pollination period for both winter and spring wheat, in the late spring and early summer. The influence of an increasing tendency for dryness, should that occur, would likely result in a switch from wheats to grain sorghum, which is currently limited by cold temperatures[3] that can be expected to rise.

According to the *Field Crops Manual* of the University of Wisconsin Extension, grain sorghum food quality and usage are virtually the same as for corn, but it has many advantages in hot and dry regions.

Because it is self-pollinated (as opposed to corn, which is cross-pollinated), short periods of dryness that are common in mid-American summers will not damage fertilization. While the density of corn plantings increases sensitivity to moisture loss, this is unimportant to sorghum, in part because, compared to corn, sorghum foliage resists drying. Most interestingly, despite its drought tolerance, sorghum is more tolerant of wet and flooded soil than most other grains.[4] The USGCRP makes absolutely no reference whatsoever to this likely adaptational switch in crops.

Ongoing shifts in the region's population have much greater effects than modest climate change

In a warming and drying climate, wheat (top) is likely to be replaced by grain sorghum (bottom), whose nutritional value is very close to that of corn.

Playa lakes in northern Texas are clearly affected by the region's agriculture.

The predominance of agriculture in the Great Plains has radically altered the surface, affecting playa lake and prairie potholes much more so than prospective climate change.

While the federal government owns approximately 10 percent of the Great Plains, much of the remaining land is dedicated to agriculture, which has substantially changed the surface from its natural condition.

The Ogallala aquifer, stretching from Nebraska to northern Texas, is an underground reservoir of water largely from the ice age, which is being increasingly drained by modern agriculture. As long as water is obtained from this source, agriculture thrives in a normally dry environment that is characterized by small-scale and ephemeral "pothole" and "playa" lakes.

As the USGCRP notes, "many playas are disappearing and others are threatened by growing urban populations, extensive agriculture, and other filling and tilling practices."

It is clear that the intensive agriculture depicted above radically alters the native playa surface. Further, as low points in the terrain, substantial runoff of soil and agrochemicals into the playas is impossible to avoid, especially because the region's rainfall tends to take place in short, high intensity thunderstorms that give rise to overland flow. Clearly, an annual rainfall change of a few inches will be lost in the great spatial and temporal variability of high plains precipitation, and the natural disturbances to the playas far outweigh the effects of small changes in seasonal rain.

While playa lakes help to recharge the Ogallala aquifer, they do not compensate for the large volumes of water drawn down to supply the massive central-pivot irrigation systems common in the region. Further, runoff of soil into the lakes decreases soil permeability, further reducing recharge.

As the aquifer becomes increasingly discharged, especially in northern Texas, water will become sufficiently expensive to shift the region back to dryland agriculture, with grain sorghum likely replacing the current culture of winter wheat.

As noted earlier, the rural Great Plains have experienced a remarkable depopulation, while the population of many of the region's large cities, such as Denver, Dallas, and Houston grew approximately 20 percent in the last decade.

While concern has been expressed about the water supply for the region's large cities, most are located either near substantial water resources (Omaha, Kansas City), have annual rainfall in excess of 30 inches (Dallas, Oklahoma City), or a substantial resource of annual meltwater (Denver and the Front Range cities).

It is very clear that doubling of a city's population affects water supply much more than changing precipitation by 20 percent or increasing evaporation a few inches per year, which are logical expectations in the coming century. While climate change may serve as the basis for rhetoric about supply and demand for water, indeed there is generally adequate supply if the political will exists to utilize it. Unfortunately, increasing resistance to impoundments for water supply create supply problems that dwarf the effects of changing climate.

The aging of rural Great Plains populations has been well-documented, with the median age in rural areas increasing over twice as fast (14 years vs. 6.4 years) as the urban population.[5] While it is true that the elderly are more susceptible to climate-related morbidity and mortality, very hot cities with high concentrations of elderly, such as Phoenix and Tampa, have very little heat-related mortality.[6] This occurs because of technological adaptations to heat that can occur in the Great Plains as well.

New Opportunities

There is growing recognition that the enormous natural gas potential from the Bakken Shale in North Dakota, and the Eagle Ford and other deposits in Texas will provide enormously more dense energy than widely distributed wind energy plantations fashionable today. It is estimated that by 2016, natural gas will produce electricity for about 60 percent of the cost of wind.[7] The collapse in the share prices of wind turbine manufacturers is striking compared to the robustness of natural gas equities as subsidies for wind power are reduced by increasingly impoverished governments. Ditlev Engel, the CEO of Vestas Corporation, the world's largest producer of wind turbines, has clearly indicated that wind energy depends upon continued government subsidies.[8]

As a result, the wind power "boom" in the Great Plains is being rapidly superceded by the subsequent boom in shale gas. This is already providing increased employment and diversification of land usage as people seek inexpensive, dependable, and abundant energy.

Two-year share price for Vestas Wind Systems (blue) versus Chesapeake Energy (green).The decline in share price of large wind turbine manufacturers, such as Vestas, has occurred as government subsidies for wind power are reduced and shale gas is increasingly exploited. This has substantial economic implications for the Great Plains.

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[4]University of Wisconsin-Extension, *Field Crops Manual*. Section at http://www.hort.purdue.edu/newcrop/afcm/sorghum.html.

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Southwest

Long term "proxy" indicators of streamflow in the Colorado River, the largest drainage basin in the Southwest, show prolonged periods of drought are the historic norm rather than the exception. Some of these are detailed in our Water Resources chapter.

Indeed, the variability of southwestern precipitation is so great that only one state (Utah) shows a statistically significant (increasing) trend since records began in 1895. Temperatures have risen significantly in every state. In combination with the lack of precipitation trends in most states, evaporation has been increasing, resulting in a tendency towards more dryness in an already arid environment.

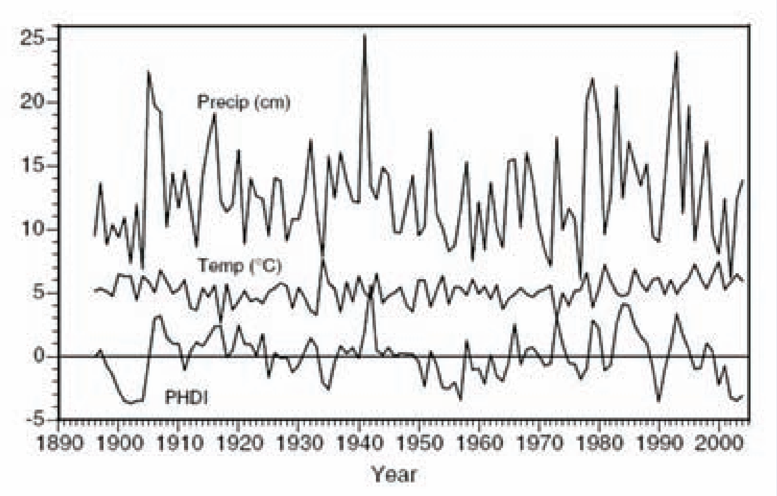
Maximum and minimum values for annual statewide trends since 1895:

- The largest annual temperature change is a rise of .24°F/decade (2.8° from 1895 to 2011) in Nevada.
- The smallest annual temperature change is a rise of .07°F/decade (0.8°F from 1895 to 2011) in California. Despite being of low magnitude, this change is statistically significant.
- The largest change in statewide average rainfall is an increase of 0.14 in./decade (1.6 in. from 1895–2011) in Utah.
- There is no significant net change in annual precipitation in Arizona, California, Colorado, New Mexico, or Nevada.

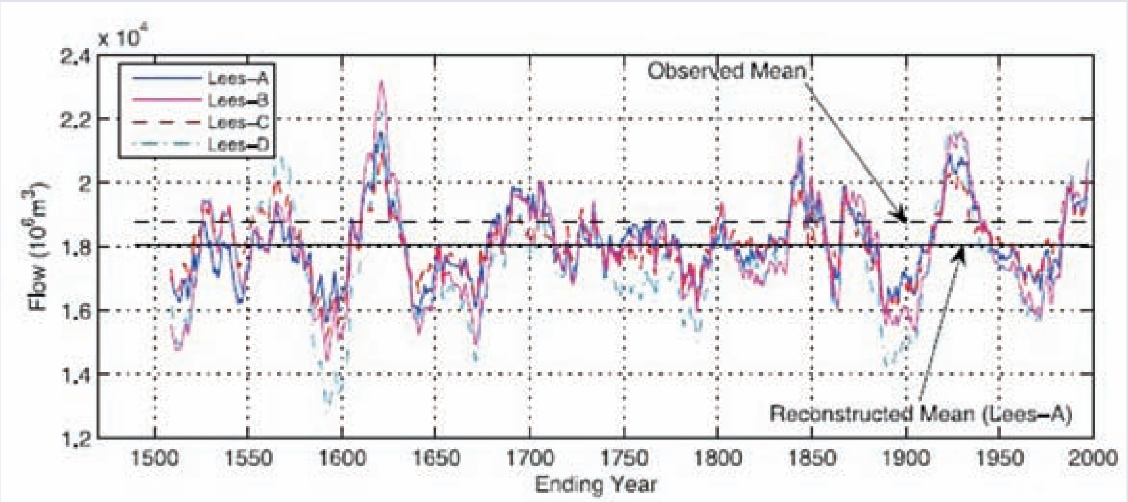
In general, climate models predict that warming would be enhanced in the summer in this region, rather than the winter, because the air in summer tends to be drier than in the winter (which is opposite to the case over most of the rest of the United States). Observed temperature changes, while all in the positive direction, are virtually the same for winter and summer, making attribution of the current warming in this region to greenhouse gases somewhat problematical.

Water-use efficiency and population are both increasing in the Southwest. The effects of population increase are much greater than what would happen if the supply of available water dropped as a result of climate change

Water, largely from the Colorado River Basin, is indeed the life blood of the Southwest, and



Time series plot of areally-averaged Colorado River Basin November–April total precipitation (cm), temperature (°C), and Palmer Hydrological Drought Index (PHDI) over the period November 1895 to April 2004.[2]



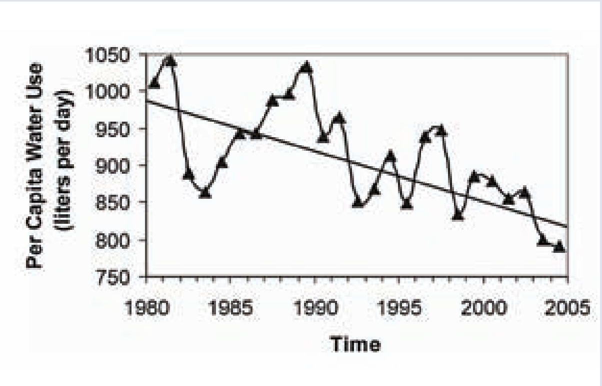
Reconstructed 20-year running means of Colorado River flow at Lees Ferry, Arizona, by various statistical models.[4]

the Colorado Basin has warmed by 0.12°F per decade over the past 100+ years. Precipitation during the recharge season, November to April, shows no significant trend over either time period; the Palmer Hydrological Drought Index showed no significant trend over the 100+ year period, while it has trended toward increased drought since 1975.[1] In other words, the recent increase in drought is not at all remarkable given historical climate records for the region.

Paleoclimatic reconstructions of Colorado River flow show that very large droughts have occurred in the past,[3] which means they will certainly occur in the future.

Large cities in the Southwest have implemented successful water conservation policies; Phoenix, for example, has reduced per capita consumption by over 15 percent in the last three decades.[5] Other potential strategies for adaptation to a dry environment include winter season cloud seeding in the head waters to increase snowpack, genetic development of more water efficient crops and grasses, and improvements to engineering structures throughout the watershed. Nonetheless, as population expands in the Southwest as predicted, water managers will certainly be challenged, with or without climate change.

While per capita water use dropped, the population of the Phoenix MSA rose by 180 percent during the same period. While for reasons detailed repeatedly in earlier text, climate model forecasts of precipitation changes in this century are of no utility, it is clear that impacts of population change dwarf those of climate change. Indeed, planners who argue for infrastructure improvements because of climate change are citing a much weaker rationale than simple projections of population, which are much more reliable and much more significant.

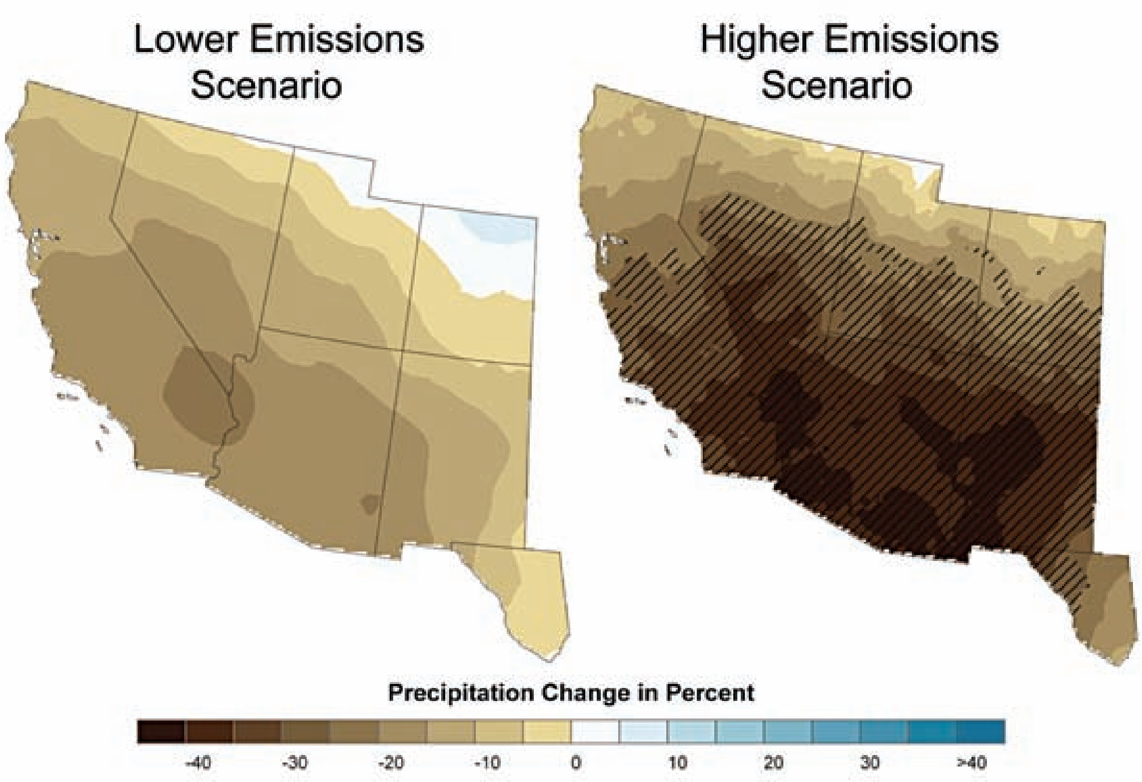


Phoenix per capita annual water use (liters per capita per day) from 1980 through 2004.[6]

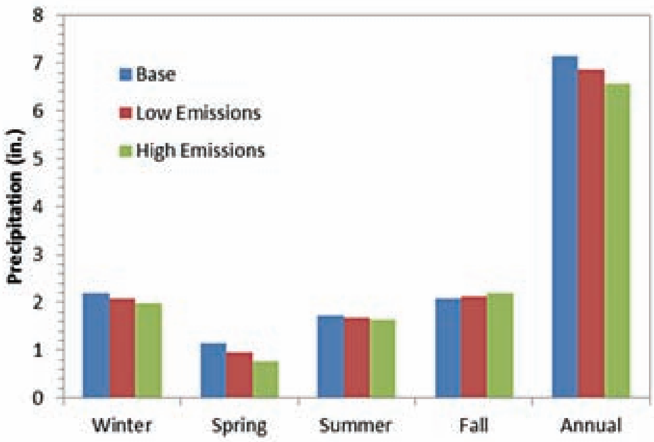
How the USGCRP Report Misleads on Southwestern Rainfall

The USGCRP chapter on the Southwest contains a fairly alarming graphic, showing large percent declines forecast in spring rainfall without providing any context.

As mentioned repeatedly, earlier in this document, the hatched areas where "confidence" is "highest" according to the USGCRP do not meet any normative criteria for statistical significance.



Projected change in spring precipitation in the Southwest, 2080–99, given in the USGCRP report. See text for details.



Seasonal and annual precipitation for Phoenix. Blue: current average; Red: under USGCRP low emissions scenario; Green: high emissions scenario. The precipitation models do not meet the normal scientific criteria for statistical significance.

The USGCRP chose to only show spring, which is the season with the largest percent declines. Because a large percent of a small number is still a small number, this is quite misleading. Had they shown all of the seasons, as well as the annual values (as is done here), it would be immediately obvious that the changes in total precipitation predicted by these inadequate models is in fact quite small.

Satellite records indicate slight but statistically significant increases in net primary productivity throughout the Southwest

Our map of changes in the Normalized Difference Vegetation index (shown in the Southeast section) showed slight but statistically significant increases in the "greenness" of the surface as measured across the coteriminous United States by satellites.[7] These records, beginning in 1981, are concurrent with a period of warming and drying in the Southwest noted by the USGCRP. If net photosynthesis is increasing in a drying environment, then either previous land management practices had produced inordinately low vegetation levels, or increases in atmospheric carbon dioxide concentrations are compensating for the loss of moisture. We noted a photographic example of this in our Ecosystems chapter.

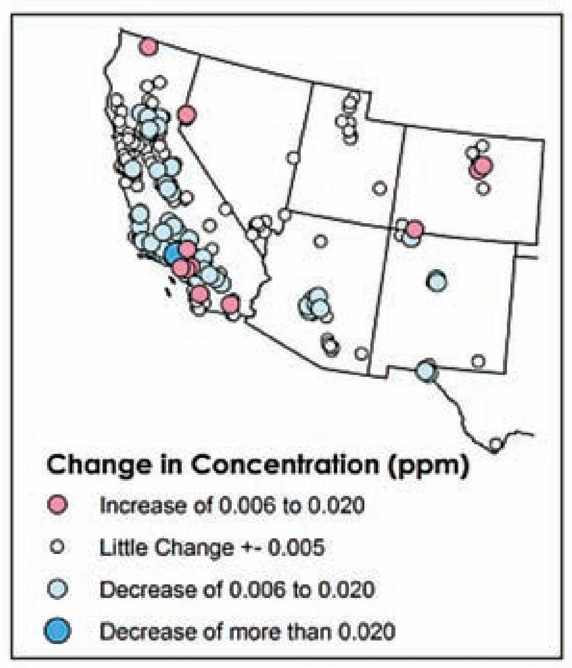
Cities will continue to adapt to very hot temperatures, and carbon dioxide mitigates heat-related pollution and drought damage to agriculture

Phoenix has one of the lowest rates of heat-related mortality in the United States, despite extremely high summer temperatures and a large elderly population. This is because heat-related mortality occurs less frequently in cities that experience frequent episodes of very high effective temperatures.[8]

Because hot weather also helps to form ozone, there are concerns that CO_2-induced global warming will further increase the concentration of this pollutant, resulting in future crop yield reductions.[9] Several experiments have been conducted to determine interactive effects of elevated CO_2 and ozone on important crops. These studies show that elevated CO_2 reduces, and frequently completely overrides, the negative effects of ozone pollution on plant photosynthesis, growth, and yield in some crops.[10,11] The mechanism appears to be that atmospheric CO_2 enrichment tends to reduce stomatal conductance, which causes less indiscriminate uptake of ozone into internal plant air spaces and reduces subsequent conveyance to tissues where damage often results to photosynthetic pigments and proteins, ultimately reducing plant growth and biomass production.

In the Southwest, surface measurements show a pattern of mostly unchanged or declining ozone concentration over the past two decades that is broadly consistent with decreases in precursor emissions. The spatial and temporal distributions of these and other observations show increasing industrialization and automotive use originally tends to increase the emissions of precursor substances that lead to the creation of greater tropospheric ozone pollution.

Indeed, the early automobile pollution in the Los Angeles basin resulted in the first limitations on atmospheric ozone precursors. Subsequent technological advances tend to ameliorate that phenomenon, as they appear to



Change in ozone concentrations in ppm, 2001–03 vs. 2006–08 (three-year average of annual fourth highest daily maximum eight-hour concentrations).[12]

gradually lead to (1) a leveling off of the magnitude of precursor emissions and (2) an ultimately *decreasing* trend in tropospheric ozone pollution, despite a warming trend in recent decades and rapidly increasing numbers of cars and trucks.

When atmospheric ozone and CO_2 concentrations both rise together, the plant-growth-enhancing effect of atmospheric CO_2 enrichment is significantly muted by the plant-growth-retarding effect of contemporaneous increases in ozone pollution, but as the troposphere's ozone concentration gradually levels off and declines—as it appears to be doing with the development of new and better anti-pollution technology in the planet's more economically advanced countries—the future could bring more-rapid-than-usual increases in the Southwest's vegetative productivity, including crop yields.

It has been suggested that the frequency and severity of drought across much of the United States will increase as greenhouse gases rise, causing crops to experience more frequent and more severe water deficits, thereby reducing crop yields.[13]

Recent droughts are not without historical precedent. Nonetheless, even if they were to increase in frequency and/or severity, agricultural crops become less susceptible to drought-induced water deficits as the air's CO_2 concentration rises. This is because water stress does not typically negate the CO_2-induced stimulation of plant productivity. In fact, the CO_2-induced percentage increase in plant biomass production is often greater under water-stressed conditions than it is when plants are well-watered.

During times of water stress, atmospheric CO_2 enrichment often stimulates plants to develop larger-than-usual and more robust root systems that invade greater volumes of soil for scarce and much-needed moisture. Elevated levels of atmospheric CO_2 also tend to reduce the openness of stomatal pores on leaves, thus decreasing plant stomatal conductance. This phenomenon, in turn, reduces the amount of water lost to the atmosphere by transpiration and, consequently, lowers overall plant water use. Atmospheric CO_2 enrichment thus increases plant water acquisition, by stimulating root growth, while it reduces plant water loss, by constricting stomatal apertures; these dual effects typically enhance plant water-use efficiency, even under conditions of less-than-optimal soil water content. These phenomena contribute to the maintenance of a more favorable plant water status during times of drought, as has been demonstrated in several studies.[14,15,16,17]

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[1]Balling, R.C., Jr., and G.B. Goodrich, 2007: Analysis of drought determinants for the Colorado River Basin. *Climatic Change*, **82**, 179-194.

Adaptation: Strategies for Fire

Living with present-day levels of fire risk and—if they occur—with gradually increasingly levels of risk involves common sense, particularly for those who live on the edge of the woods. Such common sense includes creating defensible spaces around your house by cleaning away inflammable brush and sleaze, which will also raise property values. Building with fire-resistant materials is also a good idea where there are lots of fires. Also, be sure to contact your local climate scientist who can use computer models for precipitation that do not work for your region[19,20] but nonetheless are supposed to be "useful" to planners like you! According to the USGCRP, climate scientists can also tell you the implications of the "latest climate science" on "political" (read: more government regulations), "legal" (read: do as you're told!), "economic" (read: you are poorer), and "social institutions" (read: they become more coercive).

Building homes in regions not at high-risk for fire, (i.e., avoiding the edge of the woods) is also a pretty good idea in dry and hot environments such as the Southwest.

[2]Balling, R.C., Jr., and G.B. Goodrich, 2007: Analysis of drought determinants for the Colorado River Basin. *Climatic Change*, **82**, 179-194.

[3]Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006: Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research*, **42**, doi:10.1029/2005WR004455.

[4]Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006: Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research*, **42**, doi:10.1029/2005WR004455.

[5]Balling, R.C., Jr. and P. Gober, 2007: Climate variability and residential water use in Phoenix, Arizona. *Journal of Applied Meteorology and Climatology,* **46**, 1130-1137.

[6]Balling, R.C., Jr. and P. Gober, 2007: Climate variability and residential water use in Phoenix, Arizona. *Journal of Applied Meteorology and Climatology,* **46**, 1130-1137.

[7]de Jong, R.S., et al., 2011: Analysis of monotonic greening and browning trends from global NDVI time-series. *Journal of Remote Sensing,* **115**, 692-702.

[8]Davis, R.E., et al., 2003: Changing heat-related mortality in the United States. *Environmental Health Perspectives,* **111**, 1712-1718.

[9]Karl, T.R., J.M. Melillo, and T.C . Petersen (eds.), 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, Cambridge.

[10]Mishra, S., et al., 2008: Interactive effects of elevated CO_2 and ozone on leaf thermotolerance in field-grown *Glycine max*. *Journal of Integrative Plant Biology,* **50**, 1396-1405.

[11]Bernacchi, C.J., et al., 2006: Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO_2 and ozone concentrations for 3 years under fully open-air field conditions. *Plant, Cell and Environment*, doi:10.1111/j.1365-3040.2006.01581

[12]U.S. Environmental Protection Agency, 2010. *Our Nation's Air: Status and trends through 2008*. Office of Air Quality Planning and Standards, Research Triangle Park, NC, EPA-454/R-09-002, http://www.epa.gov/airtrends/2010/.

[13]Karl, T.R., J.M. Melillo, and T.C. Petersen (eds.), 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, Cambridge.

[14]Robredo, A., et al., 2011: Elevated CO_2 reduces the drought effect on nitrogen metabolism in barley plants during drought and subsequent recovery. *Environmental and Experimental Botany,* **71**, 399-408.

[15]Chun, J.A., et al., 2011: Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn. *Agricultural and Forest Meteorology,* **151**, 378-384.

[16]Manderscheid, R., and H-J. Weigel, 2007: Drought stress effects on wheat are mitigated by atmospheric CO_2 enrichment. *Agronomy for Sustainable Development,* **27**, 79-87.

[17]Widodo, W., et al., 2003: Elevated growth CO_2 delays drought stress and accelerates recovery of rice leaf photosynthesis. *Environmental and Experimental Botany,* **49**: 259-272.

Northwest

According to data from the National Climatic Data Center, Northwest temperatures have risen an average of 0.9°F since the modern record began in 1895, or approximately half as much as global average surface temperature according to records from the United Nations.

Maximum and minimum observed annual changes by state show:

- The largest annual temperature change is a rise of .10°F/decade (1.2° from 1895 to 2011) in Idaho.
- There is no statistically significant temperature trend since 1895 in Washington.
- There is no statistically significant precipitation change in any Northwestern state.

There are generally no statistically significant trends in Pacific Northwest snowfall data when the overall record is examined. However, it is likely that a decline will develop later in this century

The subject of snowpack in the Pacific Northwest has been very controversial, involving loss of position and even professional employment for scientists who have shown complete data records rather than selected segments. Unfortunately, much of the USGCRP chapter on the Northwest also suffers from selective data analysis.

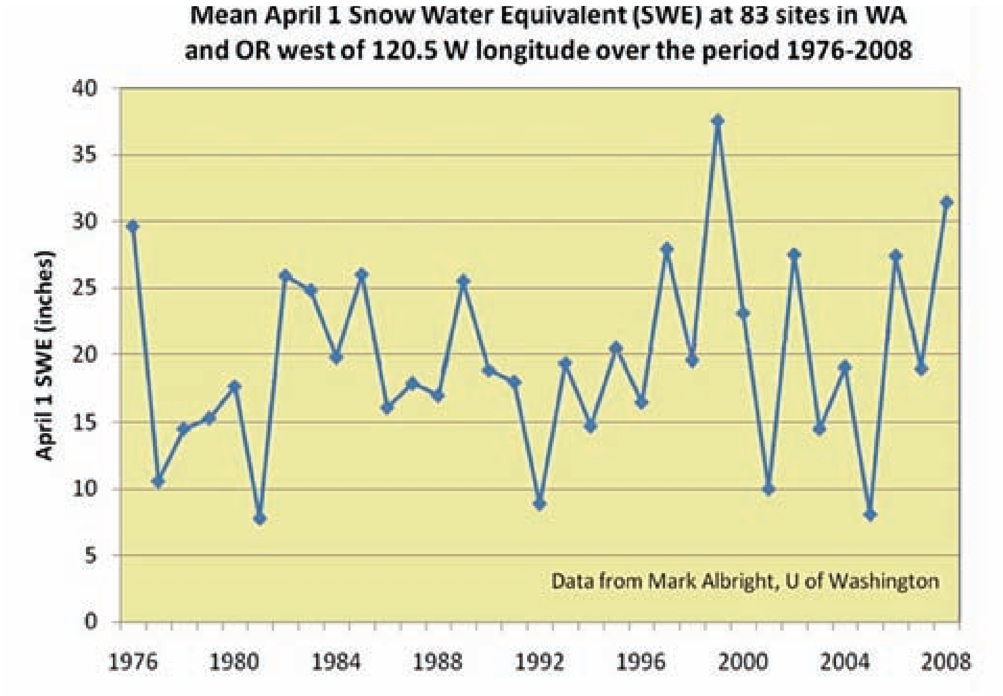
Since the publication of that report, a 2010 paper[1] has definitively examined an extended series of data from 1930 through 2007. The relevant findings are:

- The trend in snowpack in the entire record (1930–2007) is marginally statistically insignificant. If it were significant, it would be negative.
- The trend beginning in 1976, which marks the start of the second global warming of the 20th century, is also insignificant.
- From 1950–97, there was a significant decline in snowpack that was largely related to climate patterns over the North Pacific Ocean that have no obvious relationship to global climate change.
- After removing this factor, the trend in snowpack in the entire record remains marginally statistically insignificant.
- Climate models, coupled to the observed relationship between lower-atmospheric temperature and snowpack, project a 9 percent decline between 1985 and 2025, considerably lower than the 29 percent forecast by the Washington Climate Impacts Group sited by the USGCRP.[2]

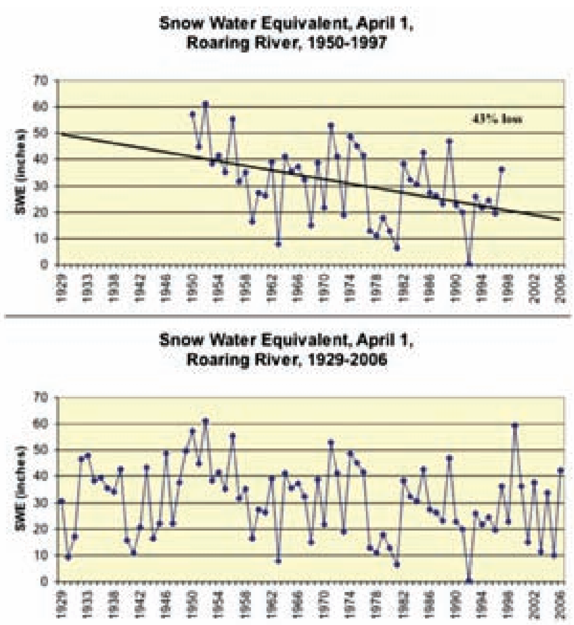
Given the year-to-year noise in the snowpack forecast data, it is not clear whether this decline would be significantly significant. In other words, the decline may not be scientifically distinguishable from no trend. The comparison to the Washington Climate Impacts Group is germane because the snowfall-related text in the USGCRP report on the Northwest appears to largely have been written by that group, or composed of material that is directly taken from their publications.

Snowpack and Snow Water Equivalent Trends

The USGCRP report contains a graphic showing a very large decline in snow water equivalent in the Northwest, with data from 1950 through 2002. The citation is the University of Washington Climate Impacts Group. Then-State Climatologist Philip Mote was instrumental in providing the data. Associate State Climatologist Mark Albright provided data beginning in the late 1970s, but ending as late as possible (at the time), which is shown below:



Assistant State Climatologist Mark Albright was removed from his position by Washington State Climatologist Philip Mote for making the data through 2008 public. There is no significant trend.



Taylor's longest record, beginning in 1929 at Roaring River, shows how beginning snowpack studies in 1950, as was done by Mote, induces a false downward trend in the data.

Then-Oregon State Climatologist George Taylor argued that Cascade snowfall was unusually heavy around 1950, which created an artifically large decline if analysis began then. Also, ending the study early, as Mote did (for no obvious technical reason) ignored data from the relatively snowy early 21st century.

However, there are not many records that go back long before 1950. One, Taylor's long record from Roaring River, is shown on the left. It is quite apparent that the inclusion of the long record provides a dramatically different picture.

Taylor's analysis, which contradicted Oregon's Governor Ted Kluongoski, resulted in a warning from the Governor to not represent his views as those of the State Climatologist.

Streamflow in the Northwest is largely modulated by snowmelt. Streamflow data have largely the same year-to-year variation as the snowpack does. In fact, the most prominent study of changes in the timing of Northwest peak streamflow used by the USGCCRP used a statistical criterion for significance that does not meet normal scientific specification.[3] The report concluded the trends would continue, despite the fact that they cannot be scientifically distinguished from no trend whatsoever in reality.

The region's water supply infrastructure was built based on the assumption that most of the water needed for summer uses would be stored naturally in snowpack. As the climate and snowpack climatology gradually changes over the course of this century, infrastructure and the regulatory structure for water management will adapt.

More intensive forest management and harvest limits infestation of Mountain and Western pine beetles. Beetle-infested forests are more resistant to severe fires than healthy ones

Western and Mountain pine beetle infestation severity is related to climate and management practices. In particular, warm temperatures in winter reduce mortality, and warmer summers extend outbreaks further in elevation. Mountain pine beetle is most common in Washington, while Western pine beetle populations increase as one moves southward through the Northwest.

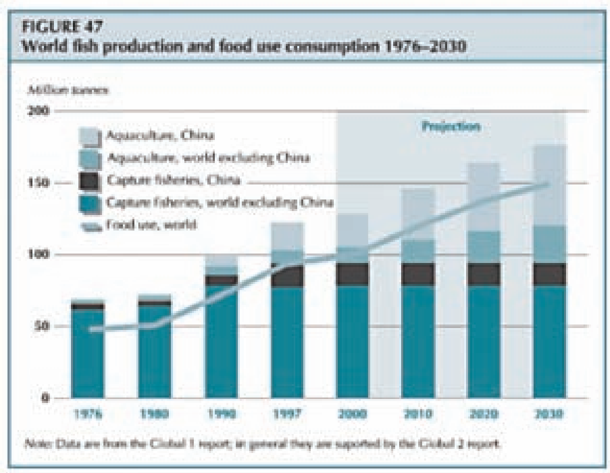
Pine bark beetles are endemic over most of the continental United States, and this endemicity results in sporadic (and sometimes severe and widespread) outbreaks. These create a patchy forest distribution that favors ecosystem diversity. The overlay of more favorable climate conditions increases the likelihood of severe outbreaks, such as those currently occurring in the Northwest.

Severe outbreaks simply cannot be stopped in a heavily infested forest. However, management of non-infested areas greatly reduces the likelihood of a severe outbreak.[4]

The severe dieback of extensive stands of Northwest forest has a counterintuitive effect on severe crown fires. While it is a "rural legend" that these large areas of dead trees provide more fuel in an already fire-prone environment (a myth that the USGCRP also uncritically propagated), in fact, modern research shows that pine beetle–killed forests result in less fuel to burn and actually suppress severe fires.[5]

Pine beetle–damaged wood is used extensively in laminates and for interior decoration, providing another example of how innovation and capital investment result in adaptation to, or even profit, from climate change.

The Western pine beetle, *Dendroctonus brevicomis*.

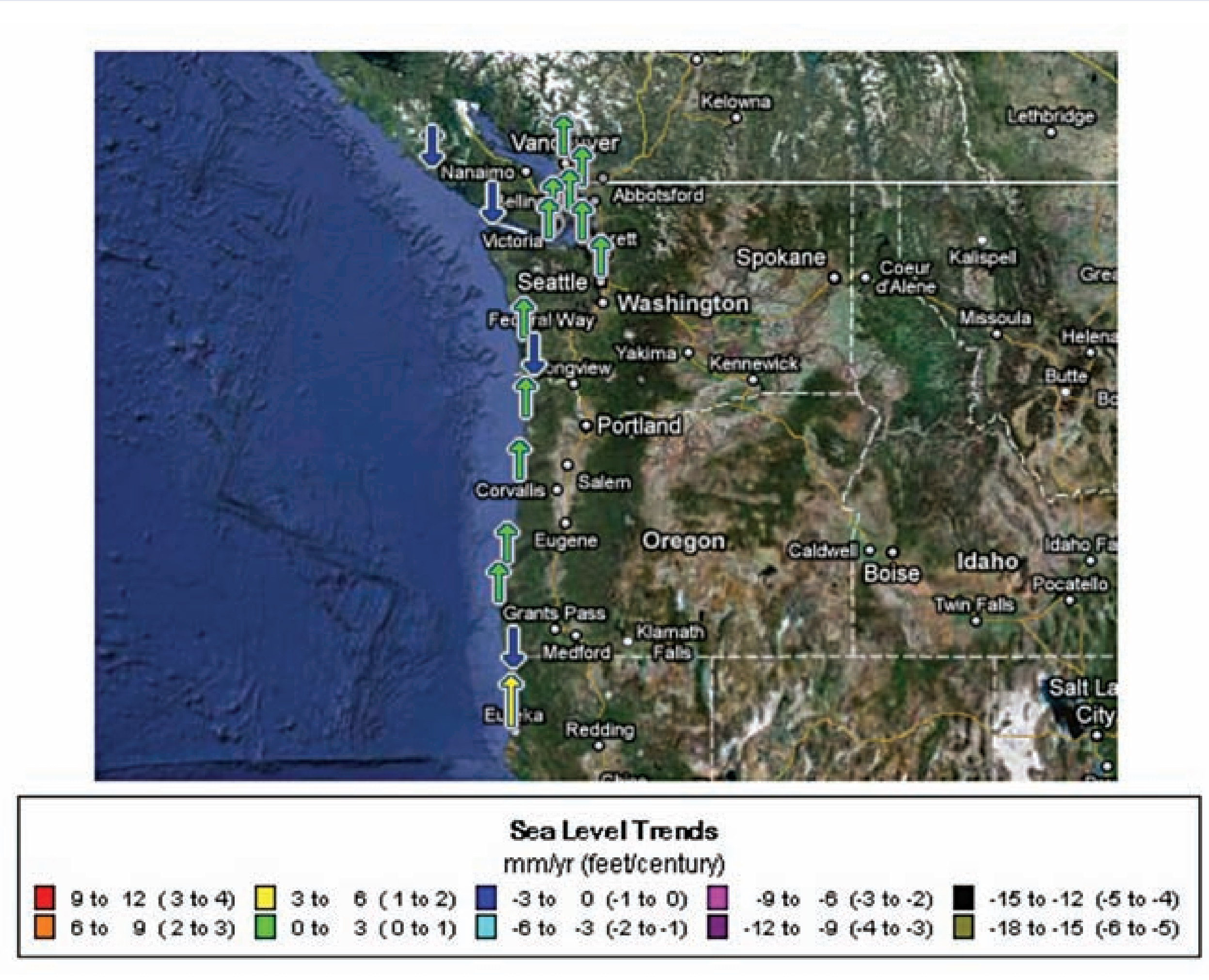


Source: Food and Agricultural Organization (FAO), United Nations.

Depleted wild salmon populations will be increasingly replaced by aquaculture

The global trend towards replacement of native fisheries with aquaculture is likely to continue, and present estimates by the United Nations' Food and Agricultural Organization (FAO) indicate that the amount of aquaculture-produced fish worldwide will likely exceed that consumed from wild catch in approximately 20 years.

In the Northwest, this will mean increasing commercial production of Atlantic salmon, which are more easily farmed than the native



NOAA sea level trends for the Northwest. The tendency for sea level fall increases with latitude in northwestern North America, resulting in major declines in Alaska (see next chapter).

Chinook. Native salmon populations are at historically low levels due to stresses imposed by a variety of human activities, including dam building, logging, pollution, and over-fishing. These are not likely to remit soon, and climate change and natural variability can supply an additional stress.

The substitution of aquacultural salmon for wild-caught is obviously very salutary to stressed populations, which are down by more than 90 percent in the Columbia River drainage, and represents another adaptation to changing economics, ecology, and climate.

Sea level rise in the Northwest has been less than the global average and is likely to remain so

Tide gauge data from the Northwest indicate that sea level rise has been averaging about 75 percent of the current global average (1.0 inch/decade for the last ten years),[6] largely for tectonic reasons. The percent rise declines with latitude in this region, with sea level falling in southwest Canada, and with marked sea level declines in southeast Alaska (see next chapter). The crustal activity that is mitigating the rise in the Northwest is a long-term geological process that can be expected to continue.

It is noteworthy that other areas of the United States, including many locations on the East Coast, have, for geological reasons, experienced approximately twice the rise in sea level that is being observed in the Northwest. As residents there generally adapted to this gradual process without particular alarm (or, in most cases, without even noticing what had happened), it is obvious that sea level rise should be of little concern for Northwest residents within any time horizon for which greenhouse gas emissions are inherently predictable.

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[1] Stoelinga, M.T., M.D. Albright, and C.F. Mass, 2010: A new look at snowpack trends in the Cascade Mountains. *Journal of Climate*, **23**, 2473-2491.

[2] Elsner, M.M., et al., 2009: Implications of 21st century climate change for the hydrology of Washington State. In: Littell., J., et al., (eds.), *The Washington Climate Change Impacts Assessment*. Climate Impacts Group, University of Washington: 69-106.

[3] Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2004: Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change,* **18**, 217-232.

[4] See http://www.ext.colostate.edu/pubs/insect/05528 .html.

[5] Simard, M., et al., 2011: Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? *Ecological Monographs*, **81**, 3-24.

[6] Nerem, R.S., et al., 2010: Estimating mean sea level change from the TOPEX and Jason Altimeter missions. *Marine Geodesy*, 33, Supp. 1, 435. Data available at http://sealevel.colorado.edu/.

Alaska

Alaskan climate change has been enigmatic and complex. One clear signal is that, in general, the statewide temperature history is characterized by a step-change in 1976–77, which was recognized in hindsight (nearly 20 years later) as a sudden reorganization of pan-Pacific climate known as the Great Pacific Climate Shift.[1] The ultimate cause of this change, and the reasons for its persistence, are currently not known.

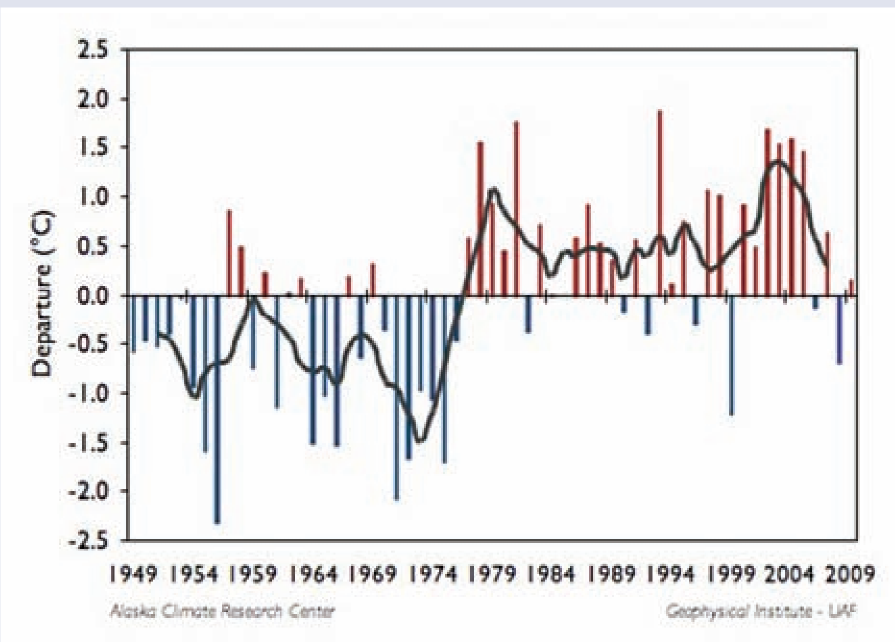
The Pacific Climate Shift involved 40 physical variables, including the climatic pattern known as the Pacific Multidecadal Oscillation.[2] Statewide average records show no net warming prior to or subsequent to this change.

As noted by the Alaska Climate Research Center at the University of Alaska (Fairbanks), a plot of gross trends is inappropriate because of the step change-nature of the Alaskan climate history. None of this is discussed in the USGCRP chapter, which simply states:

> Over the past 50 years, Alaska has warmed at more than twice the rate of the rest of the United States' average. Its average annual temperature has increased by 3.4°F, while winters have warmed even more, by 6.3°F.

Our map on the next page shows the distribution of net warming over Alaska, but the accompanying table is necessary to provide needed context.

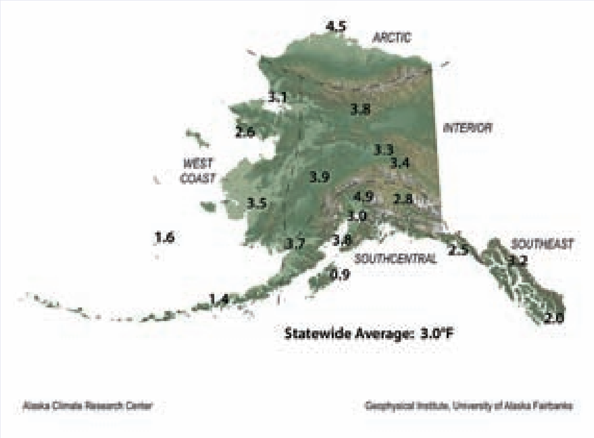
It is very apparent that since the Pacific Climate Shift, there is very little secular temperature change over all of Alaskan stations with the exception of Barrow. The very large autumn warming there is almost certainly related to the decline of sea ice, which has a strong local climate influence.



The power of the Pacific Climate Shift is evident in this post-1948 statewide temperature history.[3]

The only other station that shows a significant increase since 1976 is Talkeetna, but there is likely some type of warming bias at the site. Note that the warm anomaly from 2002–05 averages some 3.5°F above the pre- and post-period background. At Gulkana, relatively (for Alaska) nearby, the

Total Change in Mean Annual Temperature (˚F), 1949-2009



Without the accompanying table (shown below), this map is very misleading about Alaskan climate change.

anomalies are about two degrees above the background for the same period. Anchorage, which is also close (but is experiencing some development around its International Airport weather station), also changes two degrees in the same period.

One interesting aspect of Alaskan temperatures south of the Brooks Range (which divides interior Alaska from the northern coastal plain) is that satellite (microwave)-sensed lower tropospheric temperature shows a rise since the Pacific Climate Shift that is not detected by ground-based thermometers. Because both measurements (satellite microwave and thermometer) are presumably accurate, one is left to hypothesize a systematic discontinuity between the lower troposphere (satellite-sensed)

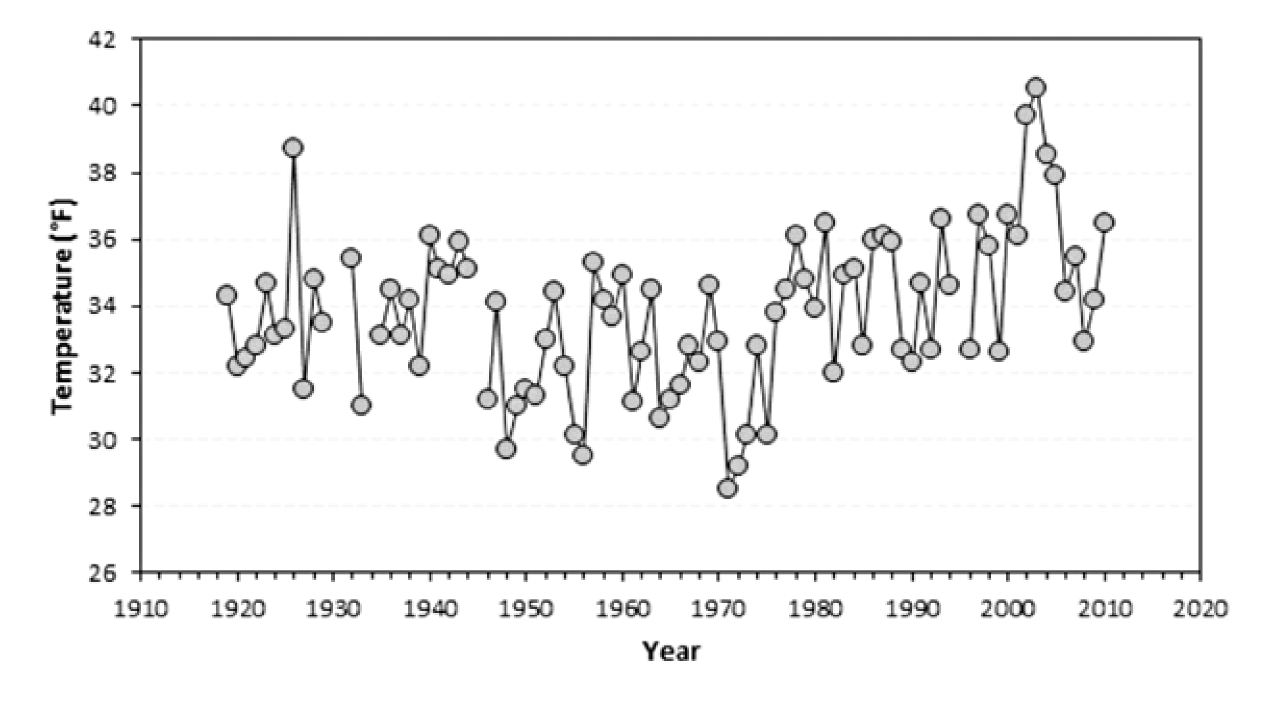
Total Change in Mean Seasonal and Annual Temperature (˚F), 1977-2008

Region	Location	Winter	Spring	Summer	Autumn	Annual
Arctic	Barrow	1.5	4.2	1.8	8.3	4.0
Interior	Bettles	2.3	-0.3	-0.4	0.7	0.1
	Big Delta	3.6	-1.5	0.1	-0.3	-0.2
	Fairbanks	-1.0	-1.7	0.6	-1.4	-1.3
	McGrath	0.7	1.7	2.3	1.1	1.2
West Coast	Kotzebue	-2.1	1.0	-0.5	1.7	-0.2
	Nome	-3.0	-0.5	-1.2	0.4	-1.4
	Bethel	-1.2	0.7	2.4	0.6	0.4
	King Salmon	-1.3	-1.3	1.3	0.6	-0.6
	Cold Bay	-1.3	-1.9	-0.1	0	-1.1
	St Paul	-2.9	-1.3	0.1	0.2	-1.0
Southcentral	Anchorage	0.6	-1.4	0.3	-0.1	-0.6
	Talkeetna	3.8	1.9	2.8	2.4	2.2
	Gulkana	2.0	-0.9	0.8	-1.3	-0.6
	Homer	0.3	-0.7	1.1	0.1	-0.2
	Kodiak	-3.0	-2.6	-0.8	-2.4	-2.3
Southeast	Yakutat	1.5	-1.8	0.4	-0.5	-0.5
	Juneau	3.7	-1.8	-0.1	-0.5	-0.1
	Annette	1.4	-0.1	0.4	0.1	0.2
	Average	0.3	-0.4	0.6	0.5	-0.1

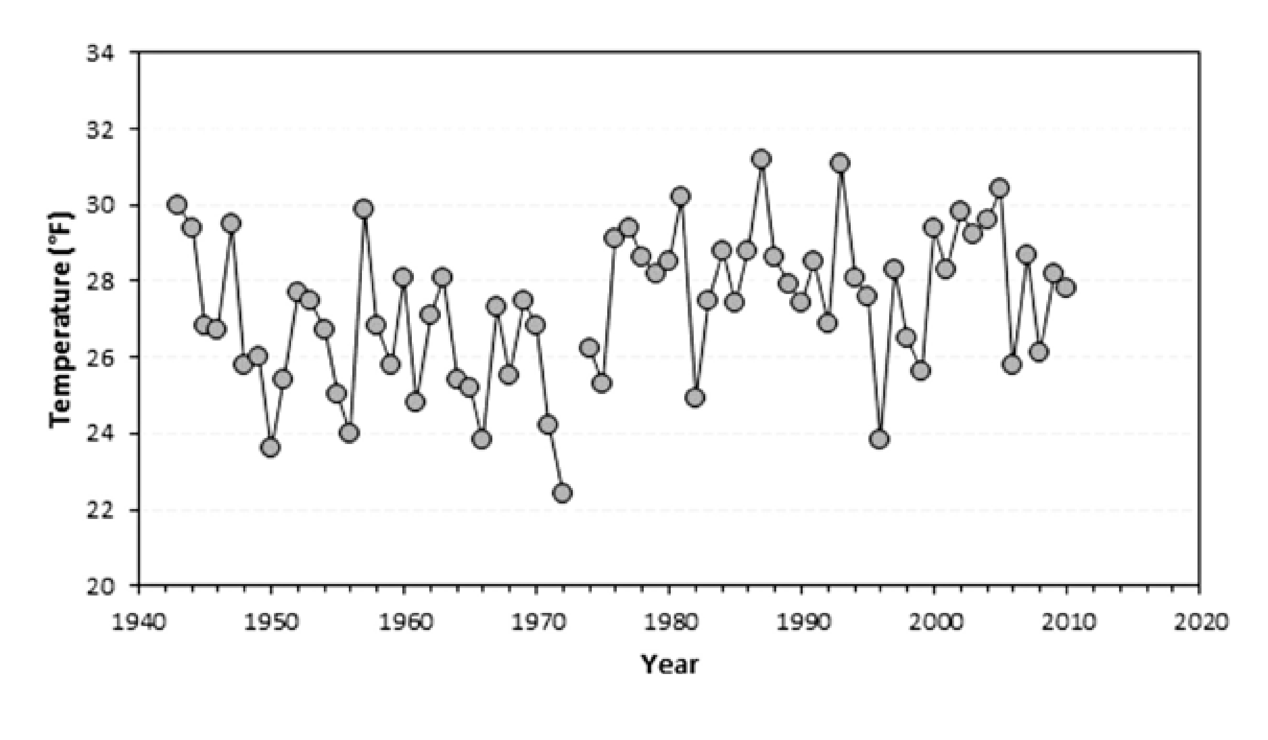
Alaska Climate Research Center Geophysical Institute, University of Alaska Fairbanks

Since the Pacific Climate Shift (beginning in 1977), there has been very little temperature change at most Alaskan stations, with the exception of Barrow, which is probably typical of the entire North Coast.

Talkeetna Mean Annual Temperature (˚F)



Gulkana Mean Annual Temperature (˚F)



The warmth of 2002–2005, which biases the Talkeetna (top) record, is much more muted at Gulkana (bottom), the nearest station. Gulkana's history is typical of that of the Alaskan stations with the exception of Barrow (see text).

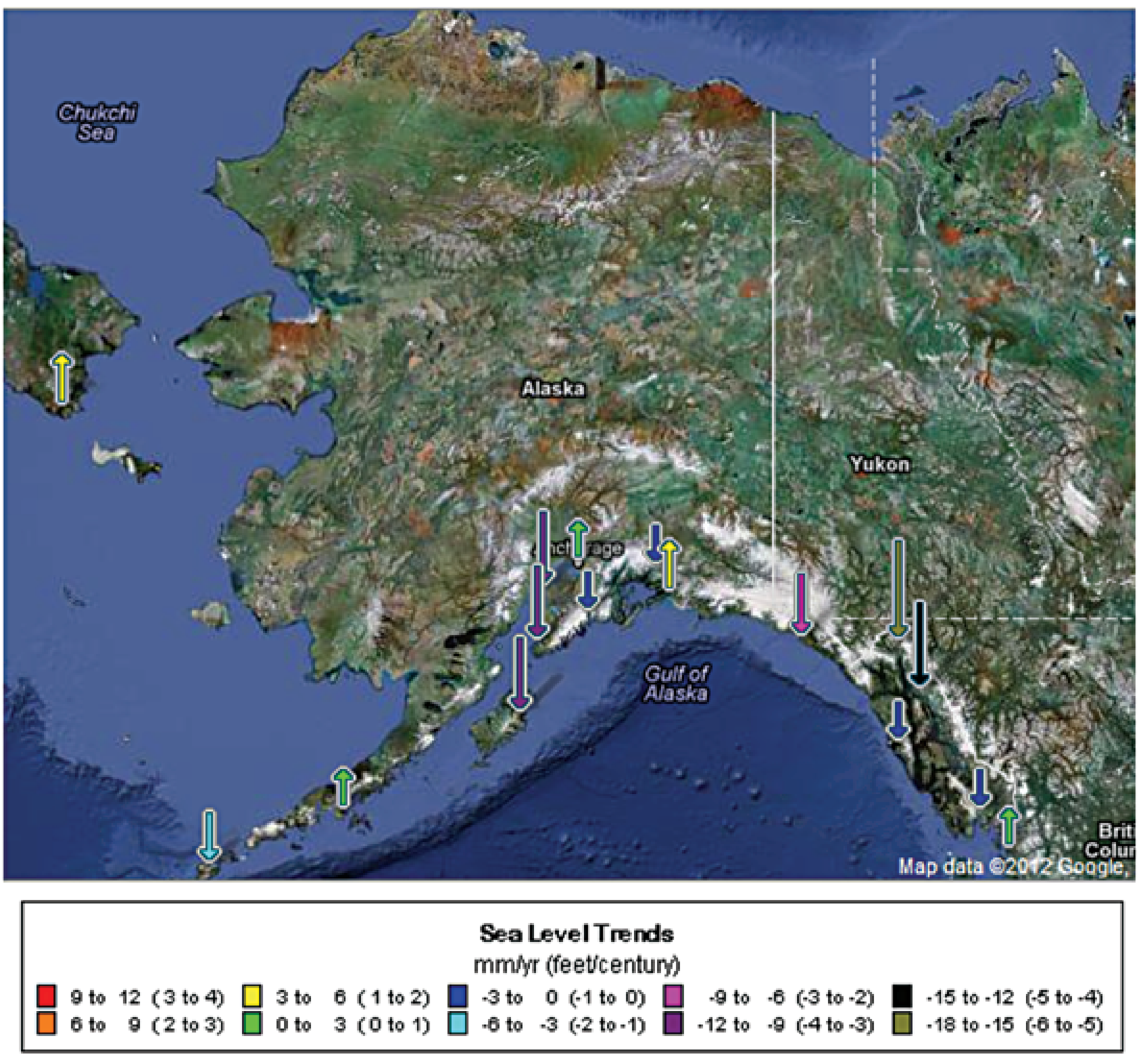
and the boundary layer (thermometrically measured) temperature over Alaska.

As a consequence of climate change, sea levels are falling dramatically from Ketchikan to the Aleutian Islands. Wave action associated with receding late summer ice is increasing erosion along the Beaufort and Bering Coasts

Beginning in 1770 with the end of the Little Ice Age, the Pacific Coast of far southeast Alaska has experienced a remarkable deglaciation, with as much as a mile thickness of ice from Glacier Bay being discharged and melting.[4] The loss from Glacier Bay alone was sufficient to raise global sea level by a third of an inch. The local result has been a precipitous uplift of the land surface, with relative sea level dropping 18.7 feet. In Juneau, tide gauge records indicate a drop in sea level of nearly three feet since 1940.

Needless to say, sea level rise from global warming is not likely to be an issue in southern Alaska as the land rebound is likely to continue through the policy-relevance of this volume.

A different situation applies to the Beaufort Sea and Alaska's north coast, where the decline



Spectacular drops in local sea level have been caused by the deglaciation of southern Alaska that began in the 1770s.

Coastal Storms Increase Risks to Villages and Fishing Fleets

USGCRP's Misuse of Citations and Data

It is fitting to close this effort with a detailed example of the problems that permeate "Global Climate Impacts in the United States."

The section "Coastal storms increase risks to villages and fishing fleets," on pages 142–43 of the USGCRP report, provides a quintessential example of the shoddy scholarship that is its unfortunate hallmark. Consider the following paragraph:

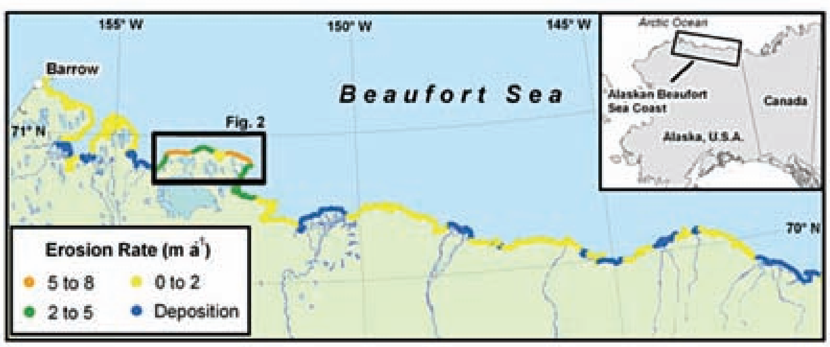
> Increasing storm activity in autumn in recent years[8] has delayed or prevented barge operations that supply coastal communities with fuel. Commercial fishing fleets and other marine traffic are also strongly affected by Bering Sea storms. High-wind events have become more frequent along the western and northern coasts. The same regions are experiencing long sea-ice-free seasons and hence longer periods during which coastal areas are especially vulnerable to wind and wave damage. Downtown streets in Nome, Alaska, have flooded in recent years...The rate of erosion along Alaska's northeastern coastline has doubled over the past 50 years.[9]

Citation 8 is a paper by Lennart Bengtsson and three colleagues called "storm tracks and climate change." It is a modeling study comparing the late 21st century to the late 20th century. It does not talk about "increasing storm activity in recent years" in the fall, because the paper is not concerned with recent trends. There is no reference whatsoever in this article to a change in Alaskan coastal storms.

Nome, 1913

The subsequent statement about "long [er?] ice free seasons" also contains no citation, but is probably reasonable, and Nome does flood.

But what of the statement that "The rate of erosion along Alaska's northeastern coastline has doubled over the past 50 years"? The citation is given as Jones et al., 2009 in *Geophysical Research Letters*. We include the relevant illustration from the paper:



Study area and erosion rates from Jones et al., the citation given in the USGCRP report .

Note that the authors are examining the place on the Beaufort coast that has the largest erosion rates. Note also that about 40 percent of the coast is experiencing deposition ("negative erosion") in the region.

The USGCRP report is replete with problems like this, so much so that this *Addendum* is over 200 pages long.

in late summer and early fall sea ice has increased the frequency of damaging wave action during strong storms. Residents have know of this problem for decades and before the advent of global warming. A 1963 storm created a 10-foot storm surge (which would be respectable for a tropical hurricane) which eroded in a period of a few days about 20 years worth of the “normal” loss of ocean front land.[5]

Erosion rates from a few feet to tens of feet per year have been common along Alaska’s north and west coasts since long before the beginning of the second warming of the 20th century that began in the mid-1970s (and, curiously, concurrent with the Great Pacific Climate Shift).[6] Despite substantial publicity in the *New York Times* in 2007, rapid erosion at Newtok was noted in scientific journals as early as 1953:

> At “Nuwuk” [today, “Newtok”] the evidence of rapid retreat is especially striking. The abandoned native village of the same name, which formerly occupied most of the area immediately surrounding the station site, is being rapidly eaten away by the retreat of the bluff and in October 1949 the remains of four old pit dwellings, then partially collapsed and filled with solid ice, were exposed in cross section in the face of the bluff. In 1951 these four dwellings had been completely eroded away and several more exposed.[7]

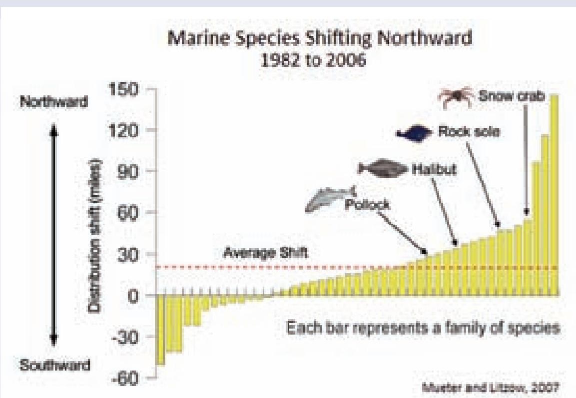


Illustration from the USGCRP report on Alaska. The cited authors, Mueter and Litzow, could find no climatic component to the species shift (see text).

Displacement of marine species with no clear cause can effect fisheries

The illustration below was in the USGCRP report, citing Mueter and Litzow. From their 2007 paper:

> A nonlinear, accelerating time trend in northward displacement (Fig. 5D), unrelated to temperature or any other climate parameter we tested (at any lag), suggests that mechanisms besides climate must be contributing to distribution shifts in the Bering Sea...The failure of our exploratory attempts to explain variability among species underlines the difficulties of this research problem. [10]

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[1]Miller, A.J., et al., 1994: The 1976-77 climate shift of the Pacific Ocean. *Oceanography,* **7**, 21-26.

[2]Miller, A.J., et al., 1994: The 1976-77 climate shift of the Pacific Ocean. *Oceanography,* **7**, 21-26.

[3]See http://climate.gi.alaska.edu/ClimTrends/Change/TempChange.html.

[4]Larsen, C.F., et al., 2005: Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat. *Earth and Planetary Science Letters,* **237**, 548-560.

[5]Hume, J.D., and M. Schalk, 1967: Shoreline processes near Barrow, Alaska: A comparison of the normal and the catastrophic. *Arctic,* **20**, 86-103.

[6]Hartwell, A.D., 1973: Classification and relief characteristics of Northern Alaska’s coastal zone. *Arctic,* **26**, 244-252.

[7]McCarthy, G.R., 1953: Recent changes in the shoreline near Point Barrow, Alaska. *Arctic,* **6**, 44-51.

[8]Bengtsson, L., K.I. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. *Journal of Climate,* **19**, 3518-3543.

[9]Jones, B.M., et al., 2009: Increase in the rate and uniformity of coastal erosion in Arctic Alaska. *Geophysical Research Letters,* **36**, L18791, doi: 10.1029/2008GL023684.

[10]Mueter, F.J., and M.A. Litzow, 2007: Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications,* **18**, 309-320.

Concluding Thoughts

Responding to changing conditions

Natural and human-induced climate change are likely happening simultaneously, perhaps beginning with the second warming of the 20th century that started with the Great Pacific Climate Shift of 1976–77. The USGCRP gives a partial synthesis of the impacts of these changes on various sectors and regions. This *Addendum* provides needed balance.

The USGCRP document played a major role in the EPA's finding of "endangerment" from carbon dioxide and other greenhouse gases. It is hoped that this *Addendum* will provided needed technical information to challenge the regulations emanating from that finding.

The lack of "climate choices"?

It is clear that any unilateral U.S. policy will have absolutely no detectable effect on the trajectory of planetary warming. This even applies to the 83 percent reductions in carbon dioxide emissions that were required in legislation that passed the House of Representatives in June 2009. Further, if these regulations were enacted—and followed—by every nation that has obligations under the Kyoto Protocol, there would still be no detectable effect on global temperature at the half-century scale. In coming decades, the enormous emissions of China and India will dwarf anything from the United States or industrialized western Europe, making our actions climatically nugatory.

Fortunately, there is strong evidence throughout this volume that climate change will not be as rapid or of the magnitude forecast by the aggregate computer models used in the USGCRP report. In addition, there is strong evidence for successful adaptation to observed climate change which includes climate change–related profits. This can be expected to continue as long as our economy is free and not stifled by completely ineffective carbon dioxide regulations.

The value of assessments

Climate change assessments such as the one produced by the USGCRP suffer from a systematic bias due to the fact that the experts involved in making the assessment have economic incentives to paint climate change as a dire problem requiring their services, and the services of their university, federal laboratory, or agency. There is no other explanation for a document that ignored so many scientific references that are included in this *Addendum*. Assessments serve a very important function for regulators. The USGCRP report was designed to provide a rationale to expand regulatory reach, power, and cost. Assessments such as this *Addendum* are designed to provide a rationale to resist such expansion of reach and regulation.

Future federal science assessments

Future assessments of climate change are likely to be as poor in quality as *Global Climate Change Impacts in the United States*. Regardless of who is President, the same figures will remain in the civil service and academia, with every incentive to expand their turf and further their careers. It is a sad fact of American life that such unelected people can impose such enormous costs on the citizenry without being subject to recall.

However, if this *Addendum* has a significant impact, each new federal assessment is likely to be answered like the USGCRP report was—with more science than our federal government chooses to recognize.

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