Technical Support Document

Endangerment Analysis for Greenhouse Gases under the Clean Air Act

Draft

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Executive Summary

This document provides technical support for the endangerment analysis concerning greenhouse gas (GHG) emissions that may be addressed under the Clean Air Act. This document itself does not convey any judgment or conclusion regarding the question of whether GHGs may be reasonably anticipated to endanger public health or welfare, as this decision is ultimately left to the judgment of the Administrator.

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Observed Trends in Greenhouse Gas Emissions andConcentrations

Greenhouse gases, once emitted, can remain in the atmosphere for decades to centuries, meaning that 1) their concentrations become well-mixed throughout the global atmosphere regardless of emission origin, and 2) their effects on climate are long lasting. The primary GHGs of concern directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Greenhouse gases have a warming effect by trapping heat in the atmosphere that would otherwise escape to space.

In 2006, U.S. GHG emissions were 7,054 teragrams[1] of CO_2 equivalent[2] ($TgCO_2eq$). The dominant gas emitted is CO_2, mostly from fossil fuel combustion. Methane is the second largest component of U.S. emissions, followed by N_2O, and the fluorinated gases (HFCs, PFCs, and SF_6). Electricity generation is the largest emitting sector (34% of total U.S. GHG emissions), followed by transportation (28%) and industry (19%).

Transportation sources under section 202 of the Act (passenger cars, light duty trucks, other trucks and buses, motorcycles, and cooling) emitted 1,665 $TgCO_2eq$ in 2006, representing almost 24% of total U.S. GHG emissions.

U.S. transportation sources under section 202 made up 4.3% of total global GHG emissions in 2005, which, in addition to China and the U.S. as a whole, ranked only behind total GHG emissions from Russia and India but ahead of Japan, Brazil, Germany and rest the world's countries. In 2005, total U.S. GHG emissions were responsible for 18% of global emissions, ranking only behind China, which was responsible for 19% of global GHG emissions.

The global atmospheric CO_2 concentration has increased about 38% from pre-industrial levels to 2009, and almost all of the increase is due to anthropogenic emissions. The global atmospheric concentration of CH_4 has increased by 149% since pre-industrial levels (through 2007); and the N_2O concentration has increased 23% (through 2007). The observed concentration increase in these gases can also be attributed primarily to anthropogenic emissions. The industrial fluorinated gases, HFCs, PFCs, and SF_6, have relatively low atmospheric concentrations but are increasing rapidly; these gases are almost entirely anthropogenic in origin.

Historic data show that current atmospheric concentrations of the two most important directly emitted, long-lived GHGs (CO_2 and CH_4) are well above the natural range of atmospheric concentrations compared to the last 650,000 years. Atmospheric GHG concentrations have been increasing because human emissions have been outpacing the ability of the natural environment to remove GHGs from the atmosphere over timescales of decades to centuries.

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[1] One teragram (Tg) = 1 million metric tons. 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

[2] Long-lived GHGs are compared and summed together on a CO_2 equivalent basis by multiplying each gas by its Global Warming Potential (GWPs), as estimated by IPCC. In accordance with UNFCCC reporting procedures, the U.S. quantifies GHG emissions using the 100-year time frame values for GWPs established in the IPCC Second Assessment Report.

Observed Effects Associated with Global Elevated Concentrations of GHGs

The global average net effect of the increase in atmospheric GHG concentrations, plus other human activities (e.g., land use change and aerosol emissions), on the global energy balance since 1750 has been one of warming. This total net heating effect, referred to as forcing, is estimated to be +1.6 Watts per square meter (W/m^2), with much of the range surrounding this estimate due to uncertainties about the cooling and warming effects of aerosols. The combined radiative forcing due to the cumulative (i.e., 1750 to 2005) increase in atmospheric concentrations of CO_2, CH_4, and N_2O is +2.30 W/m^2. The rate of increase in positive radiative forcing due to these three GHGs during the industrial era is very likely to have been unprecedented in more than 10,000 years. .

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global mean surface temperatures have risen by 0.74°C (1.3ºF) over the last 100 years. Eight of the ten warmest years on record have occurred since 2001. Global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. Climate model simulations suggest natural forcings alone (e.g., changes in solar irradiance) cannot explain the observed warming.

U.S. temperatures also warmed during the 20th and into the 21st century; temperatures are now approximately 0.7°C (1.3°F) warmer than at the start of the 20th century, with an increased rate of warming over the past 30 years. Both the IPCC and CCSP reports attributed recent North American warming to elevated GHG concentrations. In a 2008 CCSP report[3], the authors find that for North America, "more than half of this warming [for the period 1951-2006] is likely the result of human-caused greenhouse gas forcing of climate change."

Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. Over the contiguous U.S., total annual precipitation increased at an average rate of 6.5% per century from 1901-2006. It is likely that there have been increases in the number of heavy precipitation events within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate.

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate. It is not clear whether the increasing rate of sea level rise is a reflection of short-term variability or an increase in the longer-term trend. Nearly all of the Atlantic Ocean shows sea level rise during the past decade with the rate of rise reaching a maximum (over 2 mm per year) in a band along the U.S. east coast.

Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7 ± 0.6% per decade, with larger decreases in summer of 7.4 ± 2.4% per decade.

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[3] CCSP (2008) *Reanalysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Randall Dole, Martin Hoerling, and Siegfried Schubert (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, 156 pp.

Widespread changes in extreme temperatures have been observed in the last 50 years across all world regions including the U.S. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. However, attributing regional changes in climate to greenhouse gases from human activities is difficult, especially for precipitation.

Observations show that climate change is currently affecting U.S. physical and biological systems in significant ways. The consistency of these observed changes in physical and biological and observed significant warming likely cannot be explained entirely due to natural variability or other confounding non-climate factors

Projections of Future Climate Change with Continued Increases in Elevated GHG Concentrations

Most future scenarios that assume no explicit GHG mitigation actions beyond those already enacted project an increase of global GHG emissions over the century, with climbing GHG concentrations. Carbon dioxide is expected to remain the dominant anthropogenic GHG over the course of the 21st century. The radiative forcing associated with the non-CO_2 GHGs is still significant and growing over time.

Future warming over the course of the 21st century, even under scenarios of low emissions growth, is very likely to be greater than observed warming over the past century. Through about 2030, the global warming rate is affected little by the choice of different future emission scenarios. By the end of the century, projected average global warming (compared to average temperature around 1990) varies significantly depending on emissions scenario and climate sensitivity assumptions, ranging from 1.8 to 4.0°C (3.2 to 7.2°F), with an uncertainty range of 1.1 to 6.4°C (2.0 to 11.5°F), according to the IPCC.

All of the U.S. is very likely to warm during this century, and most areas of the U.S. are expected to warm by more than the global average. The largest warming is projected to occur in winter over northern parts of Alaska. In western, central and eastern regions of North America, the projected warming has less seasonal variation and is not as large, especially near the coast, consistent with less warming over the oceans.

It is very likely that heat waves will become more intense, more frequent, and longer lasting in a future warm climate, whereas cold episodes are projected to decrease significantly.

Intensity of precipitation events is projected to increase in the U.S. and other regions of the world, increasing the risk of flooding, greater runoff and erosion, and thus the potential for adverse water quality effects. Increases in the amount of precipitation are very likely in higher latitudes, while decreases are likely in most subtropical latitudes and the southwestern U.S.,, continuing observed patterns. The mid-continental area is expected to experience drying during summer, indicating a greater risk of drought.

It is likely that hurricanes will become more intense, with stronger peak winds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. Frequency changes in hurricanes are currently too uncertain for confident projections.

By the end of the century, sea level is projected by IPCC to rise between 0.18 and 0.59 meters relative to around 1990. Recent rapid changes at the edges of the Greenland and West Antarctic ice sheets show acceleration of flow and thinning. While understanding of these ice sheet processes is incomplete, their inclusion in models would likely lead to sea-level projections for the end of the 21st century that substantially exceed the IPCC's projections.

Sea ice is projected to shrink in the Arctic under all IPCC emission scenarios.

Projected Risks and Impacts Associated with Future Climate Change

Risk increases with increases in both the rate and magnitude of climate change. Climate warming may increase the possibility of large, abrupt regional or global climatic events (e.g., disintegration of the Greenland Ice Sheet or collapse of the West Antarctic Ice Sheet). The partial deglaciation of Greenland (and possibly West Antarctica) could be triggered by a sustained temperature increase of 1 to 4ºC above 1990 levels. The contribution of another 4 to 6 meters would take centuries to millennia to be realized.

CCSP reports that climate change has the potential to accentuate the disparities already evident in the American health care systems as many of the expected health effects are likely to fall disproportionately on the poor, the elderly, the disabled, and the uninsured. IPCC reports with very high confidence that climate change impacts on human health in U.S. cities will be compounded by population growth and an aging population.

Severe heat waves are projected to intensify in magnitude and duration over the portions of the U.S. where these events already occur, with potential increases in mortality and morbidity, especially among the elderly, young and frail.

The IPCC projects reduced human mortality from cold exposure through 2100. It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the U.S. due to climate change.

The IPCC projects with virtual certainty reduced air quality in U.S. and other world cities relative to air quality levels without climate change due to warmer and fewer cold days and nights and/or warmer/more frequent hot days and nights over most land areas. Climate change can lead to increases in regional ozone pollution, with associated risks in respiratory infection, aggravation of asthma, and premature death. In addition to human health effects, tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth and species composition. The directional effect of climate change on ambient particulate matter levels remains uncertain.

IPCC reported that moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture in the U.S. by 5-20%, but with important variability among regions. However, major challenges are projected for crops that are near the warm end of their suitable range or depend on highly utilized water resources. Similarly, CCSP concluded that, with increased CO_2 and temperature, the life cycle of grain and oilseed crops will likely progress more rapidly. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable. Furthermore, the marketable yield of many horticultural crops – e.g., tomatoes, onions, fruits – is very likely to be more sensitive to climate change than grain and oilseed crops.

Higher temperatures will very likely reduce livestock production during the summer season, but these losses will very likely be partially offset by warmer temperatures during the winter season. Cold-water fisheries will likely be negatively affected; warm-water fisheries will generally benefit; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges.

Overall forest growth in the U.S. will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO_2 over the next century, but with important spatial and temporal variation. However, climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior west, the Southwest, and Alaska, and will continue to do so. An increased frequency of disturbance is at least as important to ecosystem function as incremental changes in temperature, precipitation, atmospheric CO_2, nitrogen deposition, and ozone pollution.

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Sea level is rising along much of the U.S. coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion. Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt marshes, other coastal habitats, and dependent species are threatened by sea-level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate chang

Climate change will likely further constrain already over-allocated water resources in some sections of the U.S., increasing competition among agricultural, municipal, industrial, and ecological uses. Although water management practices in the U.S. are generally advanced, particularly in the West, the reliance on past conditions as the basis for current and future planning will no longer be appropriate, as climate change increasingly creates conditions well outside of historical observations. Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers, and bi-national relationships. Higher water temperatures, increased precipitation intensity, and longer periods of low flows can exacerbate many forms of water pollution. Decreased water supply and lower water levels are likely to exacerbate challenges relating to navigation in the U.S.

Climate change is likely to affect both U.S. energy use and energy production; physical infrastructures; institutional infrastructures; and will likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements, particularly in Alaska where indigenous communities are facing major environmental and cultural impacts. The U.S. energy sector, which relies heavily on water for hydropower and cooling capacity, may be adversely impacted by changes to water supply and quality in reservoirs and other water bodies.

Disturbances such as wildfire and insect outbreaks are increasing in the U.S. and are likely to intensify in a warmer future with drier soils and longer growing seasons. Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services.

Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange U.S. ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

Within settlements experiencing climate change stressors, certain parts of the population may be especially vulnerable; these include the poor, the elderly, those already in poor health, the disabled, those living alone, those with limited rights and power (such as recent immigrants with limited English skills), and/or indigenous populations dependent on one or a few resources. Thus, environmental justice issues are raised by the potential impacts of climate change.**Climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian, trade and national security issues for the U.S.** The IPCC identifies the most vulnerable world regions as the Arctic, because of high rates of projected warming on natural systems; Africa, especially the sub-Saharan region, because of current low adaptive capacity as well as climate change; small islands, due to high exposure of population and infrastructure to risk of sea-level rise and increased storm surge; and Asian mega deltas, such as the Ganges-Brahmaputra and the Zhujiang, due to large populations and high exposure to sea level rise, storm surge and river flooding. Climate change has been described as a potential threat multiplier regarding national security issues.

Section 1

Introduction and Background

The purpose of this document is to provide scientific and technical support for an endangerment analysis regarding greenhouse gas (GHG) emissions under the Clean Air Act. This document itself does not convey any judgment or conclusion regarding the question of whether GHGs may be reasonably anticipated to endanger public health or welfare, as this decision is ultimately left to the judgment of the Administrator.

1(a) Scope and Approach of this Document

The primary GHGs of concern that are directly emitted by human activities in general are those reported in EPA's annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). The primary effect of these gases is their influence on the climate system by trapping heat in the atmosphere that would otherwise escape to space. This heating effect (referred to as radiative forcing) is very likely to be the cause of most of the observed global warming over the last 50 years. Global warming and climate change, in turn, can affect health, society and the environment. There also are some cases where these gases have other non-climate effects, some of which are direct while others are indirect. For example, elevated concentrations of CO_2 can increase ocean acidification and stimulate terrestrial plant growth, and CH_4 emissions can contribute to background levels of tropospheric ozone, a criteria pollutant. These effects may in turn be influenced by climate change in certain cases. Carbon dioxide and other GHGs can also have direct health effects but at concentrations far in excess of current or projected future ambient concentrations.

This document reviews a wide range of specific and quantifiable vulnerabilities, risks and impacts due to both effects induced by climate change and effects caused directly by the GHGs. Any known or expected benefits of elevated atmospheric concentrations of GHGs or of climate change are documented as well (i.e., impacts can mean either positive or negative consequences). The extent to which observed climate change can be attributed to anthropogenic GHG emissions is assessed. The term “climate change” in this document generally refers to climate change induced by human activities, including activities that emit GHGs. Future projections of climate change, based primarily on future scenarios of anthropogenic GHG emissions, are shown for the global and national scale.

The focus of the vulnerability, risk and impact assessment is primarily within the U.S. However, given the global nature of climate change, there is a brief review of potential international impacts. Greenhouse gases, once emitted, become well mixed in the atmosphere, meaning U.S. emissions can affect not only the U.S. population and environment but other regions of the world as well; likewise, emissions in other countries can affect the U.S. Furthermore, impacts in other regions of the world may have consequences that transcend national boundaries that raise concerns for the U.S.

The timeframe over which vulnerabilities, risks and impacts are considered is consistent with the timeframe over which GHGs, once emitted, have an effect on climate, which is decades to centuries for the primary GHGs of concern. Therefore, in addition to reviewing recent observations, this document generally considers the next several decades, the time period out to around 2100, and for certain impacts the time period beyond 2100.

Adaptation to climate change is a key focus area of the climate change research community. This document, however, does not focus on adaptation because adaptation is essentially a response to any known and/or perceived risks due to climate change. Likewise, mitigation measures to reduce GHGs, which could also reduce long-term risks, are not addressed. The purpose of this document is to review the effects of climate change rather than society's response to climate change. Adaptation will be mentioned to the extent that the impacts projections themselves contain some embedded assumptions about future adaptation.[4]

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[4] A brief overview of adaptation is provided in the Appendix.

Box 1.1, Peer review, publication and approval processes for IPCC, CCSP and NRC reports

Intergovernmental Panel on Climate Change
The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. It bases its assessment mainly on peer reviewed and published scientific/technical literature. IPCC has established rules and procedures for producing its assessment reports. Report outlines are agreed to by government representatives in consultation with the IPCC bureau. Lead authors are nominated by governments and are selected by the respective IPCC Working Groups on the basis of their scientific credentials and with due consideration for broad geographic representation. For Working Group I there were 152 coordinating lead authors, and for Working Group II 48 coordinating lead authors. Drafts prepared by the authors are subject to two rounds of review; the second round includes government review. For the IPCC Working Group I report, over 30,000 written comments were submitted by over 650 individual experts, governments and international organizations. For Working Group II there were 910 expert reviewers. Review Editors for each chapter are responsible for ensuring that all substantive government and expert review comments receive appropriate consideration. For transparency, IPCC documents how every comment is addressed. Each Summary for Policymakers is approved line-by-line, and the underlying chapters are then accepted, by government delegations in formal plenary sessions. Further information about IPCC's principles and procedures can be found at: http://www.ipcc.ch/about/procd.htm.

U.S. Climate Change Science Program
The CCSP has identified 21 synthesis and assessment products (SAPs) that address the highest priorities for U.S. climate change research, observation and decision-support needs. Not all of these assessment products have been completed in time for use in this document. Different agencies have been designated the lead for different SAPs; EPA is the designated lead for three of the six SAPs addressing impacts and adaptation. For each SAP, there is first a prospectus that provides an outline, the proposed authors and process for completing the SAP; this goes through two stages of expert, interagency and public review. Authors produce a first draft which goes through expert review; a second draft is posted for public review. The designated lead agency ensures that the third draft complies with the Information Quality Act. Finally the SAP is submitted to the National Science and Technology Council (NSTC), a Cabinet-level council that coordinates science and technology research across the Federal government, for approval. Further information about the clearance and review procedures for the CCSP SAPs can be found at: http://www.climatescience.gov/Library/sap/sap-guidelines-clarification-aug2007.htm.

National Research Council of the U.S. National Academy of Sciences
The National Research Council (NRC) is part of the National Academies, which also comprise the National Academy of Sciences, National Academy of Engineering and Institute of Medicine. They are private, nonprofit institutions that provide science, technology and health policy advice under a congressional charter. The NRC has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public and the scientific and engineering communities. Federal agencies are the primary financial sponsors of the Academies' work. The Academies provide independent advice; the external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. The NRC 2001 study, *Climate Change Science: An Analysis of Some Key Questions*, originated from a White House request. The NRC 2001 study, *Global Air Quality: An Imperative for Long-Term Observational Strategies*, was supported by EPA and NASA. The NRC 2004 study, *Air Quality Management in the United States*, was supported by EPA. The NRC 2005 study, *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*, was in response to a CCSP request, and supported by NOAA. The NRC 2006 study, *Surface Temperature Reconstructions for the Last 2,000 Years*, was requested by the Science Committee of the U.S. House of Representatives. Each NRC report is authored by its own committee of experts, reviewed by outside experts, and approved by the Governing Board of the NRC.

Uncertainties and confidence levels associated with the scientific conclusions and findings in this document are reported, to the extent that such information was provided in the original scientific reports upon which this document is based.

1(b) Data and Scientific Findings Considered by EPA

This document relies most heavily on existing, and in most cases very recent, synthesis reports of climate change science and potential impacts, which have gone through their own peer-review processes including review by the U.S. Government. The information in this document has been developed and prepared in a manner that is consistent with EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility and Integrity of Information Disseminated by the Environmental Protection Agency*. In addition to its reliance on existing and primarily recent synthesis reports from the peer reviewed literature, it also underwent a technical review by 12 federal climate change experts, internal EPA review, and interagency review.

These core reference (Table 1.1) documents include the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Synthesis and Assessment Products of the U.S. Climate Change Science Program (CCSP) completed and publically released to date, National Research Council (NRC) reports under the U.S. National Academy of Sciences (NAS), and the EPA annual report on U.S. greenhouse gas emission inventories.

Table 1.1, Core references relied upon most heavily in this document. (need to update)

Science body and author	Short Title and Year of Publication
IPCC	Working Group I: The Physical Science Basis (2007)
IPCC	Working Group II: Impacts, Adaptation and Vulnerability (2007)
IPCC	Working Group III: Mitigation of Climate Change (2007)
CCSP	SAP 1.1: Temperature Trends in the Lower Atmosphere (2006)
CCSP	SAP 1.2: Past Climate Variability and Change (2009)
CCSP	SAP 1.3: Re-analyses of Historical Climate Data (2008)
CCSP	SAP 2.1: Scenarios of GHG Emissions and Atmospheric Concentrations (2007)
CCSP	SAP 2.4: Trends in Ozone-Depleting Substances (2008)
CCSP	SAP 3.1: Climate Change Models (2008)
CCSP	SAP 3.2: Climate Projections (2008)
CCSP	SAP 3.3: Weather and Climate Extremes in a Changing Climate (2008)
CCSP	SAP 3.4: Abrupt Climate Change (2008)
CCSP	SAP 4.1: Coastal Sensitivity to Sea-Level Rise (2009)
CCSP	SAP 4.2: Thresholds of Change in Ecosystems (2009)
CCSP	SAP 4.3: Effects on Agriculture, Land Resources, Water Resources, and Biodiversity (2008)
CCSP	SAP 4.5: Effects on Energy Production and Use (2007)
CCSP	SAP 4.6: (2008)
CCSP	SAP 4.7: Gulf Coast Study (2008)
CENR	Assessment of the Effects of Global Change on the United States (2008)
NRC	Climate Change Science: Analysis of Some Key Questions (2001)
NRC	Radiative Forcing of Climate Change (2005)
NRC	Surface Temperature Reconstructions for the Last 2,000 Years (2006)
NRC	Potential Impacts of Climate Change on U.S. Transportation (2008)
EPA	Inventory of U.S. Greenhouse Gas Emissions and Sinks (2008)
ACIA	Arctic Climate Impact Assessment (2004)

EPA is relying most heavily on these synthesis reports because they 1) are very recent and represent the current state of knowledge on climate change science, vulnerabilities and potential impacts; 2) have assessed numerous individual studies in order to draw general conclusions about the state of science; 3)have been reviewed and formally accepted by, commissioned by, or in some cases authored by, U.S. government agencies and individual government scientists and provide EPA with assurances that this material has been well vetted by both the climate change research community and by the U.S. government; and 4) in many cases, they reflect and convey the consensus conclusions of expert authors. Box 1.1 describes the peer review and publication approval processes of IPCC, CCSP and NRC reports. Peer review and transparency are key to each of these research organization's report development process. In compliance with the U.S. EPA's information quality guidelines, this document relies on information that is objective, technically sound and vetted, and of high integrity. Box 1.2 describes the lexicon used by IPCC to communicate uncertainty and confidence levels associated with the most important IPCC findings; this document employs the same lexicon when referencing IPCC statements.

The IPCC Fourth Assessment Report consists of three volumes: Working Group I addresses the physical science of climate change; Working Group II addresses impacts, vulnerabilities and adaptation; and Working Group III addresses mitigation (i.e., emission reduction) measures. These IPCC assessments are generally global in scope but provide information at the country and regional level as well. The Working Group II volume contains individual chapters devoted to the key climate change impact sectors, which are also addressed in this document (e.g., human health, agriculture, water resources, etc.), as well as chapters devoted to key regions. This document relies heavily on the North America chapter of the IPCC Working Group II report, though this chapter may not provide as much regional detail within the U.S. as did the 2000 report, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change* (NAST, 2000).

Box 1.2: Communication of uncertainty in the IPCC Fourth Assessment Report (perhaps combine with CCSP, since most reports attempted the same terminology)

A set of terms to describe uncertainties in current knowledge is common to all parts of the IPCC Fourth Assessment Report, based on the *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties* (http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf), produced by the IPCC in July 2005. Any use of these terms in association with IPCC statements in this Endangerment document carries the same meaning as originally intended in the IPCC Fourth Assessment Report.

Description of confidence

On the basis of a comprehensive reading of the literature and their expert judgment, authors have assigned a confidence level to major statements on the basis of their assessment of current knowledge, as follows:

Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

Description of likelihood

Likelihood refers to a probabilistic assessment of some well defined outcome having occurred or occurring in the future, and may be based on quantitative analysis or an elicitation of expert views. When authors evaluate the likelihood of certain outcomes, the associated meanings are:

Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

In some cases, this document references other reports and studies in addition to the core references of IPCC, CCSP, NRC, and, for greenhouse gas emissions, EPA. This is usually the case where IPCC, CCSP and NRC reports do not explicitly provide the regional or state-level detail for certain vulnerabilities and potential impacts, or where very recent and significant studies have been published that were not included by the IPCC and CCSP synthesis reports due to publication cut-off dates.

Because IPCC, CCSP and NRC are assessment reports in which a number of individual studies are synthesized in order to draw more general conclusions, this document often cites those individual studies that tended to be very influential in the more general findings of IPCC, CCSP; however, every effort is made to make it clear when an individual reference was incorporated into one of the broader assessments. Full citations of all references are listed at the end of this document.

1(c) Roadmap for this Document

The remainder of this document is structured as follows:

- **Part II, Section 2** describes sources of U.S. and global GHG emissions. How anthropogenic GHG emissions have contributed to changes in global atmospheric concentrations of GHGs is also described.
- **Part III, Sections 3 – 6** describe the effects of elevated concentrations of GHGs including any direct health and environmental effects; the heating or radiative forcing effects on the climate system; observed climate change (e.g., changes in temperature, precipitation and sea level rise) for the U.S. and for the globe; recent conclusions about the extent to which observed climate change can be attributed to the elevated levels of GHG concentrations; and summarize future projections of climate change—driven primarily by scenarios of anthropogenic GHG emissions—for the remainder of this century.
- **Part IV, Sections 7 – 14** review recent findings for the broad range of observed and projected vulnerabilities, risks and impacts for human health, society and the environment within the U.S. due to climate change. The specific sectors and systems include:
    - Human health (7)
    - Air Quality (8)
    - Food Production and Agriculture (9)
    - Forestry (10)
    - Water Resources (11)
    - Coastal Areas (12)
    - Energy, Infrastructure and Settlements (13)
    - Ecosystems and Wildlife (14)
- **Part V, Section 15** briefly addresses some key international impacts that may occur due to climate change, with a view towards how some of these impacts may in turn affect the U.S.
    - International Impacts (15)

Part II

Emissions and Elevated Concentrations of Greenhouse Gases

Section 2

Greenhouse Gas Emissions and Concentrations

This section first describes current U.S. and global anthropogenic greenhouse gas (GHG) emissions. Future GHG emission scenarios are described in Part III, Section 6, however, these scenarios primarily focus on global emissions, rather than detailing individual U.S. sources. This section then focuses on historic and current global GHG atmospheric concentrations.

2(a) U.S. and global greenhouse gas emissions

To track the national trend in GHG emissions and carbon removals since 1990, EPA develops the official U.S. GHG inventory each year. In accordance with Article 4.1 of the United Nations Framework Convention on Climate Change (UNFCCC), the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* includes emissions and removals of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) resulting from anthropogenic activities in the U.S.

Total emissions are presented in teragrams[5] (Tg) of CO_2 equivalent ($TgCO_2eq$), consistent with Intergovernmental Panel on Climate Change (IPCC) inventory guidelines. To determine the CO_2 equivalency of different GHGs, in order to sum and compare different GHGs, emissions of each gas are multiplied by its global warming potential (GWP), a factor which relates it to CO_2 in its ability to trap heat in the atmosphere over a certain timeframe. Box 2.1 provides more information about GWPs and the GWP values used in this section of the report.

Box 2.1: Global Warming Potentials used in this document

In accordance with UNFCCC reporting procedures, the U.S. quantifies GHG emissions using the 100-year time frame values for GWPs established in the IPCC Second Assessment Report (SAR) (IPCC, 1996). The GWP index is defined as the cumulative radiative forcing between the present and some chosen later time horizon (100 years) caused by a unit mass of gas emitted now. All GWPs are expressed relative to a reference gas, CO_2, which is assigned a GWP = 1. Estimation of the GWPs requires knowledge of the fate of the emitted gas and the radiative forcing due to the amount remaining in the atmosphere. To estimate the CO_2 equivalency of a non-CO_2 GHG, the appropriate GWP of that gas is multiplied by the amount of the gas emitted.

100-year GWPs	
CO_2	1
CH_4	21
N_2O	310
HFCs	140 to 6,300 (depending on type of HFC)
PFCs	6,500 to 9,200 (depending on type of PFC)
SF_6	23,900

The GWP for CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. These GWP values have been updated twice, in the IPCC third (TAR 2001) and fourth assessment reports (AR4 2007). The use of TAR values for GWP, instead of SAR values, increases the overall U.S. GHG inventory for 2005 by 0.4% (EPA, 2007).

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[5] 1 teragram (Tg) = 1 million metric tons. 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

The national inventory totals used in this report for the U.S. (and other countries) are gross emissions, which include GHG emissions from the electricity, industrial, commercial, residential and agriculture sectors. Emissions and sequestration occurring in the land-use, land-use change and forestry sector (e.g., forests, soil carbon etc.) are not included in gross national totals, but are reported under net emission totals (sources and sinks), according to international practice. In the U.S., this sector is a significant net sink, while in some developing countries it is a significant net source of emissions.

Also excluded from emission totals in this report are bunker fuels (fuels used for international transport). According to UNFCCC reporting guidelines, emissions from the consumption of these fuels should be reported separately, and not included in national emission totals, as there exists no agreed upon international formula for allocation between countries.

The most recent inventory was published in 2008 and includes annual data for the years 1990-2006.

U.S. Greenhouse Gas Emissions

In 2006, U.S. GHG emissions were 7,054.2 TgCO_2eq (see Figure 2.1).[6] The dominant gas emitted is CO_2, mostly from fossil fuel combustion (84.8%) (EPA, 2008). Weighted by GWP, CH_4 is the second largest component of emissions, followed by N_2O, and the high-GWP fluorinated gases (HFCs, PFCs, and SF_6). Electricity generation (2377.8 TgCO_2eq) is the largest emitting sector, followed by transportation (1969.5 TgCO_2eq) and industry (1371.5 TgCO_2eq) (EPA, 2008) (Figure 2.2). Agriculture and the commercial and residential sectors emit 533.6 TgCO_2eq, 394.6 TgCO_2eq, and 344.8 TgCO_2eq, respectively (EPA, 2008). Removals of carbon through land use, land-use change and forestry activities are not included in Figure 2.2, but are significant; net sequestration is estimated to be 883.7 TgCO_2eq in 2006, offsetting 12.5% of total emissions (EPA, 2008).

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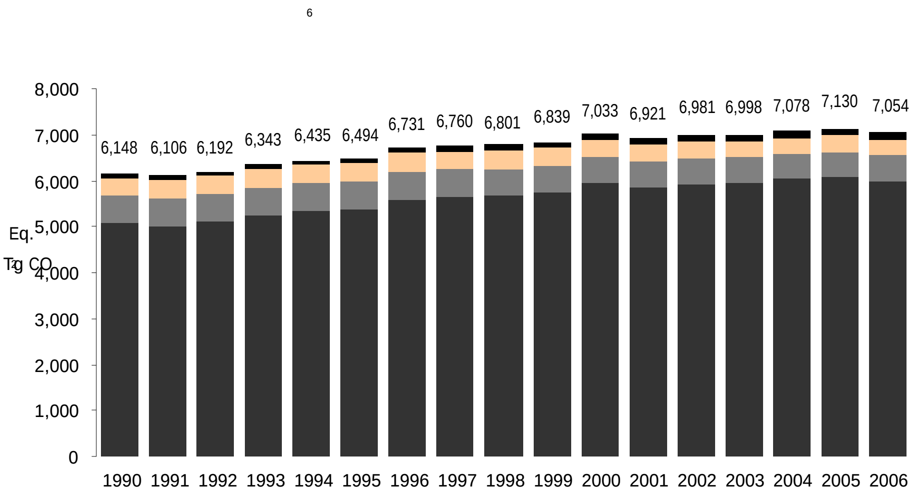
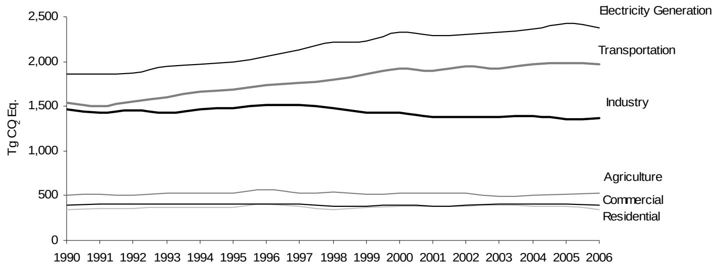
[6] Per UNFCCC reporting requirements, the U.S. reports its annual emissions in gigagrams (Gg) with two significant digits (http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/x-zip-compressed/usa_2007_crf_11apr.zip). For ease of communication of the findings, the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report presents total emissions in Tg with one significant digit.

Figure 2.1: Total U.S. Greenhouse Gas Emissions: 1990-2006



Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 (EPA, 2008). Excludes land-use change and forestry and international bunker fuels.

Figure 2.2: U.S. GHG Emissions Allocated to Economic Sector.



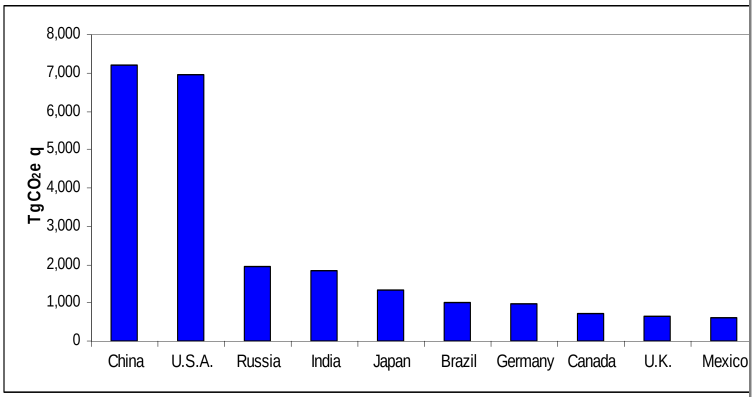
Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 (EPA, 2008). All GHGs. Excludes land use, land-use change and forestry and international bunker fuels.

U.S. emissions increased by 905.9 $TgCO_2eq$, or 14.7% between 1990 and 2006 (see Figure 2.1) (EPA, 2008). Historically, changes in fossil fuel consumption have been the dominant factor affecting U.S. emission trends. The fundamental factors driving this trend include a generally growing domestic economy over the last 16 years, leading to overall growth in emissions from electricity generation (increase of 30.7%) and transportation activities (increase of 27.9%) (EPA, 2008). Over the same time period, industrial, residential, and commercial emissions decreased by 6.0%, 0.6%, and 0.6% respectively, while emissions increased in the agriculture (5.3%) sector (Figure 2.2) (EPA, 2008).

Global Greenhouse Gas Emissions

Total global emissions are calculated by summing emissions of the six greenhouse gases, by country. The World Resources Institute compiles data from recognized national and international data sources in its Climate Analysis Indicators Tool (CAIT).[7] Globally, total GHG emissions were 38,725.9 $TgCO_2eq$ in 2005, the most recent year for which data are available for *all* countries and *all* GHGs (WRI, 2009).[8] This global total for the year 2005 represents an increase of about 26% from the 1990 global GHG emission total of 30,704.9 $TgCO_2eq$ (WRI, 2009). Excluding land use, land-use change, and forestry, U.S. emissions were 19% of the total year 2005 global emissions, (see Figure 2.3) (WRI, 2009).

Figure 2.3: Total GHG Emissions for the Year 2005 by Country



Source: WRI Climate Analysis and Indicators Tool. Available at http://cait.wri.org/. Excludes land use, land-use change and forestry, and international bunker fuels. More recent emissions data are available for the U.S. and other individual countries, but 2000 is the most recent year for which data for all countries and all gases are available. Data accessed February 20, 2009.

2(b) Historic and current global greenhouse gas concentrations

Greenhouse gas concentrations in the atmosphere vary over very long time scales in response to natural influences such as geologic activity and temperature change associated with ice age cycles, but ice core data show nearly constant concentrations of CO_2, CH_4 and N_2O over more than 10,000 years prior to the industrial revolution. However, since the industrial revolution, anthropogenic GHG emissions have resulted in substantial increases in the concentrations of GHGs in the atmosphere (IPCC 2007d; NRC, 2001).

Carbon dioxide (CO_2)

Carbon dioxide concentrations have increased substantially from pre-industrial levels (Figure 2.4). The long-term trends in the CO_2 concentrations are as follows (NOAA, 2009; Forster, P. et al., 2007[9]):

- The CO_2 concentration has increased about 38% from a pre-industrial value of about 280 parts per million (ppm) to 386 ppm (which is about 0.039% of the atmosphere by volume) in 2008[10].

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[7] Primary data sources referenced in CAIT include the U.S. Department of Energy's Carbon Dioxide Information Analysis Center, the U.S. Environmental Protection Agency, the International Energy Agency and the National Institute for Public Health and the Environment, an internationally recognized source of non-CO_2 data.

[8] Source: WRI Climate Analysis and Indicators Tool. Available at http://cait.wri.org/.

[9] Forster, P. et al., 2007 citation refers to Chapter 2, "Changes in Atmospheric Constituents and in Radiative Forcing" in IPCC's 2007 Fourth Assessment Report, Working Group I.

[10] The 2008 value is preliminary. The estimated uncertainty in the Mauna Loa annual mean growth rate is 0.11 ppm/yr.

- The present atmospheric concentration of CO_2 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores (Jansen et al., 2007).
- The annual CO_2 concentration growth rate has been larger since 2000 (2000-2008 average: 2.0 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year) although there is year-to-year variability.

Almost all of the increase in the CO_2 concentration during the Industrial Era is due to anthropogenic emissions (Forster et al., 2007). Since the 1980s, about half of the anthropogenic emissions have been taken up by the terrestrial biosphere and the oceans, but observations demonstrate that these processes cannot remove all of the extra flux due to human activities. About half of the anthropogenic emissions have remained in the atmosphere (Forster et al., 2007).

Methane (CH_4)

Methane concentrations have also risen substantially (Figure 2.4). The following trends in atmospheric methane have been observed according to the IPCC and the National Oceanographic and Atmospheric Administration (NOAA) (Horvitz, 2008; Forster et al., 2007):

- The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 parts per billion (ppb) to 1732 ppb in the early 1990s, and was 1782 ppb in 2007 – a 149% increase from pre-industrial levels.
- The atmospheric concentration of methane in 2007 exceeds by far the natural range of the last 650,000 years (320 to 790 ppb) as determined from ice cores (Jansen et al., 2007).
- Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period.

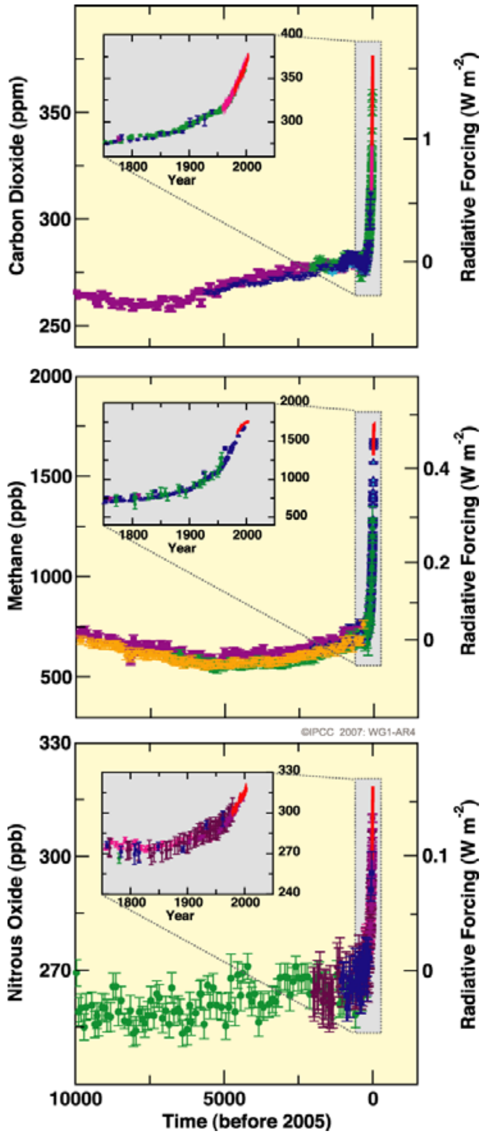
The observed increase in methane concentration is very likely due to anthropogenic activities, predominantly agriculture and fossil fuel use, but relative contributions from different source types are not well determined (Forster et al., 2007).

Nitrous Oxide (N_2O)

The N_2O concentration has increased 23% from its pre-industrial value of 262 ppb (Figure 2.4)to 321 ppb in 2007 (Horvitz, 2008). The concentration has increased linearly by about 0.8 ppb yr^{-1} over the past few decades and is due primarily to human activities, particularly agriculture and associated land use change (Forster et al., 2007). Ice core data show that the present atmospheric concentration of N_2O is higher than ever measured in the ice core record of the past 650,000 years (Jansen et al., 2007).

Fluorinated Gases

Figure 2.4: Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years



Source: IPCC (2007d). Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colors for different studies) and atmospheric samples (red lines). The corresponding radiative forcings (discussed in Section 2(e)) are shown on the right hand axes of the large panels.

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are GHGs that are entirely anthropogenic in origin. Emissions of these gases have decreased due to their phase-out under the Montreal Protocol, and the atmospheric concentrations of CFC-11 and CFC-113 are now decreasing due to natural removal processes (Forster et al., 2007). Ice core and in situ data confirm that industrial sources are the cause of observed atmospheric increases in CFCs and HCFCs (Forster et al., 2007).

Industrial fluorinated gases that serve as substitutes for CFCs and HCFCs (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)) have relatively low atmospheric concentrations but are increasing rapidly. These are also almost entirely anthropogenic in origin (Forster et al., 2007).

Ozone (O_3)

Tropospheric ozone is a short-lived greenhouse gas produced by chemical reactions of precursor species in the atmosphere and with large spatial and temporal variability. It is estimated that ozone has increased by about 36% since the pre-industrial era, although substantial variations exist for regions and overall trends (Forster et al., 2007). Relative to the other greenhouse gases, there is less confidence in reproducing the changes in ozone associated with large changes in emissions or climate, and in the simulation of observed long-term trends in ozone concentrations over the 20th century (Forster et al., 2007).

Part III

Global and U.S. Observed and Projected Effects from Elevated Greenhouse Gas Concentrations

Section 3

Direct Effects of Elevated Greenhouse Gas Concentrations

Comment [BJD3]: Considering condensing this and placing in text boxes.

This section briefly addresses some direct effects associated with GHGs, but focuses primarily on the more significant effects associated with GHGs, which is their heat-trapping ability (referred to as radiative forcing) that results in to climate change. Observed climate change, including changes in temperature, precipitation, sea level rise, for the globe and the U.S. is reviewed. Observed changes in climate-sensitive physical and biological systems are also addressed, as well as observed trends in extreme events.

Sections 7 to 15 provide more specific information on the sectoral implications of both the observed changes described here and the projected changes described in Section 5.

3(a) Carbon dioxide (CO_2)

Carbon dioxide and other GHGs can have direct effects that are independent of their radiative forcing on climate (the primary effect discussed throughout this document).

The direct effects of high CO_2 concentrations on human health were assessed in the EPA (2000) report, *Carbon Dioxide as a Fire Suppressant: Examining the Risks*, and have also been reviewed by the IPCC (2005) *Special Report on Carbon Dioxide Capture and Storage*. At concentrations above about 2%, CO_2 has a strong effect on respiratory physiology and at concentrations above 7–10%, it can cause unconsciousness and death (IPCC, 2005). Exposure studies have not revealed any adverse health effect of chronic exposure to concentrations below 1%. At concentrations greater than 17 percent, loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death occur within 1 minute of initial inhalation of CO_2 (OSHA, 1989; CCOHS, 1990; Dalgaard et al., 1972; CATAMA, 1953; Lambertsen, 1971). But CO_2 is a physiologically active gas and is a normal component of blood gases (EPA, 2000). Acute CO_2 exposure of up to 1 percent and 1.5 percent by volume is tolerated quite comfortably (EPA, 2000b).

The ambient concentration of CO_2 in the atmosphere is presently about 0.039 percent by volume (or 386 ppm). Projected increases in CO_2 concentrations from anthropogenic emissions range from 41 to 158 percent above 2005 levels (of about 380ppm) or 535 to 983 parts per million (ppm) by 2100 (Meehl et al., 2007) (see Section 5). Such increases would result in atmospheric CO_2 concentrations of 0.054 to 0.098 percent by volume in 2100, which is well below published thresholds for adverse health effects.

Carbon dioxide can have stimulatory or fertilization effect on plant growth. There is debate and uncertainty about the sensitivity of crop yields to the direct effects of elevated CO_2 levels. However, the IPCC (Easterling et al., 2007) concluded that elevated CO_2 levels are expected to result in small beneficial impacts on crop yields. The IPCC confirmed the general conclusions from its previous Third Assessment Report in 2001. Experimental research on crop responses to elevated CO_2 through the FACE (Free Air CO_2 Enrichment)[11] experiments indicate that, at ambient CO_2 concentrations of 550 ppm (approximately double the concentration from pre-industrial times) crop yields increase under unstressed conditions by 10-25% for C3 crops, and by 0-10% for C4 crops (medium confidence)[12]. Crop model simulations under elevated CO_2 are consistent with these ranges (high confidence) (Easterling et al., 2007). Globally and in

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[11] http://www.bnl.gov/face/

[12] C3 and C4 refer to different carbon fixation pathways in plants during photosynthesis. C3 is the most common pathway, and C3 crops (e.g., wheat, soybeans and rice) are more responsive than C4 crops such as maize.

the U.S., high temperatures and ozone exposure, however, can significantly limit the direct stimulatory CO_2 response (see also Section 8 on Air Quality and Section 9 on Food Production and Agriculture).

Elevated CO_2 has raised an issue about forage quality for livestock. Elevated CO_2 can increase the carbon to nitrogen ratio in forages and thus reduce the nutritional value of those grasses and thus affect animal weight and performance. The decline under elevated CO_2 of C4 grasses, however, which are less nutritious than C3 grasses, may compensate for the reduced protein. Yet the opposite is expected under associated temperature increases.

At much higher ambient CO_2 concentrations, such those areas exposed to natural CO_2 outgassing due to volcanic activity, the main characteristic of long-term elevated CO_2 zones at the surface is the lack of vegetation (IPCC, 2005). New CO_2 releases into vegetated areas cause noticeable die-off. In those areas where significant impacts to vegetation have occurred, CO_2 makes up about 20–95% of the soil gas, whereas normal soil gas usually contains about 0.2–4% CO_2. Carbon dioxide concentrations above 5% may be dangerous for vegetation and as concentration approach 20%, CO_2 becomes phytotoxic. Carbon dioxide can cause death of plants through ‘root anoxia’, together with low oxygen concentration (IPCC, 2005).

Regarding oceanic ecosystems, according to IPCC (Fischlin et al., 2007), ocean acidification due to the direct effects of elevated CO_2 concentrations will impair (medium confidence) a wide range of planktonic and other marine organisms that use aragonite to make their shells or skeletons. These impacts could result in potentially severe ecological changes to tropical and coldwater marine ecosystems where carbonate-based phytoplankton and corals are the foundation for the trophic system (Schneider et al., 2007). These CO_2 effects will also interact with the effects of temperature change (see Section 14 on Ecosystems and Wildlife).

3(b) Methane (CH_4)

Methane is flammable or explosive at concentrations of 5% to 15% by volume (50,000 to 150,000 ppm) of air (NIOSH, 1994; NRC, 2000). At high enough concentrations, CH_4 is also a simple asphyxiant, capable of displacing enough oxygen to cause death by suffocation. Threshold limit values are not specified because the limiting factor is the available oxygen (NRC, 2000). Atmospheres with oxygen concentrations below 19.5 percent can have adverse physiological effects, and atmospheres with less than 16 percent oxygen can become life threatening (MSHA, 2007). Methane displaces oxygen to 18% in air when present at 14% (140,000 ppm).

When oxygen is readily available, CH_4 has little toxic effect (NRC, 2000). In assessing emergency exposure limits for CH_4, the NRC (2000) determined that an exposure limit that presents an explosion hazard cannot be recommended, even if it is well below a concentration that would produce toxicity. As such, it recommended an exposure limit of 5000 ppm for methane (NRC, 2000). The National Institute for Occupational Health Safety (NIOSH, 1994) established a threshold limit value (TLV) for methane at 1,000 ppm.

The current atmospheric concentration of CH_4 is 1.78 ppm. The projected CH_4 concentration in 2100 ranges from 1.46 ppm to 3.39 ppm by 2100, well below any recommended exposure limits (Meehl et al., 2007).

3(c) Nitrous Oxide (N_2O)

Nitrous oxide is an asphyxiant at high concentrations. At lower concentrations, exposure causes central nervous system, cardiovascular, hepatic (pertaining to the liver), hematopoietic (pertaining to the formation of blood or blood cells), and reproductive effects in humans (Hathaway et al., 1991). At a concentration of 50 to 67 percent (500,000 to 670,000 ppm) nitrous oxide is used to induce anesthesia in humans (Rom, 1992).

NIOSH has established a recommended exposure limit (REL) for nitrous oxide of 25 ppm as a time-weighted average (TWA) for the duration of the exposure (NIOSH, 1992). The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned nitrous oxide a TLV of 50 ppm as a TWA for a normal 8-hour workday and a 40-hour workweek (ACGIH, 1994).

The NIOSH limit is based on the risk of reproductive system effects and decreases in audiovisual performance (NIOSH, 1992). The ACGIH limit is based on the risk of reproductive, hematological (related to the study of the nature, function, and diseases of the blood and of blood-forming organs), and nervous system effects (ACGIH 1991)

The current atmospheric concentration of nitrous oxide is 0.32 ppm. The projected nitrous oxide concentration in 2100 ranges from 0.36 to 0.46 ppm in 2100, well below any exposure limits (Meehl et al., 2007).

3(d) Fluorinated Gases (HFCs, PFCs, SF_6)

Most fluorinated gases emitted from anthropogenic activities are released in very small quantities relative to established thresholds for adverse health outcomes from exposure. The health effects of exposure to one illustrative HFC gas, one illustrative HCFC gas and SF_6 are given in the context of their current atmospheric concentration. Chlorofluorocarbons are not included in this discussion given their phaseout under the Montreal Protocol.

The NRC (1996) recommended a 1-hr emergency exposure guidance level (EEGL) of 4,000 ppm for HFC-134a. This recommendation was based on a no-observed-adverse-effect level of 40,000 ppm in cardiac-sensitization tests of male beagles (NRC, 1996). It recommended 24-hr EEGL of 1,000 ppm based on the fetotoxicity effects (slight retardation of skeletal ossification) observed in rats exposed to HFC-134a. Finally, it recommended a 90-day CEGL of 900 ppm based on a 2-year chronic toxicity study conducted in male rats exposed to HFC-134a at different concentrations for 6 hours/day, 5 days/week. The atmospheric concentration of HFC 134a in 2003 was in the range of 26 to 31 parts per trillion according to IPCC/TEAP (2005), many orders of magnitude below EEGLs.

For HCFC-123, the end points of pharmacological or adverse effects considered for establishing an EEGL are cardiac sensitization, anesthesia or CNS-related effects, malignant hyperthermia, and hepatotoxicity. According to the NRC (1996), concentration required to produce cardiac sensitization in 50% of the animals) for HCFC-123 was determined in dog studies to be 1.9% (19,000 ppm) for a 5-minute exposure. The NRC recommended that 1,900 ppm (19,000 ppm divided by an uncertainty factor of 10 for interspecies variability) should be considered the human no-observed-effect level for a 1-min exposure to HCFC-123 on the basis of the dog cardiac-sensitization model. The concentration of HCFC-123 in 1996 was 0.03 parts per trillion according to IPCC/TEAP (2005), many orders of magnitude below the established effect level.

Sulfur hexafluoride (SF_6) is a relatively non-toxic gas but an asphyxiant at high concentrations. The NIOSH, 1997) recommended exposure limit is 1,000 ppm. The SF_6 concentration in 2003 was around 5 parts per trillion according to IPCC/TEAP (2005), many orders of magnitude below the exposure limit.

Section 4

Radiative Forcing and Observed Climate Change

4(a) Radiative forcing due to greenhouse gases and other factors

This section describes radiative forcing and the factors that contribute to it. Radiative forcing is a measure of the change that a factor causes in altering the balance of incoming (solar) and outgoing (infrared and reflected shortwave) energy in the Earth-atmosphere system, and thus shows the relative importance of different factors in terms of their contribution to climate change. Positive forcing means the factor causes a warming effect and negative forcing means the factor causes a cooling effect.

Radiative forcing values presented here for GHGs and other factors come from the IPCC Fourth Assessment Report of Working Group I (2007). These radiative forcing values are the result of *global* changes in atmospheric concentrations of GHGs (see Section 2(c) above) and other factors, and are therefore not the result of U.S. transportation emissions in isolation. All values are for the year 2005 relative to pre-industrial times in 1750, represent global averages, and are expressed in watts per square meter[13] (W/m^2).

IPCC (2007d) concluded that the understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to *very high confidence*[14] that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 (+0.6 to +2.4) W/m^2.

Greenhouse gases have a positive forcing because they absorb and reradiate in all directions outgoing, infrared radiation that would otherwise directly escape into space. The combined radiative forcing due to the cumulative (i.e., 1750 to 2005) increase in atmospheric concentrations of CO_2, CH_4, and N_2O is +2.30 W/m^2 (with an uncertainty range of +2.07 to +2.53 W/m^2) (see Figure 4.1). This positive radiative forcing, like the observed accumulation of these gases in the atmosphere, is primarily anthropogenic in origin. Furthermore, the IPCC (2007d) stated that the rate of increase in positive radiative forcing due to these three GHGs during the industrial era is "very likely to have been unprecedented in more than 10,000 years."

The positive radiative forcing due to CO_2 is the largest (+1.66 ± 0.17 W/m^2) (Figure 4.1), and has increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years. Methane is the second largest source of positive radiative forcing (+0.48 ± 0.05 W/m^2). Nitrous oxide has a positive radiative forcing of +0.16 (±0.02) W/m^2.

The other three GHGs reported by the U.S. Inventory—HFCs, PFCs and SF_6—have a total radiative forcing in 2005 of +0.017 (±0.002) W/m^2 (Forster et al., 2007).

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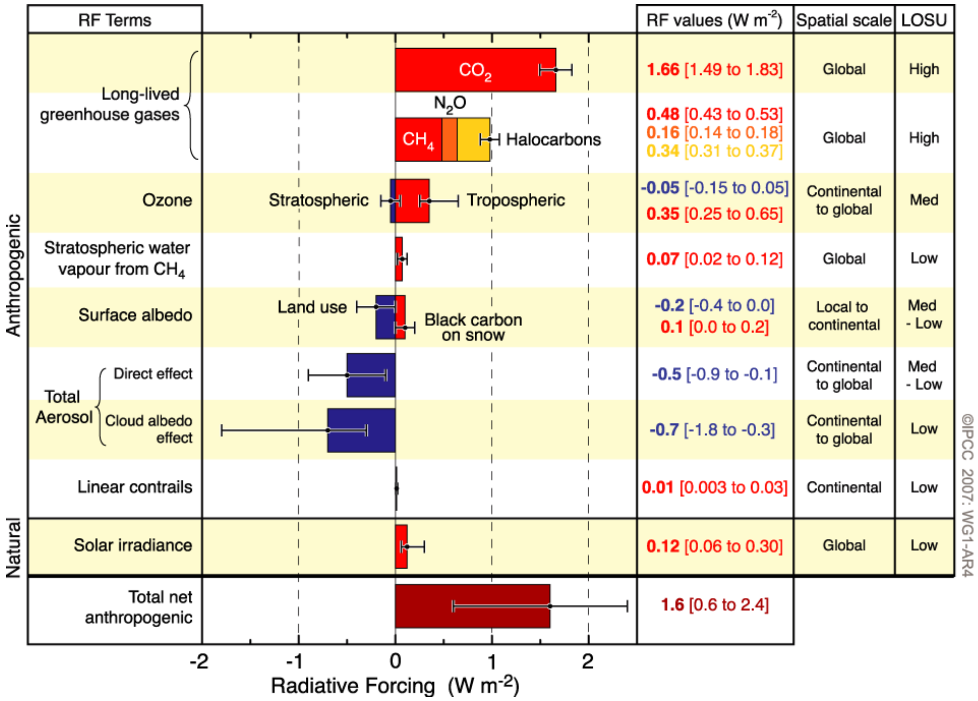
[13] Watts per square meter is the SI unit for radiative and other energy fluxes.

[14] According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Figure 4.1: Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic GHG emissions and other factors



Source: IPCC (2007d). Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and other important factors, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness.

The ozone-depleting substances covered under the Montreal Protocol (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and chlorocarbons) are also strong GHGs and, as a group, contributed +0.32 (±0.03) W/m^2 to anthropogenic radiative forcing in 2005. Their radiative forcing peaked in 2003 and is now beginning to decline (Forster et al., 2007). The radiative forcing due to the destruction of stratospheric ozone by these gases is estimated to be –0.05 ± 0.10 W/m^2 with a medium level of scientific understanding (Solomon et al., 2007[15]).

In addition to the six main GHGs directly emitted by human activities, and the gases covered by the Montreal Protocol, there are additional anthropogenic and natural factors that contribute to both positive and negative forcing. Tropospheric ozone changes due to emissions of ozone-forming chemicals, or precursors, (nitrogen oxides, carbon monoxide, and hydrocarbons including methane) contribute significantly to positive forcing, +0.35 (+0.25 to +0.65) W/m^2. Unlike the GHGs mentioned above, tropospheric ozone is not as well mixed in the global atmosphere because its atmospheric lifetime is on

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[15] Solomon et al., 2007 citation refers to the Technical Summary in IPCC's 2007 Fourth Assessment Report, Working Group I.

the order of weeks to months (versus decades to centuries for the well-mixed GHGs). Tropospheric ozone is also a criteria air pollutant under the U.S. Clean Air Act.

Anthropogenic emissions of aerosols contribute to both positive and negative radiative forcing. Aerosols are non-gaseous substances that are suspended in the atmosphere, and are either solid particles or liquid droplets. Most aerosols, such as sulfates (which are mainly the result of SO_2 emissions), exert a negative forcing or cooling effect, as they reflect and scatter incoming solar radiation. Some aerosols, such as black carbon, cause a positive forcing by absorbing incoming solar radiation. IPCC (2007d) estimated that the net effect of all aerosols (primarily sulfate, organic carbon, black carbon, nitrate and dust) produce a cooling effect, with a total direct radiative forcing of –0.5 (–0.9 to –0.1) W/m^2 and an additional indirect cloud albedo (i.e., enhanced reflectivity)[16] forcing of –0.7 (–1.8 to –0.3) W/m^2. These forcings are now better understood than at the time of the IPCC Third Assessment Report (2001), but nevertheless remain the dominant uncertainty in radiative forcing (IPCC, 2007d). Black carbon aerosols, estimated to have a direct effect of 0.34 (0.09 to .59) W/m^2, cause yet another forcing effect by decreasing the surface albedo of snow and ice (+0.1 (0.0 to +0.2) W/m^2). A more recent estimate suggests a direct black carbon effect of 0.9 (0.4 to 1.2) W/m^2, or more than half that of CO_2 (Ramanathan and Carmichael., 2008). The spatial distribution of aerosol forcing is very different from that of the well-mixed GHGs, and they do not exert simple compensating or additive effects on climate (CCSP, 2008d).

The radiative forcing from increases in stratospheric water vapor due to oxidation of CH_4 is estimated to be $+0.07 \pm 0.05$ W/m^2 (Solomon et al., 2007). The level of scientific understanding is low because the contribution of CH_4 to the corresponding vertical structure of the water vapor change near the tropopause is uncertain.

Changes in surface albedo due to human-induced land cover changes exert a forcing of –0.2 (–0.4 to 0.0) W/m^2. Changes in solar irradiance since 1750 are estimated to cause a radiative forcing of +0.12 (+0.06 to +0.30) W/m^2. This is less than half of the estimate given in IPCC's Third Assessment Report (2001), with a low level of scientific understanding (Solomon et al., 2007). Uncertainties remain large because of the lack of direct observations and incomplete understanding of solar variability mechanisms over long time scales. Empirical associations have been reported between solar-modulated cosmic ray ionization of the atmosphere and global average low-level clouds cover but evidence for a systematic indirect solar effect remains ambiguous. The lack of a proven physical mechanism and the plausibility of other causal factors make the association between galactic cosmic ray-induced changes in aerosol and cloud formation controversial (Solomon et al., 2007).

Although water vapor is the most abundant naturally occurring greenhouse gas, direct emissions of water vapor due to human activities make a negligible contribution to radiative forcing (hence its absence in Figure 3.1). However, as temperatures increase, tropospheric water vapor concentrations increase representing a key feedback but not a forcing of climate change (Solomon et al., 2007). Feedbacks are defined as processes in the climate system (such as a change in water vapor concentrations) that can either amplify or dampen the system's initial response to radiative forcing changes (NRC, 2003).

4(b) Global Changes in Temperature

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[16] In addition to directly reflecting solar radiation, aerosols cause an additional, indirect negative forcing effect by enhancing cloud albedo (a measure of reflectivity or brightness). This occurs because aerosols act as particles around which cloud droplets can form; an increase in the number of aerosol particles leads to a greater number of smaller cloud droplets, which leads to enhanced cloud albedo. Aerosols also influence cloud lifetime and precipitation but no central estimates of these indirect forcing effects are estimated by IPCC.

Multiple lines of evidence lead to the robust conclusion that the climate system is warming. The IPCC (2007d) stated in its Fourth Assessment Report:

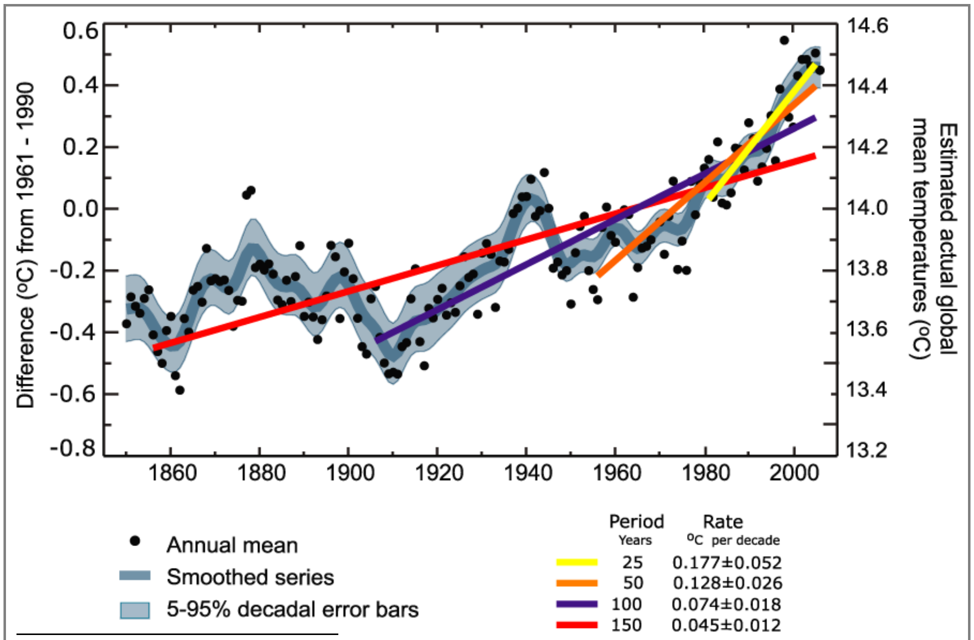
"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

Air temperature is a main property of climate and the most easily measured, directly observable, and geographically consistent indicator of climate change. The extent to which observed changes in global and continental temperature, and other climate factors, can be attributed to anthropogenic emissions of GHGs is addressed in Section 5 below.

Global Surface Temperatures

Surface temperature is calculated by processing data from thousands of world-wide observation sites on land and sea. Parts of the globe have no data, although data coverage has improved with time. The long-term mean temperatures are calculated by interpolating within areas with no measurements using the collected data available. Biases may exist in surface temperatures due to changes in station exposure and instrumentation over land, or changes in measurement techniques by ships and buoys in the ocean. It is likely that these biases are largely random and therefore cancel out over large regions such as the globe or tropics (Karl et al., 2006[17]). Likewise, urban heat island effects are real but local, and have not biased the large-scale trends (Trenberth et al., 2007[18]).

The following trends in global surface temperatures have been observed, according to the IPCC



Source: Solomon et al., (2007). The left hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right hand axis shows estimated actual temperatures, both in °C. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (magenta) and 150 years (red). The smooth blue curve shows decadal variations with the decadal 90% error range shown as a pale blue band about that line. The total temperature increase from the period 1850 to 1899 to the period 2001 to 2005 is 0.76°C ± 0.19°C (1.37°F ± 0.34°F).

here:

s 2007

(Trenberth et al., 2007):

- Global mean surface temperatures have risen by 0.74°C ±0.18°C when estimated by a linear trend over the last 100 years (1906–2005) as shown by the magenta line in Figure 4.2. The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking first in one estimate, but with 2005 slightly higher in the other two estimates. 2002 to 2004 are the 3rd, 4th and 5th warmest years in the series since 1850. Eleven of the last 12 years (1995 to 2006) – the exception being 1996 – rank among the 12 warmest years on record since 1850. Temperatures in 2006 were similar to the average of the past 5 years.

- The warming has not been steady, as shown in Figure 4.2. Two periods of warming stand out: an increase of 0.35°C occurred from the 1910s to the 1940s and then a warming of about 0.55°C from the 1970s up to the end of 2006. The remainder of the past 150 years has included short periods of both cooling and warming. The rate of warming over the last 50 years is almost double that over the last 100 years (0.13°C ± 0.03°C vs. 0.07°C ± 0.02°C per decade).

- Land regions have warmed at a faster rate than the oceans. Warming has occurred in both land and oceans and in both sea surface temperature (SST) and nighttime marine air temperature over the oceans. However, for the globe as a whole, surface air temperatures over land have risen at about double the ocean rate after 1979 (more than 0.27°C per decade vs. 0.13°C per decade), with the greatest warming during winter (December to February) and spring (March to May) in the Northern Hemisphere. Recent warming is strongly evident at all latitudes in SSTs over each of the oceans.

- Average Arctic temperatures increased at almost twice the global average rate in the past 100 years. Arctic temperatures have high decadal variability, and a warm period was also observed from 1925 to 1945.

- Between 1901 and 2005, warming is statistically significant over most of the world's surface with the exception of an area south of Greenland and three smaller regions over the southeastern U.S. and parts of Bolivia and the Congo basin. The lack of significant warming at about 20% of the locations (Karoly and Wu, 2005), and the enhanced warming in other places, is likely to be a result of changes in atmospheric circulation. Warming is strongest over the continental interiors of Asia and northwestern North America and over some mid-latitude ocean regions of the Southern Hemisphere as well as southeastern Brazil.

- Since 1979, warming has been strongest over western North America, northern Europe and China in winter, Europe and northern and eastern Asia in spring, Europe and North Africa in summer and northern North America, Greenland and eastern Asia in autumn. Temperatures over mainland Antarctica (south of 65°S) have not warmed in recent decades, but it is virtually certain that there has been strong warming over the last 50 years in the Antarctic Peninsula region (Thompson and Solomon, 2002; Turner et al., 2005).

Box 4.1: Updated Global Surface Temperature Trends through 2008

The global surface temperature trend analysis in IPCC (2007a) includes data through 2005. Three additional years of data have become available since then (2006-2008). According to NOAA's 2008 State of the Climate Report (NOAA, 2009a):

- Eight of the ten warmest years on record have occurred since 2001.

- The year 2008 tied with 2001 as the eighth warmest year on record for the Earth. The combined global land and ocean surface temperature from January-December was 0.88 degree F (0.49 degree C) above the 20th Century average of 57.0 degrees F (13.9 degrees C).

- Since 1880, the annual combined global land and ocean surface temperature has increased at a rate of 0.09 degree F (0.05 degree C) / decade. This rate has increased to 0.29 degree F (0.16 degree C) / decade over the past 30 years.

Data analyzed by NASA through 2008 show similar trends (NASA, 2009). It found 2009 was the ninth warmest year in the period of instrumental measurements, which extends back to 1880. In both analyses 1998 and 2005 remain the two warmest years on record.

Global Upper Air Temperatures

Temperature measurements have also been made above the Earth's surface over the past 50 to 60 years using radiosondes (balloon-borne instruments) and for the past 28 years using satellites. These measurements support the analysis of trends and variability in the troposphere (surface to 10-16 km) and stratosphere (10-50 km above the earth's surface).
The U.S. Climate Change Science Program prepared a report which assessed temperature changes in the atmosphere, differences in these changes at various levels in the atmosphere, and our understanding of the causes of these changes and differences. It concluded (Karl et al., 2006): "…the most recent versions of all available data sets show that both the surface and troposphere have warmed, while the stratosphere has cooled. These changes are in accord with our understanding of the effects of radiative forcing agents and with the results from model simulations."

The IPCC (Trenberth et al., 2007) re-affirmed the major conclusions of this CCSP report finding:

- New analyses of radiosondes and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record and are consistent within their respective uncertainties.

- The satellite tropospheric temperature record is broadly consistent with surface temperature trends. The range (due to different data sets) of global surface warming since 1979 is 0.16°C to 0.18°C per decade compared to 0.12°C to 0.19°C per decade for estimates of tropospheric temperatures measured by satellite.

- Lower-tropospheric temperatures measured by radiosondes have slightly greater warming rates than those at the surface over the period 1958 to 2005. The radiosonde record is markedly less spatially complete than the surface record and increasing evidence suggests that it is very likely that a number of records have a cooling bias, especially in the tropics.

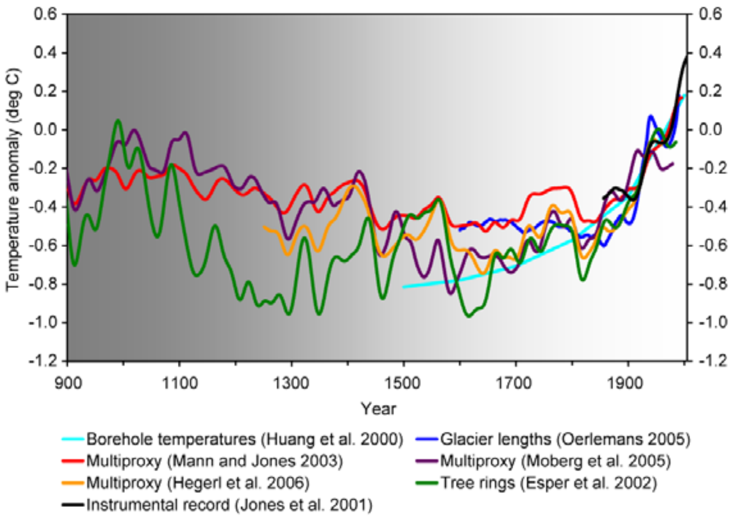
Lower stratospheric temperatures have cooled since 1979. Estimates from adjusted radiosondes, satellites and re-analyses are in qualitative agreement, suggesting a lower-stratospheric cooling of between 0.3°C and 0.6°C per decade since 1979.

The global upper air temperature trend analysis in IPCC (2007a) described above includes data through 2005. Three additional years of data have become available since then (2006-2008). The addition of these three years does not significantly alter the above trends. For example, in NOAA (2009) the satellite tropospheric temperature trend computed through 2008 ranges from + 0.11°C to + 0.15°C per decade compared to the estimate of + 0.12°C to + 0.19°C per decade given in IPCC (2007a).

Global Surface Temperatures Over the Last 2,000 Years

Instrumental surface temperature records only began in the late 19th century, when a sufficiently large global network of measurements was in place to reliably compute global mean temperatures. To estimate temperatures further back in time, scientists analyze proxy evidence from sources such as tree rings, corals, ocean and lake sediments, cave deposits, ice cores, boreholes, glaciers, and documentary evidence. A longer temperature record can help place the 20th century warming into a historical context.

Figure 4.3: Reconstructions of (Northern Hemisphere average or global average) surface temperature variations from six research teams



Source: NRC (2006b) Reconstructions of (Northern Hemisphere average or global average) surface temperature variations from six research teams (in different color shades) along with the instrumental record of global average surface temperature (in black). Each curve illustrates a somewhat different history of temperature changes, with a range of uncertainties that tend to increase backward in time (as indicated by the shading).

The National Research Council conducted a study to describe and assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the last 2,000 years and the implications of these efforts for our understanding of global climate change. It found (NRC, 2006b):

- Large-scale surface temperature reconstructions, as illustrated in Figure 4.3, yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the “Medieval Warm Period”) and a relatively cold period (or “Little Ice Age”) centered around 1700.

- It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. The observed warming in the instrumental record shown in Figure 4.2 supports this conclusion.

- Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 900 to 1600. Presently available proxy evidence indicates that temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since A.D. 900. The uncertainties associated with reconstructing hemispheric mean or global mean temperatures from these data increase substantially backward in time through this period and are not yet fully quantified.

- Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 900 because of sparse data coverage and because the uncertainties associated with proxy data and the methods used to analyze and combine them are larger than during more recent time periods.

Considering this study and additional research, the IPCC (2007d) concluded: “Paleoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years.”

4(c) U.S. changes in temperatures

Like global mean temperatures, U.S. temperatures also warmed during the 20th and into the 21st century. According to official data obtained from NOAA (2009):

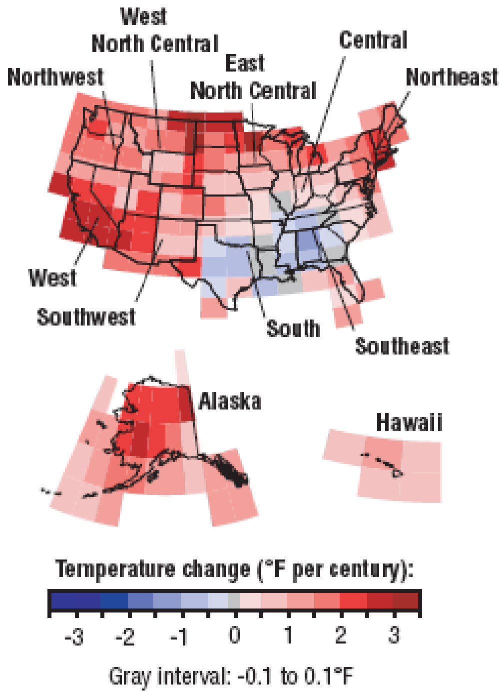
- U.S. average annual temperatures are now approximately 1.25°F (0.69°C) warmer than at the start of the 20th century, with an increased rate of warming over the past 30 years. The rate of warming for the entire period of record (1895-2008) is 0.13°F/decade while the rate of warming increased to 0.58°F/decade (0.32°C/decade) for the period from 1979-2008.

- 2005-2007 were exceptionally warm years (among the top 10 warmest on record), while 2008 was slightly warmer than average (the 39th warmest year on record), 0.2°F (0.1°C) above the 20th century (1901-2000) mean.

- The last ten 5-year periods (2004-2008, 2003-2007, 2002-2006, 2001-2005, 2000-2004, 1999-2003, 1998-2002, 1997-2001, 1996-2000, and 1995-1999), were the warmest 5-year periods (i.e. pentads) in the 114 years of national records, demonstrating the anomalous warmth of the last 15 years.

Regional data analyzed from NOAA's National Climatic Data Center U.S. Historical Climate Network[19] (USHCN), as illustrated in Figure 4.4, indicate warming has occurred throughout most of the U.S., with all but three of the eleven climate regions showing an increase of more than 1ºF since 1901 through 2006 (NOAA, 2007). The greatest temperature increase occurred in Alaska (3.3°F per century). The Southeast shows essentially no trend over the entire period, but has warmed since 1979.

Figure 4.4: Map of the United States, depicting regional U.S. temperature trends for the period 1901 to 2006.



Red shades indicate warming over the period and blue shades indicate cooling over the period.

Including all of North America in its assessment of regional temperatures, the IPCC (Field et al., 2007[20]) stated:

- For the period 1955-2005, the greatest warming occurred in Alaska and north-western Canada, with substantial warming in the continental interior and modest warming in the south-eastern U.S. and eastern Canada.

- Spring and winter show the greatest changes in temperature and daily minimum (night-time) temperatures have warmed more than daily maximum (daytime) temperatures.

4(d) Global changes in precipitation

A consequence of rising temperature is increased evaporation, provided that adequate surface moisture is available (e.g., over the oceans and other moist surfaces). The average atmospheric water vapor content has increased since at least the 1980s over land and ocean as well as in the upper troposphere (IPCC, 2007d). When evaporation increases, more water vapor is available for precipitation producing weather systems leading to precipitation increases in some areas. Conversely, enhanced evaporation and evapotranspiration from warming accelerates land surface drying and increases the potential incidence and severity of droughts in other areas.

Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. According to the IPCC (Trenberth et al., 2007):

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[19] Data obtained from: http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

[20] Field et al., 2007 citation refers to Chapter 14, "North America" in IPCC's 2007 Fourth Assessment Report, Working Group II.

- Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions.

- More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. The regions where droughts have occurred seem to be determined largely by changes in sea surface temperatures (SSTs), especially in the tropics, through associated changes in the atmospheric circulation and precipitation. Decreased snowpack and snow cover have also been linked to droughts.

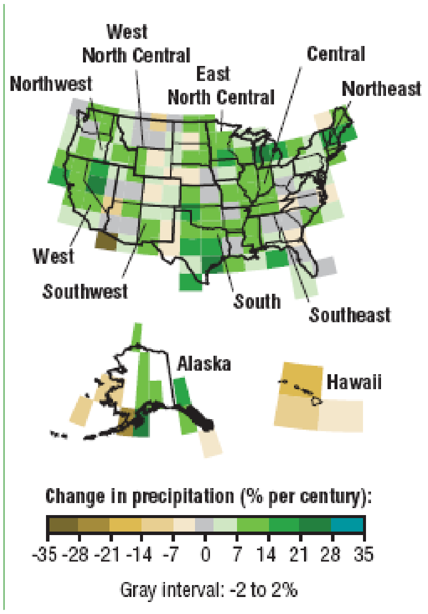
- It is likely that there have been increases in the number of heavy precipitation events (e.g., 95th percentile) within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapor in the atmosphere.

- Rising temperatures have generally resulted in rain rather than snow in locations and seasons where climatological average (1961–1990) temperatures were close to 0°C.

4(e) U.S. changes in precipitation

Data analyzed from NOAA's National Climatic Data Center U.S. Historical Climate Network (USHCN)[21] show that over the contiguous U.S., total annual precipitation increased at an average rate of 6.5% per century from 1901-2006. The greatest increases in precipitation were in the East North Central climate region (11.2% per century) and the South (10.5%). Precipitation in the Northeast increased by 8.3%, in the Southeast by 1.9%, the Central U.S. by 8.1%, the West North Central by 1.9%, the Southwest by 1.3%, the West by 9.1%, and the Northwest by 6.0%.

Figure 4.5: Map of the United States, depicting precipitation trends for the contiguous U.S. 1901-2006, Hawaii 1905-2006 and Alaska 1918-2006.



Green shades indicate a trend towards wetter conditions over the period, and brown shades indicate a trend towards dryer conditions. No data are available for areas shaded in white.

Outside the contiguous U.S., Alaska experienced a precipitation increase of about 5.9% per century (since records began in 1918) and Hawaii experienced a

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[21] Data obtained from: http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

decrease of 7.2% per century (since records begin in 1905).

Despite the overall national trend towards wetter conditions, a severe drought has affected the southwest U.S. from 1999 through 2008 (see Section 4(k) which is indicative of significant variability in regional precipitation patterns over time and space.

4(f) Global sea level rise

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate, after a period of little change between AD 0 and AD 1900 (IPCC, 2007a).

According to Bindoff et al. (2007[22]), there is high confidence that the rate of sea level rise increased between the mid-19th and mid-20th centuries (Bindoff et al., 2007[23]). The average rate of sea level rise measured by tide gauges from 1961 to 2003 was 1.8 ± 0.5 mm per year (Bindoff et al., 2007). The global average rate of sea level rise measured by satellite altimetry during 1993 to 2003 was 3.1 ±0.7 mm per year (Bindoff et al., 2007). Coastal tide gauge measurements confirm this observation. It is unclear whether the faster rate for 1993 to 2003 is a reflection of short-term variability or an increase in the longer-term trend (Bindoff et al., 2007). The total 20th century sea level rise is estimated to be 0.17 ± 0.05 m (Bindoff et al., 2007).

Two major processes lead to changes in global mean sea level on decadal and longer time scales: i) thermal expansion, and ii) the exchange of water between oceans and other reservoirs (glaciers and ice caps, ice sheets, and other land water reservoirs). It is believed that on average, over the period from 1961 to 2003, thermal expansion contributed about one-quarter of the observed sea level rise, while melting of land ice accounted for less than half; the full magnitude of the observed sea level rise was not satisfactorily explained by the available data sets (Bindoff et al., 2007). During this period, global ocean temperature rose by 0.10°C from the surface to a depth of 700 m, contributing an average of 0.4 ± 0.1 mm per year to sea level rise (Bindoff et al., 2007). The contribution from ice was approximately 0.7 ± 0.5 mm per year (Lemke et al., 2007[24]).

For recent years (1993-2003) for which the observing system is much better, thermal expansion and melting of land ice each account for about half of the observed sea level rise, although there is some uncertainty in the estimates. Thermal expansion contributed about 1.6 ± 0.5 mm per year, reflecting a high rate of warming for the period relative to 1961 to 2003 (Bindoff et al., 2007). The total contribution from melting ice to sea level change between 1993 and 2003 ranged from 1.2 ± 0.4 mm per year. The rate increased over the 1993 to 2003 period primarily due to increasing losses from mountain glaciers and ice caps, from increasing surface melt on the Greenland Ice Sheet and from faster flow of parts of the Greenland and Antarctic Ice Sheets (Lemke et al., 2007).

Thermal expansion and exchanges of water between oceans and other reservoirs cause changes in the global mean as well as geographically non-uniform sea level change. Other factors influence changes at the regional scale, including changes in ocean circulation or atmospheric pressure, and geologic processes (Bindoff et al., 2007). Satellite measurements (for the period 1993-2003) provide unambiguous evidence of regional variability of sea level change (Bindoff et al., 2007). In some regions, rates of rise have been

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[22] Bindoff et al., 2007 citation refers to Chapter 5, "Observations: Oceanic Climate Change and Sea Level" in IPCC's 2007 Fourth Assessment Report, Working Group I.

[23] Bindoff et al., 2007 refers to Chapter 5, "Observations: Oceanic Climate Change and Sea Level" in IPCC's 2007 Fourth Assessment Report, Working Group I.

[24] Lemke et al., 2007 refers to Chapter 4, "Observations: Changes in Snow, Ice and Frozen Ground" in IPCC's 2007 Fourth Assessment Report, Working Group I.

as much as several times the global mean, while sea level is falling in other regions. According to IPCC (Bindoff et al., 2007), the largest sea level rise since 1992 has taken place in the western Pacific and eastern Indian Oceans, while nearly all of the Atlantic Ocean shows sea level rise during the past decade with the rate of rise reaching a maximum (over 2 mm yr^{-1}) in a band running east-northeast from the U.S. east coast. Sea level in the eastern Pacific and western Indian Oceans has been falling.

4(g) U.S. sea level rise

Sea level[25] has been rising 0.08-0.12 inches per year (2.0-3.0 mm per year) along most of the U.S. Atlantic and Gulf coasts. The rate of sea level rise varies from about 0.36 inches per year (10 mm per year) along the Louisiana Coast (due to land sinking), to a drop of a few inches per decade in parts of Alaska (because land is rising). Records from the coast of California indicate that sea levels have risen almost 18 cm during the past century (California Energy Commission, 2006). According to the CCSP (2009a), in the mid-Atlantic region from New York to North Carolina, tide-gauge observations indicate that relative sea-level rise (the combination of global sea-level rise and land subsidence) rates were higher than the global mean and generally ranged between 2.4 and 4.4 millimeters per year, or about 0.3 meters (1 foot) over the twentieth century.

Rosenzweig et al. (2007) document studies that find 75% of the shoreline removed from the influence of spits, tidal inlets and engineering structures is eroding along the U.S. East Coast probably due to sea level rise. They also cite studies reporting losses in coastal wetlands observed in Louisiana, the mid-Atlantic region, and in parts of New England and New York, in spite of recent protective environmental regulations.

4(h) Global changes in physical and biological systems

Physical and biological systems on all continents and in most oceans are already being affected by recent climate changes, particularly regional temperature increases (very high confidence) (Rosenzweig. et al., 2007[26]). Climatic effects on human systems, although more difficult to discern due to adaptation and non-climatic drivers, are emerging (medium confidence) (Rosenzweig. et al., 2007). The majority of evidence comes from mid- and high latitudes in the Northern Hemisphere, while documentation of observed changes in tropical regions and the Southern Hemisphere is sparse (Rosenzweig. et al., 2007). Hence, the findings presented in this section apply generally to the globe but most directly to Europe and North America (including the U.S.) where these observational studies were conducted. The extent to which observed changes discussed here can be attributed to anthropogenic GHG emissions is discussed in Section 5.

Cryosphere (Snow and Ice)

Observations of the cryosphere (the "frozen" component of the climate system) have revealed changes in sea ice, glaciers and snow cover, freezing and thawing, and permafrost. According to IPCC, the following physical changes have been observed:

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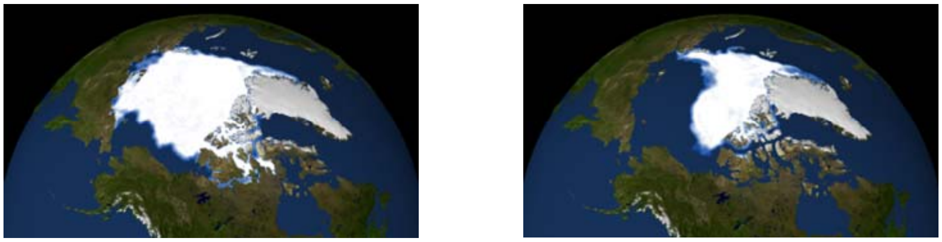
[25] U.S. sea level data obtained from the Permanent Service for Mean Sea Level < http://www.pol.ac.uk/psmsl/> of the Proudman Oceanographic Laboratory.

[26] Rosenzweig et al., 2007 refers to Chapter 1 "Assessment of observed changes and responses in natural and managed systems" in IPCC's 2007 Fourth Assessment Report, Working Group 2.

Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7 ± 0.6 % per decade, with larger decreases in summer of 7.4 ± 2.4% per decade. The latest data from NASA indicate Arctic sea ice set a record low in September 2007, 38 percent below the 1979-2007 average (NASA Goddard Space Flight Center, 2007). The extent of the sea ice loss between 1979 and 2007 can be seen in Figure 4.6. In September 2008, Arctic sea ice reached its second lowest extent on record (NASA Goddard Space Flight Center, 2008).



These two images, constructed from satellite data, compare arctic sea ice concentrations in September of 1979 and 2007 (Images courtesy of NASA).

Figure 4.6 Arctic Sea Ice Concentrations Comparisons

- Antarctic sea ice extent shows no statistically significant average trends according to IPCC (2007d). However, the U.S. National and Snow and Ice Data Center states that Antarctic sea ice underwent a slight increase from 1979 to 2007 (NSIDC, 2009).

- The average sea ice thickness in the central Arctic has very likely decreased by up to 1 m from 1987 to 1997, based upon submarine-derived data. Model-based reconstructions support this, suggesting an arctic-wide reduction of 0.6 to 0.9 m over the same period (Lemke et al., 2007).

- Mountain glaciers and snow cover have declined on average in both hemispheres. Northern hemisphere snow cover observed by satellite over the 1966 to 2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s. In the Southern Hemisphere, the few long records or proxies mostly show either decreases or no changes in the past 40 years or more. The strongest mass losses of mountain glaciers (per unit area) have been observed in Patagonia, Alaska and the northwestern U.S. and southwest Canada. Because of the corresponding large areas, the biggest contributions to sea level rise came from Alaska, the Arctic and the Asian high mountains (Lemke et al., 2007).

- Freeze-up date for river and lake ice has occurred later at a rate of 5.8 ± 1.6 days per century, averaged over available data for the Northern Hemisphere spanning the past 150 years. Breakup date has occurred earlier at a rate of 6.5 ± 1.2 days per century (Lemke et al., 2007).

- Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The permafrost base has been thawing at a rate ranging up to 0.04 m per year in Alaska since 1992 and 0.02 m per year on the Tibetan Plateau since the 1960s. The maximum area covered by seasonally frozen ground has decreased by 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15% (Lemke et al., 2007).

There are additional effects related to changes in the cryosphere. Melting of highly reflective snow and ice reveals darker land and ocean surfaces, increasing absorption of the sun's heat and further warming the planet. Increases in glacial melt and river runoff add more freshwater to the ocean, raising global sea level.

Hydrosphere

The term "hydrosphere" refers to the component of the climate system comprising liquid surface and subterranean water, such as rivers, lakes, and underground water. Several changes in these features have been observed, as summarized by the IPCC (Rosenzweig et al., 2007):

- Documented trends in severe droughts and heavy rains show that hydrological conditions are becoming more intense in some regions. Globally, very dry areas (Palmer Drought Severity Index—PDSI—less than or equal to -3.0) have more than doubled since the 1970s due to a combination of El Niño-Southern Oscillation events and surface warming. Very wet areas (PDSI greater than or equal to +3.0) declined by about 5% since the 1970s, with precipitation as the major contributing factor during the early 1980s and temperature more important thereafter. The areas of increasing wetness include the Northern Hemisphere high latitudes and equatorial regions.

- Climate change signals related to increasing runoff and stream flow have been observed over the last century in many regions, particularly in basins fed by glaciers, permafrost, and snowmelt. Evidence includes increases in average runoff of Arctic rivers in Eurasia, which has been at least partly correlated with climate warming, and earlier spring snowmelt and increase in winter base flow in North America and Eurasia due to enhanced seasonal snow melt associated with climate warming.

- Freshwater lakes and rivers are experiencing increased water temperatures and changes in water chemistry. Surface and deep lake-waters are warming, with advances and lengthening of periods of thermal stability in some cases associated with physical and chemical changes such as increases in salinity and suspended solids, and a decrease in nutrient content. Lake formation and subsequent disappearance in permafrost have been reported in the Arctic.

Changes in river discharge as well as in droughts and heavy rains in some regions indicate that hydrological conditions have become more intense but significant trends in floods and in evaporation and evapotranspiration have not been detected globally. Some local trends in reduced groundwater and lake levels have been reported, but studies have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions such as groundwater management (Rosenzweig et al., 2007).

Biosphere

According to IPCC, terrestrial ecosystems and marine and freshwater systems show that recent warming is strongly affecting natural biological systems (very high confidence) (Rosenzweig et al., 2007):

- The overwhelming majority of studies of regional climate effects on terrestrial species reveal consistent responses to warming trends, including poleward and elevational range shifts of flora and fauna. Changes in abundance of certain species, including limited evidence of a few local disappearances, and changes in community composition over the last few decades have been attributed to climate change.

- Responses of terrestrial species to warming across the northern hemisphere are well documented by changes in the timing of growth stages, especially the earlier onset of spring events, migration, and lengthening of the growing season. Changes in phenology (the timing of annual phenomena of animal and plant life) include clear temperature-driven extension of the growing season by up to 2 weeks in the second half of the 20th century in mid- and high northern latitudes, mainly due to an earlier spring, but partly due also to a later autumn. Egg-laying dates have advanced in many bird species, and many small mammals have been found to come out of hibernation and to breed earlier in the spring now than they did a few decades ago.

- Many observed changes in phenology and distribution of marine species have been associated with rising water temperatures, as well as other climate-driven changes in salinity, oxygen levels, and circulation. For example, plankton has moved poleward by 10° latitude over a period of 4 decades in the North Atlantic. While there is increasing evidence for climate change impacts on coral reefs, discerning the impacts of climate-related stresses from other stresses (*e.g.* over fishing and pollution) is difficult. Warming of lakes and rivers is affecting abundance and productivity, community composition, phenology, distribution and migration of freshwater species (high confidence).

4(i) U.S. changes in physical and biological systems

Many of the global changes in physical and biological systems mentioned in 4(h) broadly apply to the U.S. Some U.S.-specific changes in these systems cited in IPCC's Fourth Assessment Report are described in this subsection, as well as in section 11(a) for physical systems related to water resources and section 14(a) related to biological systems. Of all the observed changes to physical systems assessed by IPCC (Rosenzweig et al., 2007) for North America (totaling 355), 94% of them were consistent with changes one would expect with average warming. Similar consistency was found between observed biological system changes and warming for North America (see discussion below under *biosphere*).

Furthermore, a CCSP (2008e) assessment reported that climate changes are very likely already affecting U.S. water resources, agriculture, land resources, and biodiversity as a result of climate variability and change. It found, "The number and frequency of forest fires and insect outbreaks are increasing in the interior West, the Southwest, and Alaska. Precipitation, streamflow, and stream temperatures are increasing in most of the continental United States. The western United States is experiencing reduced snowpack and earlier peaks in spring runoff. The growth of many crops and weeds is being stimulated. Migration of plant and animal species is changing the composition and structure of arid, polar, aquatic, coastal, and other ecosystems" (Backlund et al., 2008a)

Additional findings from this CCSP assessment along with results presented in IPCC's Fourth Assessment Report are described below.

Cryosphere (Snow and Ice)

In North America, from 1915 to 2004, snow covered area increased in November, December and January due to increases in precipitation. However, snow cover decreased during the latter half of the 20th century, especially during the spring over western North America (Groisman et al., 2004 in Lemke et al., 2007). Shifts towards earlier melt by about eight days since the mid-1960s were also observed in northern Alaska (Stone et al., 2002 in Lemke et al., 2007). Consistent with these findings, Lettenmaier et al. (2008) note a trend toward reduced mountain snowpack, and earlier spring snowmelt runoff peaks across much of the western U.S.

The IPCC (Lemke et al., 2007) cites a study (Dyurgerov and Meier, 2005) documenting glacier mass balance loss in the northwest U.S. and Alaska, with losses especially rapid in Alaska after the mid-1990s. Rosenzweig et al. (2007) document evidence of present crustal uplift in response to recent glacier melting in Alaska (Larsen et al., 2005).

Hydrosphere

Lettenmaier et al. (2008) document increases in U.S. streamflow during the second half of the 20th century consistent with increases in precipitation described in 4(e).

Rosenzweig et al. (2007) indicate surface water temperatures have warmed by 0.2 to 2°C in lakes and rivers in North America since the 1960s. They also discuss evidence for an earlier occurrence of spring peak river flows and an increase in winter base flow in basins with important seasonal snow cover in North America.

Biosphere

The IPCC (Rosenzweig et al., 2007) assessed a multitude of studies that find changes in terrestrial ecosystems and marine and freshwater systems in North America. Of 455 biological observations assessed from these studies, 92% were consistent with the changes expected due to average warming.

Backlund et al. (2008a) find:

- There has been a significant lengthening of the growing season and increase in net primary productivity (NPP) in the higher latitudes of North America. Over the last 19 years, global satellite data indicate an earlier onset of spring across the temperate latitudes by 10 to 14 days.

- In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change, nearly 60 percent of the 1598 species studied exhibited shifts in their distributions and/or phenologies over the 20- and 140-year time frame.

- Subtropical and tropical corals in shallow waters have already suffered major bleaching events that are clearly driven by increases in sea surface temperatures.

In addition, Ryan et al. (2008) note, “Climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior west, the Southwest, and Alaska.”

4(j) Global extreme events

Climate is defined not simply as average temperature and precipitation but also by the type, frequency and intensity of extreme events. The IPCC documents observed changes in climate extremes related to temperature, precipitation, tropical cyclones, and sea level. The changes described apply generally to all parts of the globe, including the U.S., although there are some regional and local exceptions due to patterns of natural climate variability. Current observations are summarized here, projected trends are covered in Section 6, and the sectoral impacts of these changes are covered as relevant in Sections 7 to 15.

Temperature

Widespread changes in extreme temperatures have been observed in the last 50 years. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent (IPCC, 2007d). A widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes and a reduction in the number of daily cold extremes are observed in 70 to 75% of the land regions where data are available. The most marked changes are for cold (lowest 10%, based on 1961–1990) nights, which have become rarer over the 1951 to 2003 period. Warm (highest 10%) nights have become more frequent.

Precipitation and Storms

It is likely that there have been increases in the number of heavy precipitation events[27] within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapor in the atmosphere. Increases have also been reported for rarer precipitation events (1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably (Trenberth et al., 2007).

More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics (IPCC, 2007d). Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought (IPCC, 2007d).

Trenberth et al. (2007) report that estimates of the potential destructiveness of hurricanes show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity, and such trends are strongly correlated with tropical SST. However, the CCSP (2008i) report on extreme events notes that Kossin et al. (2007), aside from the Atlantic, were not able to corroborate the presence of upward intensity trends in the remaining tropical cyclone-prone ocean basins over the last two decades. Kunkel et al. (2008) in the same CCSP report caution that quantifying tropical cyclone variability is limited, sometimes seriously, by a large suite of problems with the historical record of tropical cyclone activity. Correspondingly, there is no clear trend in the annual numbers of tropical cyclones (IPCC, 2007d).

High Sea Level

Apart from non-climatic events such as tsunamis, extreme sea levels occur mainly in the form of storm surges generated by tropical or extra tropical cyclones. There is evidence for an increase in extreme high sea level since 1975 based upon an analysis of 99th percentiles of hourly sea level at 141 stations over the globe (Bindoff et al., 2007).

4(k) U.S. extreme events

Many of the global changes in extreme events mentioned in 4(j) broadly apply to the U.S. Additionally, the U.S. CCSP (2008i) published a report that focused on changing climate extremes in the U.S. and North America. It concluded (Karl et al., 2008 in CCSP, 2008i):

> **“**Many extremes and their associated impacts are now changing. For example, in recent decades most of North America has been experiencing more unusually hot days and nights, fewer unusually cold days and nights, and fewer frost days. Heavy downpours have become more frequent and intense. Droughts are becoming more severe in some regions, though there are no clear trends for North America as a whole. The power and frequency of Atlantic hurricanes have increased substantially in recent decades, though North American mainland land-falling hurricanes do not appear to have increased over the past century. Outside the tropics, storm tracks are shifting northward and the strongest storms are becoming even stronger.”

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[27] Heavy precipitation events refer to those in the 95th percentile of precipitation events.

Many of these changes were also assessed in IPCC's Fourth Assessment Report and are described in this subsection.

Temperature

The IPCC (Trenberth et al., 2007) cites North America regional studies that all show patterns of changes in temperature extremes consistent with a general warming. Karl et al. (2008) find the number of heat waves (extended periods of extremely hot weather) has been increasing over the past 50 years but note the heat waves of the 1930s remain the most severe in the U.S. historical record.

Extreme cold has been decreasing. Robeson (2004 in Trenberth et al., 2007) found intense warming of the lowest daily minimum temperatures over western and central North America. Trenberth et al. (2007) caution the observed changes of the tails of the temperature distributions are often more complicated than a simple shift of the entire distribution would suggest. Karl et al. (2008) note, "The last 10 years [1998-2007] have seen fewer severe cold snaps than for any other 10-year period in the historical record, which dates back to 1895." Karl et al. also indicate a decrease in frost days and a lengthening of the frost-free season over the past century.

Precipitation and Storms

In the contiguous U.S., Kunkel et al. (2003; in Trenberth et al., 2007) and Groisman et al. (2004; in Trenberth et al., 2007) found statistically significant increases in heavy precipitation (the heaviest 5%) and very heavy precipitation (the heaviest 1%) of 14 and 20%, respectively. Much of this increase occurred during the last three decades of the 20th century and is most apparent over the eastern parts of the country. There is also evidence from Europe and the U.S. that the relative increase in precipitation extremes is larger than the increase in mean precipitation (Trenberth et al., 2007).

Lettenmeir et al. (2008) find, "With respect to drought, consistent with streamflow and precipitation observations, most of the continental United States experienced reductions in drought severity and duration over the 20th century. However, there is some indication of increased drought severity and duration in the western and southwestern United States…."

Diminishing snow pack and subsequent reductions in soil moisture appear to be factors in recent drought conditions in the western U.S. (Trenberth et al., 2007). This drought has also been attributed to changes in atmospheric circulation associated with warming of the western tropical Pacific and Indian oceans as well as multidecadal fluctuations (Hoerling and Kumar, 2003; McCabe et al., 2004; in Trenberth et al., 2007).

Karl et al. (2008) indicate a northward shift in the tracks of strong low-pressure systems (also known as mid-latitude storms and/or extratropical cyclones) in both the North Atlantic and North Pacific over the past fifty years with increases in storm intensity noted in the Pacific (data inconclusive in the Atlantic). Correspondingly, they also find northward shift in snow storm occurrence, which is also consistent with the warming temperatures and a decrease in snow cover extent over the U.S.

IPCC (2007d) reports there is observational evidence for an increase in intense tropical cyclone (i.e. tropical storms and/or hurricanes) activity in the North Atlantic (where cyclones develop that affect the U.S. East and Gulf Coasts) since about 1970, correlated with increases of tropical sea surface temperatures. Similarly, Kunkel et al. (2008) conclude (for the North Atlantic): "There have been fluctuations in the number of tropical storms and hurricanes from decade to decade, and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual numbers of tropical storms, hurricanes, and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased."

High Sea Level

Studies of the longest records of extremes in sea level are restricted to a small number of locations. Consistent with global changes, U.S.-based studies document increases in extreme sea level closely following the rise in mean sea level (Bindoff et al., 2007).

Section 5

Attribution of Observed Climate Change to Anthropogenic Greenhouse Gas Emissions at the Global and Continental Scale

This section addresses the extent to which observed climate change at the global and continental or national scale (described in Section 4) can be attributed to *global* anthropogenic emissions of GHGs. Section 2 describes the share of the U.S. transportation sector to U.S. and global anthropogenic emissions of GHGs, and the resultant share of U.S. transportation emissions to global increases in atmospheric concentrations of GHGs.

Evidence of the effect of anthropogenic GHG emissions on the climate system, as well as climate-sensitive systems and sectors, has increased over the last 15 years or so and even since the last IPCC assessment published in 2001. The evidence in the recent IPCC Fourth Assessment Report (2007) is based on analyses of global- and continental-scale temperature increases, changes in other climate variables and physical and biological systems, and the radiative forcing caused by anthropogenic versus natural factors.

5(a) Attribution of observed climate change to anthropogenic emissions

Computer-based climate models are the primary tools used for simulating the likely patterns of response of the climate system to different forcing mechanisms (both natural and anthropogenic). Confidence in these models comes from their foundation in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes (IPCC, 2007a). For additional discussion on the strengths and limitations of models, see Section 6(b). Attribution studies evaluate whether observed changes are consistent with quantitative responses to different forcings (from greenhouse gases, aerosols and natural forcings such as changes solar intensity) represented in well-tested models, and are not consistent with alternative physically plausible explanations.

Studies to detect climate change and attribute its causes using patterns of observed temperature change show clear evidence of human influences on the climate system (Karl et al., 2006). Discernible human influences extend to additional aspects of climate including ocean warming, continental-average temperatures, temperature extremes and wind patterns (Hegerl et al., 2007[28]).

Temperature

IPCC statements on the linkage between greenhouse gases and temperatures have strengthened since its early assessments (Solomon et al., 2007). The IPCC's First Assessment Report in 1990 contained little observational evidence of a detectable anthropogenic influence on climate (IPCC, 1990). In its Second Assessment Report in 1995, it stated the balance of evidence suggests a discernible human influence on the climate of the 20th century (IPCC, 1996). The Third Assessment Report in 2001 concluded that most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations (IPCC, 2001b). The conclusion in IPCC's 2007 Fourth Assessment Report (2007b) is the strongest yet:

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[28] Hegerl et al., 2007 citation refers to Chapter 9, "Understanding and Attributing Climate Change" in IPCC's 2007 Fourth Assessment Report, Working Group I.

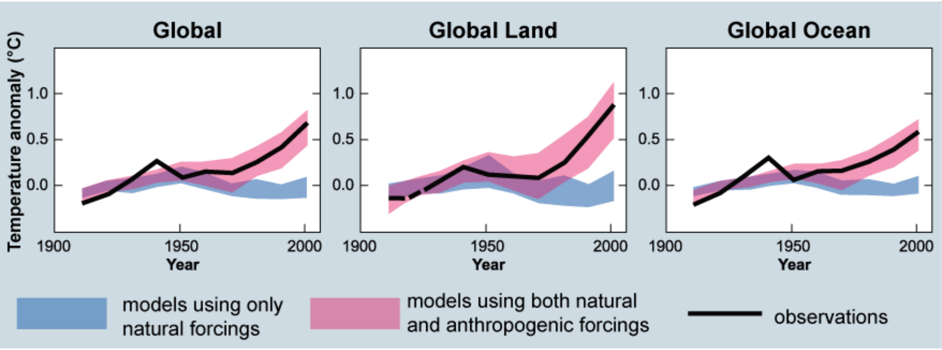
> *Most of the observed increase in global average temperatures since the mid-20th century is very likely*[29] *due to the observed increase in anthropogenic greenhouse gas concentrations.*

The increased confidence in the greenhouse gas contribution to the observed warming results from (Hegerl. et al., 2007):

- an expanded and improved range of observations allowing attribution of warming to be more fully addressed jointly with other changes in the climate system
- improvements in the simulation of many aspects of present mean climate and its variability on seasonal to inter-decadal time scales
- more detailed representations of processes related to aerosol and other forcings in models
- simulations of 20th-century climate change that use many more models and much more complete anthropogenic and natural forcings
- multi-model ensembles that increase confidence in attribution results by providing an improved representation of model uncertainty

Climate model simulations run by the IPCC, shown in Figure 5.1, suggest natural forcings alone cannot explain the observed warming (for the globe, the global land and global ocean). The observed warming can only be reproduced with models that contain both natural and anthropogenic forcings.

Figure 5.1: Comparison of observed global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.



Source: IPCC (2007d). Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

Additional evidence documented in the IPCC report supports its statement linking warming to increasing concentrations of greenhouse gases (Hegerl et al., 2007):

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[29] According to IPCC terminology, "very likely" conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

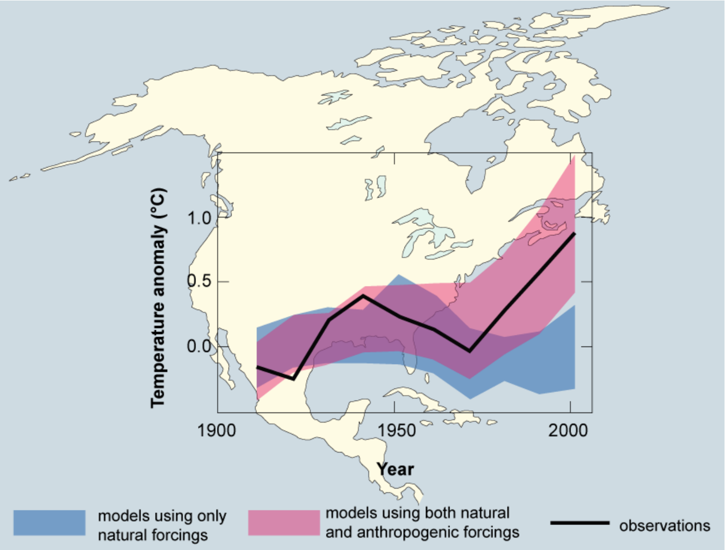
- Warming of the climate system has been detected in changes of surface and atmospheric temperatures in the upper several hundred meters of the ocean, and in contributions to sea level rise. Attribution studies have established anthropogenic contributions to all of these changes.

- Analyses of paleoclimate data have increased confidence in the role of external influences on climate. Coupled climate models used to predict future climate have been used to reproduce key features of past climates using boundary conditions and radiative forcing for those periods.

The IPCC states that it is very unlikely that the global pattern of warming observed during the past half century is due to only known natural external causes (solar activity and volcanoes) since the warming occurred in both the atmosphere and ocean and took place when natural external forcing factors would likely have produced cooling (Hegerl et al., 2007). It also states greenhouse gas forcing alone would likely have resulted in warming greater than observed if there had not been an offsetting cooling effect from aerosols and natural forcings during the past half century (Hegerl et al., 2007). Solomon et al. (2007) indicate the sum of solar and volcanic forcing in the past half century would likely have produced cooling, not warming.

Not only has an anthropogenic signal been detected for the surface temperatures, but evidence has also accumulated of an anthropogenic influence through the vertical profile of the atmosphere. Fingerprint studies[30] have identified greenhouse gas and sulfate aerosol signals in observed surface temperature records, a stratospheric ozone depletion signal in stratospheric temperatures, and the combined effects of these forcing agents in the vertical structure of atmospheric temperature changes (Karl et al., 2006). However, one important inconsistency may have been identified in the tropics. In the tropics, most observational data sets show more warming at the surface than in the troposphere, while almost

Figure 5.2: Comparison of observed North American changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.



Source: Hegerl et al. (2007). Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

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[30] Fingerprint studies use rigorous statistical methods to compare the patterns of observed temperature changes with model expectations and determine whether or not similarities could have occurred by chance. Linear trend comparisons are less powerful than fingerprint analyses for studying cause-effect relationships, but can highlight important differences and similarities between models and observations (as in Figures 5.1 and 5.2).

all model simulations have larger warming aloft than at the surface. A possible explanation for this inconsistency is error in the observations, but the issue is still under investigation (Karl et al., 2006).

The substantial anthropogenic contribution to surface temperature increases likely applies to every continent except Antarctica (which has insufficient observational coverage to make an assessment) since the middle of the 20th century (Hegerl. et al., 2007). Figure 5.2 indicates North America's observed temperatures over the last century can only be reproduced using model simulations containing both natural and anthropogenic forcings. In the CCSP (2008g) report "Reanalysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change", Dole et al. (2008) find that for North America "more than half of this warming [for the period 1951-2006] is likely the result of human-caused greenhouse gas forcing of climate change."

Difficulties remain in attributing temperature changes on smaller than continental scales and over time scales of less than 50 years. Attribution at these scales, with limited exceptions, has not yet been established (Hegerl et al., 2007).

Temperature extremes have also likely been influenced by anthropogenic forcing. Many indicators of climate extremes, including the annual numbers of frost days, warm and cold days, and warm and cold nights, show changes that are consistent with warming (Hegerl et al., 2007). An anthropogenic influence has been detected in some of these indices, and there is evidence that anthropogenic forcing may have substantially increased the risk of extremely warm summer conditions regionally, such as the 2003 European heat wave (Hegerl et al., 2007). Karl et al. (2008) conclude the increase in human-induced emissions of GHGs is estimated to have substantially increased the risk of a very hot year in the U.S., such as that experienced in 2006. They add that other aspects of observed increases in temperature extremes, such as changes in warm nights and frost days, have been linked to human influences.

Additional Climate Variables

There is evidence of anthropogenic influence in other parts of the climate system. The IPCC noted the following examples (Hegerl et al., 2007):

- Trends over recent decades in the Northern and Southern Annular Modes[31], which correspond to sea level pressure reductions over the poles, are likely related in part to human activity, affecting storm tracks, winds and temperature patterns in both hemispheres. Models reproduce the sign of the Northern Annular Mode trend, but the simulated response is smaller than observed. Models including both greenhouse gas and stratospheric ozone changes simulate a realistic trend in the Southern Annular Mode, leading to a detectable human influence on global sea level pressure patterns.

It is more likely than not that anthropogenic influence has contributed to increases in the frequency of the most intense tropical cyclones. Gutowski et al. (2008), as cited in the CCSP (2008i) report, likewise find evidence suggesting a human contribution to recent hurricane activity. However, they caution that a confident assessment of human influence on hurricanes will require further studies using models and observations, with emphasis on distinguishing natural from human-induced changes in hurricane activity through their influence on factors such as historical sea surface temperatures, wind shear, and atmospheric vertical stability.

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[31] Annular modes are preferred patterns of change in atmospheric circulation corresponding to changes in the zonally averaged mid-latitude westerly winds. The Northern Annular Mode has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation (see footnote 36). The Southern Annular Mode occurs in the Southern Hemisphere.

- The latitudinal pattern of change in land precipitation and observed increases in heavy precipitation over the 20th century appear to be consistent with the anticipated response to anthropogenic forcing.

Attributing changes in precipitation to anthropogenic forcing at continental or smaller scales is more challenging. Clark et al. (2008) conclude, "There is no clear evidence to date of human-induced global climate change on North American precipitation amounts." On the other hand, Karl et al. (2008) find heavy precipitation events averaged over North America have increased over the past 50 years, consistent with the observed increases in atmospheric water vapor, which have been associated with human-induced increases in greenhouse gases.

5(b) Attribution of observed changes in physical and biological systems

In addition to attributing the observed changes in average global- and continental-scale temperature and other climate variables to anthropogenic GHG forcing, a similar attribution can be made between anthropogenic GHG forcing and observed changes in physical systems (e.g., melting glaciers) and biological systems and species (e.g., geographic shift of species) which are shown to change as a result of recent warming.

This section includes the observed changes in physical and biological systems in North America and in other parts of the world.

The IPCC (2007b) concluded that, "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." Furthermore, the IPCC states that, "A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems." As detailed above in Section 5(a), recent warming of the last 50 years is very likely the result of the accumulation of anthropogenic GHGs in the atmosphere.

Climate variability and non-climate drivers (e.g., land-use change, habitat fragmentation) need to be considered in order to make robust conclusions about the role of anthropogenic climate change in affecting biological and physical systems. IPCC (Rosenzweig et al. 2007) reviewed a number of joint attribution studies that linked responses in some physical and biological systems directly to anthropogenic climate change using climate, process, and statistical models. The conclusion of these studies is that "the consistency of observed significant changes in physical and biological systems and observed significant warming across the globe likely cannot be explained entirely due to natural variability or other confounding non-climate factors (Rosenzweig et al. 2007)."

The physical systems undergoing significant change include the cryosphere (snow and ice systems), hydrological systems, water resources, coastal zones and the oceans**.** These effects (reported with high confidence by IPCC (Rosenzweig et al. 2007)) include ground instability in mountain and permafrost regions, shorter travel season for vehicles over frozen roads in the Arctic, enlargement and increase of glacial lakes in mountain regions and destabilization of moraines damming these lakes, changes in Arctic flora and fauna including the sea-ice biomes and predators higher in the food chain, limitations on mountain sports in lower-elevation alpine areas, and changes in indigenous livelihoods in the Arctic.

Regarding biological systems, the IPCC (Rosenzweig et al. 2007) reports with very high confidence that the overwhelming majority of studies of regional climate effects on terrestrial species reveal trends consistent with warming, including poleward and elevational range shifts of flora and fauna, the earlier onset of spring events, migration, and lengthening of the growing season, changes in abundance of certain species, including limited evidence of a few local disappearances, and changes in community composition.

Human system responses to climate change are more difficult to identify and isolate due to the larger role that non-climate factors play (e.g., management practices in agriculture and forestry, and adaptation responses to protect human health against adverse climatic conditions).

Section 6

Projected Future Greenhouse Gas Concentrations and Climate Change

According to the IPCC (2007d), “continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely[32] be larger than those observed during the 20th century.” This section describes future GHG emission scenarios, the associated changes in atmospheric concentrations and radiative forcing, and the resultant changes in temperature, precipitation and sea level at global and U.S. scales. All future GHG emission scenarios described in this section assume no new explicit GHG mitigation policies -- neither in the U.S. nor in other countries -- beyond those which were already enacted at the time the scenarios were developed. Future risks and impacts associated with the climate change projections are addressed in Part IV for domestic impacts and Part V for international impacts.

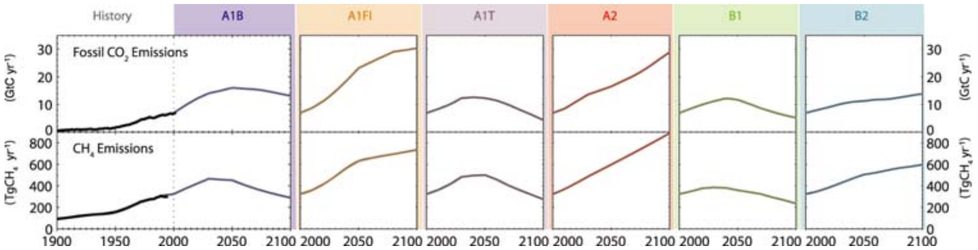
6(a) Global emission scenarios and associated changes in concentrations and radiative forcing

Greenhouse Gas Emissions

As described in Section 4(a), a number of different GHGs and other factors, including aerosols, cause radiative forcing changes and thus contribute to climate change. This section discusses the range of published global reference (or baseline) future emission projections for which no explicit GHG mitigation policies beyond those currently enacted are assumed.

The IPCC’s most recent future climate change projections from the Fourth Assessment Report (2007) (discussed in Section 6(b) below) are based on the GHG emission scenarios from the IPCC *Special Report on Emission Scenarios* (IPCC, 2000). Box 6.1 provides background information on the different SRES emission scenarios. The SRES developed a range of long-term (out to the year 2100) global reference scenarios for the major GHGs directly emitted by human activities and for some aerosols. The IPCC SRES scenarios do not explicitly account for implementation of the Kyoto Protocol. Figure 6.1 presents the global IPCC SRES projections for the two most significant anthropogenic GHGs: CO_2 emissions primarily from the burning of fossil fuels, and CH_4 emissions.

Figure 6.1 Observed, and Projected Global CO_2 and CH_4 Emissions for the IPCC SRES Scenarios



Source: Meehl et al. (2007). Projected fossil CO_2 and CH_4 emissions for six illustrative SRES non-mitigation emission scenarios. Historical emissions (black lines) are shown for fossil and industrial CO_2, and for CH_4.

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[32] According to IPCC terminology, “very likely” conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

Box 6.1: IPCC Reference Case Emission Scenarios from the Special Report on Emission Scenarios

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Box 6.2: CCSP (2007b) Reference Case Emission Scenarios from Synthesis and Assessment Product 2.1

The scenarios in this report were developed using three integrated assessment models (IAMs). These models integrate socioeconomic and technological determinants of the emissions of GHGs with models of the natural science of Earth system response, including the atmosphere, oceans, and terrestrial biosphere. The three IAMs used are:

- The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology’s Joint Program on the Science and Policy of Global Change.
- The Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute.
- The MiniCAM Model of the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland. The MiniCAM model was also used to generate IPCC SRES scenarios.

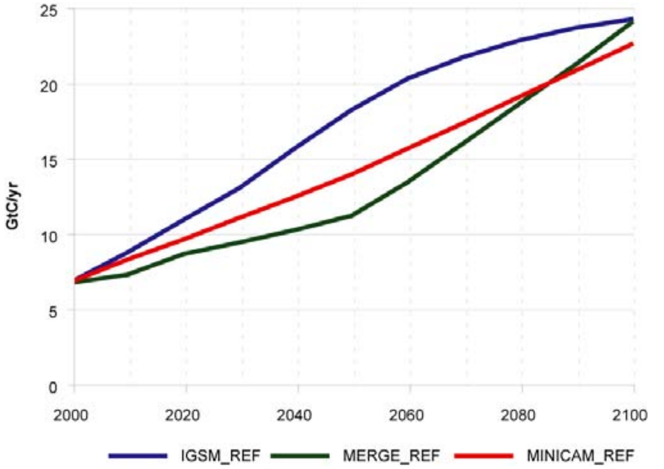
Each modeling group produced a reference scenario under the assumption that no climate policies are imposed beyond current commitments, namely the 2008-12 first period of the Kyoto Protocol and the U.S. goal of reducing GHG emissions per unit of its gross domestic product by 18% by 2012. The resulting reference cases are not predictions or best-judgment forecasts but scenarios designed to provide clearly defined points of departure for studying the implications of alternative stabilization goals. The modeling teams used model input assumptions they considered *meaningful and plausible*. The resulting scenarios provide insights into how the world might evolve without additional efforts to constrain GHG emissions, given various assumptions about principal drivers of these emissions such as population increase, economic growth, land and labor productivity growth, technological options, and resource endowments.

The main drivers of emissions are population, economic growth, technological change, and land-use activities including deforestation. The detailed underlying assumptions (including final and primary energy by major fuel types) across all scenarios, and across all modeling teams that produced the scenarios, can be found in IPCC (2000). The range of GHG emissions in the scenarios widen over time to reflect uncertainties in the underlying drivers. Similar future GHG emissions can result from different socio-economic developments. The IPCC (2000) SRES report did not assign probabilities or likelihood to the scenarios, as it was stated that there is no single most likely, central, or best-guess scenario, either with respect to SRES scenarios or to the underlying scenario literature. This is why IPCC (2000) has recommended using a range of SRES scenarios with a variety of underlying assumptions for use in analysis.

Despite the range in future emission scenarios, the majority of all reference-case scenarios project an increase of GHG emissions across the century, and show that CO_2 remains the dominant GHG over the course of the 21st century. Total *cumulative* (1990 to 2100) CO_2 emissions across the SRES scenarios range from 2,826 gigatonnes of CO_2 ($GtCO_2$) (or 770 GtC) to approximately 9,322 $GtCO_2$ (or 2,540 GtC).[33]

Since the IPCC SRES (2000), new scenarios in the literature have emerged. The emission scenario range from the recent literature is similar to the range from the IPCC SRES. The IPCC (2007c) reported that baseline annual emission scenarios published since SRES are comparable in range to those presented in the SRES scenarios (25 to 135 GtCO2eq. per year in 2100). Studies since SRES used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, resulted in little change in overall emission levels (IPCC, 2007c).

Figure 6.2: Projected Global Emissions of CO_2 from Fossil Fuels and Industrial Sources across CCSP Reference Scenarios



Source: CCSP (2007b). Global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production, increase over the century in all three reference scenarios. By 2100 emissions reach 22.5 GtC/yr 24.0 GtC/yr.

For comparison, Figure 6.2 provides global projections of CO_2 emissions from the burning of fossil fuels and industrial sources from the three reference-case scenarios developed by the U.S. Climate Change Science Program (CCSP, 2007b). Box 6.2 provides background information on the reference case scenarios developed by the CCSP. The CCSP scenarios, because they were developed more recently than the IPCC SRES scenarios, do account for the implementation of the Kyoto Protocol for participating countries, but no explicit GHG mitigation policies beyond the Kyoto Protocol. The emissions in 2100 are approximately 88 $GtCO_2$ (24 GtC). This level of emissions is above the post-SRES IPCC median of 60 $GtCO_2$ (16 GtC), but well within the 90th percentile of the IPCC range.

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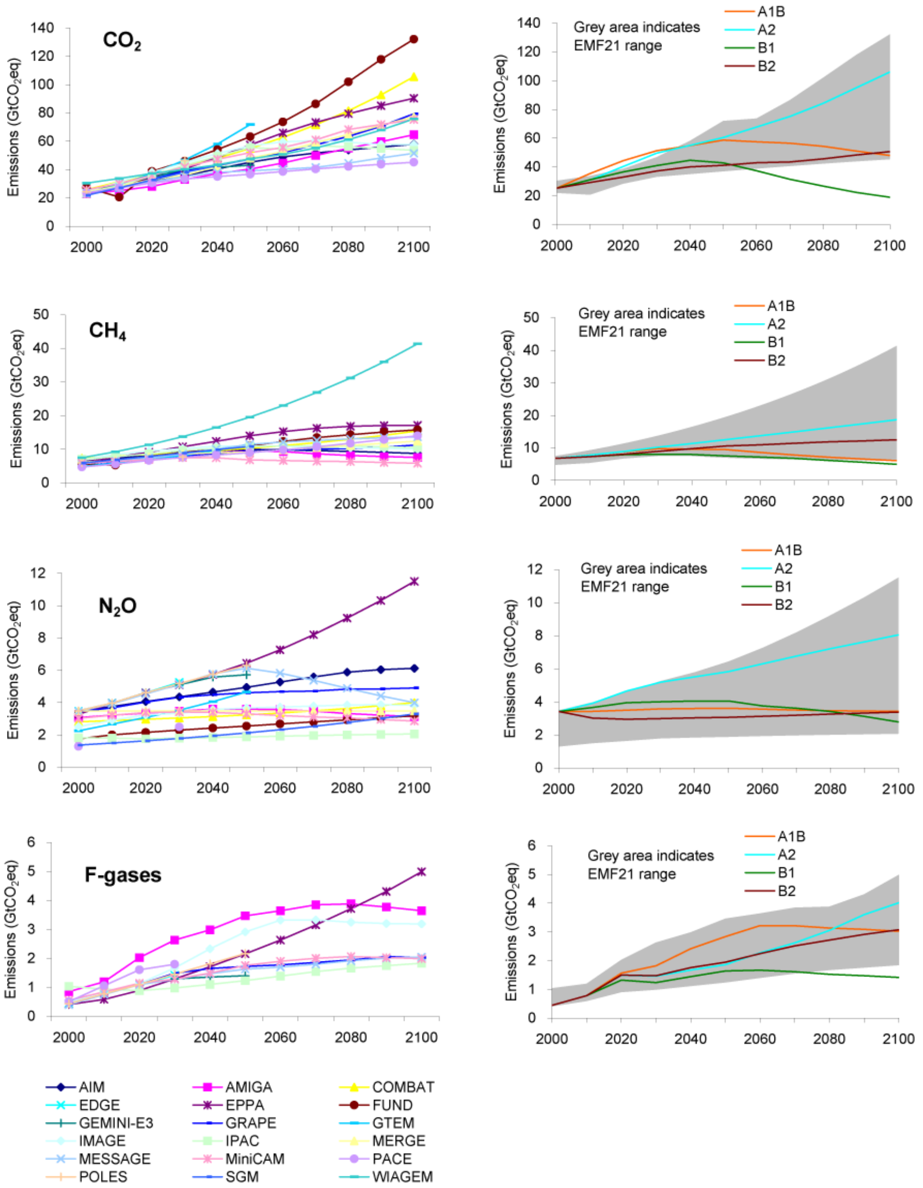
[33] 1 Gigatonne (Gt) = 1 billion metric tons.

Figure 6.3 illustrates reference case emission projections for CO_2, CH_4, N_2O, and the fluorinated gases in aggregate (HFCs, PFCs, and SF_6 or “F-gases”). The emissions projections in Figure 6.3 are from the 21st Study of Stanford University’s Energy Modeling Forum on multigas mitigation (EMF-21; see de la Chesnaye and Weyant, 2006, as referenced by the IPCC (Fisher et al., 2007)). Eighteen models participated in the EMF-21 study and the emissions ranges in Figure 6.3 are representative of the literature. The broad ranges of EMF-21 emissions projections in Figure 6.3, especially for N_2O and the F-gases, illustrate the uncertainties in projecting these future emissions, which is generally consistent with the range found in SRES.

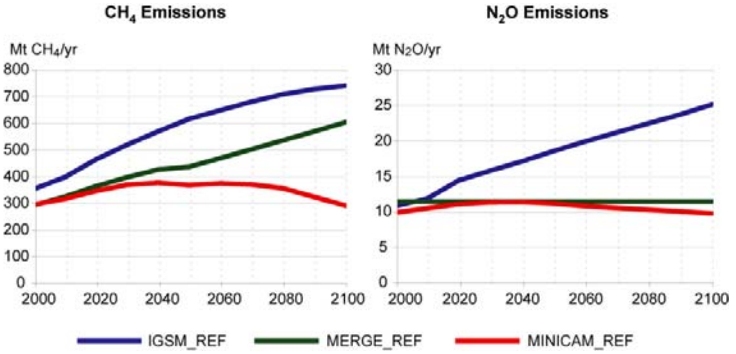
Figure 6.3: EMF-21 and IPCC Global Emissions Projections for CO_2, CH_4, N_2O, and the Fluorinated Gases



Source: CCSP (2007b). Development of baseline emissions in EMF-21 scenarios developed by a number of different modeling teams (left) and a comparison between EMF-21 and SRES scenarios (right) from DelaChesnaye and Weyant (2006), see also Van Vuuren et al. (2006b).

For comparison, Figure 6.4 provides the global CH_4 and N_2O projections from the three U.S. CCSP reference-case scenarios (CCSP, 2007b).

Figure 6.4 Projected Global CH_4 and N_2O Emissions across three CCSP Reference Scenarios



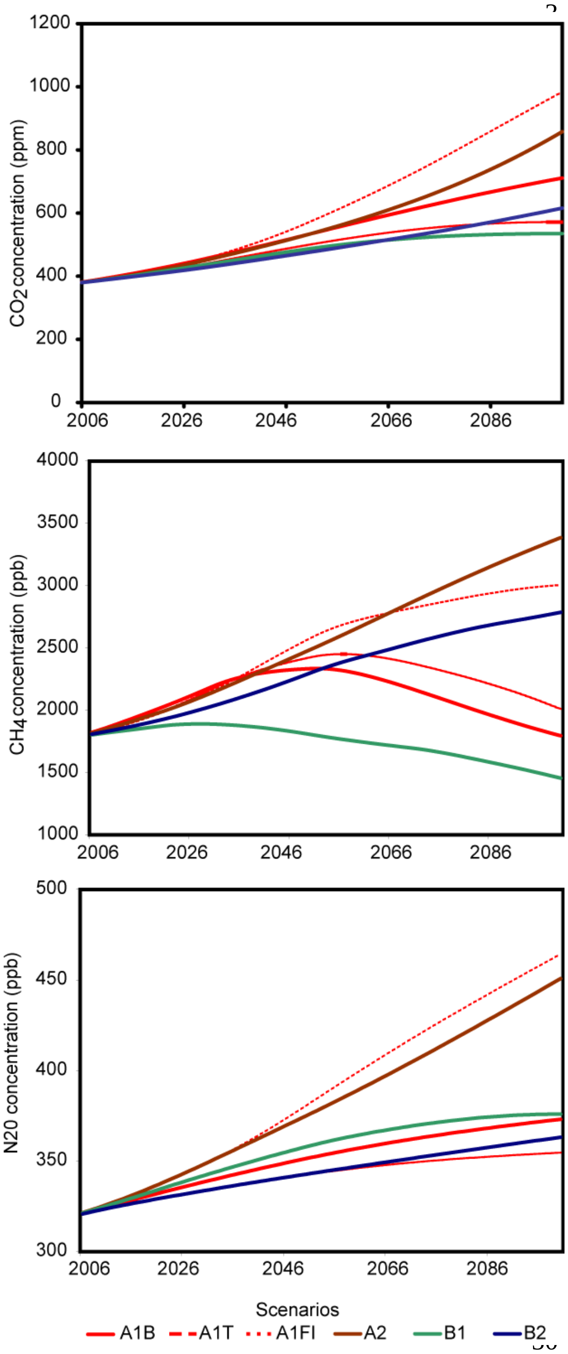
Source: CCSP (2007b). Global anthropogenic emissions of CH_4 and N_2O vary widely among the reference scenarios. There is uncertainty in year 2000 CH_4 emissions, with MIT's IGSM reference scenario ascribing more of the emissions to human activity and less to natural sources. Differences in scenarios reflect, to a large extent, different assumptions about whether current emissions rates will be reduced significantly for other reasons, for example, whether higher natural gas prices will stimulate capture of CH_4 for use as a fuel.

Future Concentration and Radiative Forcing Changes

Figure 6.5 shows the latest IPCC projected increases in atmospheric CO_2, CH_4 and N_2O concentrations for the SRES scenarios, and Figure 6.6 shows the associated radiative forcing for these CO_2 scenarios. In general, reference concentrations of CO_2 and other GHGs are projected to increase. Due to the stock nature of the atmosphere, long-lived gas concentrations increase even for those scenarios where annual emissions toward the end of the century are assumed to be lower than current annual emissions. The CCSP scenarios show a similar picture of how atmospheric concentrations of the main GHGs and total radiative forcing change over time.

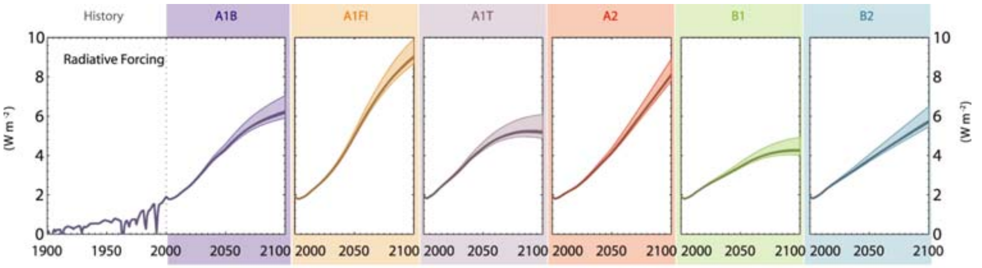
Carbon dioxide is projected to be the largest contributor to total radiative forcing in all periods and the radiative forcing associated with CO_2 is projected to be the fastest growing. The radiative forcing associated with the non-CO_2 GHGs is still significant and growing over time.

Figure 6.5 Projected Global CO_2, CH_4 and N_2O Concentrations for the IPCC SRES Scenarios



Source: Meehl et al. (2007). Projected fossil CO_2, CH_4, and N_2O concentrations for six illustrative SRES non-mitigation emission scenarios as produced by a simple climate model tuned to 19 atmosphere-ocean general circulations models (AOGCMs).

Figure 6.6 Projected Radiative Forcing from CO_2 for the IPCC SRES Scenarios



Source: Meehl et al. (2007). Projected radiative forcing from CO_2 for six illustrative SRES non-mitigation emission scenarios as produced by a simple climate model tuned to 19 AOGCMs. The lighter shaded areas depict the change in this uncertainty range, if carbon cycle feedbacks are assumed to be lower or higher than in the medium setting.

6(b) Projected changes in global temperature, precipitation patterns and sea level rise

Using the emissions scenarios described in Section 6(a), computer models project future changes in temperature, precipitation and sea level at global and regional scales. According to the IPCC (Meehl at al., 2007):

“[C]onfidence in models comes from their physical basis, and their skill in representing observed climate and past climate changes. Models have proven to be extremely important tools for simulating and understanding climate, and there is considerable confidence that they are able to provide credible quantitative estimates of future climate change, particularly at larger scales. Models continue to have significant limitations, such as in their representation of clouds, which lead to uncertainties in the magnitude and timing, as well as regional details, of predicted climate change. Nevertheless, over several decades of model development, they have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases.”[34]

Confidence decreases in changes projected by global models at smaller scales. Many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features (Randall et al., 2007[35]). Some of the most challenging aspects of understanding and projecting regional climate changes relate to possible changes in the circulation of the atmosphere and oceans, and their patterns of variability (Christensen et al., 2007[36]). Nonetheless, the IPCC (2007d) concluded that recent advances in regional-scale modeling lead to higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and of ice.

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[34] A number of climate models are developed and run at academic institutions and government supported research laboratories in the U.S. and other countries. The IPCC helps coordinate modeling efforts to facilitate comparisons across models, and synthesizes results published by several modeling teams.

[35] Randall et al., 2007 refers to Chapter 8, “Climate Models and Their Evaluation” in IPCC’s 2007 Fourth Assessment Report, Working Group I.

[36] Christensen et al., 2007 refers to Chapter 11, “Regional Climate Projections” in IPCC’s 2007 Fourth Assessment Report, Working Group I.

The CCSP (2008c) report "Climate Models: An Assessment of Strengths and Limitations" finds that models "have been steadily improving over the past several decades","show many consistent features in their simulations and projections for the future", and "are able to simulate the recorded 20th Century global mean temperature in a plausible way" . However, it cautions that projections of precipitation in some cases remain "problematic" (especially at the regional scale) and that "uncertainties in the climatic effects of manmade aerosols (liquid and solid particles suspended in the atmosphere) constitute a major stumbling block" in certain modeling experiments. It adds "uncertainties related to clouds increase the difficulty in simulating the climatic effects of aerosols, since these aerosols are known to interact with clouds and potentially can change cloud radiative properties and cloud cover."

Global Temperature

The latest IPCC assessment uses a larger number of simulations available from a broader range of models to project future climate relative to earlier assessments (IPCC, 2007d). All of the simulations performed by the IPCC project warming, for the full range of emissions scenarios.

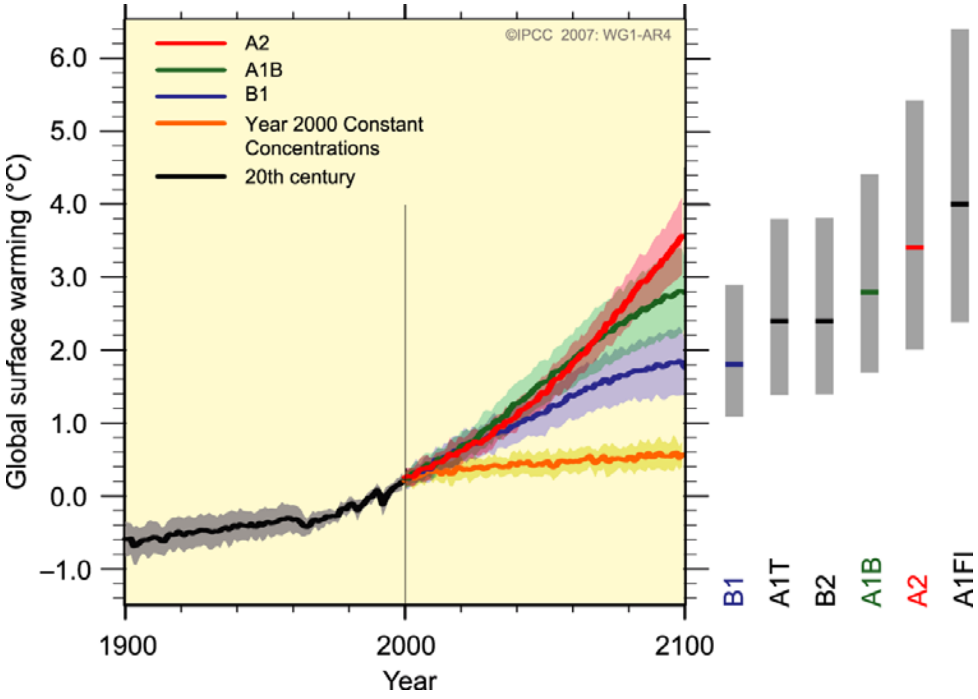
For the next two decades, a warming of about 0.2°C (0.36°F) per decade is projected for a range of SRES emission scenarios (IPCC, 2007d). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels (see the "Year 2000 Constant Concentrations" scenario in Figure 6.8), a further warming of about 0.1°C (0.18°F) per decade would be expected because of the time it takes for the climate system, particularly the oceans, to reach equilibrium (with year 2000 greenhouse gas levels). Through about 2030, the warming rate is mostly insensitive to choices between the A2, A1B, or B1 scenarios, and is consistent with that observed for the past few decades. Possible future variations in natural forcings (e.g., a large volcanic eruption) could change these values somewhat (Meehl et al., 2007). Large changes in emissions of short-lived gases could also have a near-term effect on temperatures, especially on the regional scale (CCSP, 2008d).

According to IPCC (see Figure 6.8), by mid-century (2046–2065), the choice of scenario becomes more important for the magnitude of the projected warming, with average values of 1.3°C (2.3°F), 1.8°C (3.2°F) and 1.7°C (3.1°F) from the models for scenarios B1 (low emissions growth), A1B (medium emissions growth) and A2 (high emissions growth), respectively (Meehl et al., 2007). About a third of that warming is projected to be due to climate change that is already committed (as shown in the "Year 2000 Constant Concentrations" scenario). By the 2090-2099 period (relative to the 1980-1999 range), projected warming varies significantly by emissions scenario. The full suite of SRES scenarios (given below) provides a warming range of 1.8°C to 4.0°C (3.2°F to 7.2°F) with an uncertainty range of 1.1°C to 6.4°C (2.0°F to 11.5°F). The multi-model average warming and associated uncertainty ranges for the 2090-2099 period (relative to 1980-1999) for each scenario, as illustrated in Figure 6.8 are:

Scenario	**Average Global Warming by End of Century Relative to ~1990**	**Uncertainty Range**
B1	1.8°C (3.2°F)	1.1°C to 2.9°C (2.0°F to 5.2°F)
A1T	2.4°C (4.3°F)	1.4°C to 3.8°C (2.5°F to 5.7°F)
B2	2.4°C (4.3°F)	1.4°C to 3.8°C (2.5°F to 5.7°F)
A1B	2.8°C (5.0°F)	1.7°C to 4.4°C (3.1°F to 7.9°F)
A2	3.4°C (6.1°F)	2.0°C to 5.4°C (3.6°F to 9.7°F)
A1FI	+4.0°C (+7.2°F)	2.4°C to 6.4°C (4.3°F to 11.5°F)

The wide range of uncertainty in these estimates reflects the different assumptions about future concentrations of greenhouse gases and aerosols in the various scenarios considered by the IPCC and the differing climate sensitivities of the various climate models used in the simulations (NRC, 2001a).

Figure 6.8 Multi-Model Averages and Assessed Ranges for Surface Warming



Source: IPCC (2007d). Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

Box 6.3: Climate Sensitivity

The sensitivity of the climate system to a forcing is commonly expressed in terms of the global mean temperature change that would be expected after a time sufficiently long for both the atmosphere and ocean to come to equilibrium with the change in climate forcing (NRC, 2001). Since IPCC's Third Assessment Report (IPCC, 2001b), the levels of scientific understanding and confidence in quantitative estimates of equilibrium climate sensitivity have increased substantially (Meehl et al. 2007).

Solomon et al. (2007) indicate there is increased confidence of key processes that are important to climate sensitivity due to improved comparisons of models to one another and to observations. Water vapor changes dominate the feedbacks affecting climate sensitivity and are now better understood. Observational and model evidence support a combined water vapor-lapse rate (the rate at which air temperature decreases with altitude) feedback that corresponds to about a 50% amplification of global mean warming. Cloud feedbacks remain the largest source of uncertainty.

Basing their assessment on a combination of several independent lines of evidence, including observed climate change and the strength of known feedbacks simulated in general circulation models, the authors concluded that the global mean equilibrium warming for doubling CO_2 (a concentration of approximately 540 ppm), or 'equilibrium climate sensitivity', very likely greater than 1.5°C (2.7°F) and likely to lie in the range 2°C to 4.5°C (3.6°F to 8.1°F), with a most likely value of about 3°C (5.4°F). For fundamental physical reasons, as well as data limitations, the IPCC states a climate sensitivity higher than 4.5°C cannot be ruled out, but that agreement for these values with observations and proxy data is generally worse compared to values in the 2-4.5°C range (Meehl et al., 2007).

Stated and implied IPCC Climate Sensitivity Probabilities

Less than 1.5°C	10% or less probability (stated)
Less than 2.0°C	5-17% probability (implied)
2°C to 4.5°C	66-90% probability (stated)
Greater than 4.5°C	5-17% probability (implied)

Geographical patterns of projected warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and less warming over the southern oceans and North Atlantic, consistent with observations (see Section 4b) during the latter part of the 20th century (Meehl et al., 2007).

Global Precipitation

Models simulate that global mean precipitation increases with global warming (Meehl et al., 2007). However, there are substantial spatial and seasonal variations. Increases in the amount of precipitation are *very likely* in high latitudes, while decreases are *likely* in most subtropical land regions, continuing observed patterns in recent trends in observations.

Global Sea Level Rise

By the end of the century (2090-2099), sea level is projected by IPCC (2007d) to rise between 0.18 and 0.59 meters relative to the base period (1980-1999). These numbers represent the lowest and highest projections of the 5 to 95% ranges for all SRES scenarios considered collectively and include neither uncertainty in carbon cycle feedbacks nor rapid dynamical changes in ice sheet flow. In all scenarios, the average rate of sea level rise during the 21st century very likely exceeds the 1961 to 2003 average rate (1.8 ± 0.5 mm per year). Even if greenhouse gas concentrations were to be stabilized, sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks (IPCC, 2007d). Thermal expansion of ocean water contributes 70 to 75% of the central estimate for the rise in sea level for all scenarios (Meehl et al., 2007). Glaciers, ice caps and the Greenland Ice Sheet are also projected to add to sea level. The IPCC projects a range of sea level rise contributions from all glaciers, ice caps, and ice sheets between 0.04 meters to 0.23 meters, not including the possibility of rapid dynamical changes (Meehl et al., 2007). The Antarctic ice sheet is estimated to be a negative contributor to sea level rise over the next century under these assumptions.

General Circulation Models indicate that the Antarctic Ice Sheet will receive increased snowfall without experiencing substantial surface melting, thus gaining mass and reducing sea level rise according to IPCC (Meehl et al., 2007). However, Meehl et al. (2007) note further accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets, a possibility not reflected in the projections above. For example, if ice discharge from these processes were to increase in proportion to global average surface temperature change, it would add 0.1 to 0.2 m to the upper bound of sea level rise by 2090 to 2099. Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise.

In the CCSP (2008a) report on abrupt climate change, Clark et al. (2008) find, “Recent rapid changes at the edges of the Greenland and West Antarctic ice sheets show acceleration of flow and thinning, with the velocity of some glaciers increasing more than twofold.” They add, “Inclusion of these processes in models will likely lead to sea-level projections for the end of the 21st century that substantially exceed the projections presented in the IPCC AR4 report.”

The CCSP (2009a) sea level rise report notes, “It has been suggested by Rahmstorf (2007) and other climate scientists that a global sea-level rise of 1 m (3 ft) is plausible within this century if increased melting of ice sheets in Greenland and Antarctica is added to the factors included in the IPCC estimates. Therefore, thoughtful precaution suggests that a global sea-level rise of 1m to the year 2100 should be considered for future planning and policy discussions.”

The CCSP (2008c) report on the strengths and limitations of models notes that models of glacial ice are "in their infancy" and that "recent evidence for rapid variations in this glacial outflow indicates that more-realistic glacial models are needed to estimate the evolution of future sea level."

Sea level rise during the 21st century is projected by IPCC to have substantial geographic variability due to factors that influence changes at the regional scale, including changes in ocean circulation or atmospheric pressure, and geologic processes (Meehl et al., 2007). The patterns in different models are not generally similar in detail, but have some common features, including smaller than average sea level rise in the Southern Ocean, larger than average sea level rise in the Arctic, and a narrow band of pronounced sea level rise stretching across the southern Atlantic and Indian Oceans.

6(c) Projected changes in U.S. temperature, precipitation patterns, and sea level rise

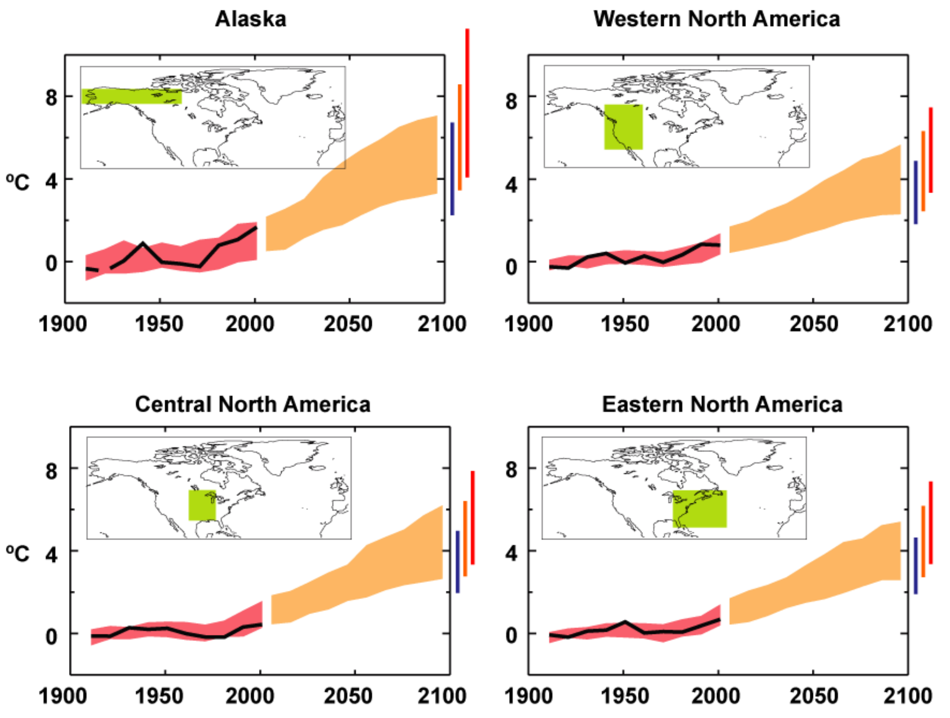
IPCC's Fourth Assessment Report includes projections for changes in temperature, precipitation and sea level rise for North America -- which can be generalized for the U.S – as well as some U.S. specific information. These projections are summarized in this section.

U.S. Temperatures

According to the IPCC, all of North America is very likely to warm during this century as shown in Figures in 6.9 and 6.10, and warm more than the global mean warming in most areas (Christensen et al., 2007). For scenario A1B (moderate emissions growth), the largest warming through 2100 is projected to occur in winter over northern parts of Alaska, reaching 7-10°C (13-18°F) in the northernmost parts as shown in Figure 6.10, due to the positive feedback from a shorter season of snow cover. In western, central and eastern regions of North America, the projected warming has less seasonal variation and is not as large, especially near the coast, consistent with less warming over the oceans. The average warming in the U.S. through 2100 is projected by nearly all the models used in the IPCC assessment to exceed 2°C (3.6°F), with 5 out of 21 models projecting average warming in excess of 4°C (7.2°F) for the A1B emissions scenario.

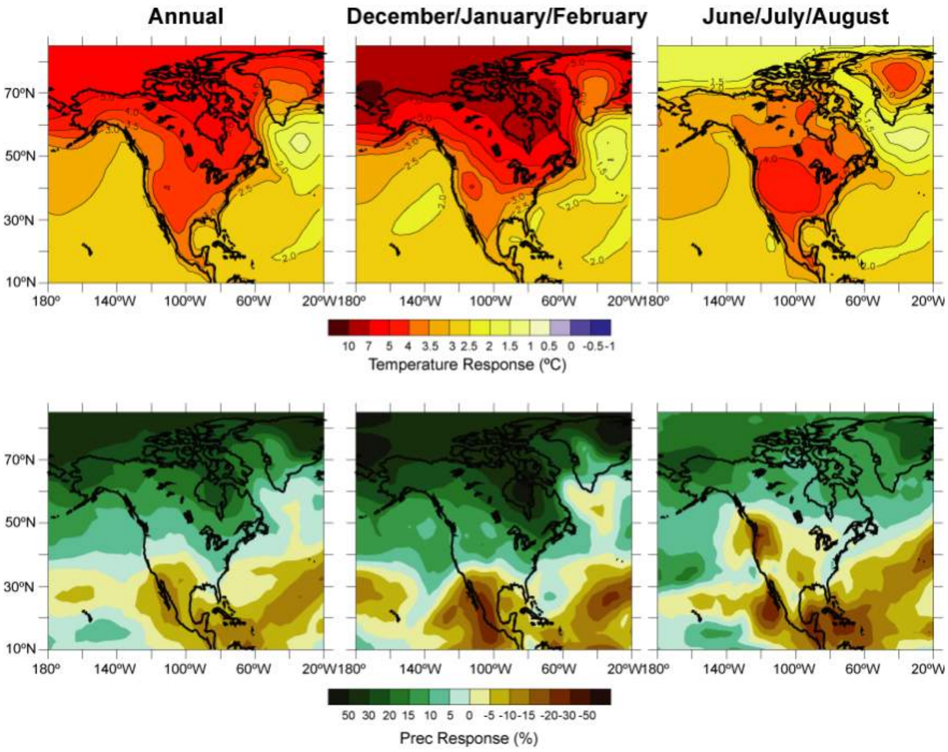
The CCSP (2008e) report "The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity" provides shorter-term temperature projections for the U.S. for the year 2030. It projects temperature a warming of approximately 1°C in the southeastern U.S., to more than 2°C in Alaska and northern Canada, with other parts of North America having intermediate values (Backlund et al., 2008b).

Figure 6.9: Temperature anomalies with respect to 1901 to 1950 for four North American land regions



Source: Christensen et al. (2007). Temperature anomalies with respect to 1901 to 1950 for four North American land regions for 1906 to 2005 (black line) and as simulated (red envelope) by multi-model dataset (MMD) models incorporating known forcings; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are present for less than 50% of the area in the decade concerned.

Figure 6.10: Projected temperature and precipitation changes over North America from the MMD-A1B simulations.



Source: Christensen et al. (2007). Top row: Annual mean, December-January-February, and June-July-August temperature between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: same as top, but for fractional change in precipitation.

U.S. Precipitation

A widespread increase in annual precipitation is projected by IPCC over most of the North American continent except the south and south-western part of the U.S. and over Mexico largely consistent with trends in recent decades (as described in Section 4) (Christensen et al., 2007). The largest increases are projected over northern North America (i.e. Canada and Alaska) associated with a poleward shift in storm tracks where precipitation increases by the largest amount in autumn and by the largest fraction in winter as shown in Figure 6.10. In western North America, modest changes in annual mean precipitation are projected, but the majority of models indicate an increase in winter and a decrease in summer. Models show greater consensus on winter increases to the north and on summer decreases to the south. These decreases are consistent with enhanced subsidence and flow of drier air masses in the southwest U.S. and northern Mexico. Accordingly, some models project drying in the southwest U.S., with more than 90% of the models projecting drying in northern and particularly western Mexico. On the windward slopes of the mountains in the west, precipitation increases are likely to be enhanced due to orographic lifting[37]. In the northeastern U.S., annual mean precipitation is very likely to increase.

U.S. Sea Level Rise

For North American coasts, emissions scenario A1B shows sea level rise values close to the global mean, with slightly higher rates in eastern Canada and western Alaska, and stronger positive anomalies in the Arctic. The projected rate of sea level rise off the low-lying U.S. South Atlantic and Gulf coasts is also higher than the global average. Vertical land motion from geologic processes may decrease (uplift) or increase (subsidence) the relative sea level rise at any site (Nicholls et al., 2007).

Impact of short-lived species on U.S. Temperature and Precipitation

Modeling results suggest that changes in short-lived species (mainly sulfates and black carbon) may significantly influence 21st century climate. A GFDL simulation of SRES scenario A1B shows that changes in short lived species could be responsible for up to 1.5°C (2.7°F) of the 4°C (7.2°F) of U.S. summertime warming projected to occur in this scenario by 2100, mainly due to a combination of domestic sulfate emissions reductions and increases in Asian black carbon emissions (CCSP, 2008d). However, the CCSP study concludes that "we could not find a consensus in this report on the duration, magnitude, or even sign (warming or cooling) of the climate change due to future levels of the short-lived gases and particles" due to uncertainties about different pollution control storylines.

6(d) Cryosphere (Snow and Ice) projections, focusing on North America and the U.S.

Snow season length and snow depth are very likely to decrease in most of North America as illustrated in Figure 6.11, except in the northernmost part of Canada where maximum snow depth is likely to increase (Christensen et al., 2007). Widespread increases in thaw depth are projected over most permafrost regions globally (IPCC, 2007d).

Lettenmaier et al. (2008) find where shifts to earlier snowmelt peaks and reduced summer and fall low flows have already been detected, continuing shifts in this direction are very likely.

Meehl et al (2007) conclude that as the climate warms, glaciers will lose mass owing to dominance of summer melting over winter precipitation increases, contributing to sea level rise.

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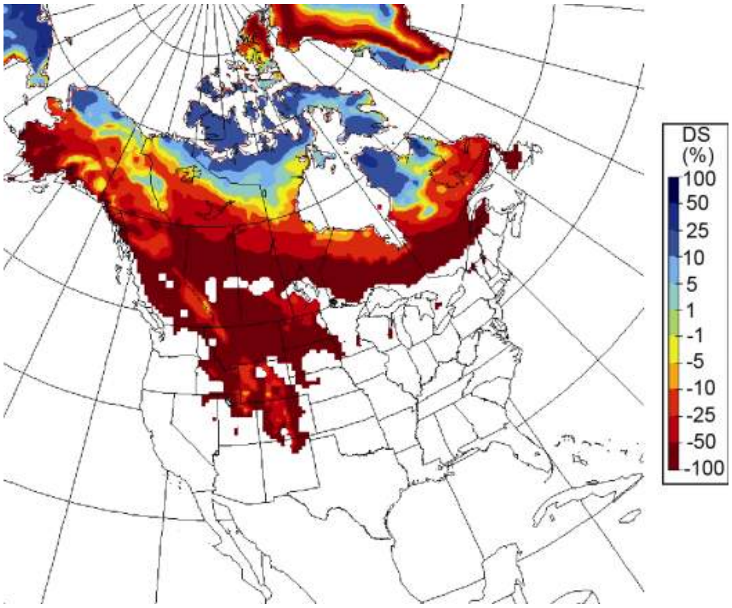
[37] Orographic lifting is defined as the ascent of air from a lower elevation to a higher elevation as it moves over rising terrain

Sea ice is projected to shrink in both the Arctic and the Antarctic under all SRES scenarios (IPCC, 2007d). In some projections, Arctic late-summer sea ice disappears almost entirely by the latter part of the 21st century.

6(e) Extreme events, focusing on North America and the U.S.

Models suggest that the human-induced climate change is expected to alter the prevalence and severity of many extreme events such as heat waves, cold waves, storms, floods, and droughts. This section describes CCSP (2008i) and IPCC's projections for extreme events focusing on North America and the U.S. Sections 7-14 summarize some of the sectoral impacts of extreme events for the U.S.

Figure 6.11 Percent Snow Depth Changes in March



Source: Christensen et al. (2007). Percent snow depth changes in March (only calculated where climatological snow amounts exceed 5mm of water equivalent), as projected by the Canadian Regional Climate Model (CCRM; Plummer et al., 2006), driven by the Canadian General Circulation Model (CGCM), for 2041 to 2070 under SRES A2 compared to 1961 to 1990.

Temperature

According to the IPCC, it is very likely that heat waves will become more intense, more frequent, and longer lasting in a future warm climate, whereas cold episodes are projected to decrease significantly. (Meehl, G.A. et al., 2007). Meehl and Tebaldi (2004; in Meehl et al., 2007) find that the pattern of future changes in heat waves, with greatest intensity increases over western Europe, the Mediterranean and the southeast and western U.S., is related in part to circulation changes resulting from an increase in greenhouse gases.

The IPCC cites a number of studies that project changes in temperature extremes in the U.S. (Christensen et al., 2007). Diffenbaugh et al. (2005) find that the frequency and the magnitude of extreme temperature events changes dramatically under a high-end emission scenario (SRES A2), with increases in extreme hot events and decreases in extreme cold events. Bell et al. (2004; in Christensen et al., 2007) examine changes in temperature extremes in their simulations centered on California and find increases in extreme temperature events, prolonged hot spells and increased diurnal temperature range. Leung et al. (2004; in Christensen et al., 2007) find increases in diurnal temperature range in six-subregions of the western U.S. in summer.

Karl et al. (2008) find for a mid-range scenario of future GHG emissions, a day so hot that it is currently experienced only once every 20 years would occur every three years by the middle of the century over much of the continental U.S. and by the end of the century, it would occur every other year or more.

Some implications for human health resulting from these projected changes in temperature extremes are discussed in Section 7(b).

Precipitation and Storms

Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation (Meehl, G.A. et al., 2007). Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. Meehl et al. (2007) note that increases in heavy precipitation events have been linked to increases in flooding.

The IPCC projects a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in those regions (Meehl et al., 2007). Extreme drought increases from 1% of present-day land area to 30% by the end of the century in the A2 (high emissions growth) scenario (Burke et al., 2006 in Meehl et al., 2007). Karl et al. (2008) indicate that for a mid-range emission scenario, daily precipitation so heavy that it now occurs only once every 20 years is projected to occur approximately every eight years by the end of this century over much of Eastern North America.

Future projections in Gutowski et al. (2008) indicate strong mid-latitude (or extratropical) storms will be more frequent though the overall number of storms may decrease.

Several regional studies in the IPCC project changes in precipitation extremes in parts of the U.S ranging from a decrease in heavy precipitation in California (Bell et al., 2004 in Christensen et al., 2007) to an increase during winter in the northern Rockies, Cascades and Sierra Nevada mountain ranges (Leung et al., 2005 in Christensen et al., 2007). For the contiguous U.S., Diffenbaugh et al. (2005 in Christensen et al., 2007) find widespread increases in extreme precipitation events under SRES A2 (high emissions growth).

Based on a range of models, it is likely that tropical cyclones (tropical storms and hurricanes) will become more intense, with stronger peak winds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures (IPCC, 2007d). Karl et al. (2008) analyze model simulations and find that for each 1ºC (1.8ºF) increase in tropical sea surface temperatures, core rainfall rates will increase by 6-18% and the surface wind speeds of the strongest hurricanes will increase by about 1-8%. Storm surge levels are likely to increase due to projected sea level rise, but note the degree of projected increase has not been adequately studied.

Karl et al. (2008) indicate projections in frequency changes in tropical cyclones are currently too uncertain for confident projections. Some modeling studies have projected a decrease in the number of tropical cyclones globally due to increased stability of the tropical atmosphere in a warmer climate, characterized by fewer weak storms and greater numbers of intense storms (Meehl et al., 2000). A number of modeling studies have also projected a general tendency for more intense but fewer storms outside the tropics, with a tendency towards more extreme wind events and higher ocean waves in several regions associated with these deepened cyclones (Meehl et al., 2007).

Possible implications of extreme precipitation events in the U.S. for health are described in Chapter 7, for food production and agriculture in Section 9, for water resources in Section 11, for coastal areas in Section 12, and for ecosystems and wildlife in Section 14.

6(f) Abrupt Climate Change

CCSP (2008a), in its report on abrupt climate change, defines it as 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." Abrupt climate changes are an important consideration because, if triggered, they could occur so quickly and unexpectedly that human or natural systems would have difficulty adapting to them (NRC, 2002). Potential abrupt climate change implications in the U.S. are not discussed in the sections 7 through 14 (the U.S. sectoral impacts) because they cannot be predicted with confidence, particularly for specific regions. This section therefore focuses on the general risks of abrupt climate change globally, with some discussion of potential regional implications where information is available.

According to the National Research Council (2002): "Technically, an abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause." Crossing systemic thresholds may lead to large and widespread consequences (Schneider et al., 2007[38]). The triggers for abrupt climate change can be forces that are external and/or internal to the climate system including (NRC, 2002):

- changes in the Earth's orbit[39]
- a brightening or dimming of the sun
- melting or surging ice sheets
- strengthening or weakening of ocean currents
- emissions of climate-altering gases and particles into the atmosphere

More than one of these triggers can operate simultaneously, since all components of the climate system are linked.

Scientific data show that abrupt changes in the climate at the regional scale have occurred throughout history and are characteristic of the Earth's climate system (NRC, 2002). During the last glacial period, abrupt regional warmings (8 to 16°C within decades over Greenland) and coolings occurred repeatedly over the North Atlantic region (Jansen et al., 2007[40]). These warmings likely had some large-scale effects such as major shifts in tropical rainfall patterns and redistribution of heat within the climate system but it is unlikely that they were associated with large changes in global mean surface temperature.

The National Research Council concluded that anthropogenic forcing may increase the risk of abrupt climate change (NRC, 2002):
"…greenhouse warming and other human alterations of the Earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events. The abrupt changes of the past are not fully explained yet, and climate models typically underestimate the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected."

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[38] Schneider et al., 2007 citation refers to Chapter 19, "Assessing key vulnerabilities and the risk from climate change" in IPCC's 2007 Fourth Assessment Report, Working Group II.

[39] According to the National Research Council (2002), changes in the Earth's orbit occur too slowly to be prime movers of abrupt change but might determine the timing of events. Abrupt climate changes of the past were especially prominent when orbital processes were forcing the climate to change during the cooling into and warming out of ice ages (NRC, 2002).

[40] Jansen et al., 2007 refers to Chapter 6, "Palaeoclimate" in IPCC's 2007 Fourth Assessment Report, Working Group I.

Changes in weather patterns (sometimes referred to as weather regimes or natural modes) can result from abrupt changes that might occur spontaneously due to dynamical interactions in the atmosphere-ice-ocean system, or from the crossing of a threshold from slow external forcing (as described above) (Meehl et al., 2007). In a warming climate, changes in the frequency and amplitudes of these patterns might not only evolve rapidly, but also trigger other processes that lead to abrupt climate change (NRC, 2002). Examples of these patterns include the El Niño Southern Oscillation (ENSO)[41] and the North Atlantic Oscillation/Arctic Oscillation (NAO/OA). [42]

ENSO has important linkages to patterns of tropical sea surface temperatures, which historically have been strongly tied to drought, including "megadroughts" that likely occurred between 900-1600 A.D. (Clark et al., 2008). The possibility of severe drought as an abrupt change resulting from changes in sea surface temperatures in a warming world is assessed by Clark et al. (2008). They find that under greenhouse warming scenarios, the cause of model-projected sub-tropical drying is an overall widespread warming of the ocean and atmosphere, in contrast to the causes of historic droughts (linked specifically to sea surface temperature). But they note models may not correctly represent the ENSO patterns of tropical SST change that could create impacts on global hydroclimate (e.g., drought) in addition to those caused by overall warming. The current model results do show drying over the southwestern U.S., potentially increasing the likelihood of severe and persistent drought there in the future. Clark et al. note this drying has already begun (see also section 4k) but caution it is not clear if the present drying is outside the range of natural variability and linked to anthropogenic causes.

Scientists have investigated the possibility of an abrupt slowdown or shutdown of the Atlantic meridional overturning circulation (MOC) triggered by greenhouse gas forcing. The MOC transfers large quantities of heat to the North Atlantic and Europe so an abrupt change in the MOC could have important implications for the climate of this region (Meehl et al., 2007). However, according to Meehl et al. (2007), the probability of an abrupt change in (or shutdown of) the MOC is low: "It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Even further into the future, Clark et al. (2008) note "it is unlikely that the Atlantic MOC will collapse beyond the end of the 21st century because of global warming, although the possibility cannot be entirely excluded." While models project a slowdown in the MOC over the 21st century and beyond, it is so gradual that the resulting decrease in heat transport to the North Atlantic and Europe would not be large enough to reverse the warming that results from the increase in GHGs (Clark et al., 2008). Clark et al. (2008) do caution that while a collapse of the MOC is unlikely, the potential consequences of this event could be severe if it were to happen. Potential impacts include a southward shift of the tropical rainfall belts, additional sea level rise around the North Atlantic, and disruptions to marine ecosystems.

The rapid disintegration of the Greenland Ice Sheet (GIS), which would raise sea levels 7 meters, is another commonly discussed abrupt change. Clark et al. (2008) report that observations demonstrate that it is extremely likely that the Greenland Ice Sheet is losing mass and that this has very likely been

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[41] ENSO describes the full range of the Southern Oscillation (see-saw of atmospheric mass or pressure between the Pacific and Indo-Australian areas) that includes both sea surface temperature (SST) increases as well as SST decreases when compared to a long-term average. It has sometimes been used by scientists to relate only to the broader view of El Niño or the warm events, the warming of SSTs in the central and eastern equatorial Pacific. The acronym, ENSO, is composed of El Niño-Southern Oscillation, where El Niño is the oceanic component and the Southern Oscillation is the atmospheric component of the phenomenon.

[42] The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia. The NAO is a large scale seesaw in atmospheric mass or pressure between the subtropical high and the polar low. Similarly, the Arctic Oscillation (AO) refers to opposing atmospheric pressure patterns in northern middle and high latitudes. The NAO and AO are different ways of describing the same phenomenon.

accelerating since the mid-1990s. In the CCSP (2009b) report "Past Climate Variability and Change in the Arctic and at High Latitudes", Alley et al. (2009) find a threshold for ice-sheet removal from sustained summertime warming of 5°C, with a range of uncertainties from 2° to 7°C. Meehl et al. (2007) in IPCC suggest the complete melting of the GIS would only require sustained warming in the range of 1.9°C to 4.6°C (relative to the pre-industrial temperatures) but suggest it would take many hundreds of years to complete.

A collapse of the West Antarctic Ice Sheet (WAIS), which would raise seas 5-6 meters, has been discussed as a low probability, high impact response to global warming (NRC, 2002; Meehl et al., 2007). The weakening or collapse of ice shelves, caused by melting on the surface or by melting at the bottom by a warmer ocean, might contribute to a potential destabilization of the WAIS. Recent satellite and in situ observations of ice streams behind disintegrating ice shelves highlight some rapid reactions of ice sheet systems (Lemke et al., 2007). Clark et al. (2008) indicate that while ice is thickening over some higher elevation regions of Antarctica, substantial ice losses from West Antarctica and the Antarctic Peninsula are very likely occurring and that Antarctica is losing ice on the whole. Ice sheet models are only beginning to capture the small-scale dynamical processes that involve complicated interactions with the glacier bed and the ocean at the perimeter of the ice sheet (Meehl et al., 2007). These processes are not represented in the models used by IPCC to project sea level rise which suggest Antarctica will gain mass due to the likelihood of increasing snowfall, (although recent studies find no significant continent-wide trends in accumulation over the past several decades; Lemke et al., 2007), reducing sea level rise. But it is possible that acceleration of ice discharge could become dominant, causing a net positive contribution. Given these competing factors, there is presently no consensus on the long-term future of the WAIS or its contribution to sea level rise (Meehl et al., 2007).

Considering the Greenland and West Antarctic ice sheets together, Schneider et al. (2007) find paleoclimatic evidence suggests that Greenland and possibly the WAIS contributed to a sea-level rise of 4-6 meters during the last interglacial, when polar temperatures were 3-5 degrees C warmer, and the global mean was not notably warmer, than at present. Accordingly, they conclude is medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the WAIS, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4 degrees Celsius (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 meters or more.

Another potential abrupt change of concern assessed by CCSP (2008a) is the catastrophic release of methane from clathrate hydrates in the sea floor and to a lesser extent in permafrost soils. Clark et al. (2008) find the following:

- The size of the hydrate reservoir is uncertain, perhaps by up to a factor of 10 making judgments about risk difficult to assess.

- Although there are a number of suggestions in the literature about the possibility of a dramatic abrupt release of methane to the atmosphere, modeling and isotopic fingerprinting of ice-core methane do not support such a release to the atmosphere over the last 100,000 years or in the near future.

Clark et al (2008) conclude:

> "While the risk of catastrophic release of methane to the atmosphere in the next century appears very unlikely, it is very likely that climate change will accelerate the pace of persistent emissions from both hydrate sources and wetlands. Current models suggest that wetland emissions could double in the next century. However, since these models do not realistically represent all the processes thought to be relevant to future northern high-latitude CH_4 emissions, much larger (or smaller) increases

> cannot be discounted. Acceleration of persistent release from hydrate reservoirs is likely, but its magnitude is difficult to estimate."

6(g) Effects on/from Stratospheric Ozone

Substances that deplete stratospheric ozone, which protects the Earth's surface from much of the sun's biologically harmful ultraviolet radiation, are regulated under Title VI of the Clean Air Act. According to the World Meteorological Organization (2007), climate change that results from changing greenhouse gas concentrations will affect the evolution of the ozone layer through changes in chemical transport, atmospheric composition, and temperature. In turn, changes in the stratospheric ozone can have implications for the weather and climate of the troposphere. The coupled interactions between the changing climate and ozone layer are complex and scientific understanding is incomplete (WMO, 2007). Specific information on climate change effects on/from stratospheric ozone in the U.S. has not been assessed. Except where indicated, the findings in this section apply generally to the globe with a focus on polar regions.

Effects of Elevated Greenhouse Gas Concentrations on Stratospheric Ozone

The World Meteorological Organization's (WMO) 2006 Scientific Assessment of Ozone Depletion (2007) concluded that future concentrations of stratospheric ozone are sensitive to future levels of the well-mixed greenhouse gases. According to the WMO (2007):

- Future increases of greenhouse gas concentrations, primarily CO_2, will contribute to the average cooling in the stratosphere. Stratospheric cooling is expected to slow gas-phase ozone depletion reactions and increase ozone.
- Enhanced methane emission (from warmer and wetter soils) is expected to enhance ozone production in the lower stratosphere.
- An increase in nitrous oxide emissions is expected to reduce ozone in the middle and high stratosphere.

Two-dimensional models that include coupling between all of these well-mixed greenhouse gases and temperature project that ozone levels between 60º S and 60º N will return to 1980 values up to 15 years earlier than in models that are uncoupled (Bodeker et al., 2007[43]). The impact of stratospheric cooling on ozone might be the opposite in polar regions where cooling could cause increases in polar stratospheric clouds, which, given enough halogens, would increase ozone loss (Bodeker et al., 2007).
Concentrations of stratospheric ozone are also sensitive to stratospheric water vapor concentrations which may remain relatively constant or increase (Baldwin et al., 2007). Increases in water vapor would cause increases in hydrogen oxide (HO_x) radicals, affecting ozone loss processes (Baldwin et al., 2007). Several studies (Dvortsov and Solomon, 2001; Shindell, 2001) cited in Baldwin et al. (2007) suggest increasing stratospheric water vapor would delay ozone layer recovery. Increases in stratospheric water vapor could also increase spring-time ozone depletion in the polar regions by raising the temperature threshold for the formation of polar stratospheric clouds (WMO, 2007).

The possible effects of climate change on stratospheric ozone are further complicated by possible changes in climate dynamics. Climate change can affect temperatures, upper level winds and storm patterns which, in turn, impact planetary waves that affect the stratosphere (Baldwin et al., 2007). Changes in the

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[43] Bodeker et al., 2007 citation refers to Chapter 6, "The Ozone Layer in the 21st Century" in WMO's Scientific Assessment of Ozone Depletion, 2006.

forcing and propagation of planetary waves[44] in the polar winter are a major source of uncertainty for predicting future levels of Arctic ozone loss (Austin et al., 2003 in Baldwin et al., 2007).

The CCSP (2008h) report "Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure" includes results from two-dimensional chemistry transport models and three-dimensional climate chemistry models estimating the recovery of the ozone layer under a greenhouse gas scenario. It finds:

- From 60°N to 60°S, global ozone is expected to return to its 1980 value up to 15 years earlier than the halogen recovery date because of stratospheric cooling and changes in circulation associated with GHG emissions. Global ozone abundances are expected to be 2 percent above the 1980 values by 2100 with values at mid-latitudes as much as 5 percent higher.

- Model simulations show that the ozone amount in the Antarctic will reach the 1980 values 10 to 20 years earlier (i.e. from 2040 to 2060) than the 2060 to 2070 time frame of when the ozone-depleting substances reach their 1980 levels in polar regions.

- Most climate chemistry models show Arctic ozone values by 2050 larger than the 1980 values, with the recovery date between 2020 and 2040.

Climate Change Effects from Stratospheric Ozone

The WMO (2007) found changes to the temperature and circulation of the stratosphere affect climate and weather in the troposphere. The dominant tropospheric response, simulated in models and identified in analyses of observations, comprises changes in the strength of mid-latitude westerly winds. The mechanism for this response is not well-understood.

Modeling experiments (that simulate observed changes in stratospheric ozone and combined stratospheric ozone depletion and GHG increases) also suggest that Antarctic ozone depletion, through its effects on the lower stratospheric vortex, has contributed to the observed surface cooling over interior Antarctica and warming of the Antarctic Peninsula, particularly in summer (Baldwin et al., 2007). While the physics of these effects are not well-understood, the simulated pattern of warming and cooling is a robust result seen in many different models, and well-supported by observational studies.

As the ozone layer recovers, tropospheric changes that have occurred as a result of ozone depletion are expected to reverse (Baldwin et al., 2007).

6(h) Land-Use and Land Cover Change

Changes in land surface (vegetation, soils, water) resulting from human activities can significantly affect local climate through shifts in radiation, cloudiness, surface roughness, and surface temperature.

Solomon et al. (2007) find the impacts of land use change on climate are expected to be locally significant in some regions, but are small at the global scale in comparison with greenhouse warming. Similarly, the release of heat from anthropogenic energy production can be significant over urban areas, but is not significant globally (Solomon et al., 2007).

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[44] A planetary wave is a large horizontal atmospheric undulation that is associated with the polar-front jet stream and separates cold, polar air from warm, tropical air.

The CCSP report (2008e) on the effects of climate change on agriculture, land resources, water resources, and biodiversity in the U.S. concludes that global climate change effects will be superimposed on and modify those resulting from land use and land cover patterns in ways that are as of yet uncertain.

Part IV

U.S. Observed and Projected Human Health and Welfare Effects from Climate Change

Section 7

Human Health

Warm temperatures and extreme weather already cause and contribute to adverse human health outcomes through heat-related mortality and morbidity, storm-related fatalities and injuries, and disease. In the absence of effective adaptation, these effects are likely to increase with climate change. Depending on progress in health care and access, infrastructure, and technology, climate change could increase the risk of heat wave deaths, respiratory illness through exposure to aeroallergens and ozone (discussed in Section 8), and certain diseases (CCSP, 2008b; Confalonieri et al, 2007). Studies in temperate areas (which would include large portions of the U.S.) have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. The balance of positive and negative health impacts as a result of climate change will vary from one location to another, and will alter over time as climate change continues (CCSP, 2008b).

In its Third Assessment Report (TAR), the IPCC produced a number of key findings summarizing the likely climate change health effects in North America. These effects, which were reaffirmed in the IPCC Fourth Assessment Report (Field et al., 2007), include:

- Increased deaths, injuries, infectious diseases, and stress-related disorders and other adverse effects associated with social disruption and migration from more frequent extreme weather.
- Increased frequency and severity of heat waves leading to more illness and death, particularly among the young, elderly and frail.
- Expanded ranges of vector-borne and tick-borne diseases in North America but with moderating influence by public health measures and other factors.

The more recent CCSP (2008b) report on human health stated as one of its conclusions that, “The United States is certainly capable of adapting to the collective impacts of climate change. However, there will still be certain individuals and locations where the adaptive capacity is less and these individuals and their communities will be disproportionally impacted by climate change.”

There are few studies which address the interactive effects of multiple climate change impacts or of interactions between climate change health impacts and other kinds of local, regional, and global socio-economic changes (Field et al., 2007). For example, climate change impacts on human health in urban areas will be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an aging population (Field et al., 2007).

Vulnerability is the summation of all the factors of risk and resilience that determine whether individuals experience adverse health impacts. Specific subpopulations may experience heightened vulnerability for climate-related health effects. Climate change is very likely to accentuate the disparities already evident in the American health care systems as many of the expected health effects are likely to fall disproportionately on the poor, the elderly, the disabled, and the uninsured (Ebi et al., 2008).

This section describes the literature on the impacts of climate change on human health in four areas: direct temperature effects, extreme events, climate sensitive diseases, and aeroallergens. The health impacts resulting from climate change effects on air quality are discussed in Section 8.

7(a) Temperature Effects

According to IPCC (2007d), it is very likely[45] that there were warmer and fewer cold days and nights and warmer and more frequent hot days over most land areas during the late 20th century (see section 4(b)). It is virtually certain that these trends will continue during the 21st century (see Section 6(b)). As a result of the projected warming, the IPCC projects increases in heat-related mortality and morbidity globally (IPCC, 2007b). The projected warming is expected to result in fewer deaths due to reduced exposure to the cold. It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the U.S. due to climate change.

Increased heat exposure

Heatwaves are associated with marked short-term increases in mortality (Confalonieri et al, 2007). Hot temperatures have also been associated with increased morbidity. Increased hospital admissions for cardiovascular disease and emergency room visits have been documented in parts of North America during heat events (Schwartz et al., 2004 in Field et al., 2007). The populations most vulnerable to hot temperatures are older adults, the chronically sick, the very young, city-dwellers, those taking medications that disrupt thermoregulation, the mentally ill, those lacking access to air conditioning, those working or playing outdoors, and the socially isolated (Ebi et al., 2008; IPCC, 2007b).

Ebi et al. (2008) report statistics from the Centers for Disease Control and Prevention (CDC, 2005a) that indicate exposure to excessive natural heat caused 4,780 deaths during the period 1979 to 2002 in the U.S., and that an additional 1,203 deaths had hyperthermia reported as a contributing factor. They state these numbers are underestimates of the total mortality associated with heat waves because the person filling out the death certificate may not always list heat as a cause.

Given projections for climate warming, heat-related morbidity and mortality are projected to increase globally (including in the U.S.) compared to a future with no climate change (Confalonieri et al, 2007). Heat exposures vary widely, and current studies do not quantify the years of life lost due to high temperatures. Estimates of heat-related mortality attributable to climate change are reduced but not eliminated when assumptions about acclimatization and adaptation are included in models. There is some indication that populations in the U.S. became less sensitive to high temperatures over the period 1964 to 1988, in part, due to these factors (Davis et al., 2002; Davis et al., 2003; Davis et al., 2004 in Confalonieri et al, 2007). On the other hand, growing numbers of older adults will increase the size of the population at risk because of a decreased ability to thermo-regulate is a normal part of the aging process (Confalonieri et al, 2007). In addition, almost all the growth in population in the next 50 years is expected to occur in cities (Cohen, 2003 in Confalonieri et al, 2007) where temperatures tend to be higher due to the urban heat island[46] effect increasing the total number of people at risk of adverse health outcomes from heat. In other words, non-climatic factors related to demographics will have a significant influence on future heat-related mortality.

Across North America, the population over the age of 65 -- the segment of the population most at-risk of dying from heat waves -- will increase slowly to 2010, and then grow dramatically as the Baby Boomers age (Field et al., 2007). Severe heat waves are projected to intensify in magnitude and duration over the portions of the U.S. where these events already occur (high confidence). The IPCC documents the following U.S. regional scenario projections of increases in heat and/or heat-related effects (Confalonieri et al, 2007; Field et al., 2007):

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[45] According to IPCC terminology, “very likely” conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

[46] A heat island refers to urban air and surface temperatures that are higher than nearby rural areas. Many U.S. cities and suburbs have air temperatures up to 10°F (5.6°C) warmer than the surrounding natural land cover.

- By the 2080s, in Los Angeles, the number of heat wave days (at or above 32ºC or 90ºF) increases 4-fold under the B1 emissions scenario (low growth) and 6-8-fold under A1FI emissions scenario (high growth) (Hayhoe, 2004). Annual number of heat-related deaths in Los Angeles increases from about 165 in the 1990s to 319 to 1,182 for a range of emissions scenarios.
- Chicago is projected to experience 25% more frequent heat waves annually by the period spanning 2080-2099 for a business-as-usual (A1B) emissions scenario (Meehl and Tebaldi, 2004).

Reduced cold exposure

Cold waves continue to pose health risks in northern latitudes in temperature regions where very low temperatures can be reached in a few hours and extend over long periods (Confalonieri et al, 2007[47]). Accidental cold exposure occurs mainly outdoors, among socially deprived people (alcoholics, the homeless), workers, and the elderly in temperate and cold climates (Ranhoff, 2000 in Confalonieri et al, 2007) but cold waves also affect health in warmer climates (EM-DAT, 2006 in Confalonieri et al, 2007). Living in cold environments in polar regions is associated with a range of chronic conditions in the non-indigenous population (Sorogin, 1993 in Confalonieri et al, 2007) with acute risk from frostbite and hypothermia (Hassi et al., 2005 in Confalonieri et al, 2007). In countries with populations well-adapted to cold conditions, cold waves can still cause substantial increases in mortality if electricity or heating systems fail (Confalonieri et al, 2007).

Fallico et al. (2005 in Ebi et al., 2008) report that from 1979 to 2002, an average of 689 reported deaths per year (range 417-1,021) in the U.S., totaling 16,555 over the period, were attributed to exposure to excessive cold temperatures.

The IPCC projects reduced human mortality from cold exposure through 2100 (Confalonieri et al, 2007). It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the U.S. due to climate change. Projections of cold-related deaths, and the potential for decreasing their numbers due to warmer winters, can be overestimated unless they take into account the effects of season and influenza, which is not strongly associated with monthly winter temperature (Ebi et al., 2008; Armstrong et al., 2004 in Confalonieri et al, 2007; McMichael et al, 2001).

Aggregated changes in heat and cold exposure

IPCC (2007) does not explicitly assess studies since the TAR which analyze changes in *both* heat- and cold-related mortality in the U.S. in the observed climate or for different future climate scenarios[48]. However, analyzing data from 1964-1998, Davis et al. (2004) find existing mortality patterns in U.S. cities are relatively insensitive to temperature variability. In a future warming climate, they do project some mortality could be reduced with a winter-dominant warming and mortality increase with pronounced summer warming. Given the paucity of recent literature on the subject and the challenges in estimating and projecting weather-related mortality, IPCC concludes additional research is needed to

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[47] Confalonieri et al., 2007 citation refers to Chapter 8, “Human Health” in IPCC’s 2007 Fourth Assessment Report, Working Group II.

[48] Some have raised the issue of the observed trend in migration within the U.S. to the “Sunbelt” (particularly among older adults – for purposes including comfort, recreation and leisure as well as health) and what this implies about potential health benefits as a result of a warmer climate. Average climate warming may indeed provide health benefits in some areas; this point is captured in this section’s statement about less cold-related mortality due to climate warming. These potential warming benefits are independent of the potential negative effects of extreme heat events.

understand how the balance of heat-and cold-related deaths might change globally under different climate scenarios (Confalonieri et al, 2007).

7(b) Extreme Events

In addition to the direct effects of temperature on heat and cold-related mortality, projected trends in climate change-related exposures of importance to human health will increase the number of people (globally, including in the U.S.) suffering from disease and injury due to floods, storms, droughts and fires (high confidence) (Confalonieri et al, 2007). Vulnerability to weather disasters depends on the attributes of the people at risk (including where they live, age, income, education, and disability) and on broader social and environmental factors (level of disaster preparedness, health sector responses, and environmental degradation) (Ebi et al., 2008).

Floods and storms

The IPCC projects a very likely increase in heavy precipitation event frequency over most areas as described in Sections 6(b and c). Increases in the frequency of heavy precipitation events are associated with increased risk of deaths and injuries as well as infectious, respiratory and skin diseases (IPCC, 2007b). Floods are low-probability, high-impact events that can overwhelm physical infrastructure, human resilience, and social organization (Confalonieri et al, 2007). Flood health impacts include deaths, injuries, infectious diseases, intoxications and mental health problems (Greenough et al., 2001; Ahern et al., 2005 in Confalonieri et al, 2007). Flooding may also lead to contamination of waters with dangerous chemicals, heavy metals, or other hazardous substances, from storage or from chemicals already in the environment (Confalonieri et al, 2007).

The IPCC (2007d) also projects likely increases in intense tropical cyclone activity as described in Section 6(b). Increases in tropical cyclone intensity are linked to increases in the risk of deaths, injuries, water and foodborne diseases as well as post-traumatic stress disorders (IPCC, 2007b). Drowning by storm surge, heightened by rising sea levels and more intense storms (as projected by IPCC), is the major killer in coastal storms where there are large numbers of deaths (Confalonieri et al, 2007). High-density populations in low-lying coastal regions such as the U.S. Gulf of Mexico experience a high health burden from weather disasters, particularly among lower income groups. In 2005, Hurricane Katrina claimed over 1800 lives in the vicinity of the low-lying U.S. Gulf Coast and lower income groups were disproportionately affected (Graumann et al., 2005 in Nicholls et al.[49]; Guidry and Margolis, 2005 in Confalonieri et al., 2007). While Katrina was a Category 3 hurricane and its path was forecast well in advance, there was a secondary failure of the levee system. This illustrates that multiple factors contribute to making a disaster and that adaptation measures may not fully avert adverse consequences (Ebi et al., 2008). Additional information about U.S. vulnerability to the potential for more intense tropical cyclones can be found in Section 12(b).

Droughts

Areas affected by droughts are likely to increase according to IPCC (2007d) as noted in Section 6(e). The health impacts associated with drought tend to most affect semi-arid and arid regions, poor areas and populations, and areas with human-induced water scarcity; hence many of these effects are likely to be experienced in developing countries and not directly in the U.S. Information about the effects of increasing drought on U.S. agriculture can be found in section 9(c).

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[49] Nicholls et al., 2007 citation refers to Chapter 6, “Coastal Systems and Low-lying Areas” in IPCC’s 2007 Fourth Assessment Report, Working Group II.

Wildfires

In some regions, changes in the mean and variability of temperature and precipitation are projected to increase the frequency and severity of fire events, including in parts of the U.S. (Easterling, W. et al., 2007[50]). Wildfires can increase eye and respiratory illnesses and injuries, including burns and smoke inhalation (Ebi, et al., 2008). Large fires are also accompanied by an increased number of patients seeking emergency services for inhalation of smoke and ash (Hoyt and Gerhart, 2004 in Confalonieri et al., 2007). The IPCC (Field et al., 2007) noted a number of observed changes in U.S. wildfire size and frequency. Additional information on the effects of forest fires can be found in Sections 8(b) and 10(b).

7(c) Climate-sensitive diseases

The IPCC (2007b) notes that many human diseases are sensitive to weather. The incidence of airborne infectious diseases (e.g., coccidioidomycosis) varies seasonally and annually, due partly to climate variations such as drought, which is projected to increase in North America (Kolivras and Comrie, 2003 in Field et al., 2007).

Waterborne disease outbreaks are distinctly seasonal (which suggests potential underlying environmental or weather control), clustered in particular watersheds, and associated with heavy precipitation. The risk of infectious disease following flooding in high-income countries is generally low, although increases in respiratory and diarrheal diseases have been reported after floods (Miettinen et al., 2001; Reacher et al., 2004; Wade et al., 2004 in Confalonieri et al, 2007). For example, after Hurricanes Katrina and Rita in 2005, contamination of water supplies with fecal bacteria led to many cases of diarrheal illness and some deaths (Ebi et al., 2008; CDC, 2005b; Manuel, 2006 in Confalonieri et al, 2007).

Foodborne diseases show some relationship with temperature (e.g., increased temperatures have been associated with increased cases of Salmonellosis) (D'Souza et al., 2004; Kovats et al., 2004; Fleury et al., 2006 in Confalonieri et al, 2007). *Vibrio* spp. infections from shellfish consumption may also be influenced by temperature (Wittmann and Flick, 1995; Tuyet et al., 2002 in Confalonieri et al, 2007). For example, the IPCC (Confalonieri et al, 2007) cited a 2004 outbreak of *V parahaemolyticus* that was linked to atypically high temperatures in Alaskan coastal waters (McLaughlin et al., 2005).

According to the CCSP (2008b) report, there will likely be an increase in the spread of several food and water-borne pathogens among susceptible populations depending on the pathogens' survival, persistence, habitat range and transmission under changing climate and environmental conditions. While the U.S. has successful programs to protect water quality under the Safe Drinking Water Act and the Clean Water Act, some contamination pathways and routes of exposure do not fall under regulatory programs (e.g., dermal absorption from floodwaters, swimming in lakes and ponds with elevated pathogen levels, etc.). The primary climate-related factors that affect these pathogens include temperature, precipitation, extreme weather events, and shifts in their ecological regimes. Consistent with our understanding of climate change on human health, the impact of climate on food and water-borne pathogens will seldom be the only factor determining the burden of human injuries, illness, and death (CCSP 2008b).

The sensitivity of many zoonotic[51] diseases to climate fluctuations is also highlighted by the IPCC (Field et al., 2007). Above average temperatures in the U.S. during the summers of 2002-2004 were linked to the greatest transmissions of West Nile virus (Reisen et al., 2006 in Field et al., 2007). Saint Louis

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[50] Easterling et al., 2007 citation refers to Chapter 5, "Food, Fibre and Forest Products" in IPCC's 2007 Fourth Assessment Report, Working Group II.

[51] A zoonotic disease is any infectious disease that is able to be transmitted from an animal or nonhuman species to humans. The natural reservoir is a nonhuman reservoir.

encephalitis has a tendency to appear during hot, dry La Nina years (Cayan et al., 2003 in Field et al., 2007). Associations between temperature (Ogden et al., 2004) and precipitation (McCabe and Bunnell, 2004) and tick-borne Lyme disease are also noted by IPCC (Field et al., 2007). A study found that the northern range limit of *Ixodes scapularis*, the tick that carries Lyme disease, could shift north by 200 km by the 2020s and 1000 km by the 2080s (Brownstein et al., 2003 in Field et al., 2007).

Although large portions of the U.S. may be at potential risk for diseases such as malaria based on the distribution of competent disease vectors, locally acquired cases have been virtually eliminated, in part due to effective public health interventions, including vector and disease control activities. (Ebi et al., 2008; Confalonieri et al, 2007).

The IPCC concludes that human health risks from climate change will be strongly modulated by changes in health care, infrastructure, technology, and accessibility to health care (UNPD, 2005 in Field et al., 2007). The aging of the population and patterns of immigration and/or emigration will also strongly influence risks (UNPD, 2005 in Field et al., 2007). Infectious diseases could become more prominent if public health systems unravel or if new pathogens arise that are resistant to our current methods of disease control (Barrett et al., 1998 in Confalonieri et al, 2007).

7(d) Aeroallergens

Exposure to allergens results in allergenic illnesses in approximately 20% of the US population (American Academy of Allergy Asthma & Immunology (AAAAI), 1996-2006). Although there is substantial evidence suggesting a causal relationship between aeroallergens and allergenic illnesses, it remains unclear which aeroallergens are most important for sensitization and subsequent disease development (Nielsen, G. D. et al., 2002). Not only the type, but also the amount of aeroallergen to which an individual is exposed influences the development of an allergenic illness.

Climate change, including changes in CO_2 concentrations, could impact the production, distribution, dispersion and allergenicity of aeroallergens and the growth and distribution of weeds, grasses and trees that produce them (McMichael. et al., 2001[52]; Confalonieri et al., 2007). These changes in aeroallergens and subsequent human exposures could affect the prevalence and severity of allergy symptoms. However, the scientific literature does not provide definitive data or conclusions on how climate change might impact aeroallergens and subsequently the prevalence of allergenic illnesses in the U.S. In addition, there are numerous other factors that affect aeroallergen levels and the prevalence of associated allergenic illnesses, such as changes in land use, air pollution, and adaptive responses, many of which are difficult to assess (Ebi et al., 2008).

It has generally been observed that the presence of elevated CO_2 concentrations and temperatures stimulates plants to increase photosynthesis, biomass, water use efficiency, and reproductive effort. The IPCC concluded that pollens are likely to increase with elevated temperature and CO_2 (Field et al., 2007). Laboratory studies that used a doubling of CO_2 stimulated ragweed-pollen production by over 50% (Wayne et al., 2002 in Field et al., 2007). A U.S.-based field study which used existing temperature/CO_2 concentration differences between urban and rural areas as a proxy for climate change found that ragweed grew faster, flowered earlier, and produced significantly greater aboveground biomass and ragweed pollen at urban locations than at rural locations (Ziska et al., 2003 in Field et al., 2007).

The IPCC (Confalonieri et al, 2007) noted that climate change has caused an earlier onset of the spring pollen season in North America (D'Amato et al., 2002; Weber, 2002; Beggs, 2004) and that there is

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[52] McMichael et al., 2001 citation refers to Chapter 4, “Human Health” in IPCC’s 2001 Third Assessment Report, Working Group II.

limited evidence that the length of the pollen season has increased for some species. However, it is unclear whether the allergenic content of these pollens has changed. The IPCC concluded that introductions of new invasive plant species with high allergenic pollen present important health risks, noting that ragweed (*Ambrosia artemisiifolia*) is spreading in several parts of the world (Rybnicek and Jaeger, 2001; Huynen and Menne, 2003; Taramarcaz et al., 2005; Cecchi et al., 2006 in Confalonieri et al, 2007).

Section 8

Air Quality

The IPCC (2007b) projects with virtual certainty[53] "declining air quality in cities" due to "warmer and fewer cold days and nights and/or warmer/more frequent hot days and nights over most land areas" across all world regions, relative to air quality levels without climate change. Furthermore, the IPCC reports with very high confidence that climate change impacts on human health in U.S. cities will be compounded by population growth and an ageing population (Field et al., 2007). Surface air concentrations of air pollutants are highly sensitive to winds, temperature, humidity and precipitation (Denman et al., 2007). Climate change can be expected to influence the concentration and distribution of air pollutants through a variety of direct and indirect processes, including the modification of biogenic emissions, the change of chemical reaction rates, wash out of pollutants by precipitation, and modification of weather patterns that influence pollutant buildup. In summarizing the impact of climate change on ozone and particulate matter (PM), the IPCC (Denman et al., 2007) states that "future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and PM generation and the strength of emissions from the biosphere, fires and dust."

This section describes how climate change may alter ambient concentrations of ozone and PM with associated impacts on public health and welfare in the U.S.

8(a) Tropospheric Ozone

According to the IPCC (Denman et al., 2007), climate change is expected to lead to increases in regional ozone pollution in the U.S. and other countries. Ozone impacts on pubic health and welfare are described in EPA's Air Quality Criteria Document for Ozone (EPA, 2006). Breathing ozone at sufficient concentrations can reduce lung function, thereby aggravating asthma or other respiratory conditions. Ozone exposure at sufficient concentrations has been associated with increases in respiratory infection susceptibility, medicine use by asthmatics, emergency department visits and hospital admissions. Ozone exposure may contribute to premature death, especially in susceptible populations. In contrast to human health effects, which are associated with short-term exposures, the most significant ozone-induced plant effects (e.g., biomass loss, yield reductions) result from the accumulation of ozone exposures over the growing season, with differentially greater impact resulting from exposures to higher concentrations and/or longer durations.

Tropospheric ozone is both naturally occurring and, as the primary constituent of urban smog, a secondary pollutant formed through photochemical reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. As described below, climate change can affect ozone by modifying (1) emissions of precursors, (2) atmospheric chemistry, and (3) transport and removal (Denman et al., 2007). There is now consistent evidence from models and observations that 21st-century climate change will worsen summertime surface ozone in polluted regions of North America (Jacob and Winner, 2009).

The IPCC (Denman et al., 2007) states that, for all world regions, "climate change affects the sources of ozone precursors through physical response (lightning), biological response (soils, vegetation, and biomass burning) and human response (energy generation, land use, and agriculture)." Nitrogen oxide

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[53] According to IPCC terminology, "virtually certain" conveys a greater than 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

emissions due to lightning are expected to increase in a warmer climate (Denman et al., 2007). Additionally, studies using general circulation models concur that influx of ozone from the stratosphere to the troposphere could increase due to large-scale atmospheric circulation shifts (i.e., the Brewer-Dobson circulation) in response to climate warming (Denman et al., 2007). The sensitivity of microbial activity in soils to temperature also points toward a substantial increase in the nitric oxide emissions (Yienger and Levy 1995; Brasseur et al., 2006). As described below, biogenic VOC emissions increase with increasing temperature.

Climate induced changes of biogenic VOC emissions alone may be regionally substantial and cause significant increases in ozone concentrations (Hauglustaine et al., 2005; Hogrefe et al., 2004; European Commission, 2003). Sensitivity simulations for the 2050s, relative to the 1990s suggest that increased biogenic emissions alone add 1–3 parts per billion (ppb) to summertime average daily maximum 8-hour ozone concentrations in the Midwest and along the eastern seaboard (Hogrefe et al., 2004). The IPCC (Meehl et al., 2007) reports that biogenic emissions are projected to increase by between 27 and 59%, contributing to a 30 to 50% increase in ozone formation over northern continental regions (for the 2090-2100 timeframe, relative to 1990-2000).

Consistent with this, for nearly all simulations in the EPA Interim Assessment (2009), climate change is associated with increases in biogenic VOC emissions over most of the U.S., with especially pronounced increases in the Southeast. These biogenic emissions increases do not necessarily correspond with ozone concentration increases, however. The report suggests that the response of ozone to changes in biogenic emissions depends on how isoprene chemistry is represented in the models—models that recycle isoprene nitrates back to NOx will tend to simulate significant O_3 concentration increases in regions with biogenic emissions increases, while models that do not recycle isoprene nitrates will tend to simulate small changes, or even O_3 decreases.

Climate change impacts on temperature could affect ozone chemistry significantly (Denman et al., 2007). A number of studies in the U.S. have shown that summer daytime ozone concentrations correlate strongly with temperature. That is, ozone generally increases at higher temperatures. This correlation appears to reflect contributions of comparable magnitude from (1) temperature-dependent biogenic VOC emissions, as mentioned above, (2) thermal decomposition of peroxyacetylnitrate (PAN), which acts as a reservoir for NOx, as described immediately below, and (3) association of high temperatures with regional stagnation, also discussed below (Denman et al., 2007).

The EPA Interim Assessment (2009), however, reports that considering a single meteorological variable, such as temperature, may not provide a sufficient basis for determining future ozone risks due to climate change in every region. This is consistent with the potential for different competing effects in different regions. The modeling studies found some regions of the country where simulated increases in cloud cover, and hence decreases in the amount of sunlight reaching the surface, partially counteracted the effects of warming temperatures on ozone concentrations in these regions, to go along with the many regions where the effects of temperature and cloud cover reinforced each other in producing O_3 increases.

Climate change is projected to increase surface layer ozone concentrations in both urban and polluted rural environments due to decomposition of PAN at higher temperatures (Sillman and Samson, 1995; Liao and Seinfeld, 2006). Warming enhances decomposition of PAN, releasing NOx, an important ozone precursor (Stevenson et al., 2005). Model simulations with higher temperatures for the year 2100 showed that enhanced PAN thermal decomposition caused this species to decrease by up to 50% over source regions and ozone net production to increase (Hauglustaine et al., 2005).

Atmospheric circulation can be expected to change in a warming climate and, thus, modify pollutant transport and removal (National Assessment, 2008). The CCSP (2008b) reports that stagnant air masses related to climate change are likely to degrade air quality in some densely populated areas. More frequent occurrences of stagnant air events in urban or industrial areas could enhance the intensity of air pollution events, although the importance of these effects is not yet well quantified (Denman et al., 2007). The IPCC (2007d) concluded that "extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century."

The IPCC (Denman et al., 2007) cites the Mickley et al. (2004) study for the eastern U.S. which found an increase in the severity and persistence of regional pollution episodes due to the reduced frequency of ventilation by storms tracking across Canada. This study found that surface cyclone activity decreased by approximately 10–20% in a future simulation (for 2050, under the IPCC A1B scenario), which is in general agreement with a number of observational studies over the northern midlatitudes and North America (Zishka and Smith, 1980; Agee, 1991; Key and Chan, 1999; McCabe et al., 2001). Northeast U.S. summer pollution episodes are projected in this study to increase in severity and duration; pollutant concentrations in episodes increase 5-10% and episode durations increase from 2 to 3-4 days. Analysis of historical data supports both the trend in decreasing frequency of ventilation and the increase in summer pollution episodes (Leibensperger et al., 2008).

Regarding the role water vapor plays in tropospheric ozone formation, the IPCC (Denman et al., 2007) reports that simulations for the 21st century indicate a decrease in the lifetime of tropospheric ozone due to increasing water vapor. The projected increase in water vapor both decelerates the chemical production and accelerates the chemical destruction of ozone (Meehl et al., 2007). Overall, the IPCC states that climate change is expected to decrease background tropospheric ozone due to higher water vapor and to increase regional and urban-scale ozone pollution due to higher temperatures and weaker air circulation (Denman et al., 2007; Confalonieri et al., 2007).

For North America, the IPCC (Field et al., 2007) reports that surface ozone concentration may increase with a warmer climate. For the continental U.S., the CCSP (2008b) report states that the northern latitudes are likely to experience the largest increases in average temperatures and they will also bear the brunt of increases in ground-level ozone and other airborne pollutants.

Modeling studies discussed in EPA's Interim Assessment (2009) show that climate change caused increases in summertime O_3 concentrations over substantial regions of the country, though this was not uniform, and some areas showed little change or decreases. For those regions that showed climate-induced increases, the increase in Maximum Daily 8-hour Average O_3 concentration, a key metric for regulating U.S. air quality, was in the range of 2-8 ppb, averaged over the summer season. The increases were substantially greater than this during the peak pollution episodes that tend to occur over a number of days each summer. While the results from the different research groups agreed on the above points, their modeling systems did not always simulate the same regional patterns of climate-induced O_3 changes across the U.S. Certain regions show greater agreement than others: for example, there is more agreement on climate-induced increases for the eastern half of the country than for the West. Parts of the Southeast also show strong disagreements across the modeling groups. Where climate-change-induced increases in ozone do occur, damaging effects on ecosystems, agriculture, and health are expected to be especially pronounced, due to increases in the frequency of extreme pollution events.

The EPA Interim Assessment (2009) suggests that climate change effects on ozone grow continuously over time, with evidence for significant increases emerging as early as the 2020s. The EPA Interim Assessment (2009) and the IPCC (Field et al., 2007; Wilbanks et al., 2007) cites Hogrefe et al. (2004) who evaluate the effects of climate change on regional ozone in 15 U.S. cities, finding that average summertime daily 8-hour maximum ozone concentrations could increase by 2.7 ppb in the 2020s and by 4.2 ppb in the 2050s.

Studies reviewed in EPA's Interim Assessment (2009) and Jacob and Winner (2009) indicate the largest increases in ozone concentrations occur during peak pollution events. Mickley et al. (2004) found that significant changes occur at the high end of the pollutant concentration distribution (episodes) in the Midwest and Northeast between 2000 and 2050. While summer average daily maximum 8-hour ozone concentrations increase by 2.7, 4.2, and 5.0 ppb in 2020s, 2050s, and 2080s (compared to 1990s), the fourth highest summertime daily maximum 8-hour ozone concentrations increase by 5.0, 6.4, and 8.2 ppb for the 2020s, 2050s, and 2080s, respectively (compared to 1990s) (Hogrefe et al., 2004). The CCSP (2008b) also reports climate change is projected to have a much greater impact on extreme values and to shift the distribution of ozone concentrations towards higher values, with larger relative increases in future decades. In addition, simulations reviewed in the EPA Interim Assessment (2009) showed that, for parts of the country with a defined summertime O_3 season, climate change expanded its duration into the fall and spring. These findings raise particular health concerns.

The IPCC (Field et al., 2007) states that, "warming and climate extremes are likely to increase respiratory illness, including exposure to pollen and ozone." And the IPCC further states that "severe heat waves, characterized by stagnant, warm air masses and consecutive nights with high minimum temperatures will intensify in magnitude and duration over the portions of the U.S. and Canada, where they already occur (high confidence) (Field et al., 2007)." Further, as described in CCSP (2008b), there is some evidence that combined effects of heat stress and air pollution may be greater than simple additive effects (Patz and Balbus, 2001). Moreover, historical data show relationships between mortality and temperature extremes (Rozenzweig and Solecki, 2001).

Holding population, dose-response characteristics, and pollution prevention measures constant, ozone-related deaths from climate change in the New York City metropolitan area are projected to increase by approximately 4.5% from the 1990s to the 2050s (under the IPCC A2 scenario) (Field et al., 2007; Bell et al., 2007; Knowlton et al., 2004). According to the IPCC (Field et al., 2007), the "large potential population exposed to outdoor air pollution, translates this small relative risk into a substantial attributable health risk." In New York City, health impacts could be further exacerbated by climate change interacting with urban heat island effects (Field et al., 2007). For the 2050s, Bell et al. (2007) report that the projected effects of climate change on ozone in 50 eastern U.S. cities increased the number of summer days exceeding the 8-hour U.S. EPA standard by 68%. On average across the 50 cities, the summertime daily 8-h maximum increased 4.4 ppb. Elevated ozone levels correspond to approximately a 0.11% to 0.27% increase in daily total mortality. The largest ozone increases are estimated to occur in cities with present-day high pollution.

As noted in CCSP (2008b), the influence of climate change on air quality will play out against a backdrop of ongoing regulatory control of both ozone and particulate matter (PM) that will shift the baseline concentrations of these two important pollutants. However, most studies to date that have examined potential future climate change impacts on air quality isolate the climate effect by holding precursor air pollutant emissions constant over time.

The IPCC reports (Denman et al., 2007) that "the current generation of tropospheric ozone models is generally successful in describing the principal features of the present-day global ozone distribution." The IPCC (Denman et al., 2007) also states that "there are major discrepancies with observed long-term trends in ozone concentrations over the 20th century" and "resolving these discrepancies is needed to establish confidence in the models."

In addition to human health effects, elevated levels of tropospheric ozone have significant adverse effects on crop yields in the U.S. and other world regions, pasture and forest growth and species composition (Easterling et al., 2007; EPA, 2006; Volk et al., 2006; Ashmore, 2005; Vandermeiren, 2005; Loya et al., 2003). Furthermore, the effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone resulted in significantly less enhancement of carbon sequestration rates under elevated CO_2 (Loya *et al.*, 2003), due to negative effects of ozone on biomass productivity and changes in litter chemistry (Booker *et al.*, 2005; Liu *et al.*, 2005).

8(b) Particulate Matter

Particulate matter impacts on public health and welfare are described in EPA's Air Quality Criteria Document for Particulate Matter (EPA, 2004). Particulate matter is a complex mixture of anthropogenic, biogenic and natural materials, suspended as aerosol particles in the atmosphere. When inhaled, the smallest of these particles can reach the deepest regions of the lungs. Scientific studies have found an association between exposure to PM and significant health problems, including: aggravated asthma; chronic bronchitis; reduced lung function; irregular heartbeat; heart attack; and premature death in people with heart or lung disease. Particle pollution also is the main cause of visibility impairment in the nation's cities and national parks.

The overall directional impact of climate change on PM levels in the U.S. remains uncertain (National Assessment, 2008), as too few data yet exist for PM to draw firm conclusions about the direction or magnitude of climate impacts (CCSP, 2008b). However, preliminary results of modeling analyses reported in the EPA Interim Assessment (2009) are listed below. These analyses show a range of increases and decreases in PM concentrations in different regions and for different component chemical species in the same region:

1. Precipitation is a more important primary meteorological driver of PM than of O_3, due to its role in removing PM from the atmosphere (wet deposition). Precipitation is particularly difficult to model and shows greater disagreement across simulations than other variables.
2. Aerosol chemical processes, especially those concerning the formation of organic aerosols, are not fully understood and therefore not well characterized in current regional air quality models.
3. Preliminary simulation results suggest that, globally, PM generally decreases as a result of simulated climate change, due to increased atmospheric humidity and increased precipitation.
4. Regionally, simulated 2050 climate change produces both increases and decreases in PM (on the order of a few percent), depending on region. For the U.S., the largest simulated increases are found in the Midwest and Northeast.
5. This PM response reflects the combined climate change responses of the individual species that make up PM (e.g., sulfate, nitrate, ammonium, black carbon, organic carbon, etc.). Depending on the region, these individual responses can be in competing directions.
6. Increase in wildfire frequency associated with a warmer climate has the potential to increase PM levels in certain regions.

Further, Jacob and Winner (2009) summarize the current state of knowledge as:

"The response of PM to climate change is more complicated than that for ozone because of the diversity of PM components, compensating effects, and general uncertainty in GCM projections of the future hydrological cycle. Observations show little useful correlation of PM with climate variables to guide inferences of the effect of climate change. Rising temperature is expected to have a mild negative effect on PM due to volatilization of semi-volatile components (nitrate, organic), partly compensated by increasing sulfate production. Increasing stagnation should cause PM to increase. Precipitation frequency, which largely determines PM loss, is expected to increase globally but to decrease in southern North America and southern Europe. PM is highly sensitive to mixing depths but there is no consensus among models on how these will respond to climate change… Increases in wildfires driven by climate change could significantly increase PM concentrations beyond the direct effect of changes in meteorological variables."

As described in the National Assessment (2008), PM and PM precursor emissions are affected by climate change through physical response (wind blown dust), biological response (forest fires and vegetation type/distribution) and human response (energy generation). Most natural aerosol sources are controlled by climatic parameters like wind, moisture and temperature; thus, human induced climate change is expected to affect the natural aerosol burden. Biogenic organic material is both directly emitted into the atmosphere and produced by VOCs. All biogenic VOC emissions are highly sensitive to changes in temperature, and are also highly sensitive to climate-induced changes in plant species composition and biomass distributions. Biogenic emissions rates are predicted to increase, on average across world regions, by 10% per 1°C increase in surface temperature (Denman et al., 2007; Guenther et al. 1993). The response of biogenic secondary organic carbon aerosol production to a temperature change, however, could be considerably lower than the response of biogenic VOC emissions since aerosol yields can decrease with increasing temperature (Denman et al., 2007).

Particulate matter emissions from forest fires can contribute to acute and chronic illnesses of the respiratory system, particularly in children, including pneumonia, upper respiratory diseases, asthma and chronic obstructive pulmonary diseases (WHO, 2002; Bowman and Johnston, 2005; Moore et al., 2006; Confalonieri et al., 2007). The IPCC (Field et al., 2007) reported with very high confidence that in North America disturbances like wildfire are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons**.** Forest fires with their associated decrements to air quality and pulmonary effects are likely to increase in frequency, severity, distribution, and duration in the Southeast, the Intermountain West and the West (CCSP, 2008b). Pollutants from forest fires can affect air quality for thousands of kilometers (Confalonieri et al., 2007). Westerling et al. (2006; as referenced in IPCC (Field et al., 2007)) found that, in the last three decades, the wildfire season in the western U.S. has increased by 78 days, and burn durations of large fires have increased from 7.5 to 37.1 days, in response to a spring-summer warming of 0.87°C. Earlier spring snowmelt has led to longer growing seasons and drought, especially at higher elevations, where the increase in wildfire activity has been greatest (Westerling et al., 2006). Analysis by the State of California suggests that large wildfires could become up to 55% more frequent in some areas toward the end of the century due to continued global warming (California Climate Change Center, 2006).

As described in the National Assessment (2008), PM chemistry is affected by changes in temperature brought about by climate change as follows. Temperature is one of the most important meteorological variables influencing air quality in urban atmospheres because it directly affects gas and heterogeneous chemical reaction rates and gas-to-particle partitioning. The net effect that increased temperature has on airborne particle concentrations is a balance between increased production rates for secondary particulate matter (increases particulate concentrations) and increased equilibrium vapor pressures for semi-volatile particulate compounds (decreases particulate concentrations). Increased temperatures may either increase or decrease the concentration of semi-volatile secondary reaction products such as ammonium nitrate depending on ambient conditions.

The IPCC (Denman et al., 2007) notes that there has been less work on the sensitivity of aerosols to meteorological conditions and cites regional model simulations by Aw and Kleeman (2003). The regional model simulations for Southern California on September 25, 1996 projected decreases in 24-hour average $PM_{2.5}$ concentrations with increasing temperatures for inland portions of the South Coast air basin, and projected increases for coastal regions. In CCSP (2008b), using the NYCHP integrated model, $PM_{2.5}$ concentrations are projected to increase with climate change, with the effects differing by component species, with sulfates and primary PM increasing markedly and with organic and nitrated components decreasing, mainly due to movement of these volatile species from the particulate to the gaseous phase (Hogrefe et al., 2005; 2006).

Increased temperatures may either increase or decrease the concentration of semi-volatile secondary reaction products such as ammonium nitrate depending on ambient conditions. Regions with relatively hot initial temperatures (>290 K) will likely experience a reduction in particulate ammonium nitrate concentrations as temperature increases, while regions with relatively cool initial temperatures (<290 K) may experience minor reductions or even small increases in particulate ammonium nitrate concentrations as temperature increases. The net effect that increased temperature has on airborne particle concentrations is a balance between increased production rates for secondary PM (increases particulate concentrations) and increased equilibrium vapor pressures for semi-volatile particulate compounds (decreases particulate concentrations).

The transport and removal of PM is highly sensitive to winds and precipitation. Removal of PM from the atmosphere occurs mainly by wet deposition (NAS, 2005). Sulfate lifetime, for example, is estimated to be reduced from 4.7 days to 4.0 days as a result of increased wet deposition (Liao and Seinfeld, 2006). Precipitation also affects soil moisture, with impacts on dust source strength and on stomatal opening/closure of plant leaves, hence affecting biogenic emissions (Denman et al., 2007). Precipitation has generally increased over land north of 30°N over the period 1900 to 2005 and it has become significantly wetter in eastern parts of North America (Trenberth et al., 2007). However, model parameterizations of wet deposition are highly uncertain and not fully realistic in their coupling to the hydrological cycle (NAS, 2005). For models to simulate accurately the seasonally varying pattern of precipitation, they must correctly simulate a number of processes (e.g., evapotranspiration, condensation, transport) that are difficult to evaluate at a global scale (Randall et al., 2007).

In 1997, EPA demonstrated that visibility impairment is an important effect on public welfare and that visibility impairment is experienced (though not necessarily attributed to climate change) throughout the U.S., in multi-state regions, urban areas, and remote Federal Class I areas[54]. Visibility impairment depends strongly on ambient relative humidity (NARSTO, 2004). Although surface specific humidity globally has generally increased after 1976 in close association with higher temperatures over both land and ocean, observations suggest that relative humidity has remained about the same overall, from the surface throughout the troposphere (Trenberth et al., 2007). Nevertheless, increases in PM due to increases in wildfires induced by climate change might increase visibility impairment.

8(c) Health Effects due to CO_2-Induced Increases in Tropospheric O_3 and Particulate Matter

In addition to the analyses described above of climate change impacts on air quality, one study specifically examined the more direct effect of CO_2 on air pollution mortality. As described in the CCSP (2008b) report, using a coupled climate-air pollution three-dimensional model, the study (Jacobson, 2008) compared the health effects of pre-industrial vs. present-day atmospheric concentrations of CO_2. The results suggest that increasing concentrations of CO_2 increased tropospheric ozone and $PM_{2.5}$, which increased mortality by about 1.1% per degree temperature increase over the baseline rate; Jacobson estimated that about 40% of the increase was due to ozone and the rest to particulate matter. The estimated mortality increase was higher in locations with poorer air quality.

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[54] The Clean Air Act defines mandatory Federal Class I areas as certain national parks (over 6,000 acres), wilderness areas (over 5,000 acres), national memorial parks (over 5,000 acres), and international parks that were in existence as of August 7, 1977.

Section 9

Food Production and Agriculture

Food production and the agricultural sector within the U.S. are sensitive to short-term climate variability and long-term climate change. This section addresses how observed and projected climate change may affect U.S. food production and agriculture. Food production and agriculture here include crop yields and production, livestock production (e.g., milk and meat), freshwater fisheries, and key climate-sensitive issues for this sector including drought risk and pests and weeds.

In addition to changes in average temperatures and precipitation patterns, this section also addresses how U.S. food production and agriculture may be affected directly by elevated CO_2 levels, as well as the frequency and severity of extreme events, such as droughts and storms. Climate change-induced effects on tropospheric ozone levels and their impacts on agriculture are discussed briefly in Section 8 on Air Quality.

Vulnerability of the U.S. agricultural sector to climate change is a function of many interacting factors including pre-existing climatic and soil conditions, changes in pest competition, water availability, and the sector's capacity to cope and adapt through management practices, seed and cultivar technology, and changes in economic competition among regions.

The IPCC (2007b) made the following general conclusion about food production and agriculture for North America:

> Moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture by 5-20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or depend on highly utilized water resources [high confidence].[55]

The CCSP report on U.S. agriculture (Backlund et al., 2008a) made the following general conclusions for the U.S.:

- With increased CO_2 and temperature, the life cycle of grain and oilseed crops will likely progress more rapidly. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable.

- The marketable yield of many horticultural crops – e.g., tomatoes, onions, fruits – is very likely to be more sensitive to climate change than grain and oilseed crops.

- Climate change is likely to lead to a northern migration of weeds. Many weeds respond more positively to increasing CO_2 than most cash crops, particularly C3 "invasive" weeds[56]. Recent research also suggests that glyphosate, the most widely used herbicide in the U.S., loses its efficacy on weeds grown at the increased CO_2 levels likely in the coming decades.

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[55] According to IPCC terminology, "high confidence" conveys an 8 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

[56] C3 and C4 refer to different carbon fixation pathways in plants during photosynthesis. C3 is the most common pathway, and C3 crops (e.g., wheat, soybeans and rice) are more responsive than C4 crops such as maize.

- Disease pressure on crops and domestic animals will likely increase with earlier springs and warmer winters, which will allow proliferation and higher survival rates of pathogens and parasites. Regional variation in warming and changes in rainfall will also affect spatial and temporal distribution of disease.

- Projected increases in temperature and a lengthening of the growing season will likely extend forage production into late fall and early spring, thereby decreasing need for winter season forage reserves. However, these benefits will very likely be affected by regional variations in water availability.

- Climate change-induced shifts in plant species are already underway in rangelands. Establishment of perennial herbaceous species is reducing soil water availability early in the growing season. Shifts in plant productivity and type will likely also have significant impact on livestock operations.

- Higher temperatures will very likely reduce livestock production during the summer season, but these losses will very likely be partially offset by warmer temperatures during the winter season. For ruminants, current management systems generally do not provide shelter to buffer the adverse effects of changing climate; such protection is more frequently available for non-ruminants (e.g., swine and poultry).

9(a) Crop yields and productivity

- Observational evidence shows that, over the last century, aggregate yields of major U.S. crops have been increasing (USDA, 2007; Troyer, 2004 as referenced in Field et al., 2007), with significant regional and temporal variation. Multiple factors contribute to these long term trends, including seed technology, use of fertilizers, management practices, and climate change (e.g., lengthening of the growing season).

For projected climate change effects, the IPCC summary conclusion of net beneficial effects in the early decades in the U.S. under moderate climate change, with significant regional variation, is supported by a number of recent assessments for most major crops, and is consistent with the previous IPCC Third Assessment (2001) conclusion.[57] Moderate climate change for temperate regions such as the U.S. is described as local increases in temperature of 1-3ºC (~2-5ºF), which may occur within the next few decades or past mid-century depending on scenario (see Section 6 for temperature projections). Increased average warming leads to an extended growing season, especially for northern regions of the U.S. Further warming, however, is projected to have increasingly negative impacts in all regions (meaning both temperate, including the U.S., and tropical regions of the world) (Easterling et al. 2007).

The CCSP report on agriculture (Hatfield et al., 2008) provides further crop-specific detail about optimum temperatures in order to assess the effects of future climate change. Crops are characterized by an upper failure-point temperature at which pollination and grain-set processes fail. Considering these aspects, Hatfield et al., (2008) detail the following optimum mean temperatures for grain yields of the major agronomic crops: 18-22ºC for maize, 22-24ºC for soybean, 15ºC for wheat, 23-26ºC for rice, 25ºC for sorghum, 25-26ºC for cotton, 20-26ºC for peanut, 23-24ºC for dry bean, and 22-25ºC for tomato.

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[57] The North America chapter from the IPCC Third Assessment Report (Cohen et al. 2007) concluded: "Food production is projected to benefit from a warmer climate, but there probably will be strong regional effects, with some areas in North America suffering significant loss of comparative advantage to other regions (high confidence)."

. Given the variable responses of different crops to temperature (and other climatic) changes, and the fact that different areas of the country specialize in different crops and have different regional climates, the variable future climate change effects among regions and crops are important to consider. The south-eastern U.S. may be more vulnerable to increases in average temperature than more northern regions due to pre-existing temperatures that are already relatively high. Likewise, certain crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to experience decreases in yields, quality, or both, even under moderate climate change scenarios (Field et al., 2007).

Without the benefit of CO_2, the anticipated 1.2ºC rise in temperature over the next 30 years (a baseline assumption assumed in the CCSP (Hatfield et al., 2008) report) is projected to decrease maize, wheat, sorghum, and dry bean yields by 4.0, 6.7, 9.4, and 8.6 percent, respectively, in their major production regions. For soybean, the 1.2ºC temperature rise will increase yield 2.5 percent in the Midwest where temperatures during July, August, September average 22.5ºC, but will decrease yield 3.5 percent in the South, where mean temperature during July, August, and September averages 26.7ºC. Likewise, in the South, that same mean temperature will result in reduced rice, cotton, and peanut yields, which will decrease 12.0, 5.7, and 5.4 percent, respectively (Hatfield et al., 2008).

Changes in precipitation patterns will play a large role in determining the net impacts of climate change at the national and sub-national scales, where uncertainties about precipitation changes remain very large. The IPCC (Field et al., 2007) reviewed integrated assessment modeling studies exploring the interacting impacts of climate and economic factors on agriculture, water resources, and biome boundaries in the U.S. and concluded that scenarios with decreased precipitation create important challenges, restricting the availability of water for irrigation and at the same time increasing water demand for irrigated agriculture, as well as urban and ecological uses. The critical importance of specific agro-climatic events, such as last frost, also introduces uncertainty in future projections (Field et al., 2007).

There is still uncertainty about the sensitivity of crop yields in the U.S. and other world regions to the direct effects of elevated CO_2 levels. The IPCC (Easterling et al., 2007) concluded that elevated CO_2 levels are expected to contribute to small beneficial impacts on crop yields. The IPCC confirmed the general conclusions from its previous Third Assessment Report in 2001. Experimental research on crop responses to elevated CO_2 through the FACE (Free Air CO_2 Enrichment)[58] experiments indicate that, at ambient CO_2 concentrations of 550 ppm (approximately double the concentration from pre-industrial times), crop yields increase under unstressed conditions by 10-25% for C3 crops, and by 0-10% for C4 crops (medium confidence). Crop model simulations under elevated CO_2 are consistent with these ranges (high confidence) (Easterling et al., 2007). High temperatures, water and nutrient availability, and ozone exposure, however, can significantly limit the direct stimulatory CO_2 response.

Hatfield et al. (2008) provides further detail about individual crop species responses to elevated CO_2 concentrations and the interactive effects with other climate change factors. Overall, the benefits of CO_2 rise over the next 30 years are projected to mostly offset the negative effects of temperature for most C3 crops except rice and bean, while the C4 crop yields are reduced by rising temperature because they have little response to the CO_2 rise (Hatfield et al., 2008). Thus, according to Hatfield et al. (2008), the 30-year outlook for U.S. crop production is relatively neutral. However, the outlook for U.S. crop production over the next 100 years would not be as optimistic, if temperature continues to rise along with climbing CO_2 concentrations, because the C3 response to rising CO_2 is reaching a saturating plateau, while the negative temperature effects will become progressively more severe (Hatfield et al., 2008).

There are continual changes in the genetic resources of crop varieties and horticultural crops that will provide increases in yield due to increased resistance to water and pest stresses. These need to be

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[58] http://www.bnl.gov/face/

considered in any future assessments of the climatic impacts; however, the genetic modifications have not altered the basic temperature response or CO_2 response of the biological system (Hatfield et al., 2008).

Although horticultural crops (fruits, vegetatbles and nuts) account for more than 40 percent of total crop market value in the U.S. (2002 Census of Agriculture), there is relatively little information on their response to CO_2, and few reliable crop simulation models for use in climate change assessments compared to that which is available for major grain and oilseed crops (Hatfield et al., 2008). The marketable yield of many horticultural crops is likely to be more sensitive to climate change than grain and oilseed crops because even short-term, minor environmental stresses can negatively affect visual and flavor quality (Hatfield et al., 2008).

9(b) Irrigation requirements

The impacts of climate change on irrigation water requirements may be large (Easterling et al., 2007). The IPCC considered this to be a new, robust finding since the Third Assessment Report in 2001. The increase in irrigation demand due to climate change is expected in the majority of world regions including the U.S. due to decreased rainfall in certain regions and/or increased evaporation arising from increased temperatures. Longer growing seasons may contribute to the increased irrigation demands as well. Hatfield et al. (2008) describe in the CCSP report studies that examined changes in irrigation requires for the U.S. under climate change scenarios. For corn, Izaurralde et al. (2003) calculated that by 2030 irrigation requirements will change from -1 (Lower Colorado Basin) to +451 percent (Lower Mississippi Basin), because of rainfall variation. Given the variation in the sizes and baseline irrigation requirements of U.S. basins, a representative figure for the overall U.S. increase in irrigation requirements is 64 percent if stomatal effects are ignored, or 35 percent if they are included. Similar calculations were made for alfalfa, for which overall irrigation requirements are predicted to increase 50 and 29 percent in the next 30 years in the cases of ignoring and including stomatal effects, respectively. These increases are more likely due to the decrease in rainfall during the growing season and the reduction in soil water availability.

9(c) Climate variability and extreme events

Weather events are a major factor in annual crop yield variation. The projected impacts of climate change often consider changes in *average* temperature and precipitation patterns alone, while not reflecting the potential for altered variability in events such as droughts and floods. The potential for these events to change in frequency and magnitude introduces a key uncertainty regarding future projections of changes in agricultural and food production due to climate change. On this issue, the IPCC (Easterling et al. 2007) drew the following conclusion: “Recent studies indicate that climate change scenarios that include increased frequency of heat stress, droughts and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone, creating the possibility for surprises. Climate variability and change also modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for food, fiber and forestry (high confidence).” The adverse effects on crop yields due to droughts and other extreme events may offset the beneficial direct effects of elevated CO_2, moderate temperature increases over the near term, and longer growing seasons.

Drought events are already a frequent occurrence, especially in the western U.S. Vulnerability to extended drought is, according to IPCC (Field et al., 2007), increasing across North America as population growth and economic development increase demands from agricultural, municipal, and industrial uses, resulting in frequent over-allocation of water resources. Though droughts occur more frequently and intensely in the western part of the U.S., the east is not immune from droughts and attendant reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Field et al., 2007).

Average annual precipitation is projected to decrease in the southwestern U.S. but increase over the rest of North America (Christensen et al., 2007). Some studies project widespread increases in extreme precipitation (Christensen et al., 2007), with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation.

One economic consequence of excessive rainfall is delayed spring planting, which jeopardizes profits for farmers paid a premium for early season production of high value horticultural crops such as melon, sweet corn, and tomatoes (Hatfield et al., 2008). Field flooding during the growing season causes crop losses associated with anoxia, increases susceptibility to root diseases, increases soil compaction (due to use of heavy farm equipment on wet soils), and causes more runoff and leaching of nutrients and agricultural chemicals into groundwater and surface water (Hatfield et al., 2008).

9(d) Pests and weeds

Pests and weeds can reduce crop yields, cause economic losses to farmers, and require management control options. How climate change (elevated CO_2, increased temperatures, altered precipitation patterns, and changes in the frequency and intensity of extreme events) may affect the prevalence of pests and weeds is an issue of concern for food production and the agricultural sector. Recent warming trends in the U.S. have led to earlier insect spring activity and proliferation of some species (Easterling, et al., 2007).

The growth of many crops and weeds is being stimulated (Backlund et al., 2008a). Weeds generally respond more positively to increasing CO_2 than most cash crops, particularly C3 invasive weeds; and while there are many weed species that have the C4 photosynthetic pathway and therefore show a smaller response to atmospheric CO_2 relative to C3 crops, in most agronomic situations, crops are in competition with both C3 and C4 weeds (Backlund et al.,, 2008a). The IPCC (Easterling et al., 2007) concluded, with high confidence, that climate variability and change modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for food, fiber and forestry across all world regions.

Climate change is likely to lead to a northern migration of weeds (Backlund et al, 2008a). Recent research also suggests that glyphosate, the most widely used herbicide in the U.S., loses its efficacy on weeds grown at the increased CO_2 levels likely in the coming decades (Backlund et al., 2008a).

Disease pressure on crops and domestic animals will likely increase with earlier springs and warmer winters, which will allow proliferation and higher survival rates of pathogens and parasites. Regional variation in warming and changes in rainfall will also affect the spatial and temporal distribution of diseases (Backlund et al., 2008a).

Most studies, however, continue to investigate pest damage as a separate function of either elevated ambient CO_2 concentrations or temperature. Pests and weeds are additional factors that, for example, are often omitted when projecting the direct stimulatory effect of elevated CO_2 on crop yields. Research on the combined effects of elevated CO_2 and climate change on pests, weeds and disease is still insufficient for U.S. and world agriculture (Easterling et al., 2007).

9(e) Livestock

Hatfield et al. (2008) describe how temperature changes and environmental stresses can result in declines in physical activity and an associated decline in eating and grazing activity (for ruminants and other herbivores), or elicit a panting or shivering response, which increases maintenance requirements of the animal and contributes to decreases in animal productivity.

Climate change has the potential to influence livestock productivity in a number of ways. Elevated CO_2 concentrations can affect forage quality; thermal stress can directly affect the health of livestock animals; an increase in the frequency or magnitude of extreme events can lead to livestock loss; and climate change may affect the spread of animal diseases. The IPCC has generated a number of new conclusions in this area compared to the Third Assessment Report in 2001. These conclusions (Easterling et al., 2007), along with those from the more recent CCSP report (Hatfield et al., 2008) include:

- Higher temperatures will very likely reduce livestock production during the summer season, but these losses will very likely be partially offset by warmer temperatures during the winter season. For ruminants, current management systems generally do not provide shelter to buffer the adverse effects of a changing climate; such protection is more frequently available for non-ruminants (e.g., swine and poultry).

- Based on expected vegetation changes and known environmental effects on forage protein, carbohydrate, and fiber contents, both positive and negative changes in forage quality are possible as a result of atmospheric and climatic change. Elevated CO_2 can increase the carbon to nitrogen ratio in forages and thus reduce the nutritional value of those grasses, which in turn affects animal weight and performance. Under elevated CO_2, a decrease of C4 grasses and an increase of C3 grasses (depending upon the plant species that remain) may occur which could potentially reduce or alter the nutritional quality of the forage grasses available to grazing livestock; however the exact effects on both types of grasses and their nutritional quality still needs to be determined.

- Increased climate variability (including extremes in both heat and cold) and droughts may lead to livestock loss. The impact on animal productivity due to increased variability in weather patterns will likely be far greater than effects associated with the average change in climatic conditions.

9(f) Freshwater and marine fisheries

Freshwater fisheries are sensitive to changes in temperature and water supply, which affect flows of rivers and streams, as well as lake levels. Climate change can interact with other factors that affect the health of fish and productivity of fisheries (e.g., habitat loss, land-use change).

The IPCC (Field et al., 2007 and references therein) reviewed a number of North American studies showing how freshwater fish are sensitive to, or are being affected by, observed changes in climate:

- Cold- and cool-water fisheries, especially salmonids, have been declining as warmer/drier conditions reduce their habitat. The sea-run salmon stocks are in steep decline throughout much of North America;
- Pacific salmon have been appearing in Arctic rivers;[59]
- Salmonid species have been affected by warming in U.S. streams;
- Success of adult spawning and survival of fry brook trout is closely linked to cold groundwater seeps, which provide preferred temperature refuges for lake-dwelling populations. Rates of fish egg development and mortality increase with temperature rise within species-specific tolerance ranges.

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[59] Arctic includes large regions of Alaska, and the Alaskan indigenous population makes up largest indigenous population of the Arctic (see ACIA, 2004).

Regarding the impacts of future climate change, IPCC concluded, with high confidence for North America, that cold-water fisheries will likely be negatively affected; warm-water fisheries will generally benefit; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges (Field et al., 2007). A number of specific impacts by fish species and region in North America are projected (Field et al., 2007 and references therein):

- Salmonids, which prefer cold water, are likely to experience the most negative impacts;
- Arctic freshwaters will likely be most affected, as they will experience the greatest warming;
- Many warm-water and cool-water species will shift their ranges northward or to higher altitudes;
- In the continental U.S., cold-water species will likely disappear from all but the deeper lakes, cool-water species will be lost mainly from shallow lakes, and warm water species will thrive except in the far south, where temperatures in shallow lakes will exceed survival thresholds.

Climate variability and change can also impact fisheries in coastal and estuarine waters, although non-climatic factors, such as overfishing and habitat loss and degradation, are already responsible for reducing fish stocks (Nichols et al., 2007). Coral reefs, for example, are vulnerable to a range of stresses and for many reefs, thermal stress thresholds will be crossed, resulting in bleaching, with severe adverse consequences for reef-based fisheries (Nichols et al., 2007). Increased storm intensity, temperature and salt water intrusion in coastal water bodies can also adversely impact coastal fisheries production.

Section 10

Forestry

This section addresses how climate change may affect forestry, including timber yields, wildfires and drought risk, forest composition, and pests in the U.S. For North America, the IPCC (Field et al., 2007) concluded:

- Overall forest growth in North America will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO_2 over the next century, but with important spatial and temporal variation (medium confidence).[60]

- Disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence). Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Over the 21st century, pressure for species to shift north and to higher elevations will fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

The CCSP report addressing forestry and land resources (Ryan et al., 2008) made the following general conclusions for the U.S.:

- Climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior west, the Southwest, and Alaska, and will continue to do so. An increased frequency of disturbance is at least as important to ecosystem function as incremental changes in temperature, precipitation, atmospheric CO_2, nitrogen deposition, and ozone pollution. Disturbances partially or completely change forest ecosystem structure and species composition, cause short-term productivity and carbon storage loss, allow better opportunities for invasive alien species to become established, and command more public and management attention and resources.

10(a) Forest Productivity

Forestry productivity is known to be sensitive to changes in climate variables (e.g. temperature, radiation, precipitation, water vapor pressure in the air, and wind speed), as these affect a number of physical, chemical, and biological processes in forest systems (Easterling, et al., 2007). However, as noted in a CCSP report addressing the forest sector (Ryan et al., 2008), it is difficult to separate the role of climate from other potentially influencing factors, particularly because these interactions vary by location.

For the U.S. as a whole, forest growth and productivity have been observed to change, in part due to observed climate change. Nitrogen deposition and warmer temperatures have very likely increased forest growth where water is not limiting (Ryan et al., 2008). The IPCC (Field et al., 2007 and references therein) outlines a number of studies demonstrating the observed connection between changes in U.S. forest growth and changes in climate variables:

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[60] According to IPCC terminology, “medium confidence” conveys a 5 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

- Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth has historically been limited by low temperatures and short growing seasons;
- The length of the vegetation growing season has increased an average of 2 days per decade since 1950 in the conterminous U.S., with most of the increase resulting from earlier spring warming;
- Growth is slowing in areas subject to drought;
- On dry south-facing slopes in Alaska, growth of white spruce has decreased over the last 90 years, due to increased drought stress;
- In semi-arid forests of the south-western U.S., growth rates have decreased since 1895, correlated with drought from warming temperatures;
- Mountain forests are increasingly encroached upon from adjacent lowlands, while simultaneously losing high altitude habitats due to warming (Fischlin et al., 2007).
- In Colorado, aspen have advanced into the more cold-tolerant spruce-fir forests over the past 100 years;
- A combination of warmer temperatures and insect infestations has resulted in economically significant losses of forest resource base to spruce bark beetle in Alaska.

Forest productivity gains may result through: (i) the direct stimulatory CO_2 fertilization effect (although the magnitude of this effect remains uncertain over the long term and can be curtailed by other changing factors); (ii) warming in cold climates, given concomitant precipitation increases to compensate for possibly increasing water vapor pressure deficits; and (iii) precipitation increases under water limited conditions (Fischlin et al., 2007).

New studies suggest that direct CO_2 effects on tree growth may be lower than previously assumed. Additionally, the initial increase in growth increments may be limited by competition, disturbance, air pollutants (primarily tropospheric ozone), nutrient limitations, ecological processes, and other factors, and the response is site- and species-specific (Easterling et al., 2007). Similarly, Ryan et al. (2008) stated that, where nutrients are not limiting, rising CO_2 increases photosynthesis and wood production, but that on infertile soils the extra carbon from increased photosynthesis will be quickly respired.

The general findings from a number of recent syntheses using data from the three American and one European CO_2-enrichment FACE study sites show that North American forests will absorb more CO_2 and might retain more carbon as atmospheric CO_2 increases. The increase in the rate of carbon sequestration will be highest (mostly in wood) on nutrient-rich soils with no water limitation and will decrease with decreasing fertility and water supply. Several yet unresolved questions prevent a definitive assessment of the effect of elevated CO_2 on other components of the carbon cycle in forest ecosystems (Ryan et al., 2008).

As with crop yields, ozone pollution will modify the effects of elevated CO_2 and any changes in temperature and precipitation, but these multiple interactions are difficult to predict because they have been poorly studied (Ryan et al., 2008). Nitrogen deposition also plays a role. Nitrogen deposition and warmer temperatures have very likely increased forest growth where water is not limiting and will continue to do so in the near future. Nitrogen deposition has likely increased forest growth rates over large areas, and interacts positively to enhance the forest growth response to increasing CO_2. These effects are expected to continue in the future as N deposition and rising CO_2 continue.

For the projected temperature increases over the next few decades, most studies support the conclusion that a modest warming of a few degrees Celsius will lead to greater tree growth in the U.S. There are many causes for this enhancement including direct physiological CO_2 effects, a longer growing season, and potentially greater mineralization of soil nutrients. Because different species may respond somewhat differently to warming, the competitive balance of species in forests may change. Trees will probably become established in formerly colder habitats (more northerly, higher altitude) than at present (Ryan et al., 2008).

Productivity gains in one area can occur simultaneously with productivity losses in other areas. For a widespread species like lodgepole pine, a 3ºC temperature increase would increase growth in the northern part of its range, decrease growth in the middle, and decimate southern forests (Field et al., 2007). Climate change is expected to increase California timber production by the 2020s because of stimulated growth in the standing forest. In the long run (up to 2100), these productivity gains were offset by reductions in productive area for softwoods growth. Risks of losses from Southern pine beetle likely depend on the seasonality of warming, with winter and spring warming leading to the greatest damage (Easterling et al., 2007 and references therein).

According to studies reviewed by IPCC (Field et al., 2007), the effects of climate change, in the absence of dramatic increases in disturbance, on the potential for commercial harvest in the 2040s ranged from mixed for a low emissions scenario to positive for a high emissions scenario (see Perez-Garcia et al., 2002). The tendency for North American producers to suffer losses increases if climate change is accompanied by increased disturbance, with simulated losses averaging US$1-2 billion/year, over the 21st century (Sohngen and Sedjo, 2005).

U.S. forestry, in addition to experiencing direct climate change effects, may be indirectly affected by changing forest productivity in different regions of the world. Sohngen and Sedjo (2005) show two climate change scenarios where North American forests undergo more dieback in general than forests in other regions of the world, and where certain North American forest yields increase but less so compared to other regions. The implication is that forests in other parts of the world (including tropical forests with shorter rotations) could have a competitive advantage within the global forestry sector under a changing climate.

Climate change will also substantially impact other non-timber goods and services, such as seeds, nuts, hunting, resins, plants used in pharmaceutical and botanical medicine, and in the cosmetics industry; these impacts will vary significantly across world regions (Easterling et al., 2007).

10(b) Wildfire and Drought Risk

While in some cases a changing climate may have positive impacts on the productivity of forest systems, changes in disturbance patterns are expected to have a substantial impact on overall gains or losses. More prevalent forest fire disturbances have recently been observed in the U.S. and other world regions (Fischlin, et al., 2007). Wildfires and droughts, among other extreme events (e.g., hurricanes) that can cause forest damage, pose the largest threats over time to forest ecosystems.

Several lines of evidence suggest that large, stand-replacing wildfires will likely increase in frequency over the next several decades because of climate warming (Ryan et al., 2008). General climate warming encourages wildfires by extending the summer period that dries fuels, promoting easier ignition and faster spread (Field et al., 2007).

The IPCC (Field et al., 2007 and references therein) noted a number of observed changes to U.S. wildfire size and frequency, often associating these changes with changes in average temperatures:

- Since 1980, an average of about 22,000 km^2/year (13,700 mi^2/year) has burned in wildfires, almost twice the 1920-1980 average of about 13,000 km^2/year (8,080 mi^2/year);
- The forested area burned in the western U.S. from 1987-2003 is 6.7 times the area burned from 1970-1986;

- Human vulnerability to wildfires has increased, with a rising population in the wildland-urban interface;
- In the last three decades, the wildfire season in the western U.S. has increased by 78 days, and burn durations of fires greater than 1,000 ha (2,470 acres) have increased from 7.5 to 37.1 days, in response to a spring/summer warming of 0.87°C (1.4°F);
- Earlier spring snowmelt has led to longer growing seasons and drought, especially at higher elevations, where the increase in wildfire activity has been greatest;
- In the south-western U.S., fire activity is correlated with el Niño-Southern Oscillation (ENSO) positive phases and higher Palmer Drought Severity Indices.[61] Major fire years tend to follow the switching from El Niño to La Niña conditions due to buildup of material during wet years followed by dessication during a dry year (Kitzberger, 2001), whereas small fires are strongly associated directly with previous year drought. Furthermore, increased temperature in the future will likely extend fire seasons throughout the western United States, with more fires occurring earlier and later than is currently typical, and will increase the total area burned in some regions (McKenzie, 2004).

Though fires and extreme events are not well represented in models, current modeling studies suggest that increased temperatures and longer growing seasons will elevate fire risk in connection with increased aridity. Some research identifies the possibility of a 10% increase in the seasonal severity of fire hazard over much of the U.S. under climate change (Easterling, et al., 2007). For Arctic regions, forest fires are expected to increase in frequency and intensity (ACIA, 2004). In California, the risk of increased wildfires as a result of climate change has been identified as a significant issue (California Energy Commission, 2006).

10(c) Forest Composition

Climate change and associated changes in disturbance regimes will cause shifts in the distributions of tree species and alter forest species composition. With warming, forests will extend further north and to higher elevations. Over currently dry regions, increased precipitation may allow forests to displace grasslands and savannas. Changes in forest composition in turn can alter the frequencies, intensities, and impacts of disturbances such as fire, insect outbreaks, and disease.

In Alaska and neighboring Arctic regions, there is strong evidence of recent vegetation composition change, as outlined by the IPCC (Anisimov et al., 2007 and references therein[62]):

- Aerial photographs show increased shrub abundance in 70% of 200 locations;
- Along the Arctic to sub-Arctic boundary, the tree-line has moved about 6 mi (10 km) northwards and 2% of Alaskan tundra on the Seward Peninsula has been displaced by forest in the past 50 years;
- The pattern of northward and upward tree-line advances is comparable with earlier Holocene changes;
- Analyses of satellite images indicate that the length of growing season is increasing by 3 days per decade in Alaska.

Likely rates of migration northward and to higher elevations are uncertain and depend not only on climate change but also on future land-use patterns and habitat fragmentation, which can impede species migration. Bioclimate modeling based on outputs from five general circulation models suggests

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[61] The Palmer Drought Severity Index is used by NOAA and uses a formula that includes temperature and rainfall to determine dryness. It is most effective in determining long-term drought. Positive PDSI indicates wet conditions, negative PDSI indicates dry conditions.

[62] The Anisimov et al. citation refers to Chapter 15, “Polar Regions (Arctic and Antarctic)” in IPCC’s 2007 Fourth Assessment Report, Working Group II.

increases in tree species richness in the Northwest and decreases in the Southwest on long time scales (millennia). Over the next century, however, even positive long-term species richness may lead to short-term decreases because species that are intolerant of local conditions may disappear relatively quickly while migration of new species into the area may be quite slow (Field, et al., 2007; Currie 2001). The Arctic Climate Impact Assessment (2004) also concluded that vegetation zones are projected to migrate northward, with forests encroaching on tundra and tundra encroaching on polar deserts. Limitations in amount and quality of soils are likely to hinder these poleward shifts. No experiments have projected the effect of changes in precipitation on forest tree species composition (Ryan et al., 2008).

10(d) Insects and Diseases

Insects and diseases are a natural part of forested ecosystems and outbreaks often have complex causes. The effects of insects and diseases can vary from defoliation and retarded growth, to timber damage, to massive forest diebacks. Insect life cycles can be a factor in pest outbreaks; and insect lifecycles are sensitive to climate change. Many northern insects have a two-year life-cycle, and warmer winter temperatures allow a larger fraction of overwintering larvae to survive. Recently, spruce budworm in Alaska has completed its life cycle in one year, rather than the previously observed duration of two years (Field et al., 2007). Recent warming trends in the U.S. have led to earlier spring activity of insects and proliferation of some species, such as the mountain pine beetle (Easterling et al., 2007). During the 1990s, Alaska's Kenai Peninsula experienced an outbreak of spruce bark beetle over 16,000 km^2 with 10-20% tree mortality. Also following recent warming in Alaska, spruce budworm has reproduced farther north reaching problematic numbers (Anisimov et al., 2007).Climate change may indirectly affect insect outbreaks by affecting the overall health and productivity of trees. For example, susceptibility of trees to insects is increased when multi-year droughts degrade the trees' ability to generate defensive chemicals (Field, et al., 2007). Warmer temperatures have already enhanced the opportunities for insect spread across the landscape in the U.S. and other world regions (Easterling et al., 2007).

The IPCC (Easterling et al., 2007) stated that modeling of future climate change impacts on insect and pathogen outbreaks remains limited. Nevertheless, the IPCC (Field et al., 2007) states with high confidence that, across North America, impacts of climate change on commercial forestry potential are likely to be sensitive to changes in disturbances from insects and diseases, as well as wildfires.

The CCSP report (Ryan et al., 2008) states that the ranges of the mountain pine beetle and southern pine beetle are projected to expand northward as a result of average temperature increases. Increased probability of spruce beetle outbreak as well as increase in climate suitability for mountain pine beetle attack in high-elevation ecosystems has also been projected in response to warming (Ryan et al., 2008).

Climate change can shift the current boundaries of insects and pathogens and modify tree physiology and tree defense. An increase in climate extremes may also promote plant disease and pest outbreaks (Easterling, et al., 2007).

Section 11

Water Resources

This section covers climate change effects on U.S. water supply, water quality, extreme events affecting water resources, and water uses. Information about observed trends as well as projected impacts is provided.

For North America, IPCC (Field et al., 2007) concluded:

- Climate change will constrain North America's over-allocated water resources, increasing competition among agricultural, municipal, industrial, and ecological uses (very high confidence)[63] . Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. Higher demand from economic development, agriculture and population growth will further limit surface and groundwater availability. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers, and bi-national relationships.

11(a) Water Supply and Snowpack

Surface Water and Snowpack

The semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with increasing dryness eventually interrupted by the Rocky Mountains. The driest climates, however, exist in the Intermountain West and Southwest, which give way as one proceeds west and north to more humid conditions on the upslope areas of the Cascade and coastal mountain ranges, especially in the Pacific Northwest (Lettenmaier et al., 2008).

IPCC reviewed a number of studies showing trends in U.S. precipitation patterns, surface water supply, and snowpack, and how climate change may be contributing to some of these trends (Field et al., 2007):

- Annual precipitation has increased throughout most of North America.
- Streamflow in the eastern U.S. has increased 25% in the last 60 years, but has decreased by about 2% per decade in the central Rocky Mountain region over the last century.
- Since 1950, stream discharge in both the Colorado and Columbia river basins has decreased.
- In regions with winter snow, warming has shifted the magnitude and timing of hydrologic events. The fraction of annual precipitation falling as rain (rather than snow) increased at 74% of the weather stations studied in the western mountains of the U.S. from 1949-2004.
- Spring and summer snow cover has also decreased in the U.S. West.
- Break-up of river and lake ice across North America advanced by 0.2 – 12.9 days over the last 100 years.

In the Arctic, precipitation has increased by about 8% on average over the past century. Much of the increase has fallen as rain, with the largest increases occurring in autumn and winter. Later freeze-up and earlier break-up of river and lake ice have combined to reduce the ice season by one to three weeks in some areas. Glaciers throughout North America are melting, and the particularly rapid retreat of Alaskan

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[63] According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

glaciers represents about half of the estimated loss of glacial mass worldwide (ACIA, 2004). Permafrost plays a large role in the hydrology of lakes and ponds. The spatial pattern of lake disappearance strongly suggests that permafrost thawing is driving the changes. These changes to Arctic precipitation, ice extent, and glacial abundance will affect key regional bio-physical systems, act as climatic feedbacks (primarily by changing surface albedo), and have socio-economic impacts (high confidence) (Anisimov et al., 2007).

The vulnerability of freshwater resources in the U.S. to climate change varies from region to region. Although water management practices in the U.S. are generally advanced, particularly in the West, the reliance on past conditions as the basis for current and future planning will no longer be appropriate, as climate change increasingly creates conditions well outside of historical observations (Lettenmaier et al., 2008). In regions including the Colorado River, Columbia River, and Ogallala Aquifer, surface and/or groundwater resources are intensively used and subject to competition from agricultural, municipal, industrial, and ecological needs. This increases the potential vulnerability to future changes in timing and availability of water (Field et al., 2007).

Projections for the western mountains of the U.S. suggest that warming, and changes in the form, timing, and amount of precipitation will very likely (high confidence) lead to earlier melting and significant reductions in snowpack by the middle of the 21st century (Lettenmaier et al., 2008; Field et al., 2007). In mountainous snowmelt-dominated watersheds, projections suggest advances in the timing of snowmelt runoff, increases in winter and early spring flows (raising flooding potential), and substantially decreased summer flows. Heavily-utilized water systems of the western U.S. that rely on capturing snowmelt runoff, such as the Columbia River system, will be especially vulnerable (Field et al., 2007). Reduced snowpack has been identified as a major concern for the State of California (California Energy Commission, 2006).

Globally, current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, and aquatic ecosystems (very high confidence) (Kundzewicz et al., 2007[64]). Less reliable supplies of water are likely to create challenges for managing urban water systems as well as for industries that depend on large volumes of water. U.S. water managers currently anticipate local, regional, or state-wide water shortages over the next ten years. Threats to reliable supply are complicated by high population growth rates in western states where many resources are at or approaching full utilization. In Eastern North America, daily precipitation so heavy that it now occurs only once every 20 years is projected to occur approximately every eight years by the end of this century, under a mid-range emission scenario (CCSP, 2008i). Potential increases in heavy precipitation, with expanding impervious surfaces, could increase urban flood risks and create additional design challenges and costs for stormwater management (Field et al., 2007). The IPCC (Field et al., 2007 and references therein) reviewed several regional-level studies on climate change impacts to U.S. water management which showed:

- In the Great Lakes – St. Lawrence Basin, many, but not all, assessments project lower net basin supplies and lake water levels. Lower water levels are likely to influence many sectors, with multiple, interacting impacts (IPCC: high confidence). Atmosphere-lake interactions contribute to the uncertainty in assessing these impacts though.
- Urban water supply systems in North America often draw water from considerable distances, so climate impacts need not be local to affect cities. By the 2020s, 41% of the water supply to southern California is likely to be vulnerable due to snowpack loss in the Sierra Nevadas and Colorado River basin.

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[64] The Kundzewicz et al. citation refers to Chapter 3, “Freshwater Resources and their Management” in IPCC’s 2007 Fourth Assessment Report, Working Group II.

- The New York area will likely experience greater water supply variability. New York City's system can likely adapt to future changes, but the region's smaller systems may be vulnerable, leading to a need for enhanced regional water distribution plans.

In the Arctic, river discharge to the ocean has increased during the past few decades, and peak flows in the spring are occurring earlier. These changes are projected to accelerate with future climate change. Snow cover extent in Alaska is projected to decrease by 10-20% by the 2070s, with greatest declines in spring (ACIA, 2004 and reference therein).

The IPCC concluded with high confidence that under most climate change scenarios, water resources in small islands around the globe are likely to be seriously compromised (Mimura et al., 2007). Most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall. Reduced rainfall typically leads to decreased surface water supply and slower recharge rates of the freshwater lens[65], which can result in prolonged drought impacts. Many islands in the Caribbean (which include U.S. territories of Puerto Rico and U.S. Virgin Islands) are likely to experience increased water stress as a result of climate change. Under all SRES scenarios, reduced rainfall in summer is projected for the Caribbean, making it unlikely that the demand for water resources will be met. Increased rainfall in winter is unlikely to compensate for these water deficits due to lack of storage capacity (Mimura et al., 2007[66]).

Groundwater

Groundwater systems generally respond more slowly to climate change than surface water systems. Limited data on existing supplies of groundwater makes it difficult to understand and measure climate effects. In general, groundwater levels correlate most strongly with precipitation, but temperature becomes more important for shallow aquifers, especially during warm periods. In semi-arid and arid areas, groundwater resources are particularly vulnerable because precipitation and streamflow are concentrated over a few months, year-to-year variability is high, and deep groundwater wells or reservoirs generally do not exist (Kundzewicz et al., 2007).

With climate change, availability of groundwater is likely to be influenced by changes in withdrawals (reflecting development, demand, and availability of other sources) and recharge (determined by temperature, timing, and amount of precipitation, and surface water interactions) (medium confidence). In general, simulated aquifer levels respond to changes in temperature, precipitation, and the level of withdrawal. According to IPCC, base flows were found to decrease in scenarios that are drier or have higher pumping rates, and increase in wetter scenarios on average across world regions (Kundzewicz et al., 2007).

Projections suggest that efforts to offset declining surface water availability by increasing groundwater withdrawals will be hampered by decreases in groundwater recharge in some water-stressed regions, such as the southwest US. Vulnerability in these areas is also often exacerbated by the rapid increase of population and water demand (high confidence) (Kundzewicz et al., 2007). Projections for the Ogallala aquifer region suggest that natural groundwater recharge decreases more than 20% in all simulations with different climate models and future warming scenarios of 2.5°C or greater (Field et al., 2007 and reference therein).

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[65] Freshwater lens is defined as a relatively thin layer of freshwater within island aquifer systems that floats on an underlying mass of denser seawater. Numerous factors control the shape and thickness of the lens, including the rate of recharge from precipitation, island geometry, and geologic features such as the permeability of soil layers.

[66] Mimura et al., 2007 refers to Chapter 16, "Small Islands" in IPCC's 2007 Fourth Assessment Report, Working Group II.

In addition, sea level rise will extend areas of salinization of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas. For a discussion of these impacts, please see Section 12.

11(b) Water Quality

The IPCC concluded with high confidence that higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution and can impact ecosystems, human health, and water system reliability and operating costs (Kundzewicz et al., 2007). A CCSP (2008e) report also acknowledges that water quality is sensitive to both increased water temperatures and changes in precipitation; however, most water quality changes observed so far in the U.S. are likely attributable to causes other than climate change.

Pollutants of concern in this case include sediment, nutrients, organic matter, pathogens, pesticides, salt, and thermal pollution (Kundzewicz et al., 2007). IPCC (Kundzewicz et al., 2007) reviewed several studies discussing the impacts of climate change on water quality that showed:

- In lakes and reservoirs, climate change effects are primarily caused by water temperature variations. These variations can be caused by climate change or indirectly through increases in thermal pollution as a result of higher demand for cooling water in the energy sector. This affects, for the U.S. and all world regions, dissolved oxygen regimes, redox potentials[67], lake stratification, mixing rates, and the development of aquatic biota, as they all depend on water temperature. Increasing water temperature affects the self-purification capacity of rivers by reducing the amount of dissolved oxygen available for biodegradation.

- Water pollution problems are exacerbated during low flow conditions where small water quantities result in less dilution and greater concentrations of pollutants.

- Heavy precipitation frequencies in the U.S. were at a minimum in the 1920s and 1930s, and have increased through the 1990s (Field, et al., 2007). Increases in intense rain events result in the introduction of more sediment, nutrients, pathogens, and toxics into water bodies from non-point sources but they also provide the pulse flow needed for some ecosystems.

North American simulations of future surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries consistently increase, with summer surface temperatures exceeding 30°C in midwestern and southern lakes and reservoirs. IPCC projects that warming is likely to extend and intensify summer thermal stratification in surface waters, further contributing to oxygen depletion (Field et al., 2007 and references therein).

Higher water temperature and variations in runoff are likely to produce adverse changes in water quality affecting human health, ecosystems, and water uses. Elevated surface water temperatures will promote algal blooms and increases in bacteria and fungi levels. Warmer waters also transfer volatile and semi-volatile compounds (ammonia, mercury, PCBs, dioxins, pesticides) from surface water bodies to the atmosphere more rapidly (Kundzewicz et al., 2007). Although this transfer will improve water quality, air quality will be negatively impacted.

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[67] Redox potential is defined as the tendency of a chemical species to acquire electrons and therefore be reduced.

Lowering of the water levels in rivers and lakes can lead to re-suspension of bottom sediments and liberating compounds, with negative effects on water supplies (Field et al., 2007 and references therein). These impacts may lead to a bad odor and taste in chlorinated drinking water and greater occurrence of toxins. More intense rainfall will lead to increases in suspended solids (turbidity) and pollutant levels in water bodies due to soil erosion (Kundzewicz et al., 2007). Moreover, even with enhanced phosphorus removal in wastewater treatment plants, algal growth in water bodies may increase with warming over the long term. Increasing nutrient and sediment loads due to more intense runoff events will negatively affect water quality, requiring additional treatment to render it suitable for drinking water.

Climate change is likely to make it more difficult to achieve existing water quality goals for sediment (IPCC: high confidence) because hydrologic changes affect many geomorphic processes including soil erosion, slope stability, channel erosion, and sediment transport (Field et al., 2007). IPCC reviewed a number of region-specific studies on U.S. water quality and projected that:

- Changes in precipitation may increase nitrogen loads from rivers in the Chesapeake and Delaware Bay regions by up to 50% by 2030 (Kundzewicz et al., 2007 and reference therein).

- Decreases in snowcover and increases in winter rain on bare soil will likely lengthen the erosion season and enhance erosion intensity. This will increase the potential for sediment related water quality impacts in agricultural areas without appropriate soil management techniques (Field et al., 2007 and reference therein). All studies on soil erosion suggest that increased rainfall amounts and intensities will lead to greater rates of erosion, within the U.S. and in other regions, unless protection measures are taken (Kundzewicz et al., 2007). Soil management practices (e.g., crop residue, no-till) in some regions (e.g., the Cornbelt) may not provide sufficient erosion protection against future intense precipitation and associated runoff (Field et al., 2007).

11(c) Extreme Events

There are a number of climatic and non-climatic drivers influencing flood and drought impacts. Whether risks are realized depends on several factors. Floods can be caused by intense and/or long-lasting precipitation events, rapid snowmelt, dam failure, or reduced conveyance due to ice jams or landslides. Flood magnitude and spatial extent depend on the intensity, volume, and time of precipitation, and the antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil composition, level of human development, existence of dikes, dams, and reservoirs, etc.) (Kundzewicz et al., 2007).

Precipitation intensity will increase across the U.S., but particularly at mid and high latitudes where mean precipitation also increases. This will affect the risk of flash flooding and urban flooding (Kundzewicz et al., 2007). Some studies project widespread increases in extreme precipitation with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation. In general, projected changes in precipitation extremes are larger than changes in mean precipitation (Field et al., 2007).

The socio-economic impacts of droughts arise from the interaction between climate, natural conditions, and human factors such as changes in land use. In dry areas, excessive water withdrawals from surface and groundwater sources can exacerbate the impacts of drought (Kundzewicz et al., 2007). Although drought has been more frequent and intense in the western part of the U.S., the East is also vulnerable to droughts and attendant reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Field et al., 2007).

In addition to the effects on water supply, extreme events, such as floods and droughts, will likely reduce water quality. Increased erosion and runoff rates during flood events will wash pollutants (e.g., organic matter, fertilizers, pesticides, heavy metals) from soils into water bodies, with subsequent impacts to species and ecosystems. During drought events, the lack of precipitation and subsequent low flow conditions will impair water quality by reducing the amount of water available to dilute pollutants. These effects from floods and droughts will make it more difficult to achieve pollutant discharge limits and water quality goals (Kundzewicz et al., 2007).

11(d) Implications for Water Uses

There are many competing water uses in the U.S. that will be adversely impacted by climate change impacts to water supply and quality. The IPCC reviewed a number of studies describing the impacts of climate change on water uses in the U.S. which showed:

- Decreased water supply and lower water levels are likely to exacerbate challenges relating to navigation in the U.S. (Field et al., 2007). Some studies have found that low flow conditions may restrict ship loading in shallow ports and harbors (Kundzewicz et al., 2007). However, navigational benefits from climate change exist as well. For example, the navigation season for the North Sea Route is projected to increase from the current 20-30 days per year to 90-100 days by 2080 (ACIA, 2004 and references therein).
- Climate change impacts to water supply and quality will affect agricultural practices, including the increase of irrigation demand in dry regions and the aggravation of non-point source water pollution problems in areas susceptible to intense rainfall events and flooding (Field et al., 2007). For more information on climate change impacts to agriculture, please see Section 9.
- The U.S. energy sector, which relies heavily on water for generation (hydropower) and cooling capacity, will be adversely impacted by changes to water supply and quality in reservoirs and other water bodies (Wilbanks et al., 2007). For more information on climate change impacts to the energy sector, please see Section 13.
- Climate-induced environmental changes (e.g., loss of glaciers, reduced river discharge in some regions, reduced snow fall in winter) will affect park tourism, winter sport activities, inland water sports (e.g., fishing, rafting, boating), and other recreational uses dependent upon precipitation (Field et al., 2007). While the North American tourism industry acknowledges the important influence of climate, its impacts have not been analyzed comprehensively.

Section 12

Sea Level Rise and Coastal Areas

This section of the document discusses areas in the U.S. vulnerable to sea level rise, associated interactions with coastal development, important coastal processes, observed and projected impacts, and how climate change effects on extreme events will impact coastal areas. Information on the observed and projected rates of sea level rise due to climate change can be found in Sections 4(g) and 6(c), respectively.

The IPCC (Field et al., 2007) concluded the following when considering how climate change may affect sea level rise and coastal areas in North America:

- Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution (very high confidence).[68] Sea level is rising along much of the coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion.
- Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt marshes, other coastal habitats, and dependent species are threatened by sea-level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change.

12(a) Vulnerable Areas

Interaction with Coastal Zone Development

Coastal population growth in deltas, barrier islands, and estuaries has led to widespread conversion of natural coastal landscapes to agriculture, and aquaculture as well as industrial and residential uses. According to NOAA (Crossett et al., 2007), approximately 153 million people (53% of the total population) lived in the 673 US coastal counties in 2003. This represents an increase of 33 million people since 1980, and by 2008, the number was projected to rise to 160 million. This population growth, the rising value of coastal property, and the projected increases in storm intensity have increased the vulnerability of coastal areas to climate variability and future climate change (IPCC, 2007b).

For small islands, the coastline is long relative to island area. As a result, many resources and ecosystem services are threatened by a combination of human pressures and climate change effects including sea-level rise, increases in sea surface temperature, and possible increases in extreme weather events (Mimura et al., 2007).

Although climate change is impacting coastal systems, non-climate human impacts have been more damaging over the past century. The major non-climate impacts for the U.S. and other world regions include drainage of coastal wetlands, resource extraction[69], deforestation, introductions of invasive species, shoreline protection, and the discharge of sewage, fertilizers, and contaminants into coastal

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[68] According to IPCC terminology, “very high confidence” conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

[69] Resource extraction activities in coastal areas include sand/coral mining, hydrocarbon production, and commercial and recreational fishing.

waters (Nicholls et al., 2007)[70]. The cumulative effect of these non-climate, anthropogenic impacts increases the vulnerability of coastal systems to climate-related stressors.

Coastal Processes

Climate change and sea-level rise affect sediment transport in complex ways. Erosion and ecosystem loss is affecting many parts of the US coastline, but it remains unclear to what extent these losses result from climate change instead of land loss associated with relative sea-level rise due to subsidence and other human drivers (Nicholls et al., 2007).

Coastal wetland loss is also being observed in the U.S. where these ecosystems are squeezed between natural and artificial landward boundaries and rising sea levels, a process known as 'coastal squeeze' (Field et al., 2007). The degradation of coastal ecosystems, especially wetlands and coral reefs, can have serious implications for the well-being of societies dependent on them for goods and services (Nicholls et al., 2007). For more information regarding climate change impacts to coral reefs, see Section 14.

Engineering structures, such as bulkheads, dams, levees, and water diversions, limit sediment supply to coastal areas. Wetlands are especially threatened by sea level rise when insufficient amounts of sediment from upland watersheds are deposited on them. If sea level rises slowly, the balance between sediment supply and morphological adjustment can be maintained if a salt marsh vertically accretes[71], or a lagoon infills, at the same rate. However, an acceleration in the rate of sea-level rise may mean that coastal marshes and wetlands cannot keep up, particularly where the supply of sediment is limited (e.g., where coastal floodplains are inundated after natural levees or artificial embankments are overtopped) (Nicholls et al., 2007).

Although open coasts have been the focus of research on erosion and shore stabilization technology, sheltered coastal areas in the U.S. are also vulnerable and suffer secondary effects from rising seas (NRC, 2006a). For example, barrier island erosion in Louisiana has increased the height of waves reaching the shorelines of coastal bays. This has enhanced erosion rates of beaches, tidal creeks, and adjacent wetlands. The impacts of accelerated sea-level rise on gravel beaches have received less attention than sandy beaches; however these systems are threatened by sea-level rise, even under high wetland accretion rates. The persistence of gravel and cobble-boulder beaches will also be influenced by storms, tectonic events, and other factors that build and reshape these highly dynamic shorelines (Nicholls et al., 2007).

Observed Changes

According to the IPCC, most of the world's sandy shorelines retreated during the past century and climate change induced sea-level rise is one underlying cause. To date in the U.S., more than 50% of the original salt marsh habitat has already been lost. In Mississippi and Texas, over half of the shorelines eroded at average rates of 2.6 to 3.1 m/yr since the 1970s, while 90% of the Louisiana shoreline eroded at a rate of 12.0 m/yr (Nicholls et al., 2007 and references therein).

In the Great Lakes where sea level rise is not a concern, both extremely high and low water levels resulting from changes to the hydrological cycle have been damaging and disruptive to shoreline communities (Nicholls et al., 2007). High lake water levels increase storm surge flooding, accelerate shoreline erosion, and damage industrial and commercial infrastructure located on the shore. Conversely,

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[70] Nicholls et al., 2007 refers to Chapter 6, "Coastal Systems and Low-lying Areas" in IPCC's 2007 Fourth Assessment Report, Working Group II.

[71] The term 'vertical accretion' is defined as the accumulation of sediments and other materials in a wetland habitat that results in build-up of the land in a vertical direction.

low lake water levels can pose problems for navigation, and expose intake/discharge pipes for electrical utilities and municipal water treatment plants, and cause unpleasant odors.

In the Arctic, coastal stability is affected by factors common to all areas (i.e., shoreline exposure, relative sea level change, climate, and local geology), and by factors specific to the high-latitudes (i.e., low temperatures, ground ice, and sea ice) (Anisimov et al., 2007). Adverse impacts have already been observed along Alaskan coasts and traditional knowledge points to widespread coastal change in Alaska. Rising temperatures in Alaska are reducing the thickness and spatial extent of sea ice. This creates more open water and allows for winds to generate stronger waves, which increase shoreline erosion. Sea level rise and thawing of coastal permafrost exacerbate this problem. Higher waves will create even greater potential for this kind of erosion damage (ACIA, 2004).

Projected Impacts

The U.S. coastline is long and diverse with a wide range of coastal characteristics. Sea level rise changes the shape and location of coastlines by moving them landward along low lying contours and exposing new areas to erosion (NRC, 2006a). Coasts subsiding due to natural or human-induced causes will experience larger relative rises in sea level. In some locations, such as deltas and coastal cities (e.g., the Mississippi delta and surrounding cities), this effect can be significant (Nicholls et al., 2007). Rapid development, including an additional 25 million people in the coastal U.S. over the next 25 years, will further reduce the resilience of coastal areas to rising sea levels (Field et al., 2007). Superimposed on the impacts of erosion and subsidence, the effects of rising sea level will exacerbate the loss of waterfront property and increase vulnerability to inundation hazards (Nicholls et al., 2007).

If sea-level rise occurs over the next century at a rate consistent with the higher range of the 2007 IPCC scenarios (i.e., 50-60 cm rise in sea level by 2100), it is about as likely as not that some barrier island coasts in the mid-Atlantic region will cross a geomorphic threshold and experience significant changes. Such changes include more rapid landward migration or barrier island segmentation (Gutierrez et al., 2009).

Up to 21% of the remaining coastal wetlands in the U.S. mid-Atlantic region are potentially at risk of inundation between 2000 and 2100 (Field et al., 2007 and reference therein). Rates of coastal wetland loss, in the Chesapeake Bay and elsewhere, will increase with accelerated sea-level rise, in part due to 'coastal squeeze' (IPCC: high confidence). It is virtually certain that those tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss will continue to lose area in the future due to both accelerated rates sea-level rise as well as changes in other environmental and climate drivers (Cahoon et al., 2009). Salt-marsh biodiversity is likely to decrease in north-eastern marshes through expansion of non-native species such as *Spartina alterniflora*. The IPCC (Field et al., 2007) projects that many U.S. salt marshes in less developed areas can potentially keep pace with sea-level rise through vertical accretion.

Climate change is likely to have a strong impact on saltwater intrusion into coastal sources of groundwater in the U.S. and other world regions. Sea-level rise and high rates of water withdrawal, promote the intrusion of saline water into the groundwater supplies, which adversely affects water quality. Reduced groundwater recharge associated with decreases in precipitation and increased evapotranspiration[72], will exacerbate sea level rise effects on salinization rates (Kundzewicz et al., 2007). This effect could impose enormous costs on water treatment infrastructure (i.e., costs associated with

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[72] Evapotranspiration is defined as the total amount of evaporation from surface water bodies (e.g., lakes, rivers, reservoirs), soil, and plant transpiration. In this context, warmer temperatures brought on by climate change will drive greater levels of evapotranspiration.

relocating infrastructure or building desalinization capacity), especially in densely populated coastal areas. Saltwater intrusion is also projected to occur in freshwater bodies along the coast. Estuarine and mangrove ecosystems can withstand a range of salinities on a short term basis; however, they are unlikely to survive permanent exposure to high salinity environments. Saltwater intrusion into freshwater rivers has already been linked with the decline of bald cypress forests in Louisiana and cabbage palm forests in Florida. Given that these ecosystems provide a variety of ecosystem services and goods (e.g., spawning habitat for fish, pollutant filtration, sediment control, storm surge attenuation), the loss of these areas could be significant (Kundzewicz et al., 2007).

The vulnerable nature of coastal indigenous communities to climate change arises from their geographical location, reliance on the local environment for aspects of everyday life such as diet and economy, and the current state of social, cultural, economic, and political change taking place in these regions (Anisimov et al., 2007). Sea ice extent in the Arctic Ocean is expected to continue to decrease and may even disappear entirely during summer months in the coming decades. This reduction of sea ice increases extreme coastal erosion in Arctic Alaska, due to the increased exposure of the coastline to strong wave action (CCSP, 2008i). These effects, along with sea level rise, will accelerate the already high coastal erosion rates in permafrost-rich areas of Alaska’s coastline, thereby forcing the issue of relocation for threatened settlements. It has been estimated that relocating the village of Kivalina, AK to a nearby site would cost US$54 million (Anisimov et al., 2007).

For small islands, some studies suggest that sea-level rise could reduce of island size, particularly in the Pacific, raising concerns for Hawaii and other U.S. territories (Mimura et al., 2007). In some cases, accelerated coastal erosion may lead to island abandonment, as has been documented in the Chesapeake Bay. Island infrastructure tends to predominate in coastal locations. In the Caribbean and Pacific Islands, more than 50% of the population lives within 1.5 km of the shore. International airports, roads, capital cities, and other types of infrastructure, are typically sited along the coasts of these islands as well. Therefore, the socio-economic well-being of island communities will be threatened by inundation, storm surge, erosion, and other coastal hazards resulting from climate change (high confidence) (Mimura et al., 2007).

12(b) Extreme Events

Although increases in mean sea level over the 21st century and beyond will inundate unprotected, low-lying areas, the most devastating impacts are likely to be associated with storm surge (Nicholls et al., 2007). For example, the Maryland Geological Survey estimated that more than 20 acres of the State’s land was lost on the western shore of Chesapeake Bay in the wake of Tropical Storm Isabel, causing approximately $84,000,000 in damages to shoreline structures (NRC, 2006a and references therein).

Superimposed on accelerated sea level rise, storm intensity, wave height, and storm surge projections suggest more severe coastal flooding and erosion hazards (Nicholls et al., 2007). Higher sea level provides an elevated base for storm surges to build upon and diminishes the rate at which low-lying areas drain, thereby increasing the risk of flooding from rainstorms (CCSP, 2009a). In New York City and Long Island, flooding from a combination of sea level rise and storm surge could be several meters deep (Field et al., 2007). Projections suggest that the return period of a 100-year flood event in this area might be reduced to 19-68 years, on average, by the 2050s, and to 4-60 years by the 2080s (Wilbanks et al., 2007; and references therein).

Additionally, some major urban centers in the U.S. are situated in low-lying flood plains. For example, areas of New Orleans and its vicinity are 1.5-3 meters below sea level. Considering the rate of subsidence and using a mid-range estimate of 480 millimeters sea-level rise by 2100, it is projected that this region could be 2.5 to 4.0 meters or more below mean sea level by 2100 (Field et al., 2007). In this scenario, a storm surge from a Category 3 hurricane (estimated at 3 to 4 meters without waves) could be six to seven meters above areas that were heavily populated in 2004 (Field et al., 2007 and references therein).

The IPCC discusses a number of other extreme event scenarios and observations with implications for coastal areas of the US:

- Very large sea-level rises that would result from widespread deglaciation of Greenland and West Antarctic ice sheets imply major changes in coastlines and ecosystems, and inundation of low-lying areas, with greatest effects in river deltas. Relocating populations, economic activity, and infrastructure would be costly and challenging (IPCC, 2007b).
- Under El Niño conditions, high water levels combined with changes in winter storms along the Pacific coast have produced severe coastal flooding and storm impacts. In San Francisco, 140 years of tide-gauge data suggest an increase in severe winter storms since 1950 and some studies have detected accelerated coastal erosion (Field et al., 2007).
- Recent winters with less ice in the Great Lakes and Gulf of St. Lawrence have increased coastal exposure to damage from winter storms (Field et al., 2007).
- Recent severe tropical and extra-tropical storms demonstrate that North American urban centers with assumed high adaptive capacity remain vulnerable to extreme events (Field et al., 2007).

Demand for waterfront property and building land in the U.S. continues to grow, increasing the value of property at risk. Of the $19 trillion value of all insured residential and commercial property in the US states exposed to North Atlantic hurricanes, $7.2 trillion (41%) is located in coastal counties. This economic value includes 79% of the property in Florida, 63% of property in New York, and 61% of the property in Connecticut (AIR, 2002 in Field et al., 2007). Highlighting this vulnerability, a recent OECD study estimated that the U.S. has five of the top ten port cities globally in terms of assets currently exposed to coastal flooding due to storm surge and damage due to high winds: Miami, Greater New York, New Orleans, Tampa-St. Petersburg, and Virginia Beach (Nicholls et al., 2008). The devastating effects of hurricanes Ivan in 2004 and Katrina, Rita and Wilma in 2005 illustrate the vulnerability of North American infrastructure and urban systems that were not designed or not maintained to adequate safety margins. When protective systems fail, impacts can be widespread and multi-dimensional (Field et al., 2007).

Section 13

Energy, Infrastructure and Settlements

According to IPCC (Wilbanks et al., 2007), "[i]ndustries, settlements and human society are accustomed to variability in environmental conditions, and in many ways they have become resilient to it when it is a part of their normal experience. Environmental changes that are more extreme or persistent than that experience, however, can lead to vulnerabilities, especially if the changes are not foreseen and/or if capacities for adaptation are limited."

Climate change is likely[73] to affect U.S. energy use and energy production; physical infrastructures; institutional infrastructures; and will likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements (Wilbanks et al., 2007), particularly in Alaska where indigenous communities are facing major environmental and cultural impacts on their historic lifestyles (ACIA, 2004). The research evidence is relatively clear that climate warming will mean reductions in total U.S. heating requirements and increases in total cooling requirements for buildings. These changes will vary by region and by season, but they will affect household and business energy costs and their demands on energy supply institutions. In general, the changes imply increased demands for electricity, which supplies virtually all cooling energy services but only some heating services. Other effects on energy consumption are less clear (CCSP, 2007a).

13(a) Heating and Cooling Requirements

With climate warming, less heating is required for industrial, commercial, and residential buildings in the U.S., but more cooling is required, with changes varying by region and by season. Net energy demand at a national scale will be influenced by the structure of the energy supply. The main source of energy for cooling is electricity, while coal, oil, gas, biomass, and electricity are used for space heating. Regions with substantial requirements for both cooling and heating could find that net annual electricity demands increase while demands for other heating energy sources decline. Critical factors for the U.S. are the relative efficiency of space cooling in summer compared to space heating in winter, and the relative distribution of populations in colder northern or warmer southern regions. Seasonal variation in total demand is also important. In some cases, due to infrastructure limitations, peak demand could go beyond the maximum capacity of the electricity transmission system (Wilbanks et al., 2007).

Recent North American studies generally confirm earlier work showing a small net change (increase or decrease, depending on methods, scenarios, and location) in net demand for energy in buildings but a significant increase in demand for electricity for space cooling, with further increases caused by additional market penetration of air conditioning (high confidence) (Field et al., 2007). Generally speaking, the net effects of climate change in the U.S. on total energy demand are projected to amount to between perhaps a 5% increase and decrease in demand per 1ºC in warming in buildings. Existing studies do not agree on whether there would be a net increase or decrease in energy consumption with changed climate because a variety of methodologies have been used (CCSP, 2007a).

In California, if temperatures rise according to a high scenario range (8-10.5ºF; ~4.5-5.6ºC), annual electricity demand for air conditioning could increase by as much as 20% by the end of the century (assuming population remains unchanged and limited implementation of efficiency measures) (California

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[73] According to IPCC terminology, "likely" conveys a 66 to 90% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Energy Commission, 2006)[74]. In Alaska, there will be savings on heating costs: modeling has predicted a 15% decline in the demand for heating energy in the populated parts of the Arctic and sub-Arctic and up to one month decrease in the duration of a period when heating is needed (Anisimov et al., 2007).

Overall, both net delivered energy and net primary energy consumption increase or decrease only a few percent with a 1ºC or 2ºC warming; however, there is a robust result that, in the absence of an energy efficiency policy directed at space cooling, climate change would cause a significant increase in the demand for electricity in the U.S., which would require the building of additional electricity generation capacity (and probably transmission facilities) worth many billions of dollars (CCSP, 2007a).

Beyond the general changes described above, general temperature increases can mean changes in energy consumption in key climate-sensitive sectors of the economy, such as transportation, construction, agriculture, and others. Furthermore, there may be increases in energy used to supply other resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses (CENR, 2008).

13(b) Energy Production

Climate change could affect U.S. energy production and supply (a) if extreme weather events become more intense, (b) where regions dependent on water supplies for hydropower and/or thermal power plant cooling face reductions or increases in water supplies, (c) where changed conditions affect facility siting decisions, and (d) where climatic conditions change (positively or negatively) for biomass, wind power, or solar energy production (Wilbanks et al., 2007; CCSP 2007a).

Significant uncertainty exists about the potential impacts of climate change on energy production and distribution, in part because the timing and magnitude of climate impacts are uncertain. Nonetheless, every existing source of energy in the U.S. has some vulnerability to climate variability. Renewable energy sources tend to be more sensitive to climate variables; but fossil energy production can also be adversely effected by air and water temperatures, and the thermoelectric cooling process that is critical to maintaining high electrical generation efficiencies also applies to nuclear energy. In addition, extreme weather events have adverse effects on energy production, distribution, and fuel transportation (CCSP, 2007a).

Fossil and Nuclear Energy

Climate change impacts on U.S. electricity generation at fossil and nuclear power plants are likely to be similar. The most direct climate impacts are related to power plant cooling and water availability. As currently designed, power plants require significant amounts of water, and they are vulnerable to fluctuations in water supply. Regional scale changes would likely mean that some areas would see significant increases in water availability while other regions would see significant decreases. In those areas seeing a decline, the impact on power plant availability or even siting of new capacity could be significant. Plant designs are flexible and new technologies for water reuse, heat rejection, and use of alternative water sources are being developed; but, at present, some impact—significant on a local level—can be foreseen (CCSP, 2007a).

Renewable Energy

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[74] Temperature projections for the State of California are based on IPCC global emission scenarios as discussed in Section 6(a).

Because renewable energy depends directly on ambient natural resources such as hydrological resources, wind patterns and intensity, and solar radiation, it is likely to be more sensitive to climate variability than fossil or nuclear energy systems that rely on geological stores. Renewable energy systems in the U.S. are also vulnerable to damage from extreme weather events (CCSP, 2007a).

Hydropower generation is sensitive to the amount, timing, and geographical pattern of precipitation as well as temperature (rain or snow, timing of melting). Reduced stream flows are expected to jeopardize hydropower production in some areas of the U.S., whereas greater stream flows, depending on their timing, might be beneficial (Wilbanks et al., 2007). In California, where hydropower now comprises about 15% of in-state energy production, diminished snow melt flowing through dams will decrease the potential for hydropower production by up to 30% if temperatures rise to the medium warming range by the end of the century (5.5-8ºF (~3.1-4.4ºC) increase in California) and precipitation decreases by 10 to 20%. However, future precipitation projections are quite uncertain so it is possible that precipitation may increase and expand hydropower generation (California Energy Commission, 2006).

North American wind and solar resources are about as likely as not to increase (medium confidence). Studies to date project wind resources that are either unchanged by climate change, or reduced by 0-40%. Future changes in cloudiness could slightly increase the potential for solar energy in North America south of 60°N, but one study projected that increased cloudiness will likely decrease the output of photovoltaics by 0-20% (Field et al., 2007).

Bioenergy potential is climate-sensitive through direct impacts on crop growth and availability of irrigation water. Warming and precipitation increases are expected to allow the bioenergy crop switchgrass, for instance, to compete effectively with traditional crops in the central U.S (Field et al., 2007). Renewable energy production is highly susceptible to localized and regional changes in the resource base. As a result, the greater uncertainties on regional impacts under current climate change modeling pose a significant challenge in evaluating medium to long-term impacts on renewable energy production (CCSP, 2007a).

Energy Supply and Transmission

Extreme weather events can threaten coastal energy infrastructures and electricity transmission and distribution infrastructures in the U.S. and other world regions (Wilbanks et al., 2007). Hurricanes in particular can have severe impacts on energy infrastructure. In 2004, hurricane Ivan destroyed seven Gulf of Mexico oil drilling platforms and damaged 102 pipelines, while hurricanes Katrina and Rita in 2005 destroyed more than 100 platforms and damaged 558 pipelines (CCSP, 2007a). Though it is not possible to attribute the occurrence of any singular hurricane to climate change, projections of climate change suggest that extreme weather events are very likely to become more intense. If so, then the impacts of Katrina may be a possible indicator of the kinds of impacts that could manifest as a result of climate change (CCSP, 2007a).

In addition to the direct effects on operating facilities themselves, U.S. networks for transport, electric transmission, and delivery would be susceptible to changes due to climate change in stream flow, annual and seasonal precipitation patterns, storm severity, and even temperature increases (e.g., pipelines handling supercritical fluids may be impacted by greater heat loads) (CCSP, 2007a).

U.S. rail transportation lines, which transport approximately 2/3 of the coal to the nation's power plants (EIA, 2002; as referenced in CCSP, 2007a), often closely follow riverbeds. More severe rainstorms can lead to flooding of rivers which then can wash out or degrade the nearby roadbeds. Flooding may also disrupt the operation of inland waterways, the second-most important method of transporting coal. With utilities carrying smaller stockpiles and projections showing a growing reliance on coal for a majority of the nation's electricity production, any significant disruption to the transportation network has serious implications for the overall reliability of the grid as a whole. (CCSP, 2007a)

In the Arctic, soil subsidence caused by the melting of permafrost is a risk to gas and oil pipelines, electrical transmission towers, and natural gas processing plants (Wilbanks et al., 2007). Along the Beaufort Sea in Alaska, climate impacts on oil and gas development in the region are likely to result in both financial benefits and costs in the future. For example, offshore oil exploration and production are likely to benefit from less extensive and thinner sea ice, although equipment will have to be designed to withstand increased wave forces and ice movement (ACIA, 2004).

13(c) Infrastructure and Settlements

Climate change vulnerabilities of industry, settlement and society are mainly related to extreme weather events rather than to gradual climate change. The significance of gradual climate change, e.g., increases in the mean temperature, lies mainly in changes in the intensity and frequency of extreme events, although gradual changes can also be associated with thresholds beyond which impacts become significant, such as in the capacities of infrastructures (Field et al., 2007). Such climate-related thresholds for human settlements in the U.S. are currently not well understood (Wilbanks et al., 2008).

Extreme weather events could threaten U.S. coastal energy infrastructure and electricity transmission and distribution infrastructures. Moreover, soil subsidence caused by the melting of permafrost in the Arctic region is a risk to gas and oil pipelines, and electrical transmission towers. Vulnerabilities of industry, infrastructures, settlements and society to climate change are generally greater in certain high-risk locations, particularly coastal and riverine areas, and areas whose economies are closely linked with climate-sensitive resources, such as agricultural and forest product industries, water demands and tourism; these vulnerabilities tend to be localized but are often large and growing (high confidence) (Wilbanks et al., 2007). Additionally, infrastructures are often connected, meaning that an impact on one can also affect others. For example, an interruption in energy supply can increase heat stress for vulnerable populations (Wilbanks et al., 2008).

A few studies have projected increasing vulnerability of U.S. infrastructure to extreme weather related to climate warming unless adaptation is effective (high confidence). Examples include the New York Metropolitan Region, the mid-Atlantic Region, and the urban transportation network of the Boston metropolitan area (Wilbanks et al., 2007). In Alaska, examples where infrastructure is projected to be at "moderate to high hazard" in the mid-21st century include Shishmaref, Nome, Barrow, the Dalton Highway, and the Alaska Railroad (Field et al., 2007). Where extreme weather events become more intense and/or more frequent with climate change, the economic and social costs of those events will increase (high confidence) (Wilbanks et al., 2007).

Buildings and Construction

In some Arctic areas, interactions between climate warming and inadequate engineering are causing problems. The weight of buildings on permafrost is an important factor; while many heavy, multi-story buildings of northern Russia have suffered structural failures, the lighter-weight buildings of North America have had fewer such problems as permafrost has warmed. Continuous repair and maintenance is also required for building on permafrost, a lesson learned because many of the buildings that failed were not properly maintained. The problems now being experienced in Russia may be expected to occur elsewhere in the Arctic if buildings are not designed and maintained to accommodate future warming (ACIA, 2004).

The cost of rehabilitating community infrastructure damaged by thawing permafrost could be significant. Even buildings designed specifically for permafrost environments may be subject to severe damage if design criteria are exceeded. The impervious nature of ice-rich permafrost has been relied on for contaminant holding facilities, and thawing such areas could result in severe contamination of hydrological resources and large cleanup costs, even for relatively small spills (Anisimov et al., 2007).

The construction season in the northern U.S. likely will lengthen with warming. In permafrost areas in Alaska, increasing depth of the "active layer" or loss of permafrost can lead to substantial decreases in soil strength. Construction methods are likely to require changes in areas currently underlain by permafrost, potentially increasing construction and maintenance cost (high confidence) (Field et al., 2007).

Transportation

In a 2008 report entitled, "Potential Impacts of Climate Change on U.S. Transportation," the National Research Council (NRC) issued the following finding:

> *Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days; intense precipitation events; intense hurricanes; drought; and rising sea levels, coupled with storm surges and land subsidence. The impacts will vary by mode of transportation and region of the country, but they will be widespread and costly in both human and economic terms and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems* (NRC, 2008).

NRC states that transportation infrastructure was designed for typical weather patterns, reflecting local climate and incorporating assumptions about a reasonable range of temperatures and precipitation levels (NRC, 2008). An increase in the frequency, intensity, or duration of heat spells in the U.S. and other world regions could cause railroad tracks to buckle, and affect roads through softening and traffic-related rutting. Warmer or less snowy winters will likely reduce delays, improve ground and air transportation reliability, and decrease the need for winter road maintenance. More intense winter storms could, however, increase risk for traveler safety and require increased snow removal. Continuation of the declining fog trend in at least some parts of North America should benefit transport (Field et al., 2007).

Warming will likely affect infrastructure for surface transport at high northern latitudes, such as Alaska. Permafrost degradation reduces surface bearing capacity and potentially triggers landslides. While the season for transport by barge is likely to be extended, the season for ice roads will likely be compressed. Other types of roads are likely to incur costly improvements in design and construction (Field et al., 2007).

Similarly, NRC found the following:

> *Potentially, the greatest impact of climate change for North America's transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence* (NRC, 2008).

Because of warming, the number of days per year in which travel on the tundra is allowed under Alaska Department of Natural Resources standards has dropped from over 200 to about 100 in the past 30 years, resulting in a 50% reduction in days that oil and gas exploration and extraction can occur (ACIA, 2004). Forestry is another industry that requires frozen ground and rivers. Higher temperatures mean thinner ice on rivers and a longer period during which the ground is thawed. This leads to a shortened period during which timber can be moved from forests to sawmills, and increasing problems associated with transporting wood (ACIA, 2004).

Lakes and river ice have historically provided major, winter transportation routes and connections to smaller settlements in the Arctic. Reductions in ice thickness will reduce the load-bearing capacity, and shortening of the ice-season will shorten period of access. Where an open-water network is viable, it will be sensible to increase reliance on water transport. In land locked locations, construction of all-weather roads may be the only viable option, with implications for significantly increased costs. Similar issues will impact the use of sea ice roads primarily used to access offshore facilities (Anisimov et al., 2007). Loss of summer sea ice will bring an increasingly navigable Northwest Passage. Increased marine navigation and longer summers will improve conditions for tourism and travel associated with research (Anisimov et al., 2007). Along with rising water temperatures, however, increased shipping will also multiply the risk of marine pests and pollution (Anisimov et al., 2007).

Negative impacts on transportation very likely will include coastal and riverine flooding and landslides. Although offset to some degree by fewer ice threats to navigation, reduced water depth in the Great Lakes would lead to “light loading” and adverse economic impacts (Field et al., 2007).

Of all the possible impacts on transportation, the greatest in terms of cost is that of flooding. The costs of delays and lost trips would be relatively small compared with damage to the infrastructure and to other property (Wilbanks et al., 2007).

The central Gulf Coast is particularly vulnerable to climate variability and change because of the frequency with which hurricanes strike, because much of its land is sinking relative to mean sea level, and because much of its natural protection—in the form of barrier islands and wetlands—has been lost. While difficult to quantify, the loss of natural storm buffers will likely intensify many climate impacts, particularly in relation to storm damage (CCSP, 2008b).

Since much of the land in the Gulf Coast is sinking, this area is facing much higher increases in relative sea level rise (the combination of local land surface movement and change in mean sea level) than most other parts of the U.S. coast. The CCSP report found that relative sea level rise in the study area is very likely to increase by at least 0.3 m (1 ft) across the region and possibly as much as 2 m (6 to 7 ft) in some parts of the study area over the next 50 to 100 years. The analysis of even a middle range of potential sea level rise of 0.3 to 0.9 m (2 to 4 ft) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be inundated in the future. The projected rate of relative sea level rise for the region during the next 50 to 100 years is consistent with historical trends, region-specific analyses, and the IPCC *Fourth Assessment Report* (2007) findings, which assume no major changes in ice-sheet dynamics (CCSP, 2008b).

Twenty-seven percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports in the region are at or below 122 cm (4 ft) in elevation, although portions of the infrastructure are guarded by protective structures such as levees and dikes. These protective structures could mitigate some impacts, but considerable land area is still at risk to permanent flooding from rising tides, sinking land, and erosion during storms. Furthermore, the crucial connectivity of the intermodal system in the area means that the services of the network can be threatened even if small segments are inundated (CCSP, 2008b).

A great deal of the Gulf Coast study area’s infrastructure is subject to temporary flooding associated with storm surge. More than half (64 percent of interstates; 57 percent of arterials) of the area’s major highways, almost half of the rail miles, 29 airports, and virtually all of the ports are subject to flooding based on the study of a 5.5- and 7.0-m (18- and 23-ft) storm surge (CCSP, 2008b).

Aviation may also be affected. Increases in precipitation and the frequency of severe weather events could negatively affect aviation. Higher temperatures affect aircraft performance and increase the necessary runway lengths. Some of these risks are expected to be offset by improvements in technology and information systems (CENR, 2008).

Settlements

According to IPCC (2007b), “The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanization is occurring (high confidence). Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities, and are more dependent on climate-sensitive resources such as local water and food supplies (high confidence)”.

Effects of climate change on human settlements in the U.S. are very likely to vary considerably according to location-specific vulnerabilities, with the most vulnerable areas likely to include: Alaska, flood-risk coastal zones and river basins, arid areas with associated water scarcity and areas where the economic base is climate sensitive (CCSP, 2007a).

In Alaska and elsewhere in the Arctic, indigenous communities are facing major economic and cultural impacts. Many indigenous peoples depend on hunting polar bear, walrus, seals, and caribou, and herding reindeer, fishing and gathering, not only for food and to support the local economy, but also as the basis for cultural and social identity. Changes in species’ ranges and availability, access to these species, a perceived reduction in weather predictability, and travel safety in changing ice and weather conditions present serious challenges to human health and food security, and possibly even the survival of some cultures (ACIA, 2004).

Communities in risk-prone U.S. regions have reason to be particularly concerned about any potential increase in severe weather events. The combined effects of severe storms and sea-level rise in coastal areas or increased risks of fire in drier arid areas are examples of how climate change may increase the magnitude of challenges already facing risk-prone communities. Vulnerabilities may be especially great for rapidly-growing and/or larger metropolitan areas, where the potential magnitude of both impacts and coping requirements are likely to be very large. On the other hand, such regions have greater opportunity to put more adaptable infrastructure in place and make decisions that limit vulnerability (CCSP, 2007a).

Climate change has the potential not only to affect U.S. communities directly but also through undermining their economic bases. In particular, some regional economies are dependent on sectors highly sensitive to changes in climate: agriculture, forestry, water resources, or tourism. Climate change can add to stress on social and political structures by increasing management and budget requirements for public services such as public health care, disaster risk reduction, and even public safety. As sources of stress grow and combine, the resilience of social and political structures are expected to suffer, especially in locales with relatively limited social and political capital (CCSP, 2007a). Additionally, as noted in Wilbanks et al. (2008), “Human settlements are the foci for many economic, social, and governmental processes, and historical experience has shown that catastrophes in cities can have significant economic, financial, and political effects much more broadly.”

Within settlements experiencing climate change stressors, certain parts of the population may be especially vulnerable . These include the poor, the elderly, those already in poor health, the disabled, those living alone, those with limited rights and power (such as recent immigrants with limited English skills), and/or indigenous populations dependent on one or a few resources. Environmental justice issues are clearly raised through examples such as warmer temperatures in urban areas having a more direct impact on those without air-conditioning (Wilbanks et al., 2008).

Finally, growth and development is generally moving toward areas more likely to be vulnerable to the effects of climate change. For example, approximately half of the U.S. population, 160 million people, will live in one of 673 coastal counties by 2008. Coastal residents – particularly those on gently-sloping coasts – should be concerned about sea level rise in the longer term, especially if these areas are subject to severe storms and storm surges and/or if their regions are showing gradual land subsidence. Areas that have been classified as highly vulnerable to climate change (based on measures of physical vulnerability and adaptive capacity) include counties lying along the east and west coasts and Great Lakes, with medium vulnerability counties mostly inland in the southeast, southwest, and northeast (CCSP, 2007a).

Section 14

Ecosystems and Wildlife

This Section of the document covers: 1) ecosystem and species-level impacts due to climate change and elevated CO_2 levels, 2) implications for ecosystem services, 3) how climate change effects on extreme event frequency and intensity may impact ecosystems, and 4) impacts to tourism and recreation.

For North America, the IPCC (Field et al., 2007; Fischlin et al., 2007[75]) concluded:

- Disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence)**.**[76] Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

14(a) Ecosystems and Species

Ecosystems, plants, and animals are sensitive to climate variability and always have been. Three clearly observable connections between climate and terrestrial ecosystems are the seasonal timing of life-cycle events (referred to as phenology), responses of plant growth or primary production, and the biogeographic distribution of species (see Figure 14.1).

IPCC reviewed a number of studies describing observations of climate change effects on plant species: (Field, et al., 2007 and references therein):

- Between 1981 and 2000, global daily satellite data indicate earlier onset of spring “greenness” by 10-14 days, particularly across temperate latitudes of the Northern Hemisphere. Field studies conducted in the same areas confirm these satellite observations.
    - Leaves are expanding earlier (e.g., apple and grape plants--2 days/decade at 72 sites in Northeastern U.S.).
    - Flowering plants are blooming earlier (e.g., lilac - 1.8 days/decade earlier from 1959-1993, at 800 sites across North America, honeysuckle -- 3.8 days/decade earlier in the western U.S.).
- The timing of autumn leaf senescence[77] across the continental US, which is controlled by a combination of temperature, photoperiod and water deficits, shows weaker trends.

IPCC also discussed several studies showing how North American animals are responding to climate change, with effects on phenology, migration, reproduction, dormancy, and geographic range (Field, et al., 2007 and references therein):

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[75] Fischlin et al., 2007 citation refers to Chapter 4, “Ecosystems, Their Properties, Goods, and Services” in IPCC’s 2007 Fourth Assessment Report, Working Group II.

[76] According to IPCC terminology, “very high confidence” conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

[77] The term ‘senescence’ is defined as the last stage of leaf development that includes changes in pigment expression, cell death, and eventual leaf drop.

- Warmer springs have led to earlier nesting for 28 migrating bird species on the East coast of the U.S. and to earlier egg laying for Mexican jays and tree swallows.
- Several frog species now initiate breeding calls 10-13 days earlier than a century ago in the Upstate New York region.
- In lowland California, 16 of 23 butterfly species advanced the date of first spring flights an average 24 days over 31 years.
- Reduced water depth, related to recent warming, in Oregon lakes has increased exposure of toad eggs to UV-B, leading to increased mortality from a fungal parasite.
- The Edith's checkerspot butterfly has become locally extinct in the southern, low elevation portion of its western North American range, but has extended its range 90 km north and 120 m higher in elevation.

Many North American species, like the Edith's checkerspot butterfly, have shifted their ranges, typically to the north or to higher elevations (Field, et al., 2007). Migrating to higher elevations with more suitable temperatures can be an effective strategy for species if habitat connectivity[78] exists and other biotic and abiotic conditions are appropriate. However, many organisms cannot shift their ranges fast enough to keep up with the current pace of climate change (Fischlin et al., 2007). In addition, species that require higher-elevation habitat (e.g., alpine pikas), or assemblages for which no substrate may exist at higher latitudes (e.g., coral reefs), often have nowhere to migrate (Fischlin et al., 2007).

The direct effects of elevated CO_2 concentrations and climate change to marine ecosystems include ocean warming, increased thermal stratification, reduced upwelling, sea level rise, increased wave height and frequency, loss of sea ice, and decreases in the pH and carbonate ion concentration of the surface oceans. With lower pH, aragonite (calcium carbonate) that is used by many organisms to make their shells or skeletons will decline or become under-saturated, affecting coral reefs, and other marine calcifiers (e.g., pteropods-marine snails). Additional compounding effects, such as higher seawater temperatures leading to bleaching events, or higher seawater temperatures and nutrients leading to increased risk of diseases in marine biota will make these ecosystems even more vulnerable to changes in ocean chemistry along the U.S. and other world regions (Fischlin, et al., 2007). Subtropical and tropical coral reefs in shallow waters have already suffered major bleaching events that are clearly driven by increases in sea surface temperatures (Janetos et al., 2008). The effects of various other stressors, particularly human impacts such as overfishing, pollution, and the introduction of invasive species, appear to be exacerbating the thermal stresses on reef systems and, at least on a local scale, exceeding the thresholds beyond which coral is replaced by other organisms (Nicholls, et al., 2007).

In the Bering Sea along the Alaskan coast, rising air and sea water temperatures have caused reductions in sea-ice cover and primary productivity in benthic ecosystems[79] (Anisimov et al., 2007). A change from Arctic to sub-Arctic conditions is happening with a northward movement of the pelagic-dominated marine ecosystem that was previously confined to the Southeastern Bering Sea (Anisimov, et al., 2007). Climate-related impacts observed in the Bering Sea include significant reductions in seabird and marine mammal populations, increases in pelagic fish, occurrences of previously rare algal blooms, abnormally high water temperatures, and smaller salmon runs in coastal rivers (ACIA, 2004). Plants and animals in polar regions are also vulnerable to attacks from pests and parasites that develop faster and are more prolific in warmer and moister conditions (Anisimov, et al., 2007). See Box 14.1 for more information on potential climate change impacts to polar bears.

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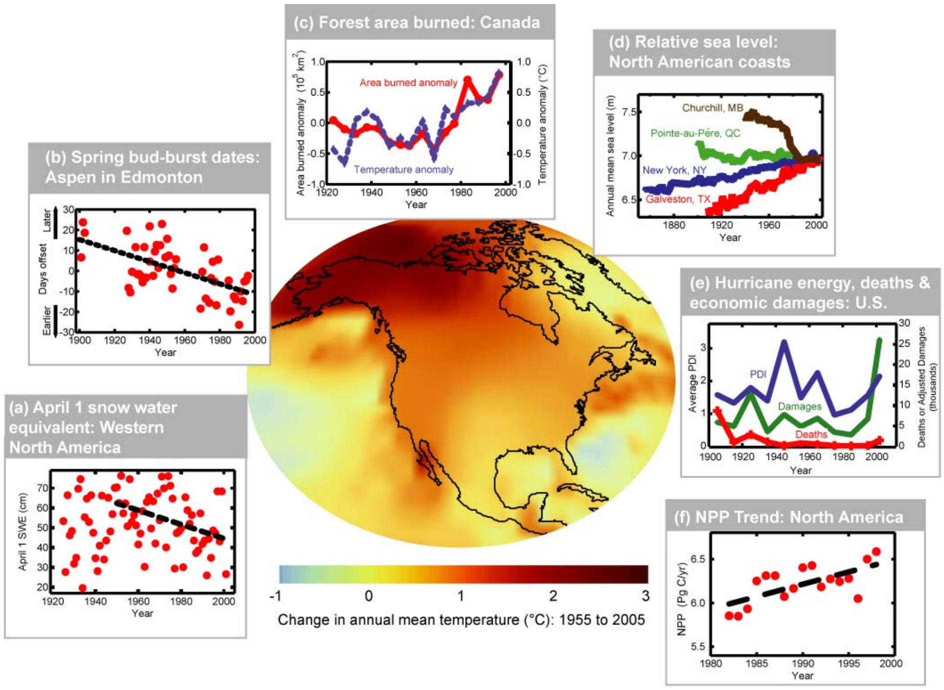
[78] Connectivity is defined as the degree to which a habitat is physically linked with other suitable areas for a particular species.

[79] Benthic is defined as the deepest environment of a water body which usually includes the seabed or lake floor.

Ecosystem Level Projections

For terrestrial ecosystems across all world regions, the IPCC concluded that substantial changes in structure and functioning of terrestrial ecosystems are very likely to occur with a global warming greater than 2 to 3°C above pre-industrial levels (high confidence) (Fischlin, et al., 2007). In North America, disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence) (Field, et al., 2007). Figure 14.1 shows the observed NPP trend in North America between 1981 and 1988.

Figure 14.1: North American Observations (Field et al., 2007)



Observed trends in some biophysical and socio-economic indicators. Background: change in annual mean temperature from 1955 to 2005 (based on the GISS2001 analysis for land from Hansen et al., 2001; and on the Hadley/Reyn_V2 analysis for sea surface from Reynolds et al., 2002). Insets: (a) trend in April 1 SWE across western North America from 1925-2002, with a linear fit from 1950-2002 (data from Mote, 2003), (b) Spring bud-burst dates for trembling aspen in Edmonton since 1900 (data from Beaubien and Freeland, 2000), (c) anomaly in 5-year mean area burned annually in wildfires in Canada since 1930, plus observed mean summer air temperature anomaly, weighted for fire areas, relative to 1920-1999 (data from Gillett et al., 2004) (d) relative sea level rise from 1850-2000 for Churchill, MB, Pointe-au-Père, QB, New York, NY, and Galveston, TX, (POL, 2006) (e) hurricane energy (PDI), economic damages, and deaths from Atlantic hurricanes since 1900 (data from Pielke Jr. and Landsea, 1999 updated through 2005; Emanuel, 2005; Saunders and Lea, 2005 updated through 2005), and, (f) trend North American NPP (Net Primary Productivity) from 1981 to 1998 (data from Hicke et al., 2002).

At high latitudes, several models project longer growing seasons and increased net primary productivity (NPP) as a result of forest expansion into tundra ecosystems. In the mid latitudes, simulated changes in

NPP are variable, depending on whether there is sufficient enhancement of precipitation to offset increased evapotranspiration in a warmer climate. By the end of the 21st century, ecosystems in the northeast and southeast U.S. are projected to become carbon sources, while the western U.S. remains a carbon sink (Field, et al., 2007).

The aerial extent of drought-limited ecosystems is projected to increase 11% per ºC warming in the continental U.S. Climate change and direct human land-use pressures are both likely to have adverse impacts on desert ecosystems and species. Increases in plant productivity resulting from the direct effects of rising atmospheric CO_2 concentrations may partially offset these adverse effects. In California, temperature increases greater than 2°C may lead to the conversion of shrubland into desert and grassland ecosystems and evergreen conifer forests into mixed deciduous forests (Fischlin, et al., 2007). Climate models suggest a warmer, drier future climate for the Prairie Pothole Region, which would result in a reduction in, or elimination of, wetlands that provide waterfowl breeding habitat (CCSP, 2009c).

The sea-ice biome accounts for a large proportion of primary production in polar waters and supports a substantial food web. In the Northern Hemisphere, projections of ocean biological response to climate warming by 2050 show contraction of the highly productive marginal sea ice biome by 42% (Fischlin, et al., 2007). In the Bering Sea, primary productivity in surface waters is projected to increase, the ranges of some cold-water species will shift north, and ice-dwelling species will experience habitat loss (ACIA, 2004).

Species Level Projections

After reviewing studies on the projected impacts of climate change on species, IPCC concluded that on a global scale (Fischlin et al., 2007 and references therein):

- Projected impacts on biodiversity are significant and of key relevance, since global losses in biodiversity are irreversible (very high confidence).
- Endemic species[80] richness is highest where regional palaeoclimatic changes have been subtle, providing circumstantial evidence of their vulnerability to projected climate change (medium confidence). With global average temperature changes of 2°C above pre-industrial levels many terrestrial, freshwater, and marine species (particularly endemics across the globe) are at a far greater risk of extinction than in the geological past (medium confidence).
- Approximately 20% to 30% of species (global uncertainty range from 10% to 40%, but varying among regional biota from as low as 1% to as high as 80%) will be at increasingly high risk of extinction by 2100.

In North America, climate change impacts on inland aquatic ecosystems will range from the direct effects of increased temperature and CO_2 concentration to indirect effects associated with alterations in hydrological systems resulting from changes to precipitation regimes and melting glaciers and snow pack (Fischlin et al., 2007). For many freshwater animals, such as amphibians, migration to breeding ponds and the production of eggs is intimately tied to temperature and moisture availability. Asynchronous timing of breeding cycles and pond drying due to the lack of precipitation can lead to reproductive failure. Differential responses among species in arrival or persistence in ponds will likely lead to changes in community composition and nutrient flow in ponds (Fischlin et al., 2007).

Bioclimate modeling based on output from five general circulation models (GCMs) suggests that on the long (millennial) timescale there may be decreases of bird and mammal species richness in warmer, low

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[80] Endemic species are unique to their location or region and are not found anywhere else on Earth.

elevation areas, but increases in cold high elevation zones, and increases of reptile species richness in all areas. Over the next century, however, even positive long-term species richness may lead to short term decreases because species that are intolerant of local conditions may disappear relatively quickly while migration of new species into the area may be quite slow (Field et al., 2007; Currie, 2001). Changes in plant species composition in response to climate change can increase ecosystem vulnerability to other disturbances, including fire and biological invasion. There are other possible, and even probable, impacts and changes in biodiversity-related relationships (e.g., disruption of the interactions between pollinators, such as bees, and flowering plants), for which we do not yet have a substantial observational database (Janetos et al., 2008).

On small oceanic islands with cloud forests or high elevation ecosystems, such as the Hawaiian Islands, extreme elevation gradients exist, ranging from nearly tropical to alpine environments. In these ecosystems, anthropogenic climate change, land-use changes, and biological invasions will work synergistically to drive several species (e.g., endemic birds) to extinction (Mimura et al., 2007).

According to IPCC, climate change (very high confidence) and ocean acidification due to the direct effects of elevated CO_2 concentrations (medium confidence) will impair a wide range of planktonic and other marine organisms that use aragonite to make their shells or skeletons (Fischlin et al., 2007). These impacts could result in potentially severe ecological changes to tropical and coldwater marine ecosystems where carbonate-based phytoplankton and corals are the foundation for the trophic system (Schneider et al., 2007). The IPCC concluded that it is very likely that a projected future sea surface temperature increase of 1 to 3°C will result in more frequent bleaching events and widespread mortality, if there is not thermal adaptation or acclimatization by corals and their algal symbionts (Nicholls et al., 2007). In Kaneohe Bay, HI, bleaching events, combined with average changes in SST and ocean acidity under the SRES A1B scenario, are projected to result in reef ecosystem collapse by 2060 for exposed reefs and by 2040 for enclosed reefs (Buddemeier et al., 2008). The ability of coral reef ecosystems to withstand the impacts of climate change will depend to a large degree on the extent of degradation from other anthropogenic pressures (Nicholls et al., 2007).

For the Arctic, IPCC (Anisimov et al., 2007 and references therein) concluded that:

- Decreases in the abundance of keystone species[81] are expected to be the primary factor in causing ecological cascades[82] and other changes to ecological dynamics.
- Arctic animals are likely to be most vulnerable to warming-induced drying of small water bodies; changes in snow cover and freeze-thaw cycles that affect access to food (e.g., polar bear dependence on sea ice for seal hunting) and protection from predators (e.g., snow rabbit camouflage in snow); changes that affect the timing of behavior (e.g., migration and reproduction); and influx of new competitors, predators, parasites, and diseases.
- In the past, sub-arctic species have been unable to live at higher latitudes because of harsh conditions. Climate change induced warming will increase the rate at which sub-arctic species are able to establish. Some non-native species, such as the North American mink, will become invasive, while other species that have already colonized some Arctic areas are likely to expand into other regions. The spread of non-native, invasive plants will likely have adverse impacts on native plant species. For example, experimental warming and nutrient addition has shown that native mosses and lichens become less abundant when non-native plant biomass increases.

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[81] Keystone species is defined as a species that has a disproportionate effect on its environment relative to its abundance or total biomass. Typically, ecosystems experience dramatic changes with the removal of such a species.
[82] Ecological cascades are defined as sequential chains of ecological effects, including starvation and death, beginning at the bottom levels of the food chain and ascending to higher levels, including apex predators.

- Bird migration routes and timing are likely to change as the availability of suitable habitat in the Arctic decreases.
- Loss of sea ice will impact species, such as harp seals, which are dependent on it for survival.
- Climate warming is likely to increase the incidence of pests, parasites, and diseases such as musk ox lung worm and abomasal nematodes of reindeer.

Box 14.1: Polar bears (adapted from Box 4.3 in Fischlin, et al., 2007)

There are an estimated 20,000 to 25,000 polar bears (*Ursus maritimus*) worldwide, mostly inhabiting the annual sea ice over the continental shelves and inter-island archipelagos of the circumpolar Arctic. Polar bears are specialized predators that hunt ice-breeding seals and are therefore dependent on sea ice for survival. After emerging in spring from a 5 to 7 month fast in nursing dens, females require immediate nourishment and thus depend on close proximity between land and sea ice before the sea ice breaks up. Continuous access to sea ice allows bears to hunt throughout the year, but in areas where the sea ice melts completely each summer, they are forced to spend several months in tundra fasting on stored fat reserves until freeze-up (Fischlin, et al., 2007).

The two Alaskan populations (Chukchi Sea- ~2,000 individuals in 1993, Southern Beaufort Seas- ~1,500 individuals in 2006) are vulnerable to large-scale dramatic seasonal fluctuations in ice movements because of the associated decreases in abundance and access to prey and increases in the energetic costs of hunting (FWS, 2007). The IPCC projects that with a warming of 2.8°C above pre-industrial temperatures and associated declines in sea ice, polar bears will face a high risk of extinction. Other ice-dependent species (e.g., walruses – for rest; small whales – for protection from predators) face similar consequences, not only in the Arctic but also in the Antarctic (Fischlin, et al., 2007).

In 2005, the World Conservation Union's (IUCN) Polar Bear Specialist Group concluded that the IUCN Red List classification for polar bears should be upgraded from *Least Concern* to *Vulnerable* based on the likelihood of an overall decline in the size of the total population of more than 30% within the next 35 to 50 years (Fischlin, et al., 2007). In May 2008, the U.S. Fish and Wildlife Service listed the polar bear as a threatened species under the Endangered Species Act. This decision was based on scientific evidence showing that sea ice loss threatens, and will likely continue to threaten, polar bear habitat (FWS, 2008).

14(b) Ecosystem Services

Ecosystems provide many goods and services that are of vital importance for biosphere function, and provide the basis for the delivery of tangible benefits to humans. These services include: maintenance of biodiversity, nutrient regulation, shoreline protection, food and habitat provisioning, sediment control, carbon sequestration, regulation of the water cycle and water quality, protection of human health, and the production of raw materials (Fischlin et al., 2007). Climate change is projected to have an increasing effect on the provisioning of ecosystem services in the U.S. Increasing temperatures and shifting precipitation patterns, along with the direct effects of elevated CO_2 concentrations, sea level rise, and changes in climatic variability, will affect the quantity and quality of these services. By the end of the 21st century, climate change and its impacts may be the dominant driver of biodiversity loss and changes in ecosystem services globally (Millennium Ecosystem Assessment-Synthesis, 2005).

Many U.S. ecosystems and the services they provide are already threatened by natural and anthropogenic non-climate stressors. Climate-related effects on ecosystems services will amplify the effects of non-climate stressors. Multiple U.S. industries, such as timber, fisheries, travel, tourism, and agriculture that are already threatened could face substantially greater impacts with concurrent effects on financial markets (Ryan et al., 2008; Field et al., 2007).

14(c) Extreme Events

Many significant impacts of climate change on U.S. ecosystems and wildlife may emerge through changes in the intensity and the frequency of extreme weather events. Extreme events, such as hurricanes, can cause mass mortality in wildlife populations and contribute significantly to alterations in species distribution and abundance following the disturbance. For example, the aftermath of a hurricane can cause coastal forest to die from storm surge-induced salt deposition, or wildlife may find it difficult to find food, thus lowering the chance of survival. Droughts play an important role in forest dynamics as well, causing pulses of tree mortality in the North American woodlands. Greater magnitude and frequency of extreme events may alter disturbance regimes in North American coastal ecosystems leading to changes in diversity and ecosystem functioning (Field et al., 2007; Fischlin et al., 2007). Species inhabiting saltmarshes, mangroves, and coral reefs are likely to be particularly vulnerable to these effects (Fischlin et al., 2007). Higher temperatures, increased drought, and more intense thunderstorms will very likely increase erosion and promote invasion of exotic grass species in arid lands (Ryan et al., 2008).

14(d) Implications for Tourism and Tribes

The U.S. ranks among the top ten nations for international tourism receipts (US $112 billion), having domestic tourism and outdoor recreation markets that are several times larger than most other countries. Climate variability affects many segments of this growing economic sector. For example, wildfires in Colorado (2002) caused tens of millions of dollars in tourism losses by reducing visitation and destroying infrastructure. Similar economic losses during that same year were caused by drought-affected water levels in rivers and reservoirs in the western U.S. and parts of the Great Lakes. The ten-day closure and clean-up following Hurricane Georges (September 1998) resulted in tourism revenue losses of approximately US $32 million in the Florida Keys. While the North American tourism industry acknowledges the important influence of climate, its impacts have not been analyzed comprehensively (Field et al., 2007 and references therein).

In Alaska and elsewhere in the Arctic, indigenous communities are facing major economic and cultural impacts. Many indigenous peoples depend on hunting polar bear, walrus, seals, and caribou, and herding reindeer, fishing and gathering, not only for food and to support the local economy, but also as the basis for cultural and social identity. These livelihoods are already being threatened by multiple climate-related factors, including reduced or displaced populations of marine mammals, caribou, seabirds, and other wildlife, losses of forest resources due to insect damage, and reduced/thinner sea ice, making hunting more difficult and dangerous (ACIA, 2004).

Part V

International Observed and Projected Human Health and Welfare Effects from Climate Change

Section 15

International Impacts

The primary focus of this document is on the observed and potential future impacts associated with elevated GHG concentrations and associated climate change within the U.S. However, EPA has considered the global nature of climate change in at least two ways for purposes of this document.

First, GHGs, once emitted, remain in the atmosphere for decades to centuries, and thus become, for all practical purposes, uniformly mixed in the atmosphere, meaning that U.S. emissions have climatic effects not only in the U.S. but in all parts of the world. Likewise, GHG emissions from other countries can influence the climate of the U.S., and therefore affect human health, society and the natural environment within the U.S. All observed and potential future climate change impacts within the U.S. reviewed in this document consider climate change driven by *global* anthropogenic GHG emissions.

Second, despite widely discussed metrics such as global average temperature, climate change will manifest itself very differently in different parts of the world, where regional changes in temperatures and precipitation patterns, for example, can deviate significantly from changes in the global average. This regional variation in climate change, coupled with the fact that countries are in very different positions with respect to their vulnerability and adaptive capacity, means that the impacts of climate change will be experienced very differently in different parts of the world. In general, the relatively poor nations may experience the most severe impacts, due to their heavier reliance on climate-sensitive sectors such as agriculture and tourism, and due to their lack of resources for increasing resilience and adaptive capacity to climate change (see Parry et al., 2007). In addition to the fact that U.S. GHG emissions may contribute to these impacts (see Section 2 for a comparison of U.S. total and transportation emissions to other countries' emissions), climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian and national security issues for the U.S.

15(a) National Security

A number of analyses and publications, both inside and outside the government, have focused on the potential U.S. national security implications of climate change.

A public report prepared for the Department of Defense (Schwartz and Randall, 2003) examined what the effects on U.S. national security might be from an abrupt climate change scenario.[83] The authors concluded that the resultant climatic conditions could lead to resource constraints and potentially de-stabilize the global geo-political environment, with resultant national security concerns for the U.S.

The Arctic Climate Impact Assessment (2004) raised security issues, stating that as Arctic sea ice declines, historically closed sea passages will open, thus raising questions regarding sovereignty over shipping routes and ocean resources. In IPCC (Anisimov, 2007), a study shows projections suggesting that by 2050, the Northern Sea Route will have 125 days per year with less than 75% sea-ice cover, which represents favorable conditions for navigation by ice-strengthened cargo ships. This may have implications for trade and tourism as well.

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[83] The abrupt climate change used for the study was the unlikely, but plausible, collapse of the thermohaline circulation in the Atlantic, modeled after an event that occurred 8,200 years ago.

The Center for Naval Analyses (CNA) Corporation, a non-profit national security analysis institution, issued a report entitled *National Security and the Threat of Climate Change* (2007), in which a dozen retired generals and admirals were briefed by climate change scientists and business leaders over the course of many months and then tasked with providing their own views and recommendations about the linkage between climate change and national security over the next 30 to 40 years. Among their conclusions was that climate change acts as a "threat multiplier" for instability in some of the most volatile regions of the world. "Projected climate change will seriously exacerbate already marginal living standards in many Asian, African, and Middle Eastern nations, causing widespread political instability and the likelihood of failed states," said the authors. Regarding the potential impact of climate change on military systems, infrastructure and operations, the report stated that climate change will stress the U.S. military by affecting weapons systems and platforms, bases, and military operations. A U.S. Navy (2001) study was cited which states that an ice-free Arctic will require an increased scope for naval operations. Given these concerns, one of the recommendations of the CNA (2007) report was for the Department of Defense to conduct an assessment of the impact on U.S. military installations worldwide of rising sea levels, extreme weather events, and other possible climate change impacts over the next 30 to 40 years.

The U.S. Congress has expressed national security concerns due to climate change by requesting that the defense and intelligence communities examine these linkages. H.R. 4986, passed in January 2008, requires the Department of Defense to consider the effect of climate change on its facilities, capabilities and missions. Specific directives in the bill include that future national security strategies and national defense strategies must include guidance for military planners to assess the risks of projected climate change on current and future armed forces missions, as well as update defense plans based upon these assessments (H.R. 4986, 2008).

In June 2008 testimony before the House, Dr. Thomas Fingar, Deputy Director of National Intelligence for Analysis, laid out a national intelligence statement on the U.S. national security implications from climate change projected out to 2030. Using a broad definition for national security,[84] the assessment found that:

> "[G]lobal climate change will have wide-ranging implications for U.S. national security interests over the next 20 years…We judge that the most significant impact for the United States will be indirect and result from climate-driven effects on many other countries and their potential to seriously affect U.S. national security interests. We assess that climate change alone is unlikely to trigger state failure in any state out to 2030, but the impacts will worsen existing problems—such as poverty, social tensions, environmental degradation, ineffectual leadership, and weak political institutions. Climate change could threaten domestic stability in some states, potentially contributing to intra- or, less likely, interstate conflict, particularly over access to increasingly scarce water resources." (Fingar, 2008)

Building on that work, the National Intelligence Council in November 2008, in its publication *Global Trends 2025: A Transformed World*, discussed climate change impacts prominently. The report posed a scenario named "October Surprise," which discussed the economic and sociopolitical ramifications of an extreme flooding event linked to global climate change in New York City in 2020 (NIC, 2008).

15(b) Overview of International Impacts

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[84] This definition considered if the effects would directly impact the U.S. homeland, a U.S. economic partner, or a U.S. ally. Additionally, the potential for humanitarian disaster was focused on as well as if an effect would result in degrading or enhancing an element of national power. For more information, see Fingar, 2008.

The IPCC Working Group II volume of the Fourth Assessment Report reviews the potential impacts in different regions of the world. The IPCC (Parry et al., 2007) identifies as the most vulnerable regions:

- The Arctic, because of high rates of projected warming on natural systems;
- Africa, especially the sub-Saharan region, because of current low adaptive capacity as well as climate change;
- Small islands, due to high exposure of population and infrastructure to risk of sea-level rise and increased storm surge;
- Asian mega deltas, such as the Ganges-Brahmaputra and the Zhujiang, due to large populations and high exposure to sea level rise, storm surge and river flooding.

Table 15.1 summarizes the vulnerabilities and projected impacts for different regions of the world, as identified by IPCC (2007b). And the paragraphs that follow provide some additional detail for key sectoral impacts that have received attention by the research community. There is currently a lack of information about how these potential impacts in other regions of the world may influence international trade and migration patterns, which in turn could raise concerns for the U.S.

On a global basis, according to IPCC, “projected climate change-related exposures are likely to affect the health status of millions of people, particularly those with low adaptive capacity,” through several factors including “the increased frequency of cardio-respiratory diseases due to higher concentrations of ground level ozone related to climate change (IPCC, 2007b).” More specifically, “cities that currently experience heat waves are expected to be further challenged by an increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts.”

Mosquito-borne diseases which are sensitive to climate change, such as dengue and malaria are of great importance globally. Studies have reported associations between spatial (Hales et al., 2002), temporal (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001), or spatiotemporal patterns (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001; Cazelles et al., 2005) of dengue and climate, although these are not entirely consistent (Confalonieri et al., 2007). Similarly, the spatial distribution, intensity of transmission, and seasonality of malaria is observed to be influenced by climate in sub-Saharan Africa (Hay et al., 2002a; Craig et al., 2004 in Confalonieri et al., 2007). In other world regions (e.g., South America, continental regions of the Russian Federation) there is no clear evidence that malaria has been affected by climate change (Benitez et al., 2004; Semenov et al., 2002 in Confalonieri et al., 2007). Changes in reporting, surveillance, disease control measures, population changes and other factors such as land use change must to be taken into account when attempting to attribute changes in human diseases to climate change (Kovats et al., 2001; Rogers and Randolph, 2006 in Confalonieri et al., 2007).

Food production is expected to be much more vulnerable to climate change in poorer regions of the world compared to food production in the U.S. and other high, northern latitude regions. The IPCC (2007b) stated with medium confidence[85] that, at lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C; ~2-3.5°F), which would increase risk of hunger. Furthermore, increases in the frequency of droughts and floods are projected to affect local production negatively, especially in subsistence sectors at low latitudes. Drought conditions, flooding, and pest outbreaks are some of the current stressors to food security that may be influenced by future climate change. Sub-Saharan Africa is currently highly vulnerable to food insecurity (Easterling et al., 2007). Felzer et al. (2005) projected increases in carbon storage on croplands globally

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[85] According to IPCC terminology, “medium confidence” conveys a 5 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC’s uncertainty terms.

under climate change up to 2100, but found that ozone damage to crops could significantly offset these gains.

Regarding global forest production, the IPCC (Easterling et al., 2007) concluded that forestry production is estimated to change modestly with climate change in the short and medium term (medium confidence). The projected change in global forest products output ranges from a modest increase to a slight decrease, with significant variations regionally. There is projected to be a production shift from low latitude regions in the short-term, to high latitude regions in the long-term. Projected changes in the frequency and severity of extreme climate events have significant consequences for forestry production in addition to impacts of projected mean climate (high confidence) (Easterling et al., 2007). Climate variability and change also modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for forestry (high confidence) (Easterling et al., 2007).

The IPCC made the following conclusions when considering how climate change may affect water resources across all world regions:

- The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level, and precipitation variability (very high confidence) (Kundzewicz et al. 2007).
- All regions show an overall net negative impact of climate change on water resources and freshwater ecosystems (high confidence). Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources (very high confidence). The beneficial impacts of increased annual runoff in other areas will be tempered by negative effects due to increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risk (high confidence) (Kundzewicz et al., 2007).
- Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse effects of climate change on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land use change, and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate changes are likely. Current water management practices are very likely to be inadequate to reduce negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems (very high confidence) (Kundzewicz et al., 2007).
- In polar regions, components of the terrestrial cryosphere and hydrology are increasingly being affected by climate change. Changes to cryospheric processes[86] are also modifying seasonal runoff (very high confidence) (Anisimov et al., 2007).

The IPCC (Nicholls et al., 2007) identified that coasts are experiencing the adverse consequences of hazards related to climate and sea level (very high confidence). They are highly vulnerable to extreme events, such as storms which impose substantial costs on coastal societies. Through the 20th century, global rise of sea level contributed to increased coastal inundation, erosion, and ecosystem losses, but with considerable local and regional variation due to other factors (Nicholls et al., 2007).

The IPCC (Fischlin et al., 2007) recently made the following conclusions when considering how climate change may affect ecosystems across all world regions:

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[86] Cryospheric processes are defined to include the annual freezing and melting of snow cover, ice sheets, lake and river ice, permafrost, and sea ice.

- During the course of this century the resilience of many ecosystems is likely to be exceeded by an unprecedented combination of changes in climate and in other global change drivers (especially land use, pollution, and overexploitation), if greenhouse gas emissions and other changes continue at or above current rates (high confidence). The elevated CO_2 levels and associated climatic changes will alter ecosystem structure, reduce biodiversity, perturb functioning of most ecosystems, and compromise the services they currently provide (high confidence). Present and future land use change and associated landscape fragmentation are very likely to impede species' migrations and geographic range shifts in response to changes in climate (very high confidence).
- Ecosystems and species are very likely to show a wide range of vulnerabilities to climate change, depending on the extent to which climate change alters conditions that could cross critical, ecosystem-specific thresholds (very high confidence). The most vulnerable ecosystems include coral reefs, the sea ice biome and other high latitude ecosystems (e.g. boreal forests), mountain ecosystems and Mediterranean-climate ecosystems[87] (high confidence). Least vulnerable ecosystems include savannas and species–poor deserts, but this assessment is especially subject to uncertainty relating to the CO_2 fertilization effect and disturbance regimes such as fire (low confidence).

Table 15.1: Examples of key regional impacts as identified by IPCC (2007b)*

Africa	• New studies confirm that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Some adaptation to current climate variability is taking place; however, this may be insufficient for future changes in climate. • By 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to climate change. If coupled with increased demand, this will adversely affect livelihoods and exacerbate water-related problems. • Agricultural production, including access to food, in many countries and regions is projected to be severely compromised by climate variability and change. The area suitable for agriculture, the length of growing seasons and yield potential, particularly along the margins of semi-arid and arid areas, are expected to decrease. This would further adversely affect food security and exacerbate malnutrition in the continent. In some countries, yields from rain-fed agriculture could be reduced by up to 50% by 2020.

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[87] Mediterranean climate ecosystems feature subtropical climate with dry summers. Despite the name, these ecosystems exist in the US along the coasts of central and southern California.

Asia	• Glacier melt in the Himalayas is projected to increase flooding, and rock avalanches from destabilized slopes, and to affect water resources within the next two to three decades. This will be followed by decreased river flows as the glaciers recede. • Freshwater availability in Central, South, East and South-East Asia, particularly in large river basins, is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s. • Coastal areas, especially heavily-populated mega delta regions in South, East and South-East Asia, will be at greatest risk due to increased flooding from the sea and, in some mega deltas, flooding from the rivers. • It is projected that crop yields could increase up to 20% in East and South-East Asia while they could decrease up to 30% in Central and South Asia by the mid-21st century. The risk of hunger is projected to remain very high in several developing countries. • Endemic morbidity and mortality due to diarrhea disease primarily associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle associated with global warming. Increases in coastal water temperature would exacerbate the abundance and/or toxicity of cholera in South Asia.
Latin America	• By mid-century, increases in temperature and associated decreases in soil water are projected to lead to gradual replacement of tropical forest by savanna in eastern Amazonia. Semi-arid vegetation will tend to be replaced by arid-land vegetation. There is a risk of significant biodiversity loss through species extinction in many areas of tropical Latin America. • In drier areas, climate change is expected to lead to salinization and desertification of agricultural land. Productivity of some important crops is projected to decrease and livestock productivity to decline, with adverse consequences for food security. In temperate zones soybean yields are projected to increase. • Sea-level rise is projected to cause increased risk of flooding in low-lying areas. Increases in sea surface temperature due to climate change are projected to have adverse effects on Mesoamerican coral reefs, and cause shifts in the location of south-east Pacific fish stocks. • Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation.
Polar Regions	• For human communities in the Arctic, impacts, particularly those resulting from changing snow and ice conditions, are projected to be mixed. Detrimental impacts would include those on infrastructure and traditional indigenous ways of life. • Beneficial impacts would include reduced heating costs and more navigable northern sea routes.
Small Islands	• Small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise and extreme events. • Deterioration in coastal conditions, for example through erosion of beaches and coral bleaching, is expected to affect local resources, e.g., fisheries, and reduce the value of these destinations for tourism. • Sea-level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities. • Climate change is projected by mid-century to reduce water resources in many small

	islands, e.g., in the Caribbean and Pacific, to the point where they become insufficient to meet demand during low-rainfall periods.
* With the exception of some very high confidence statements for small islands, all other IPCC conclusions within the table are of either high or medium confidence.	

Appendix: Brief Overview of Adaptation

Adaptation to climate change is the adjustment in the behavior or nature of a system to the effects of climate change. In the process of developing information to support the Administrator's decision regarding whether elevated combined greenhouse gas (GHG) concentrations endanger public health or welfare, various questions were raised about the relevance of adaptation. As noted in the Introduction, this document does not focus on adaptation because it (like GHG mitigation) is essentially a response to any known and/or perceived risks due to climate change. Although adaptation was not considered explicitly in the document, it does note where the underlying references already take into account certain assumptions about adaptation when projecting future risks and impacts due to climate change. This appendix provides a brief review of the state of knowledge pertaining to adaptation.

What is Adaptation?

As defined in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007),

> *Adaptation to climate change takes place through adjustments to reduce vulnerability or enhance resilience in response to observed or expected changes in climate and associated extreme weather events. Adaptation occurs in physical, ecological and human systems. It involves changes in social and environmental processes, perceptions of climate risk, practices and functions to reduce potential damages or to realise new opportunities*.

Adaptations vary according to the system in which they occur, who undertakes them, the climatic stimuli that prompts them, and their timing, functions, forms and effects. Adaptation can be of two broad types:

- Reactive or autonomous adaptation is the process by which species and ecosystems respond to changed conditions. An example is the northward migration of a species in response to increasing temperature.

- Anticipatory adaptation is planned and implemented before impacts of climate change are observed. An example is the construction of dikes in response to (and to prepare for) expected sea level rise.

Summary of the Scientific Literature on Adaptation

1. ***There is experience with adapting to weather, climate variability and the current and projected impacts of climate change.***

    - There is a long record of practices to adapt to the impacts of weather as well as natural climate variability. These practices include proactive steps like water storage and crop and livelihood diversification, as well as reactive or ex-post steps like emergency response, disaster recovery and migration.[88]

    - The IPCC (2007) states – with very high confidence[89] – that "Adaptation to climate change is already taking place, but on a limited basis."[90]

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[88] Adger et al. (2007), p. 720

[89] A set of terms to describe uncertainties in current knowledge was used throughout IPCC's Fourth Assessment Report. On the basis of a comprehensive reading of the literature and their expert judgment, IPCC authors assigned a confidence level to major statements on the basis of their assessment of current knowledge, as follows:

- A wide array of adaptation options is available, ranging from purely technological (i.e., sea walls), through behavioral changes (i.e., altered food and recreational choices), to managerial (e.g. altered farm practices), and to policy (e.g. planning regulations).[91]

2. ***Although adaptation options are known, available and used in some places, there are significant barriers to their adoption.***

   - The IPCC states -- with very high confidence -- that "there are substantial limits and barriers to adaptation." These include formidable environmental, economic, informational, social, attitudinal and behavioral barriers to the implementation of adaptation that are not fully understood.[92] The IPCC also states that there are significant knowledge gaps for adaptation as well as impediments to flows of knowledge and information relevant to adaptation decisions.[93]

3. ***Current scientific information does not provide sufficient information to assess how effective current and future adaptation options will be at reducing vulnerability to the impacts of climate change. The fact that a country has a high capacity to adapt to climate change does not mean that its actions will be effective at reducing vulnerability.***

   - While many technologies and adaptation strategies are known and developed in some countries, the available scientific literature does not indicate how effective various options are at fully reducing risks, particularly at higher levels of warming and related impacts, and for vulnerable groups.[94]

   - High adaptive capacity does not necessarily translate into actions that reduce vulnerability. For example, despite a high capacity to adapt to heat stress through relatively inexpensive adaptations, residents in urban areas in some parts of the world, including European cities, continue to experience high levels of mortality.[95] To minimize the risks of heat stress domestically, EPA (2006) has worked collaboratively with other government agencies to provide guidance to municipalities on steps they can take to reduce heat-related morbidity and mortality.[96]

   - Further research is needed to monitor progress on adaptation, and to assess the direct as well as ancillary effects of adaptation measures.[97] (IPCC, Chapter 17, p. 33)

Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

[90] Adger et al. (2007), p. 720
[91] ibid
[92] ibid
[93] Adger et al. (2007), p. 719
[94] ibid
[95] ibid
[96] Excessive Heat Events Guidebook (2006)
[97] Adger et al. (2007) p. 737

4. ***For any country – even one with high adaptive capacity -- it is particularly difficult to reduce vulnerability for all segments of the population. The most vulnerable and difficult to reach populations are the elderly, children and the poor.***

    - The IPCC states – with very high confidence – that "adaptive capacity is uneven across and within societies." There are individuals and groups within all societies that have insufficient capacity to adapt to climate change.[98]

5. ***More adaptation will be required to reduce vulnerability to climate change.***[99] ***Additional adaptation can potentially reduce, but is never expected to completely eliminate vulnerability to current and future climate change.***

    - According to the IPCC, "adaptation alone is not expected to cope with all the projected effects of climate change, and especially not over the long term as most impacts increase in magnitude." [100]

6. ***A portfolio of adaptation and mitigation measures can diminish the risks associated with climate change.***

    - Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation essential, particularly in addressing near-term impacts. Unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt.[101]

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[98] Adger et al. (2007), p. 719
[99] Adger et al. (2007), p. 719
[100] IPCC (2007), p. 19
[101] IPCC (2007), p. 20

References for Adaptation Appendix

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi, (2007) *Assessment of adaptation practices, options, constraints and capacity. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 717-743.

Excessive Heat Events Guidebook. Report from the United States Environmental Protection Agency. 52 pages. June 2006. EPA 430-B-06-005.

IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

References

ACGIH (1994) 1994-1995 *Threshold limit values for chemical substances and physical agents and biological exposure indice*s. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

ACIA (2004) *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press.

Adger, N. et al. (2007) *Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Agee, E. M. (1991) Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over the Northern Hemisphere, *J. Clim*., 4: 263– 267.

AkhtarAhern, M. J., R. S. Kovats, P. Wilkinson, R. Fewand F. Matthies (2005) Global health impacts of floods: epidemiological evidence. *Epidemiol. Rev*., 27, 36-45. [Cited in Confalonieri et al. (2001). Human Health. In: *Climate Change*., 2007*: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.]

AIR (2002) Ten Years after Andrew: What Should We Be Preparing for Now?, AIR (Applied Insurance Research, Inc.) Technical Document HASR 0208, Boston, 9 pp. [Accessed 09.02.07: http://www.air-worldwide.com/_public/NewsData/000258/Andrew_Plus_10.pdf]

Alley, R.B., Brigham-Grette, J., Miller, G.H., Polyak, L, and White, J.W.C. (2009) Key Findings and Recommendations. In Past *Climate Variability and Change in the Arctic and at High Latitudes*. A report by the U.S. Climate Change Program and Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA,pp. 421 – 430.

American Academy of Allergy Asthma & Immunology (AAAAI). 1996-2006. Allergy statistics. [Cited 2006 April 2006]. Available from: http://www.aaaai.org/media/resources/media_kit/allergy_statistics.stm

Anisimov, O.A. et al. (2007) Polar Regions. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Armstrong, B., P. Mangtani, A. Fletcher, R.S. Kovats, A.J. McMichael, S. Pattenden and P. Wilkinson (2004) Effect of influenza vaccination on excess deaths occurring during periods of high circulation of influenza: cohort study in elderly people. *Brit. Med. J.*, 329: 660-663.

Aw, J., and M.J. Kleeman (2003) Evaluating the first-order effect of intraannual air pollution on urban air pollution. *J. Geophys. Res.*, 108, 4365, doi:10.1029/2002JD002688.

Backlund, P., A. Janetos, D.S. Schimel, J. Hatfield, M.G. Ryan, S.R. Archer, and D. Lettenmaier (2008a) Executive Summary. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp

Backlund, P., D. Schimel, A. Janetos, J. Hatfield, M.G. Ryan, S.R. Archer, and D. Lettenmaier (2008b) Introduction. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United*

States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp

Baldwin, M. et al. (2007) Climate-Ozone connections, Chapter 5 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, 572pp., Geneva, Switzerland.

Barrett, R., C. Kuzawa, T. McDade and G. Armelagos (1998) Emerging and reemerging infectious diseases: the third epidemiologic transition. *Annu. Rev. Anthropol.*, 27, 247-271.

Beggs, P.J. (2004) Impacts of climate change on aeroallergens: past and future. *Clin. Exp. Allergy*, 34: 1507-1513.

Bell, J.L., L.C. Sloan, and M.A. Snyder (2004) Changes in extreme climatic events: A future climate scenario. *J. Clim.*, 17(1): 81–87.

Bell, M.L, R. Goldberg, C. Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, and J. Patz . (2007) Climate change, ambient ozone, and health in 50 U.S. cities. *Clim. Change*, DOI 10.1007/s10584-006-9166-7.

Benitez, T.A.,A. Rodriquez and M. Sojo (2004) Descripcion de un brote epidemico de malaria de altura en un areas originalmente sin malaria del Estado Trujillo, Venezuela. *Bol. Malariol. Salud Amb.*, XLIV, 999.

Bindoff, N.L. et al. (2007) Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bodeker et al. (2007) The ozone layer in the 21st century, Chapter 6 in *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, 572pp., Geneva, Switzerland.

Boko, M. et al. (2007) Africa. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Booker, F.L., S.A. Prior, H.A. Torbert, E.L. Fiscus, W.A. Pursley, and S. Hu (2005) Decomposition of soybean grown under elevated concentrations of CO_2 and O_3. *Global Change Biology*, 11: 685-698.

BP (2007) *BP Statistical Review of World Energy June 2007* (BP p.l.c., London), http://www.bp.com

Brasseur, G.P., et al (2006) Impact of Climate Change on the Future Chemical Composition of the Global Troposphere, *Journal of Climate*, 19, XX-XX.

Brownstein, J.S., T.R.Holford and D. Fish (2003) A climate-basedmodel predicts the spatial distribution of Lyme disease vector *Ixodes scapularis* in the United States. *Environ. Health. Perspect*., 111: 1152-1157.

Buddemeier, R.W., P.L. Jokiel, K.M. Zimmerman, D.R. Lane, J. M. Carey, G.C. Bohling, and J.A. Martinich (2008) A modeling tool to evaluate regional coral reef responses to changes in climate and ocean chemistry. *Limnology and Oceanography Methods*, 6: 395-411.

Burke, E.J., S.J. Brown, and N. Christidis (2006) Modelling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *J. Hydrometeorol.*, 7: 1113–1125.

Cahoon, D.R., D.J. Reed, A.S. Kolker, M.M. Brinson, J.C. Stevenson, S. Riggs, R. Christian, E. Reyes, C. Voss, and D. Kunz (2009) Coastal Wetland Sustainability. In: *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington D.C., USA, 320 pp.

California Climate Change Center (2006) *Scenarios of Climate Change in California: An Overview*. CEC-500-2005-186-SF.

California Energy Commission (2006) Our Changing Climate: Assessing the Risks to California. [Accessed 08.08.07: http://www.energy.ca.gov/2006publications/CEC-500-2006-077/CEC-500-2006-077.PDF]

CATAMA (1953) *Aviation Toxicology--an Introduction to the Subject and a Handbook of Data*. Committee on Aviation Toxicology, Aero Medical Association. The Blakiston Co.: New York, NY. pp. 6-9, 31-39, 52-55, 74-79, 110-115.

Cayan, D., M. Tyree and M. Dettinger (2003) *Climate Linkages to Female Culex Cx. Tarsalis Abundance in California*. California Applications Program (UCSD), San Diego, California. [Accessed 09.02.07: http://meteora.ucsd.edu/cap/mosq_climate.html]

Cazelles, B., M. Chavez, A.J. McMichael and S. Hales (2005) Nonstationary influence of El Niño on the synchronous dengue epidemics in Thailand. *PLoSMed.*, 2, e106.

CCSP (2009a) *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [James G. Titus (Coordinating Lead Author), K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Gutierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)], U.S. Environmental Protection Agency, Washington D.C., USA, 320 pp.

CCSP (2009b) *Past Climate Variability and Change in the Arctic and at High Latitude.* A report by the U.S. Climate Change Program and Subcommittee on Global Change Research [Alley, R.B., Brigham-Grette, J., Miller, G.H., Polyak, L., and White, J.W.C. (coordinating lead authors). U.S. Geological Survey, Reston , VA 461 pp.

CCSP (2009c) *Thresholds of Climate Change in Ecosystems.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Fagre, D.B., C.W. Charles, C.D. Allen, C. Birkeland, F.S. Chapin III, P.M. Groffman, G.R. Guntenspergen, A.K. Knapp, A.D. McGuire, P.J. Mulholland, D.P.C. Peters, D.D. Roby, and George Sugihara]. U.S. Geological Survey, Reston, VA, 156 pp.

CCSP, (2008a): *Abrupt Climate Change*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Clark, P.U., A.J. Weaver (coordinating lead authors), E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (chapter lead authors)]. U.S. Geological Survey, Reston, VA, 459 pp.

CCSP (2008b) *Analyses of the effects of global change on human health and welfare and human systems.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Gamble, J.L. (ed.), K.L. Ebi, F.G. Sussman, T.J. Wilbanks, (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA.

CCSP, (2008c): *Climate Models: An Assessment of Strengths and Limitations*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Bader D.C., C. Covey, W.J. Gutowski Jr., I.M. Held, K.E. Kunkel, R.L. Miller, R.T. Tokmakian and M.H. Zhang (Authors)]. Department of Energy, Office of Biological and Environmental Research, Washington, D.C., USA, 124 pp.

CCSP (2008d): *Climate Projections Based on Emissions Scenarios for Long-Lived and Short-Lived Radiatively Active Gases and Aerosols.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research H. Levy II, D.T. Shindell, A. Gilliland, M.D. Schwarzkopf, L.W. Horowitz (eds.). Department of Commerce, Washington, DC, USA, 100 pp.

CCSP (2008e) *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. P. Backlund, A. Janetos, D. Schimel et al. U.S. Department of Agriculture, Washington, DC., USA, 362 pp.

CCSP (2008f) *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Savonis, M. J., V.R. Burkett, and J.R. Potter (eds.)]. Department of Transportation, Washington, DC, USA, 445 pp.

CCSP (2008g) *Reanalysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Randall Dole, Martin Hoerling, and Siegfried Schubert (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, 156 pp.

CCSP, (2008h): *Trends in Emissions of Ozone-Depleting Substances, Ozone Layer Recovery, and Implications for Ultraviolet Radiation Exposure*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Ravishankara, A.R., M.J. Kurylo, and C.A. Ennis (eds.)]. Department of Commerce, NOAA's National Climatic Data Center, Asheville, NC, 240 pp.

CCSP (2008i) *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol, Anne M. Waple, and William L. Murray (eds.)]. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA, 164 pp.

CCSP (2007a): *Effects of Climate Change on Energy Production and Use in the United States.* A Report by the U.S. Climate Change Science Program and the subcommittee on Global change Research. Thomas J. Wilbanks,, Vatsal Bhatt, Daniel E. Bilello, Stanley R. Bull, James Ekmann, William C. Horak, Y. Joe Huang, Mark D. Levine, Michael J. Sale, David K. Schmalzer, and Michael J. Scott). Department of Energy, Office of Biological & Environmental Research, Washington, DC., USA, 160 pp.

CCSP (2007b) *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations (Part A) and Review of Integrated Scenario Development and Application (Part B). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research* [Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels, E. Parson, V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, H. Pitcher, C. Rosenzweig, M. Webster (Authors)]. Department of Energy, Office of Biological & Environmental Research, Washington, DC., USA, 260 pp.

CCSP (2006) *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*. Thomas R. Karl, Susan J. Hassol, Christopher D. Miller, and William L. Murray (eds.), Washington, DC.

CDC (2005a) Heat-related mortality – Arizona, 1993-2002, and United States, 1979-2002. MMWR – Morbidity & Mortality Weekly Report, 54(25), 628-630.

CDC (2005b) Vibrio illnesses after Hurricane Katrina: multiple states, August–September (2005) *MMWR–Morb. Mortal. Wkly. Rep*., 54, 928-931.

Cecchi, L., M. Morabito, P. Domeneghetti, M.,A. Crisci, M. Onorari and S. Orlandini (2006) Long distance transport of ragweed pollen as a potential cause of allergy in central Italy. *Ann. Allergy. Asthma. Im.*, 96: 86-91.

CENR (2008*) Scientific Assessment of the Effects of Global Change on the United States*, A Report of the Committee on Environment and Natural Resources, National Science and Technology Council, Washington, DC.

Choudhury A.Y. and A. Bhuiya (1993) Effects of biosocial variable on changes in nutritional status of rural Bangladeshi children, pre- and post-monsoon flooding. *J. Biosoc. Sci.*, 25: 351-35.

Christensen, J.H. et al. (2007) Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark, P.U., A.J. Weaver, E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (2008) *Executive Summary*. In: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, Reston, VA, pp. 7–18.

CNA Corporation (2007) *National Security and the Threat of Climate Change*, Alexandria, Virginia. http://securityandclimate.cna.org/

Cohen, J.C., 2003: Human population: the next half century. *Science*, 302: 1172-1175.

Cohen, S., K. Miller et al. (2001) North America. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J.J. McCarthy et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Confalonieri, U. et al. (2007) Human Health. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Corwin, A. L., R.P. Larasati, M .J. Bangs, S. Wuryadi, S. Arjoso ,N. Sukri, E. Listyaningsih, S. Hartati, R. Namursa, Z. Anwar, S. Chandra, B. Loho, H. Ahmad, J.R. Campbell and K.R. Porter (2001) Epidemic dengue transmission in southern Sumatra, Indonesia. T. *Roy. Soc. Trop. Med. H.*, 95: 257-265.

Craig, M.H., I. Kleinschmidt, J.B. Nawn, D. Le Sueur and B. Sharp (2004) Exploring 30 years of malaria case data in KwaZulu-Natal, SouthAfrica. Part I. The impact of climatic factors. *Trop. Med. Int. Health*, 9: 1247.

Crossett, K.M., T.J. Culliton, P.C. Wiley, and T.R. Goodspeed (2004). *Population Trends Along the Coastal United States: 1980-2008*. NOAA publication, Silver Spring, MD.

Cubasch et al. (2001) Projections of Future Climate Change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.)]. Cambridge University Press, United Kingdom and New York, NY, USA.

Currie, D.J. (2001) Projected effects of climate change on patterns of vertebrate and tree species in the conterminous United States. *Ecosystems*, 4: 216-225.

D'Amato, G., G. Liccardi ,M. D'Amato and M. Cazzola (2002) Outdoor air pollution, climatic changes and allergic bronchial asthma. *Eur. Respir. J.*, 20: 763-776.

Dalgaard, J.B., G. Dencker, B. Fallentin, P. Hansen, B. Kaempe, J. Steensberger, Wilhardt, P. (1972) Fatal poisoning and other health hazards connected with industrial fishing. *Br. J. Ind. Med*. 29: 307-316.

D'Souza, R., N. Becker, G. Hall and K. Moodie (2004) Does ambient temperature affect foodborne disease? *Epidemiology*, 15: 86-92.

Davis, R., P. Knappenberger, W. Novicoff and P. Michaels (2002) Decadal changes in heat-related human mortality in the eastern United States. *Climate Res*., 22: 175-184.

Davis, R., P. Knappenberger, P. Michaels and W. Novicoff (2003) Changing heat related-mortality in the United States. *Environ. Health Persp*., 111, 1712 -1718.

Davis, R., P. Knappenberger, P. Michaels and W. Novicoff (2004) Seasonality of climate-human mortality relationships in US cities and impacts of climate change. *Climate Res*., 26: 61-76.

de la Chesnaye, F.C. and J.P Weyant, (eds.) (2006) Multigas Mitigation and Climate Policy. *The Energy Journal Special Issue.*

del Ninno, C. and M. Lundberg (2005) Treading water: the long term impact of the 1998 flood on nutrition in Bangladesh. *Econ. Hum. Biol.*, 3, 67-96. [Cited in Confalonieri et al., 2007]

Denman, K.L., et al. (2007) Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Diffenbaugh, N.S., J.S. Pal, R.J. Trapp, and F. Giorgi (2005) Fine-scale processes regulate the response of extreme events to global climate change. *Proc. Natl. Acad. Sci. U.S.A.*, 102(44): 15774–15778, doi:10.1073/pnas.0506042102.

Dole, R., M. Hoerling, and S. Schubert (2008) *Executive summary*. In: Reanalysis of Historical Climate Data for Key Atmospheric Features: Implications for Attribution of Causes of Observed Change. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Randall Dole, Martin Hoerling, and Siegfried Schubert (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, pp. 1–4

Donaldson, G.C., R.S. Kovats, W.R. Keatinge and A. McMichael (2001) Heat-and cold-related mortality and morbidity and climate change. *Health Effects of Climate Change in the UK*, Department of Health, London, 70-80.

Dvortsov, V.L., and S. Solomon (2001) Response of the stratospheric temperatures and ozone to pat and future increases in stratospheric humidity, *J. Geophys. Res.*, 106 (D7): 7505-7514.

Dyurgerov, M., and M.F. Meier (2005) Glaciers and the Changing Earth System: A 2004 Snapshot. Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, 118 pp.

Easterling, W. et al. (2007) Food, Fibre and Forest Products. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ebi, K.L., J. Balbus, P.L. Kinney, E. Lipp, D. Mills, M.S. O'Neill, and M. Wilson, 2008: Effects of Global Change on Human Health. In: *Analyses of the effects of global change on human health and welfare and human systems*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Gamble, J.L. (ed.), K.L. Ebi, F.G. Sussman, T.J. Wilbanks, (Authors)]. U.S. Environmental Protection Agency, Washington, DC, USA, p. 2-1 to 2-78.

EIA (2006) Annual Energy Outlook 2006, with Projections to 2030. DOE/EIA-0383(2006). *Energy Information Administration*, Washington, D.C.

EM-DAT (2006) *The OFDA/CRED International Disaster Database*. http://www.em-dat.net.

European Commission (2003) *Ozone-climate interactions.* In: Air pollution research report [Isaksen, I.S.A. (eds.)]. Report 81, EUR 20623, Luxembourg.

Fallico, F, K. Nolte, L. Siciliano, and F. Yip (2005) Hypothermia-related deaths – United States, 2003-2004. *MMWR – Morbidity & Mortality Weekly Report*, 54(07), 173-175.

Felzer, B., et al. (2005) Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model. *Climatic Change*, 73(3): 345-373.

Field, C.B. et al. (2007) North America. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fingar, T. (2008) "National Intelligence Assessment on the National Security Implications of Global Climate Change to 2030." Testimony before the House Permanent Select Committee on Intelligence and House Select Committee on Energy Independence and Global Warming, June 25, 2008.

Fish and Wildlife Service (FWS) (2008) *Endangered and Threatened Wildlife and Plants; Determination of Threatened Status for the Polar Bear (Ursus maritimus) Throughout Its Range*. 50 CFR Part 17, RIN 1018-AV19, FWS-R7-ES-2008-0038.

Fish and Wild Service (FWS) (2007) *12-Month Petition Finding and Proposed Rule to List the Polar Bear (Ursus maritimus) as Threatened Through Its Range*. 50 CFR Part 17, RIN 1018-AV19.

Fisher, B. et al. (2007) Issues related to mitigation in the long term context. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fischlin, A. et al. (2007) Ecosystems, their Properties, Goods, and Services. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fleury, M., D.F. Charron, J. D. Holt, O.B. Allen and A. R. Maarouf (2006) A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *Int. J. Biometeorol.,* 50: 385-391.

Forster, P. et al. (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Frank, K.L., T.L. Mader, J.A. Harrington, G.L. Hahn and M.S. Davis (2001) Climate change effects on livestock production in the Great Plains. *Proc. 6th International Livestock Environment Symposium*, R.R. Stowell, R. Bucklin and R.W. Bottcher (eds.) American Society of Agricultural Engineering, St. Joseph, Michigan, 351-358.

Gagnon, A.S., A.B.G. Bush and K.E. Smoyer-Tomic (2001) Dengue epidemics and the El Niño Southern Oscillation. *Climate Res.*, 19: 35-43.

Glatte, H., B. Hartman, B.E. Welch (1967) “Nonpathologic hypercapnia in man.” Lectures in Aerospace Medicine. 6th series. #SAM-TR-68-116. U.S. Air Force School of Medicine: Brooks AFB, Texas. pp. 110-129.

Graumann, A.,T. Houston, J. Lawrimore, D. Levinson, N. Lott, S. McCown, S. Stephens and D.Wuertz, 2005: Hurricane Katrina - a climatological perpective. October 2005, updatedAugust 2006. Technical Report 2005-01. 28 p. NOAA National Climate Data Center, available at: http://www.ncdc.noaa.gov /oa/reports/tech-report-200501z.pdf

Greenough, G., M.A. McGeehin, S.M. Bernard, J. Trtanj, J. Riad and D. Engelberg (2001) The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. *Environ. Health Persp*., 109: 191-198.

Groisman, P. Ya., et al. (2004) Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *J. Hydrometeorol.*, 5: 64–85.

Guidry, V.T. and L.H. Margolis (2005) Unequal respiratory health risk: using GIS to explore hurricane related flooding of schools in Eastern North Carolina. *Environ. Res*., 98, 383-389.

Guenther, A.B., et al. (1993) Isoprene and monoterpene emission rate variability - model evaluations and sensitivity analyses. *J. Geophys. Res.*, 98(D7): 12609–12617.

Gutierrez, B.T., S. J. Williams, and E. R. Thieler (2009) Ocean Coasts. In: *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington D.C., USA, 320 pp.

Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, F.W. Zwiers (2008) Causes of Observed Changes in Extremes and Projections of Future Changes. In: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Hales, S., P. Wienstein, Y. Souares and A. Woodward (1999) El Niño and the dynamics of vectorborne disease transmission. *Environ.Health Persp.*, 107: 99-102.

Hassi, J.,M. Rytkonen, J. Kotaniemi and H. Rintamaki (2005) Impacts of cold climate on human heat balance, performance and health in circumpolar areas. *Int. J. Circumpolar Health*, 64: 459-467.

Hatfield, J., K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, and D. Wolfe (2008) Agriculture. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp.

Hathaway GJ, Proctor NH, Hughes JP, and Fischman ML (1991) *Proctor and Hughes' chemical hazards of the workplace*. 3rd ed. New York, NY: Van Nostrand Reinhold.

Hauglustaine D.A., et al. (2005) Future tropospheric ozone simulated with a climate-chemistry-biosphere model, *Geophys. Res. Lett.*, 32, L24807, doi:10.1029/2005GL024031.

Hay, S.I., J. Cox, D.J. Rogers, S.E. Randolph, D.I. Stern, G.D. Shanks, M.F. Myers and R.W. Snow (2002) Climate change and the resurgence of malaria in the East African highlands. *Nature*, 415: 905-909.

Hayhoe, K. (2004) Emissions pathways, climate change, and impacts on California. *P. Natl. Acad. Sci. USA*, 101, 12422.

Hegerl, G.C. et al. (2007) Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hoerling, M., and A. Kumar, 2003: The perfect ocean for drought. *Science*, 299, 691–694.

Hogrefe, C., B. Lynn, C. Rosenzweig, R. Goldberg, K. Civerolo, J-Y. Ku, J. Rosenthal, K. Knowlton, and P.L. Kinney (2005) Utilizing CMAQ Process Analysis to Understand the Impacts of Climate Change on Ozone and Particulate Matter. Models-3 Users' Workshop, September 26-28, Chapel Hill, North Carolina.

Hogrefe, C., K. Civerolo, J-Y. Ku, B. Lynn, J. Rosenthal, B. Solecki, C. Small, S. Gaffin, K. Knowlton, R. Goldberg, C. Rosenzweig, and P.L. Kinney (2006) Air quality in future decades – determining the relative impacts of changes in climate, anthropogenic and biogenic emissions, global atmospheric composition, and regional land use. In: Air Pollution Modeling and its Application XVII [Borrego, C. and A.L. Norman (eds.)]. Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modeling and its Application, Springer, October 25-29, 2004, Banff, Canada, 772 pp.

Hogrefe C.B. et al. (2004) Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions, *J. Geophys. Res*., 109: D22301.

Horvitz, A ed., (2008) Global Climate, *in* State of the Climate in 2007. Levinson, D.H., and J.H. Lawrimore eds., *Bulletin of the American Meteorological Society*, 89: S37-S61.

Hoyt, K.S. and A. E. Gerhart (2004) The San Diego County wildfires: perspectives of health care. *Disaster Manage. Response*, 2, 46-52.

Huynen, M. and B. Menne (2003) Phenology and human health: allergic disorders. Report of a WHO meeting in Rome, Italy, 16–17 January 2003.Health and Global Environmental Series, EUR/03/5036791. World Health Organization, Copenhagen, 64 pp.

H.R. 4986 (PL 110-181, Jan. 28, 2008). Available from *Thomas* (Library of Congress) http://thomas.loc.gov; accessed 2/23/09.

IPCC (2007a) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b) Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007c) Summary for Policymakers. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007d) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2005) *Special Report on Carbon Dioxide Capture and Storage*. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.

IPCC (2001a) Summary for Policymakers. In *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J.J. McCarthy et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2001b) Summary for Policymakers. In. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J.T. Houghton et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2000) *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change* [N. Nakicenovic et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds. Cambridge University Press. Cambridge, U.K.

IPCC Technology and Economic Assessment Panel (2005) IPCC/TEAP Special Report on Safe-guarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. Prepared by Working Group I and III of the IPCC, and the TEAP. Edited by B. Metz, L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. de Jager, T. Kestin, M. Manning, and L.A. Meyers, 488 pp., Cambridge University Press, Cambride, U.K., and New York, NY, USA.

Izaurralde, R.C., N.J. Rosenberg, R.A. Brown, and A.M. Thomson (2003) Integrated assessment of Hadley Centre climate change projections on water resources and agricultural productivity in the conterminous United States. II. Regional agricultural productivity in 2030 and 2095. *Agricultural and Forest Meteorology,* 117: 97-122

Jacob, D.J., and D.A. Winner (2009) Effect of climate change on air quality , *Atmospheric Environment*., 43: 51-63.

Jacobson M.Z. (2008) On the causal link between carbon dioxide and air pollution mortality. *Geophysical Research Letter*s, 35, L03809, doi: 10.1029/2007GL031101.

Janetos, A., L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw (2008) Biodiversity. In: T*he effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp.

Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba and D. Zhang (2007) *Palaeoclimate*. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kalkstein, L.S. and J.S. Greene, 1997: An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of a climate change. *Environmental Health Perspectives,* 105: 84-93.

Karl, T.R., G.A. Meehl, T.C. Peterson, K.E. Kunkel, W.J. Gutowski, Jr., D.R. Easterling (2008) *Executive Summary* in Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.) (2006) *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Keeling, C.D. and T.P. Whorf (2005) Atmospheric carbon dioxide record from Mauna Loa, Carbon Dioxide Research Group, Scripps Institution of Oceanography, May.

Key, J.R., and A.C.K. Chan (1999) Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies, *Geophys. Res. Lett*., 26: 2053–2056.

Kitzberger, T., T.W. Swetnam and T.T. Veblen (2001) Inter-hemispheric synchrony of forest fires and the El Nino-Southern Oscillation. *Global Ecol. Biogeogr.*, 10: 315-326.

Klein Tank, A.M.G., and G.P. Können (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *J. Clim.*, 16: 3665–3680.

Knowlton, K., et al. (2004) Assessing ozone-related health impacts under a changing climate. *Environ. Health. Perspect.*, 112: 1557-1563.

Kolivras, K.N. and A.C. Comrie (2003) Modeling valley fever (coccidioidomycosis) incidence on the basis of climate conditions. *Int. J. Biometeorol.*, 47: 87-101.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper (2007) A globally consistent reanalysis of hurricane variability and trends. *Geophys. Res. Lett*., 34, L04815, doi:10.1029/2006GL028836.

Kovats, R.S., D. Campbell-Lendrum, A. McMichael, A. Woodward and J. Cox (2001) Early effects of climate change: do they include changes in vector-borne disease? *Philos. T. Roy. Soc. Lond. B*, 356: 1057-1068.

Kovats, R.S., S. Edwards, S. Hajat, B. Armstrong, K.L. Ebi and B. Menne (2004) The effect of temperature on food poisoning: time series analysis in 10 European countries. *Epidemiol. Infect.*, 132: 443-453.

Kundzewicz, Z.W. et al. (2007) Freshwater Resources and Their Management. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kunkel, K.E., P.D. Bromirski, H.E. Brooks, T. Cavazos, A.V. Douglas, D.R. Easterling, K.A. Emanuel, P.Ya. Groisman, G.J. Holland, T.R. Knutson, J.P. Kossin, P.D. Komar, D.H. Levinson, R.L. Smith (2008) Observed Changes in Weather and Climate Extremes in *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*. T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (eds.). A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

Kunkel, K.E., et al. (2003) Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophys. Res. Lett.*, 30, 1900, doi:10.1029/2003GL018052.

Lambertsen, C.J. (1971) “Therapeutic Gases—Oxygen, Carbon Dioxide, and Helium.” Drill’s Pharmacology in Medicine. Chapter 55, Ed. By J.R. DiPalma. McGraw-Hill Book Co.: New York, NY.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer and E.R. Ivins (2005) Rapid uplift of southern Alaska caused by recent ice loss. *Geophys. J. Int.*, 158: 1118-1133.

Leibensperger, E. M., L. J. Mickley, D. J. Jacob (2008) Sensitivity of U.S. air quality to mid-latitude cyclone frequency and implications of 1980-2006 climate change, Atmos. Chem. Phys., 8: 7075-7086.

Lemke, K. et al. (2007) Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lettenmaier, D., D. Major, L. Poff, and S. Running (2008) Water Resources. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity*. A Report by the U.S. Climate Change Science Program and the subcommittee on Global change Research. Washington, DC., USA, 362 pp.

Leung, L.R., et al. 2004) Mid-century ensemble regional climate change scenarios for the western United States. *Clim. Change*, 62, 75–113.

Liao, C. and Seinfeld (2006) Role of climate change in global predictions of future tropospheric ozone and aerosols, *J. Geophys. Res*., 111, D12304, doi:10.1029/2005JD006852.

Liu, L., J.S. King, and C.P. Giardina (2005) Effects of elevated concentrations of atmospheric CO_2 and tropospheric O_3 on leaf litter production and chemistry in trembling aspen and paper birch communities. *Tree Physiology*, 25: 1511-1522.

Loya, W.M., et al. (2003) Reduction of soil carbon formation by tropospheric ozone under increased carbon dioxide levels. *Nature*, 425: 7075-7077.

Marland, G., T.A. Boden and R.J. Andres (2006) Global, Regional, and National Fossil Fuel CO_2 Emissions. In: *Trends: A Compendium of Data on Global Change* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA).

McCabe, G.J., M. Palecki, and J.L. Betancourt, 2004: Pacific and Atlantic Ocean influences on multi-decadal drought frequency in the United States. *Proc. Natl. Acad. Sci.* U.S.A., 101, 4136–4141.

McCabe, G.J. and J.E. Bunnell (2004) Precipitation and the occurrence of Lyme disease in the northeastern United States. *Vector-Borne and Zoonotic Diseases*, 4: 143-148.

McCabe, G.J., M.P. Clark, and M.C. Serreze (2001) Trends in Northern Hemisphere surface cyclone frequency and intensity, *J. Clim*., 14: 2763–2768.

McKenzie, D., A.E. Hessl, and D.L. Peterson (2001) Recent growth of conifer species of western North America: Assessing spatial patterns of radial growth trends. *Can. J. For. Res.*, 31: 526-538.

McLaughlin, J.B., A. DePaola, C.A. Bopp, K.A. Martinek, N.P. Napolilli, C.G.Allison, S.L. Murray, E.C. Thompson, M.M. Bird and J.P. Middaugh (2005) Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New Engl. J. Med.*, 353: 1463-1470.

McMichael et al. (2001). Human Health. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meehl, G.A. et al. (2007) Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meehl, G.A. and C. Tebaldi, 2004: More intense, more frequent and longer lasting heat waves in the 21st century. *Nature*, 305: 994-997.

Menne, B. and R. Bertollini, 2000: The health impacts of desertification and drought. *Down to Earth,* 14: 4-6.

Mickley, L.J., D.J. Jacob, B.D. Field, and D. Rind (2004) Effects of future climate change on regional air pollution episodes in the United States. *Geophys. Res. Lett.*, 30, 1862, doi:10.1029/2003GL017933.

Miettinen, I.T., O. Zacheus, C.H. von Bonsdorff and T. Vartiainen (2001) *Waterborne epidemics in Finland in 1998-1999*. Water Sci. Technol., 43, 67-71.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Mills, E. (2005) Insurance in a climate of change. *Science* 309:1040-1044.

Mimura, N. et al. (2007) Small Islands. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mine Safety and Health Administration (MSHA) (2007) *The Danger of Oxygen Deficiency in Underground Coal Mines*. Department of Labor Program Information Bulletin NO. P07-05. Internet site located at http://www.msha.gov/regs/complian/PIB/2007/pib07-05.asp

Najjar, R.G., H.A.Walker, P.J.Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele and R.S. Swanson (2000) The potential impacts of climate change on themid-Atlantic coastal region. *Climate Res.*, 14: 219-233.

NARSTO (2004) *Particulate Matter Assessment for Policy Makers: A NARSTO Assessment*. P. McMurry, M. Shepherd, and J. Vickery, eds. Cambridge University Press, Cambridge, England. ISBN 0 52 184287 5.

NAST (2000) Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.

National Aeronautical and Space Administration (NASA) Goddard Space Flight Center (2008) 2008 Arctic Sea Ice from AMSR-E. http://svs.gsfc.nasa.gov/vis/a000000/a003500/a003556/

National Aeronautical and Space Administration (NASA) Goddard Space Flight Center (2007) 2007 Arctic Sea Ice from AMSR-E. http://svs.gsfc.nasa.gov/vis/a000000/a003400/a003464/index.html

National Aeronautical and Space Administration (NASA) (2009) GISS Surface Temperature Analysis. http://data.giss.nasa.gov/gistemp/2008/

National Aeronautical and Space Administration (NASA) (2007) GISS Surface Temperature Analysis. http://data.giss.nasa.gov/gistemp/2007/

National Intelligence Council (NIC) (2008) *Global Trends 2025: A Transformed World*. Office of the Director of National Intelligence, Washington DC, 120 pp.

National Oceanic and Atmospheric Administration (NOAA) (2009) *The Climate of 2008.* http://www.ncdc.noaa.gov/oa/climate/research/2008/ann/ann08.html

National Oceanic and Atmospheric Administration (NOAA) (2007) *The Climate of 2006*. http://www.ncdc.noaa.gov/oa/climate/research/2006/perspectives.html

National Oceanic and Atmospheric Administration (NOAA) (2007). U.S. Historical Climate Network Data. http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

National Research Council (NRC) (2008) *Potential Impacts of Climate Change on U.S. Transportation*. National Academy Press, Washington, DC.

National Research Council (NRC) (2006a) *Mitigating Shore Erosion Along Sheltered Coasts*, National Academy Press, Washington, DC.

National Research Council (NRC) (2006b) *Surface Temperature Reconstructions For the Last 2,000 Years*. National Academy Press, Washington, DC.

National Research Council (2005) *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties,* Committee on Radiative Forcing Effects on Climate, Climate Research Committee, ISBN: 0-309-54688-5.

National Research Council (NRC) (2004) *Air Quality Management in the United States*. National Academy Press, Washington, DC.

National Research Council (NRC) (2003) *Understanding Climate Change Feedbacks.* National Academy Press, Washington, DC.

National Research Council (NRC) (2002) *Abrupt Climate Change, Inevitable Surprises*. National Academy Press, Washington, DC.

National Research Council (NRC) (2001) *Climate Change Science: An Analysis of Some Key Questions*. National Academy Press, Washington, DC.

National Research Council (NRC) (2001) *Global Air Quality: An Imperative for Long-Term Observational Strategies*. National Academy Press, Washington, DC.

National Research Council (NRC) (2000) *Emergency and Continuous Exposure Limits for Selected Airborne Contaminants*, Volume 1. National Academy Press, Washington, D.C.

National Research Council (NRC) (1996) Toxicity of Alternatives to Chlorofluorocarbons: HFC-134a and HCFC-123. National Academy Press, Washington, D.C.

National Science and Technology Council (2008) *Scientific Assessment of the Effects of Global Change on the United States*. A Report of the Committee on Environment and Natural Resources, Washington, DC.

National Snow and Ice Data Center (NSIDC) (2009) Cryospheric Climate Indicators, http://www.nsidc.org/data/seaice_index/

Nicholls, R.J. et al. (2008) *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates*. OECD Environment Working Papers, No. 1, OECD Publishing.

Nicholls, R.J. et al. (2007) Coastal Systems and Low-lying Areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nielsen, G.D., et al. (2002) IgE-Mediated Asthma and Rhinitis I: A Role of Allergen Exposure? *Pharmacology & Toxicology*, 90: p. 231-242.

NIOSH (1997) NIOSH Pocket Guide to Chemical Hazards. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, Washington, D.C. NIOSH Publication no. 97-140; NTIS no. PB-97177604. Internet site located at http://www.cdc.gov/niosh/npg/npgd0576.html

NIOSH (1994) International Chemical Safety Cards - Methane. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, Washington, D.C. Internet site located at http://www.cdc.gov/niosh/ipcsneng/neng0291.html

NIOSH (1992) Recommendations for occupational safety and health: Compendium of policy documents and statements. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health (NIOSH) Publication No. 92-100.

Ogden, N.H., L.R. Lindsay, G. Beauchamp, D. Charron, A. Maarouf, C.J. O'Callagjan, D.Waltner-Toews and I.K. Barker (2004) Investigation of the relationships between temperature and developmental rates of tick Ixodes Scapularis (Acari: Ixodidae) in the laboratory and field. *J. Med. Entomol.*, 41: 622-633.

OSHA (1989) *Carbon Dioxide, Industrial Exposure and Control Technologies for OSHA Regulated Hazardous Substances*, Volume I of II, Substance A - I. Occupational Safety and Health Administration. Washington, DC: U.S. Department of Labor. March.

Patz, J.A. and J.M. Balbus (2001) *Global climate change and air pollution*. In: Ecosystem Change and Public Health. A Global Perspective [Aron J.L. and J.A. Patz (eds.)]. The Johns Hopkins University Press, Baltimore, pp. 379–408.

Parry, M.L. et al. (2007) Technical Summary. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 23-78.

Perez-Garcia, J., L.A. Joyce, A.D. McGuire and X.M.Xiao (2002) Impacts of climate change on the global forest sector. *Clim. Change*, 54: 439-461.

Plummer, D.A., et al., 2006: Climate and climate change over North America as simulated by the Canadian Regional Climate Model. J. Clim., 19, 3112–3132.

Rahmstorf, S. (2007) A Semi-Empirical Approach to Projecting Future Sea Level Rise. *Nature*, 315: 368-370.

Ramanathan V. and Carmichael, G. (2008) Global and regional climate changes due to black carbon. *Nature Geoscience*, 1: 221–227.

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi and K.E. Taylor (2007) *Climate Models and Their Evaluation*. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ranhoff, A.H. (2000) Accidental hypothermia in the elderly. *Int. J. Circumpolar Health*, 59: 255-259.

Raper, S.C.B., T.M.L. Wigley and Warrick R.A. (1996) in *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies* J.D. Milliman, B.U. Haq, Eds., Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 11–45.

Reacher, M., K. McKenzie, C. Lane, T. Nichols, I. Kedge, A. Iverson, P. Hepple, T.Walter, C. Laxton and J. Simpson (2004) Health impacts of flooding in Lewes: a comparison of reported gastrointestinal and other illness and mental health in flooded and non flooded households. *Communicable Disease and Public Health*, 7: 1-8.

Reisen, W.K., Y. Fang and V. Martinez (2006) Effects of temperature on the transmission of West Nile virus by Culex tarsalis (Diptera: Culicidae). *J. Med. Entomol*., 43: 309-317.

Ribeiro et al. (2007) Transport and its Infrastructure. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Robeson, S. (2004) Trends in time-varying percentiles of daily minimum and maximum temperature over North America. *Geophys. Res. Lett*, 31, L04203, doi:10.1029/2003GL019019.

Rogers, D.J. and S.E. Randolph (2006) Climate change and vector-borne diseases. *Adv. Parasitol.*, 62: 345-381.

Rom, WN (1992) *Environmental and occupational medicine*. 2nd ed. Boston, MA: Little, Brown and Company.

Rosenzweig, C., et al. (2007) Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 79-131.

Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills and J. Bloomfield (2002) Increased crop damage in the US from excess precipitation under climate change. *Global Enviornmental Change*, 12: 197-202.

Rosenzweig, C., and W. Solecki (eds.) (2001) Climate Change and a Global City: The Potential Consequences of Climate Variability and Change – Metro East Coast. Columbia Earth Institute, New York.

Ryan, M., S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, and W. Schlesinger (2008) Land Resources. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC., USA, 362 pp

Rybnicek, O. and S. Jaeger (2001) Ambrosia (ragweed) in Europe. *ACI International***,** 13: 60-66.

Schneider, S.H. et al. (2007) *Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 779-810.

Schwartz, P. and D. Randall (2003) “An Abrupt Climate Change Scenario and Its Implications for United States National Security.” Prepared for the Department of Defense by the Global Business Network.

Schwartz, J., J.M. Samet and J.A. Patz (2004) Hospital admissions for heart disease: the effects of temperature and humidity. Epidemiology, 15: 755-761.

Semenov, S.M., E.S. Gelver and V.V. Yasyukevich (2002) Temperature conditions for development of two species of malaria pathogens in Russia in 20th century. *Dokl. Akad. Nauk*, 387: 131-136.

Shanklin, E. (1988) Beautiful Deadly Lake Nyos: The Explosion and its Aftermath. *Anthropology Today*, 4,(1): 12-14.

Shindell, D.T. (2001) Climate and ozone response to increased stratospheric water vapor, *Geophys. Res. Lett., 28* (8): 1551-1554.

Sillman, S., and P. J. Samson (1995) Impact of temperature on oxidant photochemistry in urban, polluted rural and remote environments, *J. Geophys. Res.*, 100: 11,497–11,508.

Smith, S.J. and G.P. Kyle (2007) *Impact of Light-Duty Vehicle Emissions on 21st Century Carbon Dioxide Concentrations, PNNL Research Brief.* Prepared for the U.S. Environmental Protection Agency under Contract DE-AC06-76RL01830, Joint Global Change Research Institute, College Park, Maryland.

Sohngen, B. and R. Sedjo (2005) Impacts of climate change on forest product markets: Implications for North American producers. *Forestry Chron.*, 81: 669-674.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt (2007) Technical Summary. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sorogin, V.P. et al. (1993) Problemy Ohrany Zdoroviya i Socialnye AspectyOsvoeniya Gazovyh I Neftyanyh Mestorozhdenij v Arcticheskih Regionah [Problems of Public Health and Social Aspects of Exploration of Oil and NaturalGas Deposits in Arctic Regions]. Nadym.

Stevenson, D.S., et al. (2005) Impacts of climate change and variability on tropospheric ozone and its precursors. *Faraday Discuss.*, 130, doi:10.1039/b417412g.

Stone, R.S., E.G. Dutton, J.M. Harris, and D. Longnecker (2002) Earlier spring snowmelt in northern Alaska as an indicator of climate change. *J. Geophys. Res.*, 107(D10), doi:10.1029/2000JD000286.

Taramarcaz, P., B. Lambelet, B. Clot, C. Keimer and C. Hauser (2005) Ragweed (Ambrosia) progression and its health risks: will Switzerland resist this invasion? *Swiss Med. Wkly.*, 135: 538-548.

Trenberth, K.E. et al. (2007) Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Troyer,A.F. (2004) Background of U.S. Hybrid Corn II: Breeding,climate, and food. *Crop Science*, 44: 370-380.

Turner, J., et al. (2005) Antarctic climate change during the last 50 years. *Int. J. Climatol.*, 25: 279–294.

Tuyet, D.T., V.D. Thiem, L. Von Seidlein, A. Chowdhury, E. Park, D.G. Canh, B.T. Chien, T.Van Tung,A.Naficy,M.R. Rao,M.Ali,H. Lee, T.H. Sy,M.Nichibuchi, J. Clemens and D.D. Trach (2002) Clinical, epidemiological, and socioeconomic analysis of an outbreak of *Vibrio parahaemolyticus* in KhanhHoa Province, Vietnam. *J. Infect. Dis.*, 186: 1615-1620.

UNPD (2005) *World Population Prospects*: The 2004 Revision.United Nations Population Division, New York, New York. [Accessed 12.02.07: http://esa.un.org/unpp/]

USDA (2007) *Crop Production Historical Track Records*, National Agricultural Statistics Service (NASS): http://usda.mannlib.cornell.edu/usda/current/htrcp/htrcp-04-27-2007.pdf.

U.S. EPA (2009) *Assessment of the Impacts of Global Change on Regional U.S. Air Quality: A Synthesis of Climate Change Impacts on Ground-Level Ozone*. An Interim Report of the U.S. EPA Global Change Research Program.

U.S. EPA (2008) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2006*. EPA-430-R-08-005, Washington, DC.

U.S. EPA (2006a) *Air Emissions Trends—Continued Progress Through 2005*. EPA, Washington, DC. December 19.

U.S. EPA (2006b) *Air Quality Criteria for Ozone and Related Photochemical Oxidants*, EPA 600/R-05/004aF, February.

U.S. EPA (2004) *Air Quality Criteria for Particulate Matter,* EPA/600/P-99/002aF, October.

U.S. EPA (2000a) *Carbon Dioxide as a Fire Suppressant: Examining the Risks*, EPA 430-R-00-002, May.

U.S. EPA (2000b) *Carbon Dioxide as a Fire Suppressant: Examining the Risks, Appendix B – Overview of Acute Health Effects*, EPA 430-R-00-002, May.

U.S. Navy (2001) *Naval Operations in an Ice-Free Arctic: Symposium*, Office of Naval Research, Naval Ice Center, April 17-18.

Victor Cruz, R. et al. (2007) Asia. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [(eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wade, T.J., S.K. Sandhu, D. Levy, S. Lee, M.W. LeChevallier, L.Katz and J.M. Colford (2004) Did a severe flood in the Midwest cause an increase in the incidence of gastrointestinal symptoms? *Am. J. Epidemiol*., 159: 398-405.

Wayne, P., S. Foster, J. Connolly, F. Bazzaz and P. Epstein (2002) Production of allergenic pollen by ragweed (Ambrosia artemisiifolia L.) is increased in CO_2-enriched atmospheres. *Ann. Alerg. Asthma Im.*, 88: 279-282.

Weber, R.W. (2002) Mother Nature strikes back: global warming, homeostasis, and implications for allergy. *Ann. Allergy. Asthma Im*., 88: 251-252.

Westerling, A. L., et al (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, 313: 940-943.

WMO (World Meteorological Organization) (2007) *Scientific Assessment of Ozone Depletion: 2006,* Global Ozone Research and Monitoring Project—Report No. 50, 572pp., Geneva, Switzerland.

Wigley, T.M.L. and S. Raper, S.C.B. (2002) Reasons for larger warming projections in the IPCC Third Assessment Report *J. Climate*, 15: 2945–2952.

Wigley, T.M.L. and S. Raper, S.C.B. (1992) Implications for Climate And Sea-Level of Revised IPCC Emissions Scenarios *Nature*, 357: 293–300.

Wilbanks, T.J., P. Kirshen, D. Quattrochi, P. Romero-Lankao, C. Rosenzweig, M. Ruth, W. Solecki, and J. Tarr (2008) Effects of Global Change on Human Settlements. In: *Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC, USA, pp. 3-1 – 3-31.

Wilbanks, T. et al. (2007) Industry, Settlement and Society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental*

Panel on Climate Change [M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wittmann, R. and G. Flick (1995) Microbial contamination of shellfish: prevalence, risk to human health and control strategies. *Annu. Rev. Publ.Health*, 16, 123-140.

WRI (2007) *Climate Analysis Indicators Tool (CAIT) Version 4.0*. Available at http://cait.wri.org/. Accessed June 30, 2007.

Yienger, J. J., and H. Levy II (1995) Empirical model of global soil-biogenic NOx emissions. *J. Geophys. Res.*, 100(11): 447– 11 464.

Zishka, K. M., and P. J. Smith (1980) The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–1977, *Mon. Weather Rev*., 108: 387–401.

Ziska, L.H., D.E. Gebhard, D.A. Frenz, S. Faulkner, B.D. Singer and J.G. Straka, 2003: Cities as harbingers of climate change: Common ragweed, urbanization, and public health. *J. Allergy Clin. Immunol*., **111**, 290-295. [Cited in Field et al., 2007]