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

Section I. Executive Summary

I.1 Introduction

The climate is changing, and these changes are affecting the world around us. In order to deal with the changes that are taking place now and to prepare for those that are likely to happen in the future, decisionmakers need information about global change and its effects on the Nation and the world we live in.

This national scientific assessment integrates, evaluates, and interprets the findings of the U.S. Climate Change Science Program (CCSP) and draws from and synthesizes findings from previous assessments of the science, including reports and products by the Intergovernmental Panel on Climate Change (IPCC). It analyzes current trends in global change, both natural and human-induced, and it projects major trends for the future. It analyzes the effects of these changes on the natural environment, agriculture, water resources, social systems, energy production and use, transportation, and human health. It is intended to help inform discussion of the relevant issues by decisionmakers, stakeholders, and the public. As such, this report addresses the requirements for assessment in the Global Change Research Act of 1990.[1]

This assessment addresses not only climate change, but also other change in the global environment—including water resources, oceans, atmospheric chemistry, land productivity, and ecological systems—that may alter the capacity of Earth to sustain life. This broader set of changes is referred to as 'global change,' as defined in the Global Change Research Act.

Over the past several years, our understanding of climate variability and change and our ability to estimate their future effects has improved significantly. The conclusions in this assessment build on the vast body of observations, modeling, decision support, and other types of activities conducted under the auspices of CCSP and from previous assessments of the science, including reports and products by the IPCC, CCSP, and others. This assessment and the underlying assessments have been subjected to and improved through rigorous peer reviews.

I.2 Causes of Climate Change

Our understanding of climate change continues to grow, enabling scientists to draw increasingly certain conclusions about its causes and impacts. For example, in their most recent assessment of climate change science, the IPCC concluded that it is unequivocal that the average temperature of Earth's surface has warmed recently and it is *very likely* (greater than 90% probability)[2] that most of this global warming is due to increased concentrations of human-generated greenhouse gases. Several lines of evidence, including those outlined in the following sections, point to a strong human influence on climate. Although these individual lines of evidence vary in their degrees of certainty, when considered together they provide a compelling and scientifically sound explanation of the changes to Earth's climate—including changes in

[1] 15 USC Chapter 56A
[2] Definitions for terms used in statements of confidence and likelihood can be found in Section II.3: Characterization of Uncertainty.

surface temperature, ice extent, and sea level rise—observed at global and continental scales over the past few decades. [IV.1 and IV.2][3]

Several different types of gases in the atmosphere warm the planet by trapping energy that would otherwise be emitted to space. These 'greenhouse gases' include water vapor, carbon dioxide, methane, ozone, nitrous oxide, and several fluorine- and chlorine-containing gases. Of the greenhouse gases that are increasing in atmospheric concentration as a direct result of human activities, carbon dioxide is contributing most to the recent warming. The globally averaged concentration of carbon dioxide in the atmosphere has increased from about 280 parts per million (ppm) in the 18th century to 383 ppm in 2007. Emissions of carbon dioxide from fossil fuel use and from the effects of land use change are the primary sources of this increase. The current atmospheric concentration of carbon dioxide greatly exceeds the natural range of the last 650,000 years (180 to 300 ppm) as determined from ice cores. Indeed, the atmospheric levels of all major greenhouse gases have also increased significantly in the past century. [IV.1.a]

An increasing body of scientific research supports the conclusion that, while greenhouse gases are but one of many factors that affect climate, they are *very likely* the single largest cause of the recent warming. Other factors that affect climate may contribute either a warming or cooling influence. For example, some types of tiny particles in the air introduce a cooling influence. These particles, known as aerosols, include sulfate, organic carbon, nitrate, and mineral dust. Black carbon aerosols introduce a warming influence. Deposition of black carbon on snow and ice also contributes a warming influence on the climate by decreasing surface reflectivity that would otherwise deflect more solar energy back into space. Aerosols have been observed to increase cloudiness and cloud reflectivity, both of which have a cooling influence. Other changes to surface reflectivity, as well as variations in solar irradiance, can have either warming or cooling influences. [IV.1.a]

Studies that rigorously quantify the effect of different external influences on observed changes (attribution studies) conclude that most of the recent global warming is *very likely* due to human-generated increases in greenhouse gas concentrations. A large number of climate model simulations show that natural factors alone cannot explain the observed warming in the second half of the 20th century of Earth's land masses and oceans, or that of the North American continent. On the other hand, simulations that include human factors are able to reproduce important large-scale features of the recent changes. Several studies indicate that natural factors played an important role in the warming of the first half of the 20th century. Attribution studies show that it is *likely* (greater than 66% probability) that there has been a substantial human contribution to the surface temperature increase in North America.

According to the IPCC, model simulations of regional (sub-continental-scale) climate have improved, and a limited number of regional climate features are consistently captured in multiple climate model projections. Regional changes in the United States that are consistently projected in climate models are discussed throughout the report, and include some significant regional changes in temperature and precipitation. There are limits to how effectively climate change and

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[3] The report section(s) denoted in square brackets are where information supporting a particular statement can be found.

its impacts can be projected on small scales, such as at the scale of a single city or county, a single state, or even a group of states, especially over the next decade or two. Climate changes on small scales are difficult to discern, in part, because climate variability averaged over small regions is greater than the variability averaged over large regions. For these and other reasons, attribution of the drivers of long-term temperature changes on time scales of less than 50 years and at regional scales (e.g., county, state, or multiple states, as opposed to continental), with limited exceptions, has not yet been established. [IV.2.]

In addition to average temperatures, recent work shows that human activities have also *likely* influenced extremes in temperature. 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. For example, there is evidence that human-induced warming may[4] have substantially increased the risk of extremely warm summer conditions in some regions. Discernible human influences extend to additional aspects of climate, including the recent decreases in Arctic sea ice extent, patterns of sea level pressure and winds, and the global-scale pattern of land precipitation. [IV.2.a]

According to CCSP Synthesis and Assessment Product (SAP) 3.3, it is *very likely* that the human-induced increase in greenhouse gases has contributed to the increase in sea surface temperatures in the hurricane formation regions. There is a strong statistical connection between tropical Atlantic sea surface temperatures and Atlantic hurricane activity as measured by an index that accounts for storm intensity, frequency, and duration on decadal timescales over the past 50 years. This evidence suggests a substantial human contribution to recent hurricane activity. However, a confident assessment of human influence on hurricanes will require further studies using models and observations. [IV.2.a]

I.3 Trends and Projections of Physical Changes

This section describes observed historical trends and model-based projections of future changes to physical and chemical components of the environment.

I.3.a Temperature

The climate system is warming, as is now evident from direct observations of increases in global average air and ocean temperatures and inferences from widespread melting of snow and ice, rising global average sea level, and other indicators. As determined by the IPCC, the globally averaged temperature rise over the last 100 years (1906–2005) is 1.33 ± 0.32 °F when estimated by a linear trend. The rate of global warming over the last 50 years (0.23 ± 0.05 °F per decade) is almost double that for the past 100 years (0.13 ± 0.04 °F per decade). In addition, as assessed by the IPCC, it is *very likely* that average Northern Hemisphere temperatures during the second half of the 20th century were warmer than any other 50-year period in the last 500 years, and it is *likely* that this 50-year period was the warmest Northern Hemisphere period in the last 1,300 years. Land regions have warmed faster than the oceans—about double the ocean rate after 1979

[4] Non-italicized terms and phrases such as "may," "are expected," and "are projected" are used to indicate the possibility of the occurrence of an event or phenomenon without assignment of a formal level of likelihood.

(more than 0.49 °F per decade). The greatest warming is at high northern latitudes during spring and winter. [IV.1.b]

Like global average temperatures, U.S. average temperatures also increased during the 20th and into the 21st century, according to federal statistics. The last decade is the warmest in more than a century of direct observations in the United States. Average temperatures for the contiguous United States have risen at a rate near 0.6 °F per decade in the past few decades. But warming is not distributed evenly across space or time. [IV.1.b]

The number of U.S. heat waves has been increasing since 1950, though it should be noted that the heat waves associated with the severe drought of the 1930s remain the most severe in the U.S. historical record. There have also been fewer unusually cold days during the last few decades, and the last 10 years have seen fewer severe cold waves than for any other 10-year period in the historical record, which dates back to 1895. [IV.1.b]

The IPCC concluded that continued greenhouse gas emissions at or above current rates are expected to cause further warming and to induce many changes during the 21st century that will *very likely* be larger than those of the 20th century. For the next 20 years, a globally averaged warming of about 0.3 to 0.4 °F per decade is projected for a range of scenarios of greenhouse gas emissions[5]. Through about 2030, there is little difference in the warming rate projected using a variety of emissions scenarios. Possible future variations in natural factors, such as a large volcanic eruption, could introduce variations to this long-term warming projection. Even if atmospheric greenhouse gas levels remained constant, the globally averaged warming would continue to be nearly 0.2 °F per decade during the next two decades because of the time it takes for the climate system, particularly the oceans, to reach equilibrium. [IV.3.b]

By the mid-21st century, the effect of the choice of emission scenario becomes more important in terms of the magnitude of the projected warming, with model projections of increases in globally averaged temperature of approximately 2 to 3 °F for several of the IPCC scenarios. According to the IPCC, all of North America is *very likely* to warm during this century, and to warm more than the global average increase in most areas. Nearly all the models assessed by the IPCC project that the average warming in the United States will exceed 3.6 °F, with 5 out of 21 models projecting that average warming will exceed 7.2 °F by the end of the century. The largest warming in the United States is projected to occur in winter over northern parts of Alaska. In regions near the coasts, the projected warming during the 21st century is expected to be less than the national average. According to CCSP SAP 3.3, abnormally hot days and nights and heat waves are *very likely* to become more frequent, and cold days and cold nights are *very likely* to become much less frequent over North America. [IV.3.b]

I.3.b Precipitation, runoff, and drought

[5] A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. The scenarios cited in this document do not include greenhouse gas emission reduction initiatives.

According to historical records, the total annual precipitation over the contiguous United States has increased at an average rate of 6% per century from 1901 to 2005, with significant variability over time and by region. The greatest increases in precipitation were in the northern Midwest and the South. The contiguous United States has had statistically significant increases in heavy precipitation, primarily during the last three decades of the 20th century and over the eastern parts of the country. [IV.1.c]

In keeping with the overall precipitation trends, most of the United States has experienced decreases in drought severity and duration during the second half of the 20th century. However, a severe drought has affected the southwestern United States from 1999 through 2007. The southeastern United States has also recently experienced severe drought. On a longer time scale, reconstructions of droughts using tree rings and geological evidence show that much more severe droughts have occurred over the last 2,000 years than those that have been observed in the instrumental record, notably, the Dust Bowl drought of the 1930s and extensive drought in the 1950s. [IV.1.d]

Streamflow in the eastern United States has increased 25% in the last 60 years. However, it has decreased by about 2% per decade in the central Rocky Mountain region over the past century. The annual peak of streamflow in snowmelt-dominated western mountains is now generally occurring at least a week earlier than in the middle of the 20th century. Winter stream flow is increasing in basins with seasonal snow cover. The fraction of annual precipitation falling as rain (rather than snow) increased in the last half century. [IV.1.d]

Most climate models project an increase in winter precipitation in the northern tier of states and a decrease in portions of the Southwest during the 21st century. Summer precipitation is projected to decrease in the Northwest of the contiguous United States and increase in Alaska; it is uncertain whether summer precipitation will increase or decrease over large portions of the interior United States. In northern regions of North America, the magnitude of precipitation increase is projected to be greatest in autumn, whereas winter precipitation is projected to increase by the largest fraction relative to its present amount. A majority of climate models generally show winter increases in northern regions and summer decreases in western and southern regions. [IV.3.b]

In the 21st century, precipitation over North America is projected to be less frequent but more intense. This increase in storminess is projected to be accompanied by greater extreme wave heights along the coasts. [IV.3.b]

I.3.c Ice and snow

Observations indicate that annual average Arctic sea ice extent decreased by 2.7 ± 0.6% per decade between 1978 and 2005. Larger decreases were observed in summer (7.4 ± 2.4% per decade). In 2007, Arctic sea ice extent was approximately 23% below the previous all-time minimum observed in 2005. In addition to the decreased extent, the average sea ice thickness in the central Arctic *very likely* decreased by up to approximately 3 feet from 1987 to 1997, according to the Arctic Climate Impacts Assessment and the IPCC. Along the Alaskan coast, reductions in the thickness and spatial extent of sea ice are creating more open water, allowing winds to generate stronger waves, which increase shoreline erosion. Antarctic sea ice extent shows no statistically significant average trend. [IV.1.d]

The snow-covered area of North America increased in the November to January season from 1915 to 2004 due to increases in precipitation. However, spring snow cover in mountainous regions of the western United States generally decreased during the latter half of the 20th century. The IPCC determined that this latter trend is *very likely* due to long-term warming, with potential influence from decadal-scale natural variability. In Alaska, where the warming has been particularly pronounced, the permafrost base has been thawing at a rate of up to 1.6 inches per year since 1992. [IV.1.d]

The date that rivers and lakes freeze over has become later (average rate of 5.8 ± 1.6 days per century) and the ice breakup date has happened earlier (average rate of 6.5 ± 1.2 days per century), according to an analysis of 150 years of available data for the Northern Hemisphere. In addition to these changes in seasonal ice and snow, glaciers have been losing mass in the northwestern United States and Alaska, with losses especially rapid in Alaska after the mid-1990s. [IV.1.d]

Snow cover is projected to continue to decrease as the climate warms. According to the IPCC, results from multiple model simulations indicate that an Arctic Ocean free of summer ice is *likely* by the end of the century, with some models suggesting that this could occur as soon as 2040. Glaciers and terrestrial ice sheets are projected to continue to lose mass as increases in summertime melting outweigh increases in wintertime precipitation. This will contribute to sea level rise. Widespread increases in thaw depth are projected over most permafrost regions. [IV.3.b]

I.3.d Sea level

There is strong evidence that global average sea level gradually rose during the 20th century, after a period of little change between A.D. 0 and A.D. 1900, and is currently rising at an increased rate. The global average rate of sea level rise from 1993 to 2003 was 0.12 ± 0.03 inches per year, significantly higher than the 20th century average rate of 0.067 ± 0.02 inches per year. Two major processes lead to changes in global mean sea level on decadal and longer time scales, and each currently account for about half of the observed sea level rise: expansion of the ocean volume due to warming, and the exchange of water between the oceans and land reservoirs of water, including glaciers and land ice sheets. [IV.1.d]

U.S. sea level data from at least as far back as the early 20th century show that along most of the U.S. Atlantic and Gulf Coasts, sea level has been rising 0.8 to 1.2 inches per decade. The rate of relative sea level rise varies from a few inches per decade along the Louisiana Coast (due to sinking land) to a drop of a few inches per decade in parts of Alaska (due to rising land). [IV.1.d]

Along with increases in global ocean temperatures, the IPCC projects that global sea level will rise between 7 and 23 inches by the end of the century (2090–2099) relative to the base period (1980–1999). According to the IPCC, the average rate of sea level rise during the 21st century is *very likely* to exceed the 1961–2003 average rate. Storm surge levels are expected to increase due to projected sea level rise. Combined with non-tropical storms, rising sea level extends the zone of impact from storm surge and waves farther inland, and will *likely* result in increasingly greater coastal erosion and damage according to the IPCC. Potential 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 to sea level, a possibility not reflected in the aforementioned projections. Understanding of these processes is limited and there is no consensus on their magnitude and thus on the upper bound of sea level rise rates. [IV.3.b]

I.3.e Atlantic hurricanes

As recognized in recent assessments, detection of long-term trends in tropical cyclone activity is complicated by multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations that began in about 1970. Even taking these factors into account, CCSP SAP 3.3 concluded that 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. Additionally, there is evidence for an increase in extreme wave height characteristics over the past couple of decades, associated with more frequent and more intense hurricanes. [IV.1.c]

It is *likely* that hurricane rainfall and wind speeds will increase in response to human-caused warming, according to CCSP SAP 3.3. There is less confidence in the projected changes in the number of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period, highlighting the uncertainty associated with this issue. [IV.3.b]

Trends in other extreme weather events that occur at small spatial scales—such as tornadoes, hail, lightning, and dust storms—cannot be determined at the present time due to insufficient evidence. [IV.3.b]

I.3.f Abrupt climate change

An abrupt climate change occurs when the climate system crosses a threshold, which triggers a transition into a new state that may have large and widespread consequences. Over at least the last 100,000 years, abrupt regional warming (up to 29 °F within decades over Greenland) and cooling events occurred repeatedly over the North Atlantic region. Greenhouse warming and other human alterations of the Earth system may increase the possibility of abrupt climate change. One such possible change is a rapid decrease in the rate of flow of the major deep ocean circulation pattern in the North Atlantic that affects North American and European climate. The IPCC reported that an abrupt slowdown of this circulation during the 21st century is *very unlikely* (less than 10% probability), but longer-term changes cannot currently be assessed with confidence. Other possible abrupt changes are rapid disintegrations of the Greenland Ice Sheet and the West Antarctic Ice Sheet, both of which could raise sea level by several feet. Although models suggest the complete melting of the Greenland Ice Sheet (leading to at least 20 feet of sea level rise) would only require sustained warming in the range of 3.4 to 8.3 °F (relative to pre-industrial temperatures), it is expected to be a slow process that would take many centuries to complete. There is presently no consensus on the long-term future of the West Antarctic Ice Sheet or its contribution to sea level rise. [IV.3.b]

I.3.g Stratospheric ozone

Ozone at very high altitudes in the atmosphere plays an important role in shielding life on Earth from harmful ultraviolet radiation. Springtime polar ozone depletion continues to be severe when winter temperatures in the polar stratosphere (above approximately 6 miles) are particularly cold. According to the World Meteorological Organization, the average concentration of atmospheric ozone outside of polar regions is no longer declining, as it was in the 1990s. Measurements from some stations in relatively unpolluted locations indicate that ultraviolet radiation levels have been decreasing since the late 1990s, in accordance with observed ozone increases. However, ultraviolet radiation levels are still increasing at some Northern Hemisphere stations as a consequence of long-term changes in other factors such as clouds and atmospheric particulates that also affect ultraviolet radiation. [IV.1.a]

According to the World Meteorological Organization, it is *unlikely* that total ozone averaged over the region 60° S to 60° N will decrease significantly below the low values of the 1990s, because the abundances of ozone-depleting substances have peaked and are in decline. The current best estimate is that ozone between 60° S and 60° N will return to pre-1980 levels around the middle of the 21st century. Model simulations suggest that changes in climate, specifically the cooling of the stratosphere associated with increases in the abundance of carbon dioxide, may hasten the return of global column ozone to pre-1980 values by up to 15 years. [IV.3.d]

I.4 Effects of Global Change on the Natural Environment and Human Systems

According to CCSP SAP 4.3, it is *very likely* that temperature increases, increasing carbon dioxide levels, and altered patterns of precipitation are already affecting U.S. water resources, agriculture, land resources, biodiversity, and human health, among other things. SAP 4.3 also concluded that it is *very likely* that climate change will continue to have significant effects on these resources over the next few decades and beyond. [V.]

I.4.a Biological diversity, ecosystem composition, and the natural environment

Ecosystems provide society with a number of goods (e.g., food, fiber, fuel, pharmaceutical products) and services (e.g., cycling of water and nutrients, regulation of weather and climate, removal of waste products, recreational and spiritual opportunities), and are essential to human health and well-being. Biodiversity (i.e., the variety of all forms of life, from genes to species to ecosystems) is a fundamental building block of many of the services that ecosystems provide. It is intrinsically important both because of its contribution to the functioning of ecosystems and because it is difficult or impossible to recover or replace once it has eroded. The effects of climate change on U.S. ecosystems include changes in the timing and length of the growing season, primary production, and species distributions. According to CCSP SAP 4.3, it is *very likely* that climate change will increase in importance as a driver for changes in biodiversity over the next several decades, although for most ecosystems it is not currently the largest driver of change. Other elements of global change (e.g., land management and use and nitrogen deposition) will continue to play a significant role in determining the future fate of ecosystems. Adaptive responses will as well. [V.1]

Some general findings from CCSP SAP 4.3, the IPCC, and other assessments, are provided below:

- The consistency of observed significant changes in physical and biological systems and observed significant warming across the globe *likely* cannot be explained entirely by natural variability or other confounding non-climate factors. [V.1]
- There has been a significant lengthening of the growing season and increase in net primary productivity in the higher latitudes of North America. Over the last 19 years, global satellite data indicate that the onset of spring is taking place 10 to 14 days earlier across the temperate latitudes. Net primary productivity is projected to increase at high latitudes due to extended growing seasons and carbon dioxide fertilization. Projections for temperate latitudes are unclear due to uncertainty in whether precipitation increases will be great enough to offset evapotranspiration increases. [V.1.a]
- In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change worldwide, nearly 60% of the 1,598 species studied exhibited shifts in their distributions and/or timing of their annual cycles that correspond to recent large-scale climate change patterns. [V.1]
- The resilience of many ecosystems is *likely* to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other global change drivers (e.g., land use change, pollution). [V.1.a]
- In North America, warming has generally resulted in and is expected to continue to result in shifts of species ranges poleward and to higher altitudes. However, species that require higher-elevation habitat, such as alpine ecosystems, may have nowhere to migrate. [V.1.a]
- Over the course of this century, net carbon uptake by terrestrial ecosystems is projected to peak before mid-century and then weaken or even reverse, thus amplifying climate change. [V.1.a]
- Changes in temperature and precipitation will *very likely* decrease the cover of vegetation that protects the ground surface from wind and water erosion. [V.1.e]
- Many effects of climate change on U.S. ecosystems and wildlife may emerge most strongly through potential changes in the intensity and frequency of extreme events such as hurricanes and disturbances such as wildfires. In the near term, fire effects are expected to generally exceed direct climate effects on ecosystems. [V.1.c]
- While there will always be uncertainties associated with the future extent of climate change, the response of ecosystems to climate impacts, and the effects of management, it is both possible and essential for management practices to help protect climate-sensitive ecosystems. [V.1.f]

Some regional and biome-specific findings from CCSP SAP 4.3 and the IPCC are provided below:

- The rapid rates of warming that have been seen in the Arctic in recent decades (and are projected for at least the next century) are dramatically reducing the snow and ice covers that provide denning and foraging habitat for polar bears and other ice-dependent species. [V.1.e]
- The Alaskan tree line is expected to move northward and to higher elevations. Forests will replace significant amounts of existing tundra, and tundra vegetation will move into polar deserts. These changes are projected to increase carbon uptake, which would tend to offset warming effects. However, the reduced reflectivity associated with the vegetation land cover is expected to outweigh this, causing further warming. [V.1.e]
- Where adequate water is available, nitrogen deposition and warmer temperatures have *very likely* increased forest growth and will continue to do so in the near future. However, it is difficult to separate the role of climate from other factors. Rising carbon dioxide levels will *very likely* increase photosynthesis in forests, but this increase will *likely* only enhance wood production in young forests on fertile soils. [V.1.e]
- In the last three decades, the wildfire season in the western United States has lengthened and burn durations have increased. Climate change has also *very likely* increased the size and number of insect outbreaks and tree mortality that help to fuel wildfires in the interior West, the Southwest, and Alaska. These trends are *very likely* to continue. [V.1.c]
- Many plants and animals in arid ecosystems are near their physiological limits for tolerating temperature and water stress and even slight changes in stress will have significant consequences. Climate change in arid regions is *very likely* to be detrimental to river and riparian ecosystems, increase erosion, and promote invasion of exotic grass species in arid lands. Climate change in arid regions is also *likely* to create physical conditions conducive to wildfire. In arid regions where ecosystems have not co-evolved with a fire cycle, the loss of iconic megaflora, such as saguaro cacti and Joshua trees, is *very likely*. [V.1.a]
- On small oceanic islands with cloud forests or high-elevation ecosystems, such as the Hawaiian Islands, human-induced climate change, land use changes, and invasive species are *likely* to have synergistic effects that drive several species (e.g., some endemic birds) to extinction. [V.1.c]
- Erosion and ecosystem loss is affecting many parts of the U.S. coastline, but it is unclear to what extent these losses result from temperature and precipitation changes, sea level rise, and other human drivers. Coastal wetland loss is occurring where these ecosystems are squeezed between natural and artificial landward boundaries and rising sea levels. To date, more than 50% of the original salt marsh habitat in the United States has been lost. Approximately 20% of the remaining coastal wetlands in the U.S. mid-Atlantic region are potentially at risk of inundation between 2000 and 2100. Salt marsh biodiversity is projected to decrease in northeastern marshes through expansion of non-native species such as *Spartina alterniflora*. Erosion of barrier islands has increased the height of waves that reach the shorelines of coastal bays. [V.1.c]
- The increasing carbon dioxide level in the atmosphere has made the oceans more acidic. This acidification is expected to have negative impacts on marine shell-forming organisms and consequently large portions of the marine food chain. Corals in many tropical regions are experiencing substantial mortality from increasing water temperatures and increasing storm intensity in some regions, on top of a host of other ongoing challenges from development and tourism, fishing, and pollution. Increasing ocean acidification is expected to exacerbate these effects. [V.1.a]

- Land-based ecosystems in the northeastern and southeastern United States will *likely* become carbon sources, while the western United States will *likely* remain a carbon sink. [V.1.a]

I.4.b Agriculture and food production

The many U.S. crops and livestock (valued at about $200 billion in 2002) are strongly affected by weather and climate factors (such as temperature, precipitation, carbon dioxide concentrations, and water availability). Vulnerability of this 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 [V.2]. The following findings are based on CCSP SAP 4.3 and the IPCC:

- With increased carbon dioxide levels and temperature, the lifecycle of grain and oilseed crops will *likely* progress more rapidly. But, as temperatures rise, these crops will increasingly begin to fail, especially if climate variability increases and precipitation lessens or becomes more variable. [V.2]
- The marketable yield of many horticultural crops (e.g., tomatoes, onions, and fruits) is *very likely* to be more sensitive to climate change than grain and oilseed crops. [V.2.c]
- Climate change is *likely* to lead to northward migration of weed species. Increasing carbon dioxide levels are *likely* to help many weeds, particularly some types of invasive weeds, more than most cash crops. Recent research also suggests that glyphosate, the most widely used herbicide in the United States, loses its efficacy on weeds grown at the increased carbon dioxide levels that are projected for the coming decades. [V.2.d]
- 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. [V.2.e]
- Projected increases in temperature and a longer 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. [V.2.f]
- Climate-change-induced shifts in plant species are already underway in rangelands. Establishment of perennial herbaceous species is reducing the availability of soil moisture early in the growing season. [V.3.e]
- Shifts in the productivity and type of plants 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). [V.2.f]
- Cold freshwater fisheries are *likely* to be negatively affected. Warm freshwater fisheries will generally benefit. The results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges. Effects of increasing temperature on marine fisheries are already occurring, with rapid poleward shifts in some regions. These shifts are expected to continue in the future. [V.2.g]

I.4.c Water resources

Plants, animals, natural and managed ecosystems, and human settlements are susceptible to variations in the storage, fluxes, and quality of water, all of which are sensitive to climate change. The effects of climate on the Nation's water storage capabilities and hydrologic functions will have significant implications for water management and planning as natural processes become more variable. Other factors affecting water resources include water pollution, damming of rivers, wetland drainage, reduced stream flow, and lowering of the groundwater table (e.g., due to irrigation). Although climate-related changes have been small compared to these other pressures to date, climate change is expected to result in increasing effects in the future. [V.4]

Although U.S. water management practices are generally quite advanced, particularly in the West, the reliance on past conditions as the foundation for current and future planning and practice will no longer be tenable as climate change and variability increasingly create conditions that are well outside of historical parameters, eroding predictability. The findings below, reported by the IPCC, CCSP SAP 4.3, and other sources, are based on the ongoing and projected water cycle changes described earlier. [V.4]

- In some mountain areas, earlier snowmelt peaks result in reduced low flows in the summer and fall. Continuing shifts in this direction are *very likely* and may substantially affect the performance of reservoir systems through changes in the seasonality of streamflow. [V.4.a]
- Water quality is sensitive to increased water temperatures, changes in precipitation, and other climate-related factors. However, most water quality changes observed so far across the continental United States are *likely* attributable to causes other than climate change. Higher temperatures and nutrient loads will tend to reduce the oxygen content of water with potential negative impacts on aquatic organisms. Increases in intense rain events will tend to result in the introduction of more sediment, nutrients, pathogens, and toxics into water bodies from non-point sources. The intrusion of saline water into groundwater supplies is *likely* to adversely affect water quality in coastal regions around the United States. These water quality changes could impose enormous costs on water treatment infrastructure. [V.4.c]
- Stream temperatures are *likely* to increase as the climate warms and are *very likely* to have effects on aquatic ecosystems and water quality. Changes in temperature will be most evident during low flow periods, when they are of greatest concern. [V.4.d]
- Projections suggest that efforts to offset the declines in available surface water by increasing withdrawal of groundwater will be hampered by decreases in groundwater recharge in some water-stressed regions, such as the southwestern United States. [V.4.b]
- Less reliable supplies of water are expected to create challenges for managing urban water systems as well as for industries that depend on large volumes of water. Across North America, vulnerability to extended drought is increasing as population growth and economic development create more demands from agricultural, municipal, and industrial uses, resulting in frequent over-allocation of water resources. Examples of vulnerable U.S. regions include: the heavily-used water systems of the West that rely on capturing snowmelt runoff, such as the Columbia and Colorado River systems; portions of California; the New York area, as a

consequence of greater water supply variability; and many islands such as the U.S. territories of Puerto Rico and U.S. Virgin Islands. [V.4.e]

- Trends toward more efficient water use are *likely* to continue in the coming decades. Pressures for reallocation of water will be greatest in areas of highest population growth, such as the Southwest. Declining per capita (and, in some cases, total) water consumption will help mitigate the impacts of climate change on water resources. [V.4.d]

I.4.d Social systems and settlements

Human systems include social, economic, and institutional structures and processes. These systems are influenced by multiple factors and stresses (e.g., access to financial resources, urbanization, and shifts in demographics). U.S. settlements will feel the effects of climate change as they interact with these other factors. Climate change effects could push stressed systems beyond sustainable thresholds. Climate sensitivity varies across settlements and industrial sectors. While it may appear that industrialized countries like the United States are well equipped to cope with gradual climate change at a national level, at a local level there may be substantial variability in climate effects and capacities to adapt. On the other hand, some U.S. settlements may find opportunities in climate change. [V.5]

According to CCSP SAP 4.6, some of the key aspects of human settlements that are affected by climate change include: human health; water and other urban infrastructures; energy requirements; urban metabolism (e.g., the welfare and activities of urban communities); economic competitiveness, opportunities, and risks; and social and political structures. Several of these challenges are discussed in other sections of the Executive Summary (and the body of the report).

Globally, 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 in places that are being rapidly urbanized. Poor communities can be especially vulnerable, particularly those concentrated in high-risk areas. According to the IPCC, the most vulnerable areas in the United States are *likely* to be Alaska (e.g., indigenous communities dependent on hunting climate-sensitive species), coastal and river basin locations that are susceptible to flooding, arid areas where water scarcity is a pressing issue, and areas whose economic bases are climate-sensitive. It is possible that regions exposed to risks from climate change will see movement of population and economic activity to other locations. One reason is public perceptions of risk, but a more powerful driving force may be the availability of insurance. [V.5]

Some of the key findings from CCSP SAP 4.6 and the IPCC related to settlements are outlined below.

- Population growth is generally shifting toward areas (e.g., coastal regions) more likely to be vulnerable to the effects of climate change. Demand for waterfront property and land for building in the United States continues to grow, increasing the value of property at risk. [V.5.b]

- Coastal population increases together with *likely* increases in hurricane rainfall and wind speeds and greater storm surge due to sea level rise will continue to increase coastal vulnerabilities in the Southeast and Gulf Coast. Urban centers that were once assumed to have a high adaptive capacity remain vulnerable to extreme events such as hurricanes. [V.5.b]
- The degradation of coastal ecosystems, especially wetlands and coral reefs, can have serious implications for the well-being of societies that depend on them. The costs of adaptation for vulnerable coasts are generally much less than the costs of not acting. [V.5.c]
- For small islands, particularly in the Pacific, some studies suggest that sea level rise could reduce island size, raising concerns for parts of Hawaii and other U.S. territories. [V.5.c]
- Climate and extreme events can have substantial effects on local economies. For example, tourism could be affected by drought-influenced water levels in rivers and reservoirs, cleanup following multiple storm outbreaks, and changes in the length of the tourist season (e.g., ski season and beach season). [V.5.d]
- As discussed elsewhere, wildfires have increased in extent and severity in recent years and are *very likely* to intensify in a warmer future. At the same time, the population has been expanding into fire-prone areas, increasing society's vulnerability to wildfire. [V.5.d]

I.4.e Human health

Climate variability and change can affect health directly and indirectly. The heat stress associated with a warmer environment can directly affect the body. Climate change can also make it possible for animal-, water-, and food-borne diseases to spread or emerge in areas where they had been limited or had not existed, or it can make it possible for such diseases to disappear by making areas less hospitable to the disease carrier or pathogen. Climate can also affect the incidence of diseases associated with air pollutants and aeroallergens.

Climate impacts on health are complex and will be influenced by multiple factors, including demographics; population and regional vulnerabilities; the social, economic, and cultural context; availability of resources and technological options; built and natural environments; public health infrastructure; and the availability and quality of health and social services. CCSP SAP 4.6 concluded that climate change is *very likely* to accentuate the disparities already evident in the American health care system. As discussed in CCSP SAP 4.6 and the IPCC, the extent to which communities are prepared and have the capacity to adapt will determine the severity of the following climate change impacts. Conclusions from those reports are discussed below. [V.6]

Temperature-related conclusions include the following:

- It is *very likely* that heat-related morbidity and mortality will increase over the coming decades, however net changes in mortality are difficult to estimate because, in part, much depends on complexities in the relationship between mortality and global change. High temperatures tend to exacerbate chronic health conditions. An increased frequency and severity of heat waves is expected, leading to more illness and death, particularly among the young, elderly, frail, and poor. [V.6]
- In many cases, the urban heat island effect may increase heat-related mortality. High temperatures and high air pollution can interact to result in additional health impacts. [V.6]
- Climate change is projected to lead to fewer deaths from cold exposure. [V.6.a]

Conclusions related to animal-, food-, and water-borne diseases include the following:

- Climate change is *likely* to increase the risk and geographic spread of vector-borne infectious diseases, including Lyme disease and West Nile virus. [V.6.c]
- 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. However, major human epidemics of these diseases in the United States are *unlikely* if the public health infrastructure is maintained and improved as needed. [V.6 and V.6.c]
- Federal and state laws and regulatory programs protect much of the U.S. population from waterborne disease. However, if climate variability increases, current and future deficiencies in watershed protection, infrastructure, and storm drainage systems will tend to increase the risk of contamination events. [V.6.c]

Conclusions related to air quality include the following:

- As the climate becomes warmer and more variable, air quality is *likely* to be affected. [V.6.e]
- Climate change can be expected to influence the concentration and distribution of air pollutants through a variety of 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. [V.6.e]
- In studies holding pollution emissions constant, climate change was found to lead to increases in regional ground-level ozone pollution in the United States and other countries. It is well-documented that breathing air containing ozone can reduce lung function, increase susceptibility to respiratory infection, and contribute to premature death in people with heart and lung disease. [V.6.e] (The health effects of stratospheric ozone depletion on the United States have not been assessed here.)
- Climate change and changes in carbon dioxide concentration could increase the production and allergenicity of airborne allergens and affect the growth and distribution of weeds, grasses, and trees that produce them, which may increase the incidence of allergic rhinitis. [V.6.e]
- Uncertainties in climate models make the direction and degree of change in air quality and aeroallergens somewhat speculative. [V.6.d]

Conclusions related to extreme events include the following:

- Increases in extreme weather (e.g., storms, flooding) and accompanying events (e.g., wildfire resulting from prolonged drought) may lead to increases in deaths, injuries, infectious diseases, interruptions of medical care for chronic disease treatment, and stress-related disorders and other adverse effects associated with social disruption and migration. [V.6.d]
- Extreme climate events may also have substantial mental health impacts (e.g., post-traumatic stress disorder and depression). [V.6]
- 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. [V.6]
- Wildfires pose significant direct health threats. They can also have substantial effects through increased eye and respiratory illnesses due to fire-related air pollution and mental health impacts from evacuations, lost property, and damage to resources. Wildfires, 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. [V.6 and V.6.b]

- Morbidity and mortality due to an event will tend to increase with the intensity and duration of the event, but will tend to decrease with advance warning and preparation. [V.6.a]

I.4.f Energy production, use, and distribution

To date, most discussions on energy and climate change have focused on mitigating human effects on climate. However, along with this role as a *driver* of climate change, the energy sector will be subject to the *effects* of climate change. As discussed in the IPCC and CCSP SAP 4.5, climate change is *likely* to affect the use and production of energy in the United States. It is *likely* to affect physical and institutional infrastructures and is *likely* to interact with and possibly exacerbate ongoing environmental change and environmental and population-related pressures in settlements. Concerns about climate change impacts could change perceptions and valuations of energy technology alternatives. Responses to climate change may lead to the following changes in energy demand according to the IPCC and CCSP SAP 4.5: [V.7]

- decreases in the amount of energy consumed in residential, commercial, and industrial buildings for space heating and water heating; [V.7.a]
- increases in energy used in residential, commercial, and industrial buildings for space cooling; [V.7.a]
- increases in energy consumed for residential and commercial refrigeration and industrial process cooling (e.g., in thermal power plants or steel mills); [V.7.a]
- increases in peak demand for electricity in most regions of the country, except in the Pacific Northwest; [V.7.a]
- increases in energy used to supply other resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses; [V.7.a]
- changes in the balance of energy use among delivery forms and fuel types, as between electricity used for air conditioning and natural gas used for heating; [V.7] and
- changes in energy consumption in key climate-sensitive sectors of the economy, such as transportation, construction, agriculture, and others. [V.7]

According to CCSP SAP 4.5, in the absence of energy efficiency measures directed at space cooling, climate change is expected to cause a significant increase in the demand for electricity in the United States, which would require the building of additional electricity production facilities (and probably transmission facilities) at an estimated cost of many billions of dollars. [V.7.a]

Climate change could affect production, supply, and transmission of energy in the United States in the following ways according to the IPCC and CCSP SAP 4.5:

- direct impacts from increased intensity of extreme weather events, [V.7.b]
- reduced water supplies in regions dependent on water resources for hydropower and/or thermal power plant cooling, [V.7.b]
- facility siting decisions affected by changing conditions, [V.7.b] and

- positive or negative impacts on production of biomass, wind power, or solar energy where climate conditions change. [V.7.b]

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 United States has some vulnerability to climate variability. Although effects on the existing infrastructure might be categorized as modest, local and industry-specific impacts could be large, especially in areas that may be prone to disproportional warming (e.g., Alaska) or weather disruptions (e.g., the Gulf Coast and Gulf of Mexico). [V.7.b]

I.4.g Transportation

Increasing global temperatures, rising sea levels, and changing weather patterns pose significant challenges to our country's transportation venues including: roadways, railways, transit systems, marine transportation systems, airports, and pipeline systems. The U.S. transportation network is vital to the Nation's economy, safety, and quality of life. The following findings, derived from the IPCC and CCSP SAP 4.7 (focused on Gulf Coast transportation impacts), relate to the relationship between climate change and transportation in North America: [V.8]

- Warmer or less snowy winters are *likely* to reduce delays, improve ground and air transportation reliability, and decrease the need for winter road maintenance. However, more intense winter storms could increase risks for traveler safety and require increased localized snow removal. [V.8]
- Increasing frequency, intensity, or duration of heat spells could cause railroad tracks to buckle or kink and could affect roads through softening and traffic-related rutting. [V.8]
- Coastal and riverine flooding and landslides are *very likely* to cause negative impacts on roads, rails, and ports. The crucial connectivity of the transportation system means that the services of the network can be threatened even if small segments are wiped out. [V.8]
- Transportation infrastructure is *likely* to be particularly affected in more northerly latitudes. Permafrost degradation reduces surface load-bearing capacity and potentially triggers landslides. While the season for transport by barge is *likely* to be extended, the season for ice roads that utilize waterways is *likely* to be compressed. [V.8]
- Climate change may worsen the vulnerability of Gulf Coast and eastern transportation systems to hurricanes and tropical storms as warming seas give rise to more energetic storms and as sea level rises. [V.8.d]
- An increase in the frequency of extreme precipitation events may contribute to increased accident rates; more frequent short-term flooding and bridge scour, as well as more culvert washouts; exceeding the capacity of storm drain infrastructure; and more frequent landslides, requiring increased maintenance. [V.8]
- 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. [V.8]
- Some of these risks are expected to be offset by improvements in technology and information systems. [V.8]

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