Chapter 2
Climate Change in the 21st Century: Looking Beyond the Paris Agreement

Donald J. Wuebbles

Abstract The science is clear that the Earth's climate, including that of the United States, is changing, changing much more rapidly than generally occurs naturally, and it is happening primarily because of human activities. This chapter discusses the science underlying climate change and the current understanding of how our planet is being affected. In addition to the global analysis, there is special attention given to the findings for the United States. Humanity is already feeling the effects from increasing intensity of certain types of extreme weather and from sea level rise that are fueled by the changing climate. Climate change affects many sectors of our society, including threats on human health and well-being. Climate change will, absent other factors, amplify some of the existing threats we now face. The effects on humanity are already significant, costing us many billions of dollars each year along with the effects on human lives and health. Policy to respond to climate change is imperative—we have three choices, mitigation, adaptation, or suffering. Right now we are doing some of all three. The Paris Agreement begins the process internationally of really doing something to slow down change. But the current agreement is just the beginning and we will need to do much more.

Introduction

The science is clear: the Earth's climate is changing, it is changing extremely rapidly, and the evidence shows it is happening primarily because of human activities (IPCC 2013, 2014; Melillo et al. 2014; UKRS-NAS 2014; and the thousands of papers referenced in these assessments). Climate change is happening now—it is not just a problem for the future—and it is happening throughout the world. There are many indicators of the changing climate. Surface temperature is just one of them. Trends in the severity of certain types of severe weather events are

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increasing. Sea levels are also rising because of the warming oceans and because of the melting land ice. Observations show that the climate is changing extremely rapidly, about ten times more rapidly than natural changes in climate based on paleoclimatic observations of the changes that occurred since the end of the last ice age. And the evidence clearly points to climate changes over the last half century as being primarily due to human activities, especially the burning of fossil fuels and also land use change, especially through deforestation. As a result, it is not surprising that many national and world leaders have concluded that climate change, often referred to as global warming in the media, has become one of the most important issues facing humanity.

There is essentially no debate in the peer-reviewed scientific literature (or in the national and international assessments of the science prepared by hundreds of scientists) about the large changes occurring in the Earth's climate and the fact that these changes are occurring as a response to human activities. Natural factors such as changes in the energy output of the Sun have always affected our climate in the past and continue to do so today; but over the last century, human activities have become the dominant influence in producing many, if not most, of the observed changes occurring in our current climate.

People throughout the world are already feeling the effects from increasing intensity of certain types of extreme weather and from sea level rise that are fueled by the changing climate. Prolonged periods of heat and heavy downpours, and in some regions, floods and in others, drought, are affecting our health, agriculture, water resources, energy and transportation infrastructure, and much more.

The harsh reality is that the present amount of climate change is already dangerous and will become far more dangerous in the coming decades. Climate change is itself likely to increase the risks for impacts on human society and on ecosystems, and the more intense extreme events associated with a changing climate pose a serious risk to human health.

The chapter begins with a discussion of the changes happening and projected to happen in the climate system and a summary of the underlying scientific basis for the human cause for these changes. Much more on each of these topics, and the projections of future changes in climate, can be found in the international (IPCC 2013, 2014) and U.S. National Climate (Melillo et al. 2014) assessments of the science mentioned earlier. The connections between potential impacts and the changing climate are then examined, with a special focus on the United States based on discussion in the 3rd National Climate Assessment (NCA: Melillo et al. 2014). Issues associated with mitigation and adaptation policy, including the effects of the Paris Agreement are then assessed.

Our Changing Climate

The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2013, 2014) is the most comprehensive analysis to date of the science of climate change and how it is affecting our planet. Over 800 scientists and other experts were involved in the four volumes of this assessment. Similarly, the 3rd U.S. National Climate Assessment (Melillo et al. 2014) is the most comprehensive analysis to date of how climate change is affecting the United States now and how it could affect it in the future. A team of more than 300 scientists and other experts (see complete list online at http://nca2014.globalchange.gov), guided by a 60-member National Climate Assessment and Development Advisory Committee, produced the assessment. Stakeholders involved in the development of the assessment included decision-makers from the public and private sectors, resource and environmental managers, researchers, representatives from businesses and non-governmental organizations, and the general public. The resulting report went through extensive peer and public review before publication, including two sets of reviews by the National Academy of Sciences. The NCA collects, integrates, and assesses observations and research from around the country, helping us to see what is actually happening and understand what it means for our lives, our livelihoods, and our future. The report includes analyses of impacts on seven sectors—human health, water, energy, transportation, agriculture, forests, and ecosystems—and the interactions among sectors at the national level. The report also assesses key impacts on all parts of the United States and evaluated for specific regions: Northeast, Southeast and Caribbean, Midwest, Great Plains, Southwest, Northwest, Alaska, Hawaii and Pacific Islands, as well as the country's coastal areas, oceans, and marine resources. By being so comprehensive, the NCA aim is to help inform Americans' choices and decisions about investments, where to build and where to live, how to create safer communities and secure our own and our children's future. The 4th National Climate Assessment is now underway and will be published in 2018.

Climate is defined as long-term averages and variations in weather measured over multiple decades. The Earth's climate system includes the land surface, atmosphere, oceans, and ice. Scientists from around the world have compiled the evidence that the climate is changing, changing much more rapidly than tends to occur naturally (by a factor of ten or more relative to the natural changes that occurred following the end of the last ice age 20,000 years ago), and that it is changing because of human activities; these conclusions are based on observations from satellites, weather balloons, thermometers at surface stations, ice cores, and many other types of observing systems that monitor the Earth's weather and climate. A wide variety of independent observations give a consistent picture of a warming world. There are many indicators of this change, not just atmospheric surface temperature. For example, ocean temperatures are also rising, sea level is rising, Arctic sea ice is decreasing, most glaciers are decreasing, Greenland and Antarctic land ice is decreasing, and atmospheric humidity is increasing.

Climate Change Effects on Temperature

Temperatures at the surface, in the troposphere [the active weather layer extending from the ground to about 8–16 km (5–10 miles altitude)], and in the oceans have all increased over recent decades. Consistent with our scientific understanding, the largest increases in temperature are occurring closer to the poles, especially in the Arctic (this is especially related to ice-albedo feedback, which, as snow and ice decrease, indicates that the exposed surface will absorb more solar radiation rather than reflect it back to space). Snow and ice cover have decreased in most areas on Earth. Atmospheric water vapor (H_2O) is increasing in the lower atmosphere, because a warmer atmosphere can hold more water (the basic physics is captured by the Clausius–Clapeyron equation, which provides the relationship between temperature and available water vapor). Sea levels are also increasing. All of these findings are based on observations.

As seen in Fig. 1, global annual average temperature (as measured over both land and oceans) has increased by more than 0.8 °C (1.5 °F) since 1880 (through 2012). Since then, 2014 was the warmest year on record, but this was greatly eclipsed by 2015, when a strong El Niño event (unusually warm water in the eastern portion of the Pacific Ocean) added to the effects of climate change. So far, it looks like 2016 will be warmer still. While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are related to natural processes, such as the effects of ocean events like El Niños and La Niñas, and the cooling effects of atmospheric emissions from volcanic eruptions. At the local to regional scale, changes in climate can be influenced by natural variability for a few decades (Deser et al. 2012). Globally, natural variations can be as large as human-induced climate change over

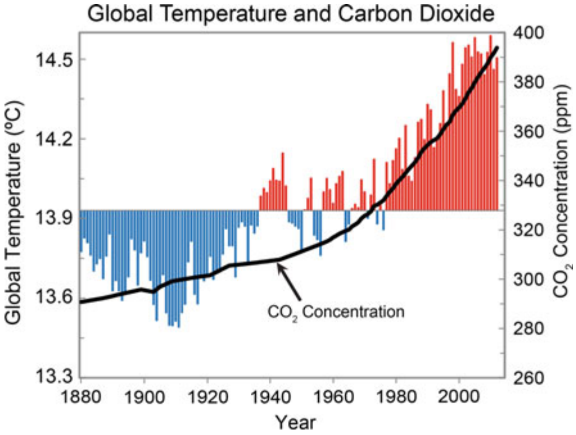

Fig. 1 Changes in observed globally-averaged temperature since 1880. Red bars show temperatures above the long-term average, and blue bars indicate temperatures below the long-term average. The black line shows the changes in atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm) over the same time period (Melillo et al. 2014; temperature data from NOAA National Climate Data Center)

timescales of up to a decade (Karl et al. 2015). However, changes in climate at the global scale observed over the past 50 years are far larger than can be accounted for by natural variability (IPCC 2013).

While there has been widespread warming over the past century, not every region has warmed at the same pace (Fig. 2). A few regions, such as the North Atlantic Ocean and some parts of the U.S. Southeast, have even experienced cooling over the last century as a whole, though the U.S. Southeast has warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to the oceans. These findings are not surprising given the larger heat capacity of the oceans leading to land-ocean differences in warming and the ice-albedo feedback

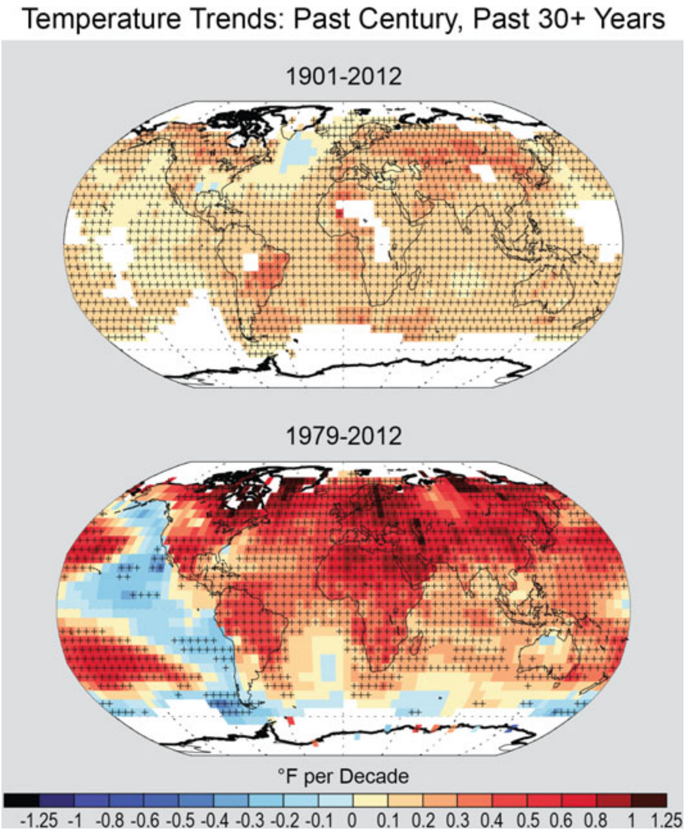

Fig. 2 Surface temperature trends for the period 1901–2012 (top) and 1979–2012 (bottom) from NOAA National Climate Data Center’s surface temperature product. Updated from Vose et al. (2012). From Melillo et al. (2014)

leading to larger warming at higher latitudes. As a result, land areas can respond to the changes in climate much more rapidly than the ocean areas even though the forcing driving a change in climate occurs equally over land and the oceans.

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Figure 3 shows a number of examples of the indicators that show the climate on Earth is changing very rapidly over the last century. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Basic physics tells us that a warmer atmosphere can hold more water vapor; this is exactly what is measured from the satellite data showing that humidity is increasing. Arctic sea ice,

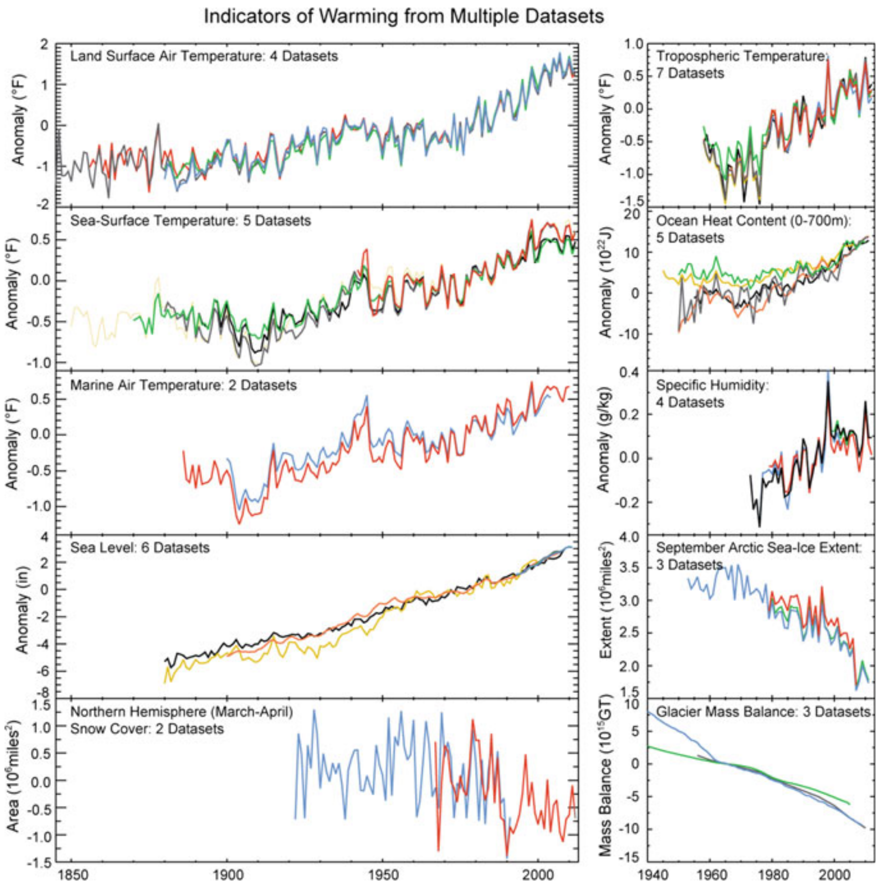

Fig. 3 Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. From Melillo et al. (2014)

mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. Over 90% of the glaciers in the world are decreasing at very significant rates. The amount of ice on the largest masses of ice on our planet, on Greenland and Antarctica, are decreasing. As with temperature, many scientists and associated research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming planet.

Climate Change Effects on Precipitation

Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (e.g., it can rain several inches in Washington, DC, but not a drop in nearby Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, there does not appear to have been significant changes in globally averaged precipitation since 1900 (although as we will discuss later there has been a significant trend for an increase in precipitation coming as larger events). However, in looking at total precipitation there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole (see Fig. 4). Stronger trends are generally found over the last four decades. In general, the findings are that wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to the warming climate (IPCC 2013).

As mentioned earlier, it is well known that warmer air can contain more water vapor than cooler air. Global analyses show that the amount of water vapor in the atmosphere has in fact increased over both land and oceans. Climate change also alters dynamical characteristics of the atmosphere that in turn affect weather patterns and storms. At mid-latitudes, there is an upward trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms. Locally, natural variations can also be important. In contrast, the subtropics are generally tending to have less overall rainfall and more droughts. Nonetheless, many areas show an increasing tendency for larger rainfall events when it does rain (Janssen et al. 2014; Melillo et al. 2014; IPCC 2013).

Climate Change Effects on Severe Weather

Along with the overall changes in climate, there is strong evidence of an increasing trend over recent decades in some types of extreme weather events, including their frequency, intensity, and duration, with resulting impacts on our society. The changing trends in severe weather resulting from climate change are already

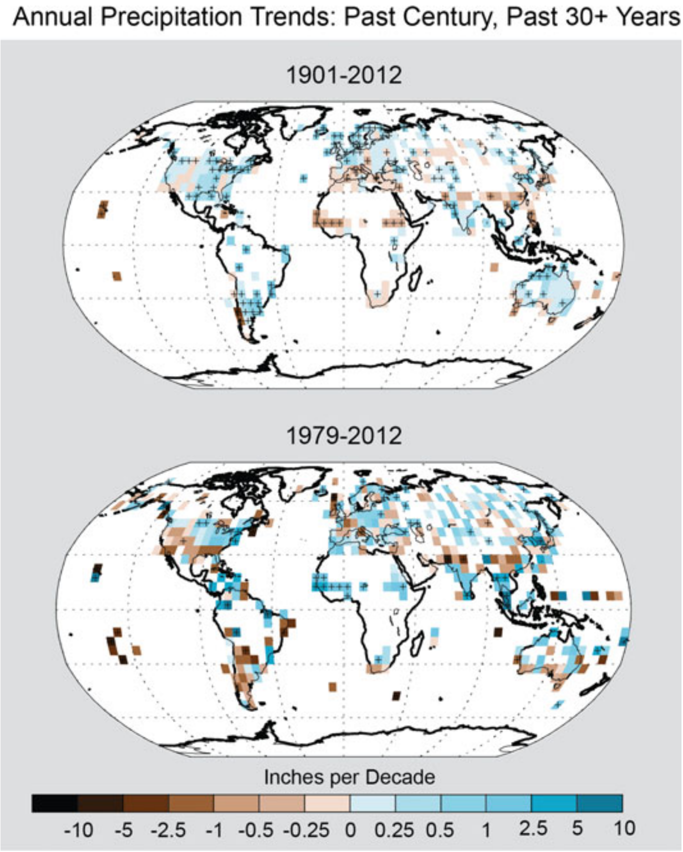

Fig. 4 Global precipitation trends for the period 1901–2012 (top) and 1979–2012 (bottom). Based on date from NOAA NCDC. From Melillo et al. (2014)

affecting the world, including the United States. The United States has sustained over 178 weather/climate disasters since 1980 where damages/costs reached or exceeded $1 billion per event (including CPI adjustment to 2013), with an overall increasing trend (http://www.ncdc.noaa.gov/billions/; also Smith and Katz 2013). The total cost of the 178 events through 2014 is over $1 trillion. In the years 2011 and 2012, there were more such weather events than previously experienced in any given year, with 14 events in 2011 and 11 in 2012, with costs greater than $60 billion in 2011 and greater than $110 Billion during 2012. There were 8 billion dollar plus events in the United States in 2014. The events in these analyses include major heat waves, severe storms, tornadoes, droughts, floods, hurricanes, and wildfires. A portion of these increased costs can be attributed to the increase in population and infrastructure near coastal regions. However, even if hurricanes and their large, mostly coastal, impacts were excluded, there still would be an overall increase in the number of billion dollar events over the last 34 years. Similar analyses by Munich Re and other organizations show that there are growing numbers of severe weather events worldwide causing extensive damage and loss of lives. Figure 5 shows the overall increase in the number of severe events since 1980 through 2015. Even though geophysical events like earthquakes are included in Fig. 5, they are roughly a constant number each year, while the number of severe climate and weather related events has increased dramatically. In summary, there is a clear trend in the impacts of severe weather events on human society not only in the United States, but throughout the world.

Throughout the world, the trends in extreme events are changing; these include increases in the number of extremely hot days, less extreme cold days, more precipitation events coming as unusually large precipitation, and more floods in some regions and more drought in others (Min et al. 2011; IPCC 2012, 2013; Zwiers et al. 2013; Melillo et al. 2014; Wuebbles et al. 2014a, b). For the United States, analyses of atmospheric observations (e.g., Kunkel et al. 2013; Peterson et al. 2013; Vose et al. 2014; Wuebbles et al. 2014a), have shown a pattern of responses in weather extremes relative to the changing climate. These analyses have shown that there are some events, especially those relating to temperature and precipitation extremes, where there is strong understanding of the trends in extreme weather and also of the underlying causes of the observed changes. For some other extremes, the detection of trends in floods, droughts, and extratropical cyclones is also high, but there is less

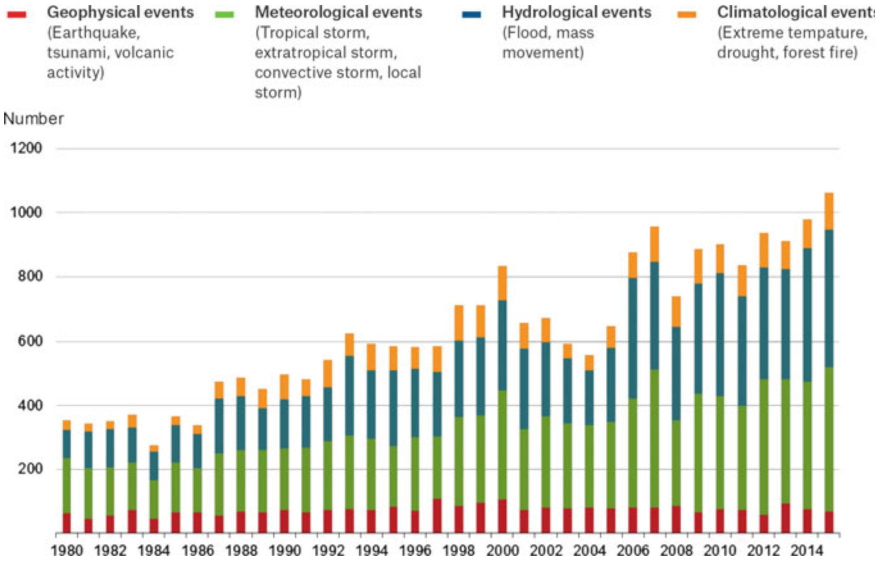

Fig. 5 The number of severe loss events from natural catastrophes per year since 1980 through 2015 as evaluated by Munich Re. Overall losses totaled $90 billion dollars (2015 was not a high year in terms of total costs; the previous year was $110 billion), of which roughly $27 billion was insured. In 2015, natural catastrophes claimed 23,000 lives (average over the last 30 years was 54,000). Figure from Munich Re (https://www.munichre.com/us/weather-resilience-and-protection/media-relations/news/160104-natcatstats2015/index.html)

(only medium) understanding of the underlying cause of the trends. Similarly, there is medium understanding of the observed trends and cause of changes in hurricanes and also in snow events. There is insufficient data to accurately determine trends in strong winds, hail, ice storms, and tornadoes, so there response to a changing climate are not as well understood. Findings for the United States correlate well with analyses of climate extremes globally (IPCC 2012, 2013).

Modeling studies of the changes in climate are generally consistent with the observed trends in extreme weather events over recent decades. Extreme weather events obviously occur naturally. However, the overall changes in climate occurring globally are also altering the frequency and/or severity of many of these extreme events. Trends in extreme weather events, especially in more hot days, less cold days, and more precipitation coming as extreme events, are expected to continue and to intensify over the coming decades.

In most of the United States over the four decades or so, the heaviest rainfall events have become more frequent (e.g., see Fig. 6) and the amount of rain falling in very heavy precipitation events has been significantly above average. This increase has been greatest in the Northeast, Midwest, and upper Great Plains (Melillo et al. 2014).

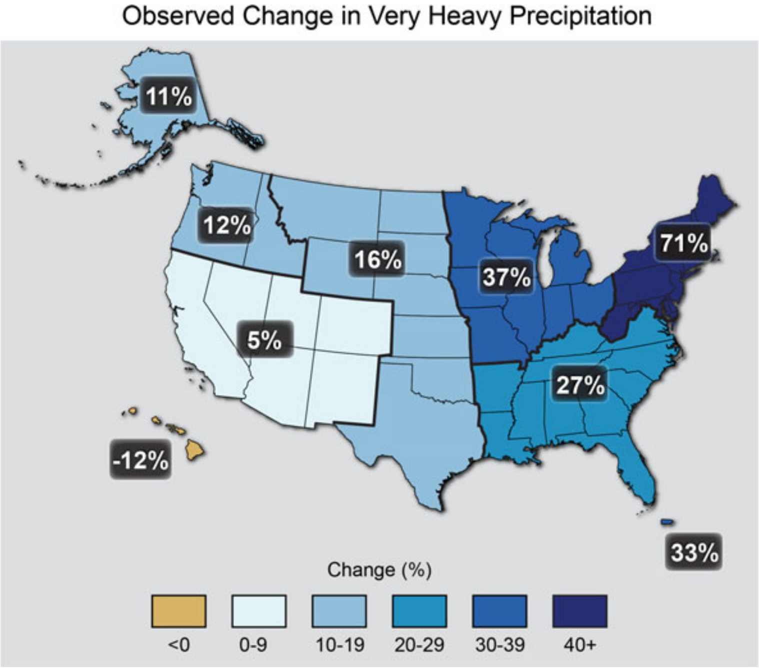

Fig. 6 Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental U.S. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawaii, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 to 2012. From Melillo et al. (2014)

Similar findings are being found in many other parts of the world. Basic physics tells us that a warmer atmosphere should generally hold more water vapor, so this finding is not so surprising. A number of studies suggest that these trends will continue (Janssen et al. 2014; Melillo et al. 2014; Wuebbles et al. 2014a, b).

Heat waves occur naturally within the climate system—while the timing and location of an individual heat wave may be largely a natural phenomenon, this event can also be affected by human-induced climate change (Trenberth and Fasullo 2012). There is emerging evidence that climate change is affecting most of the increasing heat wave severity over our planet. There has been a detectable human influence for major recent heat waves in the United States (Meehl et al. 2009; Rupp et al. 2012; Duffy and Tebaldi 2012), Europe (Stott et al. 2010; Trenberth 2011), and Russia (Christidis et al. 2011). For example, analyses of the summer 2011 heat wave and drought in Oklahoma and Texas, which cost Texas an estimated $8 billion in agricultural losses, have shown that human-driven climate change approximately doubled the probability that the heat was record-breaking (Hoerling et al. 2013). The possibility of record-breaking temperature extremes has increased and will likely continue to increase as the global climate continues to warm. The changes in climate are thus increasing the likelihood for these types of severe events.

The largest, most damaging, storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer smaller (category 1 and 2) hurricanes and more intense (category 4 and 5) hurricanes. A variety of studies have suggested that the intensity of hurricanes should increase under a changing climate but that the overall number of hurricanes may not be affected or possibly even decrease. Observations show no significant trend in the global number of tropical cyclones (IPCC 2012, 2013) nor has any trend been identified in the number of U.S. landfalling hurricanes (Melillo et al. 2014).

Trends remain uncertain in some types of severe weather, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds, but such events are under scrutiny to determine if there is a climate change influence. Initial studies do suggest that tornadoes could get more intense in the coming decades (Diffenbaugh et al. 2013).

After at least two thousand years of little change, the world's sea level rose by roughly 0.2 m (8 in.) over the last century, and satellite data provide evidence that the rate of rise over the past 20 years has roughly doubled. Sea level is rising because ocean water expands as it heats up and because water is added to the oceans from melting glaciers and ice sheets. Also, the observed increase in atmospheric carbon dioxide (CO_2) resulting largely from fossil fuel burning also results in increasing the amount of CO_2 in the oceans and thus, a larger amount of carbonic acid. The oceans are currently absorbing about a quarter of the carbon dioxide emitted to the atmosphere annually (Le Quéré et al. 2009) and are becoming more acidic as a result, leading to concerns about intensifying impacts on marine ecosystems (Melillo et al. 2014).

The Basis for a Human Cause for Climate Change

External forcings on the Earth's climate can occur naturally or from the effects of human activities. Natural forcings on climate include variations in energy received from the Sun, the effects of volcanic eruptions, and changes in the Earth's orbit, with associated variations in sunlight across the world. There are also factors that are internal to the climate system that are the result of complex interactions between the atmosphere with the ocean, land surface, and life on Earth. These internal factors include natural modes of climate system variability, such as those that form El Nino events in the Pacific Ocean.

Natural changes in external forcings and internal factors have been entirely responsible for climate changes in the distant past. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5 °F (Swanson et al. 2009)). At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, it is now understood that human activities are the primary cause of the changes in climate for at least the last six decades and perhaps much longer: specifically, human activities that increase atmospheric levels of CO_2 and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on climate (Melillo et al. 2014).

The greenhouse effect is key to understanding how human activities affect the Earth's climate. As the Sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including H_2O, CO_2, ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then reradiate the energy, with the result of effectively trapping some of the heat inside the climate system (e.g., see Melillo et al. 2014). This greenhouse effect is a natural process, first proposed in 1824 by the French mathematician and physicist Joseph Fourier and confirmed in laboratory studies by British scientist John Tyndall starting in 1859. The Earth is as we know it because of the greenhouse effect. The Earth would be a frozen planet, about 60 °F colder than today, without this natural greenhouse effect (but assuming the same albedo, or reflectivity, as today).

Over the last five decades, natural drivers of climate such as solar forcing and volcanoes would actually have led to a slight cooling. For example, accurate observations of the Sun from satellites since 1978 show that the solar output has actually decreased slightly from 1978 to now. Natural drivers cannot explain the observed warming over this period. The majority of the warming can only be explained by the effects of human influences (Stott et al., 2010; Gillet et al. 2012; IPCC 2013; Santer et al. 2013), especially the emissions from burning fossil fuels (i.e., coal, oil, and natural gas), and from changes in land use, such as deforestation. As a result of human activities, atmospheric concentrations of various gases and particles are changing, including those for CO_2, CH_4, and N_2O, and particles such as black carbon (soot), which has a warming influence, and sulfates, which have an overall cooling influence (because they reflect sunlight). The most important changes are occurring in the concentration of CO_2; its atmospheric concentration has now reached 400 ppm (400 molecules per 1 million molecules of air; this small amount is important because of the heat-trapping ability of CO_2). 400 ppm of CO_2 has not been seen on Earth for over 1 million years, well before the appearance of humans—preindustrial levels of CO_2 were approximately 280 ppm. The increase in CO_2 over the last several hundred years is almost entirely due to burning of fossil fuels and to a lesser extent, from land use change (IPCC 2013).

The conclusion that human influences are the primary driver of recent climate change is based on multiple lines of independent evidence. The first line of evidence is our fundamental understanding of how certain gases trap heat (these so-called greenhouse gases include H_2O, CO_2, CH_4, N_2O, and some other gases and particles that can all absorb the infrared radiation emitted from the Earth that otherwise would go to space), how the climate system responds to changing concentrations of these gases, and how other factors, both natural and human induced, affect climate.

Also the reconstructions of past climates (e.g., from a variety of datasets including those from tree rings, ice cores, and corals) show that recent changes in global surface temperatures are highly unusual and outside the range of natural variability. These studies show that the last decade (2000–2009) has been much warmer than any period in the last 1300 years and perhaps much longer (IPCC 2013; PAGES 2K Consortium 2013; Mann et al. 2008). Through 2016, it appears that this decade will be much warmer than the previous decade.

The rate of globally averaged surface air temperature increase was slower in the period from 2000 to 2009 than it was in the prior three decades, but such variability is to be expected and does not conflict with the understanding of the processes affecting climate change. This past decade was still the warmest decade in the observational record. Global surface air temperature can be affected by natural variability on the scale of about a decade (for further discussion, see IPCC 2013; Melillo et al. 2014; Karl et al. 2015). Also, other climate change indicators, like the decrease in Arctic sea ice and sea level rise, have not seen a slower change in the rate of change during the same period.

Climate models provide additional evidence through studies to simulate the climate of the past century that separate the human and natural factors that influence climate. As shown in Fig. 7, when the human-related emissions are removed, these models show that natural factors (solar variations and volcanic activity) would have tended to lead to a slight cooling, and other natural variations are too small to explain the observed warming (IPCC 2013). Human influences are the only way to reproduce the temperature increase observed over the past six decades.

21st Century Projections of Climate Change

Climate models have analyzed projections of future conditions under a range of emissions scenarios (that depend on assumptions of population change, economic

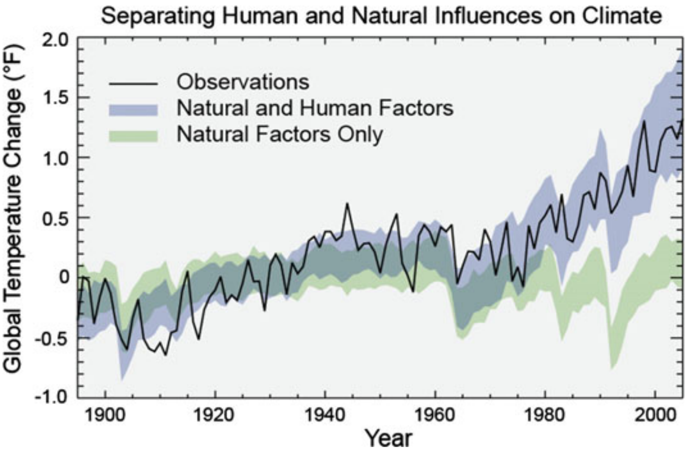

Fig. 7 Observed global average changes (black line), and model simulations using only changes in natural factors (solar and volcanic) in green, and with the addition of human-induced emissions (blue). Climate changes since 1950 cannot be explained by natural factors or variability, and can only be explained by human factors. *Figure source* adapted from Huber and Knutti (2011). From Melillo et al. (2014)

development, our continued use of fossil fuels, changes in other human activities, and other factors). All of the 20+ models used in IPCC (2013) show warming by late this century that is much larger than historical variations nearly everywhere (see Fig. 8). For precipitation, the climate models show decreases in precipitation in the subtropics and increases in precipitation at higher latitudes. As discussed earlier, extreme weather events associated with extremes in temperature and precipitation are likely to continue and to intensify.

Choices made now and in the next few decades about emissions from fossil fuel use and land use change will determine the amount of additional future warming over this century and beyond. Global emissions of CO_2 and other heat-trapping gases continue to rise. Climate changes over the rest of this century and beyond depend primarily on the extent of human activities and resulting emissions; and the sensitivity of the climate system to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions).

Important factors in future emissions include growth in the economy, the types of energy used, and the future efficiency of cities, buildings, and vehicles; these limit the ability to accurately project future changes in climate. Thus a range of plausible projections of what might happen, under a given set of assumptions, are used. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

A certain amount of climate change is inevitable as the CO_2 concentration increases in the atmosphere. There is a lag in the response in the Earth's climate system due to the large heat capacity of the oceans and other factors. An additional 0.2–0.3 °C

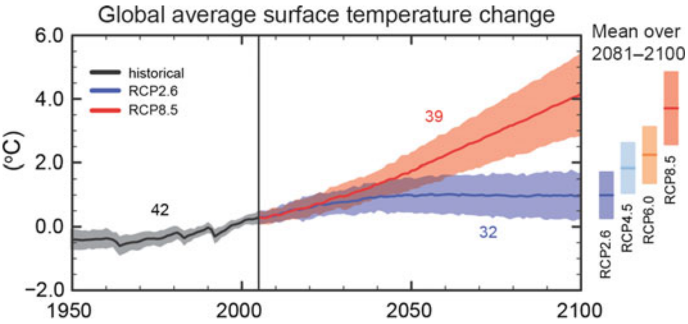

Fig. 8 Multi-model simulated time series from 1950 to 2100 for the change in global annual mean surface temperature relative to 1986–2005 for a range of future emissions scenarios that account for the uncertainty in future emissions from human activities [as analyzed with the 20 + models from around the world used in the most recent international assessment (IPCC 2013)]. The mean and associated uncertainties [1.64 standard deviations (5–95%) across the distribution of individual models (shading)] based on the averaged over 2081–2100 are given for all of the RCP scenarios as colored vertical bars. The numbers of models used to calculate the multi-model mean is indicated. (Figure 7a from IPCC (2013) Summary for Policymakers)

(about 0.5 °F) increase in temperature is inevitable over the next few decades (Matthews and Zickfeld 2012), although natural variability could also be important role on these time scales (Hawkins and Sutton 2011). Higher emissions of CO_2 and other heat-trapping gases would be expected to result in larger climate changes expected by mid-century and beyond. By the second half of the century, uncertainty in what will be the level of future emissions from human activities becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects (Hawkins and Sutton 2009, 2011).

A range of future scenarios are examined in Figs. 8 and 9 that vary from assuming strong continued dependence on fossil fuels in energy and transportation systems over the 21st century (scenario RCP8.5) to assuming major mitigation actions (RCP2.6). In all cases, global surface temperature change for the end of the 21st century is *likely* to exceed an increase of 1.5 °C (2.7 °F) relative to the period from 1850 to 1900 for all projections, with the exception of the RCP2.6 scenario (IPCC 2013). The RCP2.6 scenario has much lower effects on climate than the other scenarios because it assumes both significant mitigation to reduce emissions and also that technologies are developed that can remove CO_2 from the atmosphere (thus achieving net negative carbon dioxide emissions).

A number of research studies have examined the potential criteria for dangerous human interferences in climate where it will be difficult to adapt to the changes in climate without major effects on our society (e.g., Hansen et al. 2007). These studies have generally concluded that an increase in globally average temperature of roughly 1.5 °C (2.7 °F) is an approximate threshold for dangerous human interferences with the climate system (see IPCC 2013, 2014 for further discussion; earlier studies had proposed 2 °C). However, this threshold is not exact and the changes in climate vary geographically and resulting impacts are sector dependent.

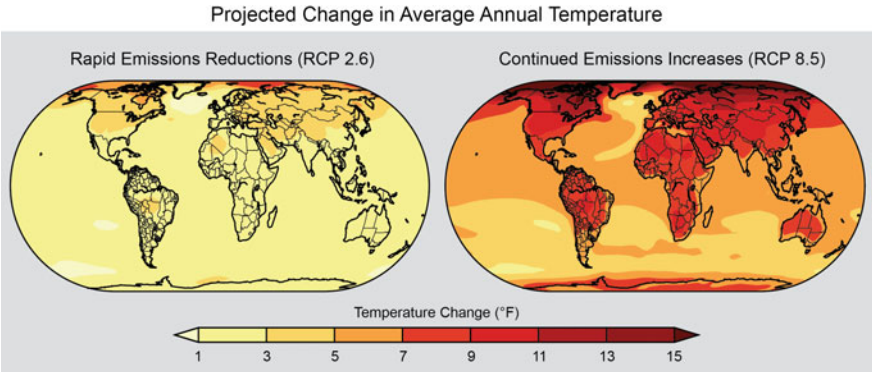

Fig. 9 Projected change in average annual temperature over the period 2071–2099 (compared to the period 1971–2000) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gases (RCP2.6), and a higher scenario that assumes continued increases in emissions (RCP8.5). From Melillo et al. (2014)

The warming and other changes in the climate system will continue beyond 2100 under all RCP scenarios, except for a leveling of temperature under RCP2.6. In addition, it is fully expected that the warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

Projections of future changes in precipitation show small increases in the global average but substantial shifts in where and how precipitation falls (see Fig. 10). Generally, areas closest to the poles are projected to receive more precipitation, while the dry subtropics (the region just outside the tropics, between 23° and 35° on either side of the equator) will generally expand toward the poles and receives less rain. Increases in tropical precipitation are projected during rainy seasons (such as monsoons), especially over the tropical Pacific. Certain regions, including the western U.S. [especially the Southwest (Melillo et al. 2014) and the Mediterranean (IPCC 2013)], are presently dry and are expected to become drier. The widespread trend of increasing heavy downpours is expected to continue, with precipitation becoming more intense (Gutowski et al. 2007; Boberg et al. 2009; Sillmann et al. 2013). The patterns of the projected changes of precipitation do not contain the spatial details that characterize observed precipitation, especially in mountainous terrain, because of model uncertainties and their current spatial resolution (IPCC 2013).

As mentioned earlier, some areas both in the United States and throughout the world are already experiencing climate-related changes in trends for extreme weather events. These trends are likely to continue throughout this century and perhaps beyond (depending on the actions we take). The following trends are expected based on the existing science understanding over the coming decades (see Melillo et al. 2014, or IPCC 2013, for more details):

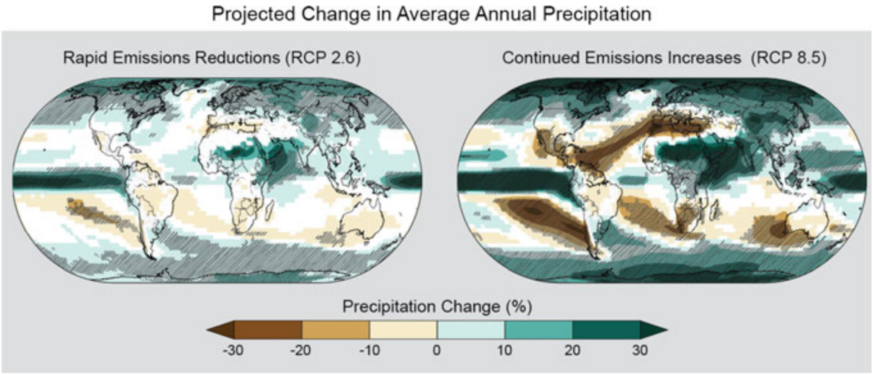

Fig. 10 Projected change in average annual precipitation over the period 2071–2099 (compared to the period 1971–2000) under a low scenario that assumes rapid reductions in emissions and concentrations of heat-trapping gasses (RCP2.6), and a higher scenario that assumes continued increases in emissions (RCP8.5). Hatched areas indicate confidence that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In general, northern parts of the U.S. (especially the Northeast and Alaska) are projected to receive more precipitation, while southern parts (especially the Southwest) are projected to receive less. From Melillo et al. (2014)

- It is likely that over the coming decades the frequency of warm days and warm nights will increase in most land regions, while the frequency of cold days and cold nights will decrease. As a result, an increasing tendency for heat waves is likely in many regions of the world.
- Some regions are likely to see an increasing tendency for droughts while others are likely to see an increasing tendency for floods. This roughly corresponds to the wet getting wetter and the dry getting drier.
- It is likely that the frequency and intensity of heavy precipitation events will increase over land. These changes are primarily driven by increases in atmospheric water vapor content, but also affected by changes in atmospheric circulation.
- Tropical storm (hurricane)-associated storm intensity and rainfall rates are projected to increase as the climate continues to warm.
- Initial studies also suggest that tornadoes are likely to become more intense. However, this is more uncertain.
- For some types of extreme events, like wind storms, and ice and hail storms, there is too little understanding currently of how they will be affected by the changes in climate.

Around the world, many millions of people and many assets related to energy, transportation, commerce, and ecosystems are located in areas at risk of coastal flooding because of sea level rise and storm surge. Sea level is projected to rise an additional 0.3–1.2 m (1–4 ft) in this century (see Fig. 11; Melillo et al. 2014; similar findings in IPCC 2013). The best estimates for the range of sea level rise projections for this century remain quite large; this may be due in part to what emissions scenario we follow, but more importantly it depends on just how much melting occurs from the ice on large land masses, especially from Greenland and Antarctica. Recent projections show that for even the lowest emissions scenarios, thermal expansion of ocean waters (Yin 2012) and the melting of small mountain glaciers (Marzeion et al. 2012) will result in 11 in. of sea level rise by 2100, even without any contribution from the ice sheets in Greenland and Antarctica. This suggests that about 0.3 m (1 ft) of global sea level rise by 2100 is probably a realistic low end. Recent analyses suggest that 1.2 m (4 ft) may be a reasonable upper limit (Rahmstorf et al. 2012; IPCC 2013; Melillo et al. 2014). Although scientists cannot yet assign likelihood to any particular scenario, in general, higher emissions scenarios would be expected to lead to higher amounts of sea level rise.

Because of the warmer global temperatures, sea level rise will continue beyond this century. Sea levels will likely continue to rise for many centuries at rates equal to or higher than that of the current century. Many millions of people live within areas than can be affected by the effects of storm surge within a rising sea level. The Low Elevation Coastal Zone (less than 10 m elevation) constitutes 2% of the world's land area, yet contains 10% of the world's population (over 600 million people) (McGranahan et al. 2007; Neumann et al. 2015). Most of the world's megacities are within the coastal zone. By 2030, with sea level rise, the area will expand and 800–900 million people will be exposed (Güneralp et al. 2015; Neumann et al. 2015).

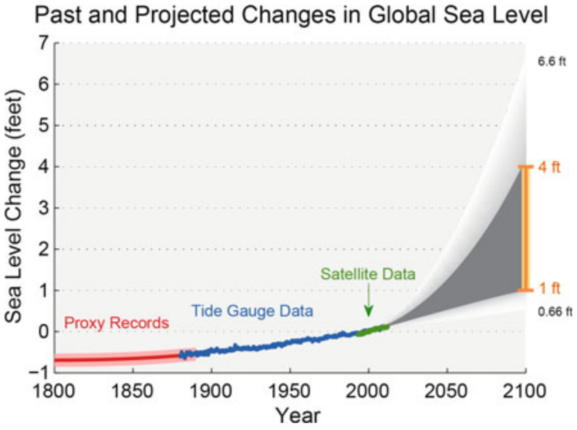

Fig. 11 Estimated, observed, and projected amounts of global sea level rise from 1800 to 2100, relative to the year 2000. Estimates from proxy data (for example, based on sediment records) are shown in red (1800–1890, pink band shows uncertainty), tide gauge data in blue for 1880–2009 (Church and White 2011; Church et al. 2011) and satellite observations are shown in green from 1993 to 2012 (Nerem et al. 2010). The future scenarios range from 0.66 to 6.6 ft in 2100 (Parris et al. 2012). These scenarios are not based on climate model simulations, but rather reflect the range of possible scenarios based on scientific studies. The orange line at right shows the currently projected range of sea level rise of 1–4 ft by 2100, which falls within the larger risk-based scenario range. The large projected range reflects uncertainty about how glaciers and ice sheets will react to the warming ocean, the warming atmosphere, and changing winds and currents. As seen in the observations, there are year-to-year variations in the trend. From Melillo et al. (2014)

As mentioned earlier, CO_2 is dissolving into the oceans where it reacts with seawater to form carbonic acid, lowering ocean pH levels (“acidification”) and threatening a number of marine ecosystems (Doney et al. 2009). The oceans have absorbed 560 billion tons of CO_2 over the last 250 years, thus increasing the acidity of surface waters by 30% (Melillo et al. 2014). The current observed rate of change is roughly 50 times faster than known historical change (Hönisch et al. 2012; Orr 2011; Caldeira and Wickett 2003). Ocean acidification hotspots are occurring due to regional factors such as coastal upwelling (Feely et al. 2008), changes in discharge rates from rivers and glaciers (Mathis et al. 2011) sea ice loss (Yamamoto-Kawai et al. 2009), and urbanization (Feely et al. 2010).

The acidification of the oceans is suppressing carbonate ion concentrations that are critical for marine calcifying animals such as corals, zooplankton, and shellfish. Many of these animals form the foundation of the marine food web. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Ocean acidification puts this important resource at risk.

Higher emission scenario projections could reduce the ocean pH from the current 8.1 to as low as 7.8 by the end of the century (Orr et al. 2005). This is unprecedented in human history—such large rapid changes in ocean pH have probably not been experienced for the past 100 million years, and it is unclear whether and how quickly ocean life could adapt to such rapid acidification (Hönisch et al. 2012). Potential impacts on food supplies from the oceans are unclear. Unfortunately, since sustained efforts to monitor ocean acidification worldwide are only beginning, it is currently impossible to quantify this risk or to be able to predict exactly how ocean acidification impacts will cascade throughout the marine food chain and affect the overall structure of marine ecosystems.

Responding to Climate Change: A Look Forward

It has become increasingly clear that our future depends on how we act to limit climate change. Science is the basis for developing responses to climate change, by providing the:

- Motivation for seeking to develop a cost-effective plan to reduce those impacts;
- Sense of urgency for doing so now rather than waiting;
- Awareness that such a plan must include both mitigation and adaptation;
- Knowledge of the sources of the offending emissions and the character of society’s vulnerabilities that allows appropriate specificity in designing a plan; and
- Recognition that any U.S. plan must include a component designed to bring other countries along.

We basically have three choices:

- Mitigation, meaning measures to reduce the pace and magnitude of the changes in global climate being caused by human activities.

- Adaptation, meaning measures to reduce the adverse impacts on human well-being resulting from the changes in climate that do occur.
- Suffering the adverse impacts and societal disruption that are not avoided by either mitigation or adaptation.

Right now we are doing some of all three. What's up for grabs is the future mix. Minimizing the amount of suffering in that mix can only be achieved by doing a lot of mitigation and a lot of adaptation. Mitigation alone would be inadequate; climate is already changing and can't be stopped quickly. Adaptation alone would also be inadequate; adaptation gets costlier and less effective as climate change grows.

We must reduce emissions of the heat-trapping gases and particles to avoid unmanageable levels of climate change and the resulting impacts. At the same time we need to adapt to the changes in climate that are unavoidable. Adaptation is not a choice—our choice is whether to adapt proactively or respond to the consequences. Adaptation requires a paradigm shift, focusing on managing risks. Proactively preparing for climate change can reduce impacts while also facilitating a more rapid and efficient response to changes as they happen. Such efforts are beginning in the United States and other parts of the world, to build adaptive capacity and resilience to climate change impacts. Using scientific information to prepare for climate changes in advance can provide economic opportunities, and proactively managing the risks can reduce impacts and costs over time.

In the United States, the first major steps were taken on June 25, 2013, when President Obama announced the Climate Action Plan, a national plan for tackling climate change. The plan, is divided into three sections that outline steps to (1) cut carbon pollution in the United States, including standards for both new and existing power plants, (2) actions to prepare the United States for the impacts of climate change, and (3) plans to lead international efforts to address global climate change. Also, the President's Climate Action Plan fast-tracks permitting for renewable energy projects on public lands, increases funding for clean energy technology and efficiency improvements, and calls for improved efficiency standards for buildings and appliances, as well as heavy trucks. The plan additionally establishes the first-ever Federal Quadrennial Energy Review to encourage strategic national energy planning. As part of the plan, the American Business Act on Climate Pledge has received commitments from 154 companies (so far) from across the American economy for their contributions to mitigation and adaptation. Agreements made with China, India, and other countries have been important in getting to an international agreement on climate change.

Large reductions in global emissions of heat-trapping gases will be important if we are to reduce the risks associated with many of the worst impacts of climate change. The international agreement made in Paris by 195 countries in December 2015 is an important start to achieving this. The 21st annual Conference of Parties (COP21) resulted in a global action plan to reduce emissions of carbon dioxide and other greenhouse gases. The current Paris Agreement only extends through 2030 but the long term goal is to keep the increase in global average temperature to well below 2 °C (3.6 °F) above pre-industrial levels. This itself will be extremely difficult to do, but the ultimate aim would be to keep the temperature change below 1.5 °C (2.7 °F). This would be roughly equivalent to following the extremely low RCP2.6 scenario discussed earlier (about half of the global climate models used in the 2013 IPCC assessment produced a change of about 1.5 °C).

The current agreement is not sufficient to reach even the 2 °C limit but it is an important step towards getting there and perhaps to 1.5 °C. Its full implementation throughout the world, including the United States, should lead to incentives for the development of new energy and transportation technologies that should further reduce emissions. This is an important step. It is clear that the choices we make to reduce climate change over the next few decades will not only affect us, they will affect our children, our grandchildren, and future generations.

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