Statement of
Christopher B. Field, PhD[1]

Director, Department of Global Ecology
Carnegie Institution for Science[2]
Co-chair, Working Group II of the IPCC

Mailing Address:
Carnegie Institution for Science
260 Panama Street
Stanford, CA 94305

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The Foundations for Climate Science

Introduction

I thank Chairman Markey, Ranking Member Sensenbrenner, and the other Members of the Select Committee for the opportunity to speak with you today on observed and likely future changes in climate and the contribution from human activity to those changes. My name is Christopher Field. I am director of the Department of Global Ecology at the Carnegie Institution for Science, a not-for-profit organization dedicated to basic research for the benefit of humanity. In addition, I am a professor in the Department of Environmental Earth System Science and the Department of Biology at Stanford University. Since September of 2008, I have served as co-chair of Working Group 2 of the Intergovernmental Panel on Climate Change. Working Group 2 is tasked with assessing scientific information concerning impacts of climate change, options for adaptation to climate changes that cannot be avoided, and vulnerability to climate change.

My personal research focuses on interactions among climate, the carbon cycle, and ecosystem processes, using approaches that range from ecosystem-scale climate manipulations to global climate models. I have published over 200 peer-reviewed papers in leading scientific journals, and was a coordinating lead author on the topic "North America" for the Working Group 2 contribution to the IPCC Fourth Assessment Report. I have served on many committees of the National Research Council and International Scientific Organizations. I am an elected member of the US National Academy of Sciences and the American Academy of Arts and Sciences as well as an elected Fellow of the American Association for the Advancement of Science.

In today's testimony, I will address all four of the questions in the charge, with a focus on observed impacts on land systems. All of the observations and projections concerning questions 1-3 in my statement are based on publications in peer-reviewed scientific journals or on national or international assessments of thousands of scientific sources.

Two sources are particularly valuable in providing systematic, thoroughly assessed responses to the questions. These are the 2009 report from the US Global Change Research Program, "Global Climate Change Impacts in the United States" (Karl et al. 2009) and the Fourth Assessment Report of the IPCC (IPCC 2007a, c, b). These documents provide a scientifically rich picture of a changing climate, the mechanisms that underlie observed and projected changes, impacts of climate change on individuals, ecosystems, economies, and regions, and the costs and benefits of changing practices to decrease the amount of climate change from a business-as-usual scenario. To assure consistency with these sources, the points here are either verbatim or changed only as necessary for the sake of clarity.

1. What are the observed changes to the climate system?

- Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The

global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. (IPCC 2007d)

- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. (IPCC 2007d)

- Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. (IPCC 2007e)

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

- At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones. (IPCC 2007d)

- Some aspects of climate have not been observed to change. (IPCC 2007d)

- Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 m of sea level rise. (IPCC 2007d)

- Climate-related changes have already been observed globally and in the United States. These include increases in air and water temperatures, reduced frost days, increased frequency and intensity of heavy downpours, a rise in sea level, and reduced snow cover, glaciers, permafrost, and sea ice. A longer ice-free period on lakes and rivers, lengthening of the growing season, and increased water vapor in the atmosphere have also been observed. Over the past 30 years, temperatures have risen faster in winter than in any other season, with average winter temperatures in the Midwest and northern Great Plains increasing more than 7°F. Some of the changes have been faster than previous assessments had suggested (Karl et al. 2009).

- U.S. average temperature has risen more than 2°F over the past 50 years and is projected to rise more in the future; how much more depends primarily on the amount of heattrapping gases emitted globally and how sensitive the climate is to those emissions (Karl et al. 2009).

- U.S. precipitation has increased an average of about 5 percent over the past 50 years. Projections of future precipitation generally indicate that northern areas will become wetter, and southern areas, particularly in the West, will become drier (Karl et al. 2009).

- In the U.S. the amount of rain falling in the heaviest downpours has increased approximately 20 percent on average in the past century, and this trend is very likely to continue, with the largest increases in the wettest places (Karl et al. 2009).

- Many types of extreme weather events, such as heat waves and regional droughts, have become more frequent and intense during the past 40 to 50 years (Karl et al. 2009).

2. What evidence provides attribution of these changes to human activities?

- Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the TAR's (Third Assessment Report's) conclusion that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations". Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns (IPCC 2007d).

- The scientific evidence for a human influence on global climate has accumulated over the past several decades, from many hundreds of studies. No single study is a "smoking gun." Nor has any single study or combination of studies undermined the large body of evidence supporting the conclusion that human activity is the primary driver of recent warming (Karl et al. 2009).

- The first line of evidence is our basic physical understanding of how greenhouse gases trap heat, how the climate system responds to increases in greenhouse gases, and how other human and natural factors influence climate. The second line of evidence is from indirect estimates of climate changes over the last 1,000 to 2,000 years. The third line of evidence is based on the broad, qualitative consistency between observed changes in climate and the computer model simulations of how climate would be expected to change in response to human activities. Finally, there is extensive statistical evidence from so-called "fingerprint" studies. Each factor that affects climate produces a unique pattern of climate response, much as each person has a unique fingerprint. Fingerprint studies exploit these unique signatures, and allow detailed comparisons of modeled and observed climate change patterns (Karl et al. 2009).

3. What are the observed and anticipated impacts of climate change in the United States and throughout the world?

- The United States frequently experiences weather-related challenges, with substantial economic costs from severe storms, drought, flood, extreme heat, and extreme cold (Field et al. 2007). Weather-related impacts are persistent features of the American landscape. Over the last several decades, however, the United States has experienced substantial

amounts of warming, especially in Alaska, and recent scientific research documents an increasing number of impacts that appear to be a result of climate changes that have already occurred (Field et al. 2007). For one-time events, like heat waves, drought, or wildfires, it will rarely be possible to say with certainty that a single event was caused by climate change (Hegerl et al. 2007). Nevertheless, several kinds of extremes will likely become more common with climate change. Increasingly, it is possible to assess the probability that a heat wave, wildfire, or drought would have occurred in the absence of climate change (Hegerl et al. 2007).

- In recent decades, the United States has experienced an increasing number of stresses projected to increase in a warming climate. Some of these are iconic one-time events like the need to move the Alaskan village of Shishmaref, which is being progressively lost to the sea after 400 years of habitation, a consequence of melting of the permafrost on which it sits and increased wave action related to a decreased period when ice protects the village (http://www.arctic.noaa.gov/detect/human-shishmaref.shtml). Others are more gradual and progressive. Examples include the clear decrease in the season for high-latitude ice roads, the dramatic decrease in water stored in the snowpack of the Western mountains, or the strong increase in the area burned in Western wildfires (Field et al. 2007). Drought is among the largest climate-related concerns for the United States. Many parts of the Western US have limited water security. Some of these are in parts of the country where decreased snowpack is cutting into water storage capacity or where groundwater pumping has led to large drops in the water table (Field et al. 2007). Projected decreases in precipitation (Meehl et al. 2007) could push many of these areas from water insecure to chronically critically short of water.

- With climate change in coming decades, the United States will have vulnerable people, businesses, and activities in all regions. The people most vulnerable to impacts of climate change tend to be those who are very young, old, sick, or poor. People who live in communities dependent on single industries based on resources at risk (e.g. fisheries) will likely experience large impacts, especially if they cannot switch activities or relocate (Field et al. 2007). Continuing increases in the value of the infrastructure in the coastal zone exacerbate the risks from sea-level rise. The United States has abundant adaptive capacity with the potential to provide an important measure of protection, but deploying that capacity to effectively provide protection will require mainstreaming adaptation at a level far above the historical norm (Field et al. 2007).

- For the next two decades, a warming at the global scale of about 0.36°F per decade is projected for a range of emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.18°F per decade would be expected. (IPCC 2007d)

- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century. (IPCC 2007d)

- Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized. (IPCC 2007d)

Sector-Specific Projected Impacts

- **Water Resources**: Climate change has already altered, and will continue to alter, the water cycle of the United States, affecting where, when, and how much water is available for all uses. Floods and droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change, and rainfall becomes more concentrated into heavy events (with longer, hotter dry periods in between). Precipitation and runoff are likely to increase in the Northeast and Midwest in winter and spring, and decrease in the West, especially the Southwest, in spring and summer. In areas where snowpack dominates, the timing of runoff will continue to shift to earlier in the spring and flows will be lower in late summer. Surface water quality and groundwater quantity will be affected by a changing climate. Climate change will place additional burdens on already stressed water systems. The past century is no longer a reasonable guide to the future for water management (Karl et al. 2009).

- **Energy**: Warming in the United States will be accompanied by decreases in demand for heating energy and increases in demand for cooling energy. The latter will result in significant increases in electricity use and higher peak demand in most regions. Energy production is likely to be constrained by rising temperatures and limited water supplies in many regions. Energy production and delivery systems are exposed to sea-level rise and extreme weather events in vulnerable regions. Climate change is likely to affect some renewable energy sources across the nation, such as hydropower production in regions subject to changing patterns of precipitation or snowmelt (Karl et al. 2009).

- **Transportation**: Sea-level rise and storm surge will increase the risk of major coastal impacts on the United States, including both temporary and permanent flooding of airports, roads, rail lines, and tunnels. Flooding from increasingly intense downpours will increase the risk of disruptions and delays in air, rail, and road transportation, and damage from mudslides in some areas. The increase in extreme heat will limit some transportation operations and cause pavement and track damage. Decreased extreme cold will provide some benefits such as reduced snow and ice removal costs. Increased intensity of strong hurricanes would lead to more evacuations, infrastructure damage and failure, and transportation interruptions. Arctic warming will continue to reduce sea ice, lengthening the ocean transport season, but also resulting in greater coastal erosion due to waves. Permafrost thaw in Alaska will damage infrastructure. The ice road season will become shorter (Karl et al. 2009).

- **Agriculture**: Many crops show positive responses to elevated carbon dioxide and low levels of warming, but higher levels of warming often negatively affect growth and yields. In the United States, extreme events such as heavy downpours and droughts are likely to reduce crop yields because excesses or deficits of water have negative impacts on plant growth. Weeds, diseases, and insect pests benefit from warming, and weeds also benefit from a higher carbon dioxide concentration, increasing stress on crop plants and

requiring more attention to pest and weed control. Forage quality in pastures and rangelands generally declines with increasing carbon dioxide concentration because of the effects on plant nitrogen and protein content, reducing the land's ability to supply adequate livestock feed. Increased heat, disease, and weather extremes are likely to reduce livestock productivity (Karl et al. 2009).

- **Ecosystems**: Ecosystem processes, such as those that control growth and decomposition, have been affected by climate change. Large-scale shifts have occurred in the ranges of species and the timing of the seasons and animal migration, and are very likely to continue. In the United States, fires, insect pests, disease pathogens, and invasive weed species have increased, and these trends are likely to continue. Deserts and drylands are likely to become hotter and drier, feeding a self reinforcing cycle of invasive plants, fire, and erosion. Coastal and near-shore ecosystems are already under multiple stresses. Climate change and ocean acidification will exacerbate these stresses. Arctic sea ice ecosystems are already being adversely affected by the loss of summer sea ice and further changes are expected. The habitats of some mountain species and coldwater fish, such as salmon and trout, are very likely to contract in response to warming. Some of the benefits ecosystems provide to society will be threatened by climate change, while others will be enhanced (Karl et al. 2009).

- **Human Health**: In the United States, increases in the risk of illness and death related to extreme heat and heat waves are very likely. Some reduction in the risk of death related to extreme cold is expected. Warming is likely to make it more challenging to meet air quality standards necessary to protect public health. Extreme weather events cause physical and mental health problems. Some of these events are projected to increase. Some diseases transmitted by food, water, and insects are likely to increase. Rising temperature and carbon dioxide concentration increase pollen production and prolong the pollen season in a number of plants with highly allergenic pollen, presenting a health risk. Certain groups, including children, the elderly, and the poor, are most vulnerable to a range of climate-related health effects (Karl et al. 2009).

- **Society**: Population shifts and development choices are making more Americans vulnerable to the expected impacts of climate change. Vulnerability is greater for those who have few resources and few choices. City residents and city infrastructure have unique vulnerabilities to climate change. Climate change affects communities through changes in climate-sensitive resources that occur both locally and at great distances. Insurance is one of the industries particularly vulnerable to increasing extreme weather events such as severe storms, but it can also help society manage the risks. The United States is connected to a world that is unevenly vulnerable to climate change and thus will be affected by impacts in other parts of the world (Karl et al. 2009).

- Many estimates of aggregate net economic costs of damages from climate change across the globe (i.e., the social cost of carbon (SCC), expressed in terms of future net benefits and costs that are discounted to the present) are now available. Peer-reviewed estimates of the SCC for 2005 have an average value of US$43 per ton of carbon (i.e., US$12 per ton of carbon dioxide), but the range around this mean is large. For example, in a survey

of 100 estimates, the values ran from US$-10 per ton of carbon (US$-3 per ton of carbon dioxide) up to US$350 per ton of carbon (US$95 per ton of carbon dioxide). (IPCC 2007f)

- Non-climate stresses can increase vulnerability to climate change by reducing resilience and can also reduce adaptive capacity because of resource deployment to competing needs. For example, current stresses on some coral reefs include marine pollution and chemical runoff from agriculture as well as increases in water temperature and ocean acidification. Vulnerable regions face multiple stresses that affect their exposure and sensitivity as well as their capacity to adapt. These stresses arise from, for example, current climate hazards, poverty and unequal access to resources, food insecurity, trends in economic globalisation, conflict, and incidence of diseases such as HIV/AIDS. Adaptation measures are seldom undertaken in response to climate change alone but can be integrated within, for example, water resource management, coastal defense and risk-reduction strategies. (IPCC 2007f)

4. How is the climate science community furthering public understanding of climate change and its consequences?

- Climate change is one of the most important, complex, and far-reaching challenges we face in the 21st century. The complexity and technical nature of the challenge place a special burden of responsibility on the scientific community to provide balanced, accurate, timely, and understandable information to governments and other stakeholders. Especially in an environment with high economic and political stakes, it is critical for the information from the scientific community to be absolutely trustworthy.

- Broad-based scientific assessments, like the US National Assessments and the IPCC Assessments, are the scientific community's central tool for insuring that balanced, thoroughly vetted information receives the prominence it deserves. Especially the IPCC assessments, which involve a unique partnership between the scientific community and the world's governments, function effectively to insure balance and accuracy. Assessments like these deserve the broad support of the scientific community, national governments, and other stakeholders.

- Because climate change is so important and so complex, the challenge of advancing public understanding must be addressed with strategies that go beyond the existing assessment model. The scientific community needs to make extra investments in providing sufficient information for the public to understand the issue, and the public needs to make a genuine commitment to educating itself. This kind of novel partnership, extending across whole societies, will be critically important for enabling smart decisions on dealing with climate change.

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