The Physics of Climate Change, Climate Models and Changes in Weather and Climate Extremes

Statement of

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Introduction

I thank the chairman and other Members of the Committee for the opportunity to communicate to you today information regarding processes involved with climate change, climate models, and extreme weather and climate events. My name is Gerald Meehl, Senior Scientist at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. My research interests include tropical climate involving the monsoons and El Nino Southern Oscillation, climate variability and climate change. I have authored or co-authored more than 185 peer-reviewed scientific journal articles and book chapters. I was a lead author on the U.S. Climate Change Science Program (CCSP) Report 1.1 on temperature trends in the atmosphere, and was co-coordinator of the CCSP Report 3.3 on weather and climate extremes in a changing climate. I have been involved with the Intergovernmental Panel on Climate Change (IPCC) assessments since the first one that was published in 1990. I was a Contributing Author on that first assessment and its update in 1992, a Lead Author for the 1995 Assessment, a Coordinating Lead Author for the 2001 and the 2007 assessments, and I am currently a lead author for the recently initiated IPCC Fifth Assessment Report (AR5) due to be completed in 2013. I am chair of the National Academy of Sciences/National Research Council Climate Research Committee (CRC). I have been involved with committees of the World Climate Research Program (WCRP) on Climate Variability and Predictability (CLIVAR), and am currently co-chair of the WCRP/CLIVAR Working Group on Coupled Models (WGCM). This committee organized and coordinated the international modeling groups in performing climate model experiments for assessment in the AR4, and in the collection and analysis of data from those model experiments that was made openly available to the international climate research community. Our committee is currently involved in performing similar coordination activities for climate change experiments now being run by about 20 international climate modeling groups to increase our understanding of climate model performance and to provide insight into the climate system response to future climate change mitigation scenarios. As before, these experiments will be made openly available for analysis by the international climate science community, and will also be assessed as part of the IPCC AR5.

The greenhouse effect and how increasing greenhouse gases warm the climate

Since roughly the beginning of the Industrial Revolution in the second part of the 19th century, human societies have come to rely on fossil fuels for an energy source. These fossil fuels—coal, oil, and natural gas—produce greenhouse gases when they are burned. Thus, as humans have excavated fossil fuels from beneath the surface of the earth where they have been sequestered for millions of years, those fuels have been burned for energy and have released forms of carbon into the air—greenhouse gases such as CO2 and methane. These greenhouse gases in trace amounts occur naturally in the atmosphere and effectively trap some heat in the climate system that would otherwise escape to space. This occurs because molecules with more than two atoms (e.g. CO2, CH4, H2O) have the well-known property of being able to absorb and re-emit infrared or heat energy.

Most molecules are transparent to incoming sunlight, and almost all sunlight that is not reflected by clouds reaches the earth's surface. That sunlight heats the surface, and heat (infrared radiation) is emitted upwards. If greenhouse gases were not in the atmosphere, most of this heat energy would make it out of the system to space, leaving the earth a much colder and inhospitable place. However, greenhouse gases intercept some of this heat or infrared energy, absorb it, and re-radiate some of it upwards where it continues on out to space, and some of it is re-radiated downwards, thus staying in the system to warm the planet. Thus, this heat-trapping effect of greenhouse gases makes the planet habitable for human, plant and animal life.

Greenhouse gases have been present in our atmosphere for millennia. It has been shown, from air bubbles trapped in ice sheets, that greenhouse gases such as CO2 have fluctuated naturally over at least the past 800,000 years with the ice ages. Of course humans were not present to cause these fluctuations, but, due to well-understood orbital variations that change the intensity of solar input, the planet cools and warms naturally over thousands of years producing the ice ages and inter-glacial periods. We also know that warmer oceans tend to emit more CO2 to the atmosphere, while cooler oceans absorb CO2. Thus, as the orbital variations produce differences in the intensity of solar input to the climate system that contribute to the ice ages, the oceans warm and cool as the ice ages come and go naturally, and there is an amplifying effect from CO2 to enhance the warmth between ice ages (i.e. the warmer oceans emit more CO2 that warms the climate more), while the opposite occurs during ice ages to contribute to even colder conditions.

The concept that CO2 and other greenhouse gases, released when fossil fuels are burned, would cause a warming of the climate is not a new idea. In 1895 Svante Arrhenius postulated that increasing levels of greenhouse gases in the air would warm the climate such that a doubling of CO2 would warm the planet on average by about 5 to 6C (he later revised this number downward to 1.6C). These numbers, calculated very simply from early radiative theory, are not that far off from modern estimates of 2C to 4.5C derived from global climate models and inferred from observational data. In the late 1930s Guy Callendar suggested that the burning of fossil fuels should increase greenhouse gases in the atmosphere, and that these increases should warm the climate. It wasn't until the late-1950s, when Charles Keeling started to directly measure the time evolution of CO2 in the atmosphere to show that there was, indeed, an increasing trend, that the earlier theoretical estimates of CO2 increase from the burning of fossil fuels had a basis in a definitive time series measurement.

The concept that equations from fluid dynamics, physics and thermodynamics could be used to simulate weather was addressed early in the 20th century when L.F. Richardson attempted to use a set of those equations to calculate, by hand, a simple weather forecast for a single location. However, due to the complexity of the equations and considerable numerical calculations required, it was not until electronic computers came into use in the 1950s that the equations could be solved to produce simulations of the weather in a rapid enough manner to be used for actual weather forecasts. This new science of numerical weather prediction became feasible for operational forecasts in the 1960s, and is still in use today to produce weather forecasts.

Using the same principles, and even many of the same equations, early climate models were devised that could be integrated forward in time, much like numerical weather forecasts, but for much longer into the future. It was well-known that after about a week, due to the chaotic nature of the atmosphere, the time evolution of individual storms cannot be resolved by climate models. Instead, the climate simulations attempted to capture the statistics of weather over months, seasons, years and decades. Since climate models looked at weather and climate in this new way, other factors that could change slowly and thus affect the statistics of weather had to be included. Therefore, equations that took into account the effects of greenhouse gases were refined. The varying output of the sun could also be included, as well as the effects of volcanic eruptions in equations that accounted for how visible air pollution could cause cooling of the climate. Perhaps most importantly for longer term variations of the statistics of weather and climate, the slowly varying parts of the climate system had to be included, namely the oceans and sea ice, as well as land surface processes. Unlike weather prediction where there was only an atmospheric numerical model, climate models had an atmosphere (similar to a numerical weather prediction model), as well as components of ocean, land surface, sea ice, and sophisticated equations that accounted for the heating of greenhouse gases or the cooling of visible air pollution. All of these components were linked together in one large computer program that had be run on the fastest supercomputers available so that as much detail in the equations could be included as possible, balanced by the need to run the models for tens and even hundreds of years (as opposed to only about a week for numerical weather prediction models). Thus, most of the physics, processes, and feedbacks known to be operating in the climate system were included in even the earliest global climate models that began to be used in the 1960s.

The warming produced by increases of greenhouse gases, along with the first order feedbacks, were shown to occur in these very early climate models. This led to the "Charney Report" published by the National Academy of Sciences in 1979, over 20 years ago. That report noted that the measured increases in CO2 in the atmosphere, when included in the basic climate models of that time, produced significant warming on average over the planet, and that, with further increases in CO2, the climate would continue to warm. Interestingly, this report was published after over 30 years of the observed climate not warming (there was warming until the 1940s, and then little warming until the late 1970s). Thus, based on the physics of climate already known in the 19th century, and the basic understanding of that time of the processes that could be captured in equations and included in climate models to study the statistics of climate, future warming was predicted as a result of ongoing increases of greenhouse gases, even though the observed climate had not been warming for decades. Since the time the Charney Report was published in the late 1970s, there has been an overall average warming trend. It was not until over 20 years later, at the beginning of the 21st century, that a generation of improved climate models, along with better observed datasets, was able to show how the combinations of natural and human factors that influence climate produced the time evolution of observed temperature change over the 20th century.

Results from those studies showed that the warming in the early part of the 20th century was mainly due to natural causes; a hiatus of warming from the 1940s to the 1970s was mostly due to a balance between the warming that would have occurred due to the increases of greenhouse gases, and the cooling from the visible air pollution in part produced by the burning of fossil fuels; and finally in the 1970s after air quality was improved, thereby reducing cooling from visible air pollution, the ongoing increases of greenhouse gases produced a multi-decadal warming trend over the past 35 years or so. This warming trend is not uniform in time (i.e. each year is not warmer than the year before) due to internally generated natural variability of the climate system. Depending on the start and end points used to calculate ten year trends, there are some decades when the warming trend is nearly flat (e.g.1986-1995; 1998-2007) and times when the warming trend for a given decade is greater than the longer term trend (e.g. 1975-1984; 1988-1997)

Measurements from the ice cores of air bubbles trapped over the last 800,000 years indicate the CO2 amount in the atmosphere only ever got about as high as 280 ppm. In just the last 100 years, that CO2 amount has increased to an unprecedented (over the last 800,000 years) amount of about 380 ppm currently. Since we know CO2 traps heat in the atmosphere, the increase in CO2 alone would warm the climate somewhat. But, just as CO2 acts as an amplifier to past ice ages and inter-glacials, it also produces other amplifying effects in the atmosphere called “feedbacks”. The main ones are water vapor feedback and ice albedo feedback.

As the oceans warm from the effects of increasing human-produced greenhouse gases, more moisture evaporates and goes into the atmosphere as water vapor. Water vapor itself is a greenhouse gas, and also contributes to trapping heat in the atmosphere, thus amplifying the effects from increasing CO2 and other greenhouse gases. Ice-albedo feedback involves ice that covers high latitude oceans (“sea ice”) as well as snow cover over land. As the climate warms, there is less snow and sea ice during winter. Because snow and sea ice are highly reflective (“high albedo”), when there are decreases in snow and sea ice there are more areas with lower reflectivity. The land and ocean surfaces with lower reflectivity absorb more energy from sunlight in the non-winter months. That increase in surface heat content then inhibits snow and ice from forming in the following winter, thus leaving even more open ocean and snow-free land to absorb even more heat the next summer, and so on.

Another feedback that is less certain is cloud feedback. That is, if clouds increase in a warming climate, there would be more sunlight reflected and that would be a check on warming (a “negative feedback”). However if clouds decrease in a warming climate, the cloud feedback would be positive and would contribute to even more warming. To first understand how cloud feedback works, and then incorporate those processes in climate models, there have to be high quality observations of the three dimensional structure of clouds. However, this three dimensional structure has traditionally been very difficult to observe, though a new generation of recent satellites is, for the first time, providing observations of just that three dimensional structure. It is hoped that these new data, coupled with improved representations of clouds in climate models, will be better able to pin down the sign and magnitude of cloud feedback. However, even in models that have a negative cloud feedback, the climates of those models still warm significantly over the 20th and 21st centuries due to contributions to warming from increasing greenhouse gases and the other feedbacks, such as those involved with water vapor, snow and sea ice. Those have been observed to operate on various timescales that can be measured, such as the seasonal cycle, and then validated in climate models.

Many climate change impacts will be experienced through changes in weather and climate extremes

Droughts, floods, hurricanes, record heat and cold extremes affect human societies, economies and ecosystems in significant ways, from effects on human health and mortality, to disruptions of agriculture and economic activity, to impacts on outdoor activities and tourism. Though there are many types and categories of extremes, I will focus here on changes in daily temperature and precipitation extremes.

Weather and climate extremes are a naturally occurring part of our climate system, and thus have always had a disruptive effect on humans and the natural system. As such there has been a certain degree of adaptation to such extreme events. These adjustments range from such mundane things as air conditioning, to insurance programs that cover losses from extreme events. However, if the naturally occurring aspects of weather and climate extremes change significantly, so will the impacts, and thus weather and climate extremes in a changing climate become of interest for a variety of applications.

A small change in average climate produces a disproportionately large change in extremes

Since the end of the 19th century, globally averaged temperatures have warmed about 0.8C or about 1.4F. Projections for the end of the 21st century made with climate models using a variety of scenarios of future climate change show temperature increases that range from a couple of degrees Centigrade (about 3.5F) for a low emissions scenario to over 8C (about 14F) for a high emission scenario by the end of this century. However, these are seemingly small increases when the day-night temperature differences at certain locations are often tens of degrees. Many wonder why we should worry about such seemingly small increases in temperature.

Of course these small changes in globally averaged temperature do not reflect the geographic pattern of change where some regions so far have seen very little warming (e.g. the southeastern part of the U.S.) to other areas that have already experienced substantial warming of nearly 10C in some high latitude areas of the Arctic. And these average changes are reflected by a host of impacts that happen over the long term that have already affected human societies.

However, even such small changes in average temperature produce disproportionately large changes in extremes. A good example is temperature. A weather station with a record long enough to capture most of the eventualities of weather at that location usually has a probability of a certain temperature occurring at that location in the form of the familiar "bell-shaped curve". There is the highest probability of a temperature occurring that is near the long term average (near the center of the curve), with a much smaller probability of an extremely hot or cold temperature occurring (out near the right and left "tails" of the curve, respectively). Thus, if there is even a small warming in the average temperature, all else being equal, the curve shifts to the right a bit. But this small shift is reflected in a much higher probability of an extremely hot temperature occurring, and a much lower probability of an extremely cold temperature happening. Therefore, seemingly small warming can produce very large and more noticeable changes in extremes.

The physical processes involved in changes in daily temperature and precipitation extremes are relatively straightforward to understand in the observed system, and can be captured by climate models

There are a couple of relatively simple physical principles that govern daily extremes of temperature and precipitation. For temperature, as noted above, a small average warming produces a disproportionately large increase in hot extremes and a greater decrease in cold extremes. It stands to reason that in a warmer climate, there will be more very hot days, and fewer very cold days. For precipitation, there is a temperature-related connection in that warmer air can hold more moisture. Thus, as the climate warms, more moisture evaporates from the warming oceans, the warmer atmosphere can hold that increased moisture, and when that more moist air gets caught up in a storm, there is a greater moisture source for precipitation. Therefore, we typically see a greater intensity of precipitation in a warmer climate (i.e. greater daily rainfall totals, or "when it rains it pours").

Have we already seen a change in daily temperature and precipitation extremes over the U.S.?

Since there are thousands of weather stations over the U.S. (and internationally) that routinely collect daily temperature and rainfall data, there have been a number of studies that have catalogued an increase in extreme heat over the past 50 years, a decrease in extreme cold, and an increase in precipitation intensity. During this time period, average temperatures have warmed, and, from the physical principles noted above, we would expect to see just these kinds of changes in extremes in a warming climate. Such changes have been documented not only in numerous publications in the peer-reviewed scientific literature, but also summarized in various assessments of that literature (e.g. the IPCC AR4, CCSP3.3, and the recent National Academy of Sciences America's Climate Choices Science Panel Report).

For example, there has been a documented observed trend of decreases of "frost days" (i.e. when the nighttime temperatures go below freezing), with greater decreases of frost days in the western U.S. compared to the eastern U.S., also reflecting average warming patterns over the second half of the 20th century when there has been a good coverage of stations reporting daily temperature data. The reduction of extreme cold has had numerous impacts, one being an increase of pine bark beetles in the western U.S. Extreme cold is needed to kill the dormant insects during the winter. Due to the average warming, there has been less extreme cold, and more live to become active in summer, and they kill even more pine trees. Increases in extreme warm days have also been documented in observations over the U.S.

The shift to warmer temperatures has also produced an increase in daily record high temperatures compared to daily record low temperatures over the U.S., with this ratio currently being about two to one. For example, Since January 1, 2000, there have been 311,734 record daily high maximum temperatures set, and only 152,329 daily record low minimum temperatures, a ratio of about two to one. Since January 1, 2010, this year, there have been 17,148 daily record highs, and 6,315 daily record lows, more than a ratio of two to one. Thus, as the average temperature has warmed, the probabilities have shifted towards more unprecedented heat, and less unprecedented cold.

For precipitation, the intensity of daily precipitation has also been observed to increase since the second half of the 20th century, again when we have a good geographic coverage of daily temperature data.

Climate models are able to reproduce these observed changes of temperature and precipitation extremes, and thus build credibility that we can believe what they tell us about the future. Projections of future climate change in the models with scenarios of future greenhouse gas emissions show ever-increasing heat extremes and reductions in cold extremes, ongoing increases of precipitation intensity, and a growing ratio of record-setting heat compared to record-setting cold, with, in one model for one scenario, the current ratio of about two to one increasing to twenty to one by mid-century, and about fifty to one by late century. However, even in the late 21st century when warming averaged over the U.S. is about 4C (or roughly 7F) in the model, there are still record-setting daily low temperatures occurring. Thus, even in a climate that has warmed significantly in the model, winter still occurs, and it does occasionally get extremely cold in some locations, cold enough to set a few daily record low temperatures every year. However, those few record daily lows occur in the context of many more daily record high maximum temperatures that would occur every year.

Summary

The concept that greenhouse gases in the atmosphere make the planet warm enough to be habitable, and that increasing those greenhouse gases by the burning of fossil fuels could make the planet even warmer, is not a new idea and has been studied for over a century. Early attempts at numerical weather prediction, solving the relevant equations that describe the physics and thermodynamics of the atmosphere by hand for a single location in the early 1900s, presaged modern numerical weather predictions performed routinely by atmospheric models run on supercomputers. Those atmospheric models attempt to resolve the time evolution of individual storm systems over the next few days. Subsequently developed global climate models include atmospheric components similar to those used in numerical weather prediction, but add components of the slowly varying parts of the climate system (ocean, sea ice, and land surface processes). The dynamical coupling of those components in the models, as in the real world, is relevant to the statistics of weather over climate timescales of months to years to decades to centuries. Climate models also have equations that capture the effects of greenhouse gases and relevant feedbacks in the climate system that can influence climate. These climate models can reproduce, to first order, the observed changes in temperature and precipitation extremes observed over the past 50 years or so. These have included more heat extremes, fewer cold extremes, greater increases in daily record high temperatures compared to daily record low temperatures, and increased precipitation intensity. This lends credibility to the climate models such that there is likely to be useful information in their climate projections about future changes of extremes. With continued increases of greenhouse gases and consequent warming, these model projections depict a world with ongoing increases in heat extremes and record heat, reductions in cold extremes and record cold, and greater precipitation intensity.