With this background on the history of climate modeling, features of their design and evaluations of their performance, let's have a look at the latest projections of climate models under different kinds of greenhouse gas emission scenarios over the next few hundred years.

In its latest report, the Intergovernmental Panel on Climate Change, or IPCC, considered several different representative radiative forcing pathways, or RCPs, which are shown in the diagram on this chart. So these are projections forward of the total radiative forcing due to anthropogenic greenhouse gas changes.

And they range from a fairly mild scenario, RCP3PD-- the green curve at the bottom that you see here-- all the way up to RCP 8.5. By the way, these numbers denote expected ultimate radiative forcings in watts per meter squared. So part of the problem of predicting future climate change is predicting what we will do-- predicting the amount of the total emissions of greenhouse gases into our atmosphere.

With that as a backdrop, here is one rendition of projections of climate change going forward to the end of this century. This shows the temperature change relative to its average over the interval 1986 to 2005, considering both hind casts by the suite of global climate model shown in gray and black and white up to about the year 2005, and forward projections to the end of the century. So in the hind cast, the gray shading denotes the historical model spread. Observations are shown by the black, full line.

Going forward, you can see an enormous spread in the envelope of model predictions. The green part of that is owing to the spread in emissions scenarios. That is the way the models are being forced, with the bottom of the envelope representing the scenario in which we actually control greenhouse gases, and the top of the curve representing the scenario where we continue to increase our consumption of fossil fuels, and our emissions of greenhouse gases into the atmosphere.

The blue shading that you see in this curve represents the spread owing to model uncertainty. That is, it's a measure of the spread among the different models for the same scenario. And the orange represents natural chaotic internal variability in the system. So the uncertainty going forward increases because of uncertainty in the models, because of internal variability and uncertainty in greenhouse gas emissions.

This chart compares projections going forward to the middle of the century, with historical records, and with historical hind casts by various models. So the black curve and shaded region show observations of global mean temperature anomaly going back for the last few decades. This is based on four different observational data sets. And the gray lines that surround it are hind casts made using 42 different climate models, which all scatter about this.

The colored curves that you see here going forward to the middle of this century represent various different climate models run under various different emission scenarios. What one can see is that the observed temperature here in the last few years has been running on the low side of these projections--whether this is due to model error on the one hand, or simply internal variability of the climate system on the other hand, remains to be seen. And this is an active area of research at the present time.

Going forward over a longer time frame, this shows forward projections to the end of the 23rd century for scenarios 2.6, 4.5, 6.0, and 8.5. This chart shows forward projections by 42 models under four different emission scenarios, with the red curve giving the high emission scenario RCP 8.5, and the deep blue curve giving a modest emission scenario, RCP 2.6. The colored shading in the background is an indication of the spread among the different models making these projections, so one can see that the spread is in some sense proportional to the mean indicated temperature change.

Notice that there's a discontinuity in the year 2100. This is due to different numbers of models performing the runs beyond the 21st century. This has no physical meaning.

Notice that the spread amongst various models is more or less proportional to the change in the mean temperature. This graph gives some indication of the spatial distribution of temperature and precipitation changes predicted by the CMIP5 models reported in the fifth assessment report of the IPCC. These have been normalized by the global mean temperature predicted by each model under each scenario.

The top row is for the end of the 21st century, while the bottom row is for the last 20 years of the 22nd century. So on the left side, this is degrees C per degree C global mean temperature change. The right-hand side is the percentage change in precipitation per degree predicted global temperature change.

What one sees when one looks at these graphs is, first of all, the patterns are quite similar between the top row and the bottom row. That is, the temperature change is in some sense linear. The fractional temperature change at the end of the 22nd century is very similar to the fractional temperature change at the end of the 21st century.

The patterns show that there is somewhat more warming over continents than over the ocean, and somewhat more warming at high latitudes than low latitudes. The change between the continents and the oceans can be explained fairly simply in terms of thermodynamics, given roughly longitudinally uniform temperature change well above the earth's surface. You're going to get more temperature change at the surface where it's relatively dry. And continents are relatively dry compared to the ocean.

Looking at the precipitation changes on the right, one sees an interesting pattern of large percentage changes in both directions. So for example, the models predict a drying out of the subtropical Atlantic-- both North and South-- and the southeastern Pacific Ocean, and heightened precipitation over the North Indian Ocean and over much of Northern Asia. The hatching in these diagrams shows places where the mean change averaged over all the realizations is larger than the 95th percentile of the distribution of the models.

This chart shows the multi-model median change in extreme temperatures. The left-hand panels show changes in the 20-year return values of annual warm temperature extremes. And the right panels show the 20-year return values of cold temperature extremes. This is for emission scenario 2.6 at the top, 4.5 in the middle, and 8.5 in the bottom.

What one sees in these diagrams is, first of all, that temperature extremes become more extreme, principally over land, and again at high latitudes. And that there is a greater change in the frequency of low temperatures. That is, low temperatures are becoming warmer in some sense faster than the extreme high temperatures are.

Patterns in relative humidity are interesting as well. Here are projected changes in near-surface relative humidity from CMIP5 models. Under the RCP 8.5 scenario-- for December, January, and February at the left, June, July, August in the middle, and for the annual mean at the right-- the hatching indicates regions where the multi-model mean change is less than a standard deviation-- owing to internal variability-- while the stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability, and where at least 90% percent of the models agree on the sign of change.

So one can see that in the earlier periods, 2046 to 2065, there are not that many places with stippling. That is, the changes in any one place really haven't emerged from the background climate noise, whereas this is more the case at the end of the century.

Notice that in general, the continents are drying out, with a few interesting exceptions, while the air over the oceans is getting perhaps slightly more humid. This chart shows changes in extreme precipitation. The chart at the top shows percentage change in the annual maximum five-day accumulated precipitation under scenario RCP 8.5, whereas the bottom chart shows the projected changes in the maximum number of consecutive dry days when the precipitation is less than a millimeter. Once again, the stippling indicates places where changes are significant at the 5% level.

So looking at the top chart, one sees that just about everywhere, extremely heavy rainfall becomes more frequent. That is, the maximum five-day precipitation increases. Looking at the bottom chart, it's a mixed bag. There are places where the number of consecutive dry days increases, and other places where that number goes down.

There are, of course, many other quantities that are projected to change by the suite of climate models being run for the IPCC scenarios. But the overall picture is one of a warming planet, with continents warming somewhat faster than oceanic regions, and high latitudes warming faster than low latitudes.

Mean precipitation does not change very much. There's a gentle increase in mean precipitation, but a somewhat more interesting increase in extremes of precipitation, with a greater instance both of heavy precipitation events, and of long periods without any precipitation at all.