To understand the state of the art of climate modeling, and to get some idea of where it might be headed in the future, it's instructive to put today's climate modeling in some historical context. Arguably the roots of numerical weather prediction and climate modeling trace back to this man, Vilhelm Bjerknes, a Norwegian meteorologist who lived from the middle of the 19th century to the middle of the 20th century. Vilhelm Bjerknes was the first to formulate in a coherent form the equations that govern the behavior of the atmosphere.

In the early 1920s, this very creative British scientist, Lewis Fry Richardson, had the idea that the equations that had been developed by Bjerknes and others might be solved by means of numerical computation. He speculated in 1922-- long before the invention of the digital computer-- that "perhaps someday in the dim future it will be possible to advance the computations faster than the weather advances, and at a cost less than the saving to mankind due to the information gained. But that is a dream."

Richardson envisioned that this dream could be made into reality through the device of a human computer. Here is a drawing of what might have been Richardson's concept of what a human computer might have looked like. We have a large auditorium with galleries and galleries and galleries of human computers arranged around it geographically, and a conductor in the middle who coordinated the hand calculations of these thousands and thousands of human computers, in an effort to make a forecast that would actually proceed faster than the weather itself.

Richardson himself attempted a forecast for a very limited place in a limited period of time by hand. It took him a very long time to do it-- just a 24-hour forecast. And that forecast was spectacularly wrong, because Richardson could not have known about some of the phenomena of numerical instability that we talked about a while ago. Numerical weather prediction became a reality only after the invention of the digital computer.

Here is a photograph of one of the very early computers, the electronic numerical integrator and computer, or ENIAC. This photo was taken in 1946. It was an enormous machine. It had over 17,000 vacuum tubes, more than 7,000 diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors, and around 5 million hand-soldered joints. It weighed about 30 tons.

It did 350 floating point operations per second, or FLOPS. And the PC that you're probably using to monitor this course operates at 21 gigaFLOPS. That's 10 to the ninth FLOPS, so it's almost infinitely powerful compared to this 30-ton behemoth you see in the photograph.

At the Advanced Study Institute in Princeton in the late 1940s, John von Neumann, a gifted mathematician from Hungary, put together a team of scientists to see if we could do numerical weather prediction, among other things. In this particular team, the work of the meteorologist Jule Charney-- whose picture you see at the left here-- was essential. Charney figured out how to write down a somewhat simplified set of equations that could be solved by the numerical computers of that day. And incidentally, he was the thesis advisor of your narrator.

The team is shown in the picture on the right, and includes von Neumann, this man here. Here is Charney. And there are other very famous scientists of that day involved in that numerical weather prediction. Charney solved very simple two-dimensional equations governing the vertically integrated behavior of the atmosphere on a domain that looked like this that you see here. And the grid notes are represented by these dots, so they're quite far apart.

And he was able to produce the very first numerical weather forecast. So what you see on the left is the observed distribution of pressure about five or six kilometers above the surface, and on the right, the 24-hour forecast of that pressure distribution by Charney's methods. If you look carefully at these two diagrams, you can see that they are very similar, but there are some noticeable differences as well.

By modern standards, this was a very imperfect forecast, but it was certainly a huge advance at the time. By the mid 1950s, numerical weather forecasts by the US Joint Numerical Weather Prediction Unit were being done routinely. And this coincided with the first efforts to regularly collect observations of the atmosphere above the surface.

And this also coincided with the development of a major effort in the modeling of the general circulation of the atmosphere by the Geophysical Fluid Dynamics Laboratory at Princeton, which exists up to this day. Its former director Joe Smagorinsky was instrumental in advancing the art of general circulation model.

A decade later, we began to develop ocean models, and couple them to atmospheric models. We began to explore the roles of sea ice, snow, land surface processes, and the biosphere.

Here, for example, is an image of the average sea surface temperature as simulated by a modern climate model. And as time progressed, we got progressively better at numerical weather prediction. There are various different ways of measuring the skill of numerical weather forecasts. This particular metric I'm going to show you here has to do with the skill in forecasting the height of the 500 millibar pressure surface over North America.

The blue curve pertains to a 36-hour forecast, and the red curve here to a 72-hour forecast. This is the skill metric as a function of time from the beginning of numerical weather prediction in the mid 1950s to about the present. You can see the steady improvement in weather forecasts, such that a 72-hour forecast in 2005 was about as skillful as a 36-hour forecast in the mid 1980s.

So there's a very satisfying improvement in the skill of operational weather forecasts. This improvement has been made possible by increasingly good models, by finer resolution-- ultimately, by the enormous increase in the computational firepower that we can bring to bear upon the problem, and also-- in the case of weather forecasts-- on better data and better ways of incorporating observations into the models.

Here is another metric of skill from 1980 to about 2010, showing the three-day in blue, five-day, seven-day, and 10-day forecast. The forecast skill for the entire northern hemisphere is indicated by the upper line in each of these sets of curves. And the southern hemispheric forecast skill is indicated by the lower line.

So one of the other things that one sees in these forecasts is that the skill of southern hemispheric forecast is catching up to the skill of northern hemispheric forecast. This is largely attributable to the incorporation of satellite-based observations into the initial conditions that these models use to forecast the weather.

Here is an example of a 48-hour forecast on a very fine grid, where the nodes are only about 20 kilometers apart, with an advanced regional weather forecasting model showing the distribution of pressure at the surface in blue, and also the distribution of rainfall accumulated over three hours in the filled colors that you see on this diagram.

So weather forecasting has become more accurate, and more detailed at the same time. Here's a similar forecast, but showing the surface pressure and surface air temperature forecast.