Let's talk about the individual components of a general circulation model, beginning with the atmosphere. The atmospheric component of a climate model is similar to that of a weather forecast model, except that because we have to integrate the model for much longer periods of time, necessarily we have to compromise and that usually means lower spatial resolution. And we pay more attention to processes operating on long time scales compared to weather predictability horizons-- processes like radiation, clouds insofar as they affect radiation, and aerosols.

When we look at the ocean component of the GCM, we see that the governing equations are similar to those of the atmosphere-- except, of course, oceans are liquid rather than a gas. Salinity must be carried as an important variable, and we don't have to worry about water vapor or suspended water, as we do in the atmosphere.

The ocean basin geometry, of course, is much more complex. Oceans are bounded, typically, at their sides in a way the atmosphere is not. Many important features of the ocean are too small to be resolved in most of today's climate models, such as eddies that do significant transport of heat and tracers. The Gulf Stream is an example. The Kuroshio currents are less than a degree wide, so they really press the resolution of such models.

In addition to the atmosphere and ocean components, we have to have a land component, which must contain heat and moisture balance equations, and a snow cover model. We should try to simulate vegetation as it affects albedo and evapotranspiration. GCMs have been shown to be quite sensitive to surface albedo and moisture characteristics, so this is important.

We should also model sea ice. This is important, because it increases the albedo of the surface. It inhibits the exchanges of heat, moisture, and momentum between the oceans and the atmosphere. The process of forming sea ice alters the local salinity. Ditto when sea ice melts.

And usually in models, one assumes that ice forms if the sea surface temperature falls below some threshold. Good models of sea ice also predict the drift of sea ice. Here is a photograph of sea ice in the Arctic. And here is a depiction of the distribution of sea ice in the summertime in the Arctic, based upon satellite measurements.

One of the great challenges in modeling both weather and climate is how does one deal with physical processes that are terribly important for weather and climate, but which can't be explicitly resolved considering the limited resolution of the models itself. These have to be handled through something called a parameterization. Kind of an ugly word-- it's a representation of that process in which the small scales are calculated-- or their effects are calculated-- as a function of the explicitly resolved variables. And the tendencies that those processes would create in fields like temperature or momentum are fed back into the explicit model.

A classical case, which we've already discussed earlier in this course, is deep convection. Convection has a horizontal scale of kilometers to maybe tens of kilometers-- well under the typical grid spacing of today's climate models, although convection generally extends a significant distance into the atmosphere and may span many of the climate model's levels [in the vertical].

Thin and broken clouds may have very strong effects on radiative transfer, and should be represented. Cloud microphysical properties affect the optical characteristics of clouds, and therefore we need to pay attention to those. Aerosols, which have an important direct effect in radiative transfer, and possibly very important indirect effect through their alteration of the optical properties of cloud. Chemistry, which results in changes in distributions of certain kinds of gases-- like ozone-- that in turn have a strong effect on radiative transfer, have to be handled.

Turbulence, including surface fluxes, turbulent surface fluxes from the ocean and land need to be represented. They can't be explicitly simulated. We've already talked about the sea ice. Sea ice can certainly develop on scales which can't be resolved in the vertical. Land ice is the development of snow and ice on land, which affects albedo and exchanges between the atmosphere and the land surface-- land surface processes that affect, for example, the availability of water to the atmosphere.

If we think about convection, here is a photograph of some deep moist convection from space. These cumulus towers have typical dimensions of, say, 10 kilometers or so. And the grid points of a climate model are separated by distances large compared to the distance covered in a photograph like this.

We need to represent those clouds, because they transport terrific amounts of energy and water in the vertical. We talked about the representation of clouds briefly in an earlier section of the course. Clouds in the boundary layer have to be represented, because they have strong effects on radiative transfer. And as we talked about before, cloud microphysical processes.

So here's a nice photograph of a kind of cloud, which is called an altocumulus cloud. These are generally layered clouds, but they're broken. This photograph, all by itself, illustrates the complexity of the transfer and scattering of solar radiation through clouds like these.

But one can also imagine that the structure and water content of these clouds strongly affects long-wave radiative transfer. So how do you use a model whose grid points are spaced 100 kilometers apart to represent cloud layers like this, where the breaks in the clouds may only be a few 10s of meters apart?

Another type of cloud that we worry about is altostratus and a related variety of cloud called cirrostratus. These clouds can be horizontally quite uniform, as you see in this photograph over Hong Kong. Nevertheless, they can be very shallow in the vertical, sometimes only a few 10s of meters, and therefore cannot really be explicitly represented in models whose layers are a kilometer or so thick. Yet clearly, clouds like these have an important effect on both solar and terrestrial radiation.

Another kind of somewhat layered cloud is stratocumulus. It's like altocumulus, but occurs usually close to the surface. Here is a satellite photograph of stratocumulus off the southwestern coast of the United States and Mexico.

In looking down at these clouds, you can see that they're covering thousands of kilometers in dimensions. But there are breaks in the clouds, such as you see down here, which may have characteristic scales of only a few kilometers. It's quite clear from looking at this photograph that stratocumulus clouds greatly affect the albedo of the region. But they are also quite thin-- usually only 100 meters or so deep-- and therefore, it's very difficult to actually resolve them in the vertical with a weather forecast or climate model. Yet clearly, they have to be represented in such models.

The parameterization of clouds is widely recognized to be the main source of uncertainty and difference among different climate models. This chart simply shows the fractional cloud amount globally simulated by 25 different atmospheric general circulation models. So each one of these bars represents a different model.

And you can see that the global fraction ranges from just under 30% percent to almost 80%. So there's wide disagreement even in the mean state of cloudiness simulated by climate models. And this represents, to some extent, the different kinds of ways of representing layered clouds in climate models.

The situation is even worse when we talk about the effect of clouds on climate sensitivity. So here is a graph showing the change in low cloud amounts simulated by two different climate models, the Princeton GFDL climate model at the top, and the NCAR CAM2.0 at the bottom. So this is a graph showing simply the change in low cloud amounts between an experiment in which carbon dioxide is doubled, and an experiment representing today's climate, more or less.

Just a very cursory inspection of these two difference charts shows that by and large, they're not even agreeing on the sign of the change. There is also a sensitivity of these models to the way microphysics is represented, both in layered clouds and in cumulus clouds. So here, from more or less the same one-dimensional column model that you're able to run for this class, is a profile of relative humidity in radiative convective equilibrium.

Now, if we go back and we run that model, and change by 10% different terms that appear in the convective parameterization-- governing, for example, the terminal velocities of rain and snow, the coefficient of re-evaporation of rain and snow, and fractional areas of rain that fall outside of clouds. We get these changes that you see in this graph in the relative humidity.

So what you see along the bottom axis is changes in the humidity. So this is a 1% change, 2% change, and so forth. So relatively modest changes in fairly poorly represented processes, like the fall speed of rain and snow, can have significant effects on the relative humidity profile.