Abstract. Cloud processes are very important for the global circulation of the atmosphere. It is now possible, though very expensive, to simulate the global circulation of the atmosphere using a model with resolution fine enough to explicitly represent the larger individual clouds. An impressive preliminary calculation of this type has already been performed by Japanese scientists, using the Earth Simulator. Within the next few years, such global cloud-resolving models (GCRMs) will be applied to weather prediction, and later they will be used in climate-change simulations. The tremendous advantage of GCRMs, relative to conventional lower-resolution global models, is that GCRMs can avoid many of the questionable “parameterizations” used to represent cloud effects in lower-resolution global models. Although cloud microphysics, turbulence, and radiation must still be parameterized in GCRMs, the high resolution of a GCRM simplifies these problems considerably, relative to conventional models. The United States currently has no project to develop a GCRM, although we have both the computer power and the expertise to do it. A research program aimed at development and applications of GCRMs is outlined.

1. Cloud processes
Clouds affect the global circulation of the atmosphere, and other components of the climate system, in several important ways. They reflect solar radiation back to space, thus tending to cool the Earth. They trap infrared radiation inside the atmosphere, thus tending to warm the Earth. They precipitate, which dries the air, and also warms the air through the release of the latent heat of water vapor. Obviously, precipitation also moistens the land surface, and it reduces the salinity of sea water. In addition, deep convective clouds produce very powerful vertical fluxes of energy, moisture, and momentum, which strongly couple the upper and lower troposphere. Many important cloud processes occur on horizontal scales on the order of a few kilometers, about the width of a thunderstorm cell. These processes interact strongly with each other on the same relatively small scales.

Clouds are obviously important for weather forecasting. The public wants to know whether or not the sun will be out, and whether or not it will rain. Cloudy winter nights tend to be relatively warm, while the coldest nights are clear.

In addition, clouds are very important for understanding and predicting anthropogenic climate change [1]. If a warmer climate has more low clouds, the increased reflection of sunlight will tend to limit the warming. But if a warmer climate has more high clouds, the increased trapping of terrestrial infrared radiation will tend to amplify the warming.
2. Cloud parameterizations

Current global atmospheric models have grid cells with horizontal scales on the order of 100 km. These models have several important practical applications including weather forecasting and simulation of anthropogenic climate change. Their coarse horizontal grids make it impossible for them to directly simulate cloud processes. The cloud processes are too important to be neglected, however, so they are included indirectly, through “parameterizations,” which are statistical theories, analogous to thermodynamics. Cloud parameterizations aim to link the large-scale circulations resolved by the global model to the cloud processes. The large-scale circulations determine the cloud field, and the cloud processes feed back to alter the large-scale circulations. The formulation of cloud parameterizations is a scientific problem in its own right.

Cloud parameterizations have been under development for about 40 years. Steady progress is being made, but we are far short of having a satisfactory cloud parameterization, and we will not have one in the foreseeable future. Current parameterizations do a poor job with (or even completely neglect) many important aspects of real cloud systems, including interactions with the near-surface boundary layer, mesoscale organization, and the effects of aerosols. The variety and complexity of cloud processes will not be adequately captured in a cloud—parameterization theory for many more decades to come [2] [3].

3. Cloud-resolving models

Since the 1970s, atmospheric scientists have developed “cloud-resolving models” (CRMs), which have horizontal grid spacings on the order of a few kilometers or less. These models can directly represent the dynamical processes associated with large clouds. The models must still rely on parameterizations of the effects of smaller-scale clouds and turbulence, as well as cloud-microphysical processes (e.g., the conversion of micron-scale cloud drops into train drops) and radiative transfer. Because of limited computational power, CRMs have, until very recently, been applied in domains not more than a few hundred kilometers on a side, and for simulation times of just a few simulated days.

4. Global cloud-resolving models

Even with today’s most powerful computers, it is not possible to do routine weather forecasting or climate simulation with a global cloud-resolving model (GCRM).

It is, however, now possible to run a GCRM in an experimental, research-oriented mode. This can only be done on the most powerful computers currently available; five years ago it would have been impossible. The only GCRM calculations that have been carried out to date have been done under the auspices of the Frontier Research System for Global Change (FRSGC), in Japan, using the Earth Simulator [4]. European scientists are currently organizing to perform similar calculations. At present, there is no U.S. project to construct and conduct scientific research using a GCRM.

5. Prospects for GCRM research

The U.S. has both the computational prowess and the atmospheric-science expertise to pursue a program of GCRM research. What would such a program look like? Its several components are discussed below.

5.1. Model development

5.1.1. Dynamics Obviously, a GCRM would be based on a discretization of the equations governing the flow of a thermodynamically active fluid on a gravitating, rotating sphere. Spectral methods based on global basis functions, such as spherical harmonics, become inefficient at very high resolution. Latitude-longitude grids suffer from the well-known problem of the convergence of the meridians at the poles. A GCRM would probably be formulated using a fine grid generated by projecting the sphere onto a Platonic Solid. The two approaches enjoying the most interest include geodesic grids based on the icosahedron [5], and quadrilateral grids derived from the “cubed sphere” [6]. The FRSGC used a geodesic grid.
A GCRM must have a horizontal grid spacing that is as small possible, ideally on the order of 100 m. Experience shows that the grid spacing cannot be coarser than about 4 km. Practical tradeoffs between the benefits of increased resolution and the benefits of longer integrations (which are possible only with lower resolution) will probably lead to the adoption of grid spacings on the order of 2 to 4 km for the foreseeable future.

A GCRM must be non-hydrostatic, i.e., it must integrate the full equation of vertical motion, including the acceleration term. There are many non-hydrostatic models in routine use today, including several global models [4] [7], although most current global atmospheric models continue to use the hydrostatic approximation.

In most current global atmospheric models, the number of layers used to represent the troposphere is on the order of 20. Again, higher resolution is better, and in fact a GCRM can probably benefit from increased vertical resolution more than a conventional global model can, simply because a GCRM can better represent the physical processes that are at work on small vertical scales. A good target resolution for a GCRM might be on the order of 100 layers, extending from the surface to above the stratopause (about 70 km high), with variable grid spacing.

5.1.2. Physics. A GCRM must have parameterizations of radiative transfer, cloud microphysics, and turbulence. The radiation parameterization is important for simulating the flows of radiation into and out of the Earth system, and also for simulating the radiative warming and cooling of the atmosphere, the land-surface, and the ocean. The microphysics parameterization is important for simulating the particles that make up the clouds, for predicting the optical properties of the clouds, and for simulating precipitation processes. The turbulence parameterization is important for simulating the near-surface boundary layer, the turbulence inside the larger clouds, and the occurrence of smaller-scale clouds.

Each of these parameterizations can be formulated with various degrees of physical sophistication. As always, there will be tradeoffs between physical realism and computational cost. Experimentation will be needed to find the proper balance.

Parameterizations of radiation, microphysics, and turbulence are also needed in conventional global models, but they are much more readily formulated for a high-resolution GCRM, simply because the GCRM can represent the native scales on which these processes operate.

5.2. Testing the model
A new model can be tested first in various idealized frameworks. The parameterizations of the GCRM can and should be tested first in relatively inexpensive regional simulations, perhaps based on case studies [8], many of which have been developed through the ARM Program funded by the U. S. Department of Energy.

Ultimately, however, will be necessary to test the full global model against observations. Weather forecasting provides an excellent framework for such tests. Forecasts of just a few simulated days can be used to directly compare model results against observations over the whole globe, and for a very wide variety of physical regimes and scales.

A challenge to be overcome in setting up such forecasting experiments is that it will be difficult or impossible to obtain the data needed to initialize the model on the smallest scales that can be represented on the grid. Larger scales can be initialized through well established data assimilation techniques. Research will be needed to determine to what extent the smallest scales can be initialized through indirect methods.

5.3. GCRM Applications
The forecasting experiments suggested above for use in testing the model can lead directly to operational forecasting when computer power increases enough to make this practical.

Climate simulation is much more computationally demanding and so will take longer to realize. It should be possible to simulate an annual cycle, however, using computers that will become available in the next few years. The annual cycle can be considered as the smallest tick of the climate clock, so an analysis of annual cycle simulations with a GCRM will be a major landmark. The production of such an annual cycle should therefore be a major goal of GCRM research.
Many deficiencies of an atmospheric model can be hidden when the model is run with prescribed realistic sea surface temperatures. When the state of the ocean is predicted, through coupling with an ocean model, these deficiencies become readily apparent. In addition, coupling with an ocean model is absolutely essential for climate simulation. For these reasons, it will also be important to gain experience with the GCRM’s performance when it is coupled with an ocean model.

Finally, and perhaps most importantly, the results obtained with a GCRM can be those produced with conventional global models. In this way, we can clearly identify the deficiencies of the cloud parameterizations used in the conventional models.

6. Conclusions

Global cloud-resolving models are just becoming possible, thanks to the relentless increase of computing power. GCRMs represent a radically new and very promising way to explore the effects of cloud processes on the climate system. They also have great potential for weather forecasting. It will take time to learn how to formulate and apply GCRMs. We should start now. Work of this type has already been carried out in Japan, and will soon be under way in Europe. The United States should move quickly to join this exciting research frontier.

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