Chapter 3

Global Climate Models

3.1 introduction

Mathematical models of planetary climate range from simple zero-dimensional statements of energy balance to complicated coupled climate system models that attempt to embrace the physical, chemical, and biological processes of the atmosphere, oceans, and terrestrial surfaces. The equations for coupled system models describe conservation of mass, momentum, and energy through a three dimensional grid that represents the oceans, atmosphere, and land surface. Physical processes that are sources or sinks for certain quantities, or that transpire on spatial scales finer than the grid resolution are treated in *parameterized* form. The sets of equations are integrated forward in time numerically (that is, in some sort of discretized form).

The basic physics used in climate models is well understood, although some processes, especially those operating on regional or smaller spatial scales or in places where observational data are limited, are not well described. Even if we knew all of the governing (partial differential) equations perfectly well, climate models would still be guaranteed to be imperfect because the numerical methods required to solve the governing equations rely on finite approximations of what are really continuous functions and because the grids on which the equations are solved have limited spatial resolution.

Another source of error is the quality of the model *initialization.* All model calculations must start from somewhere, and these initial conditions are guaranteed to be imperfect, usually because they are based on observations, which have error and are not abundant enough to specify a value for every variable at every model grid point. Even if we could do that, there is no reason to suppose that the "real world" values for those variables would be in balance according to the model equations. In fact, they are probably not. It's a busy busy planet.

Differences arise among models developed and used at various research centers due to differences in details of the governing equations and in the schemes used to solve the equations. The uncertainties associated with individual models and differences among models can be used to our advantage. When the products of models run with the same forcings but slightly different initializations (or parameterizations) are, differences among the resulting *ensemble* forcast can be use to evaluate the liklihood of any given model outcome (and perhaps to identify errors in the models).

A good overview of climate modeling can be found in Thorpe (2005).

3.2 EdGCM

EdGCM is an easy-to-use interface for a research-grade global climate model (GCM) bundled with a data viewier called EVA. EdGCM uses models developed at the NASA Goddard Institute for Space Studies (GISS GCM Model II) and is also supported by the National Science Foundation. We will use EdGCM and its associated data visualization tools to investigate some aspects of change in the cryosphere over time. The model outputs we will use required about two days (each) to compute on a dual-cpu 2.7 GHz desktop computer. Thus, we can't run the models from scratch in the lab but you may wish to consider conducting model runs in addition to those provided for you in this lab as part of your research project in this class. The software and installation directions are available at `http://edgcm.columbia.edu`.

GISS GCM Model II is a three dimensional model that solves conservation equations for energy, mass, momentum, and moisture. The model resolution is 8° and 10° longitude, with nine layers in the atmosphere and two ground hydrology layers. Fundamental sub-grid processes are parameterized, including the role of cloud particles and greenhouse gasses in radiative transfer in the atmosphere, and cloud formation. Sea surface temperature can be fixed using observational data or calculated using surface energy fluxes. The model ocean includes a shallow mixed layer and a deep layer. Snow depth is calculated as the balance among snowfall, melting and sublimation.

3.2.1 getting started

Getting started with EdGCM is straightforward. Everything is managed from the same toolbar, using the four icons at its top, and the run controls just below them. Below the run controls you will see a *run list* of existing experiment setups. These setups can be used as they are and new setups can be defined, either from scratch or as modifications of existing setups. New setups are made using the *Setup Simulations* interface. If a particular model has already been run, the circle next to it in the *run list* will appear blue. While the GCM behind EdGCM is efficient enough for desktop computing, it still requires more time to run than is available to us in our lab. A set of model results will thus be provided for use in this class. We will use primarily the *analyze output* tool.

You might wish to conduct additional model runs, perhaps as part of your class project, if so, we ca plan to complete the runs.

3.2.2 model runs: sensitivity studies and scenarios

We will use output from at least two model runs. The first, Modern_PredictedSST, is a spin-up used to generate a reference "modern" climate against which other experiments may be compared. The model is run for a number of years with the same (time varying) boundary conditions year after year in order to create both a *model* steady mean state and variability about that mean. The second model we will use is `Doubled_CO2`. This is a classic *sensitivity* experiment in which the objective is to study how different attributes of a coupled system respond to a change in a particular boundary condition, in this case, atmospheric CO_2 concentration. Both final equilibrium states and the time scales required for components of the system to reach a new equilibrium may be explored.

If time permits, we will develop a climate projection experiment during the first lab. Unlike a perturbation experiment, here we are interested in how the system changes over time in response to a forcing that also changes in time. The goal is to simulate coupled system behavior rather than to explore its fundamental properties.

3.2.3 postprocessing model output

The GCM computes and stores a number of variables. The first step in analyzing model output is extracting data of interest for a particular research question (say monthly mean temperature or snow depth). The EdGCM *Analyze Output* window is used to extract any or all of about 80 different model variables. *Analyze Output* prepares data for maps, vertical slices, zonal means, time series, and data tables. There is a tab near the top of the *Analyze Output* window for each of these.

At the left-hand side of the window is a list of years in the model run. It is typical to work with multi-year averages so buttons for creating 5 and 10 year averages are provided. Recall that 30 years is the standard used by the World Meteorological Organization and others to define a climatology.

The central part of the window is a listing of available data sets. Check the boxes for the variables you wish to investigate and then press the average button at the bottom of the window to prepare the model output for visualization. Once the averaging is complete, an *extract data* button will appear. Press it to produce the finished file (in netCDF format). The file then appears in the list at the right. The file is moved into the EVA Data Browser list by selecting it from the list and pushing the *view* button.

You may select as many variables from the *Postprocessing: Maps* list as you wish but it would be a good idea to review the questions before hand to make sure you have what you need.

3.2.3.1 *Time Series* tab

You may also wish to extract variables for the complete run of an experiment. The procedure is similar to that for the map data though it will produce a directory containing one file for each variable you choose to extract.

3.2.4 visualization tools

EVA, the EdGCM visualization tool, is an easy-to-use window into the output from a model run. The EVA Data Browser gives you a heirarchical display of file contents in three columns: file name, variable (file contents), and time/region. Plots are made by selecting the desired file, variable, and time/region in the upper part of the Data Browser and then pushing the *Plot Selected* button at the lower right. A complete description of EVA is in the manual in the EdGCM Documents directory.

The Data Browser can also be used to calculate the difference between two data sets. This is accomplisehed by selecting two data sets in the lower talbe in the Data Browser and setting the desired operation with the pull-down menu at the lower right. Differences are often used in the presentation of climate data and model output.

EVA can be used to display model output in several ways, including zonal and vertical averages, flat maps (with a range of projection and colorbar options), and time series. Once a map is rendered, it appears in a map window, where you can use the toolbar modify attributes such as map title, projection, and colorbar.

After you have generated your first map, try unchecking the *interpolate* box in the map tools. This is the true resolution of the model data. You may also wish to compare shaded color maps (the grid tab) with contour maps (the contour tab).

3.3 Questions

Please use EdGCM model output to answer the following questions, making maps as necessary. In some cases, there is more than one pathway to a correct answer, making it important to explain how you arrived at each answer.

1. Did the CO_2 doubling experiment reach steady state? What variable(s) did you examine to answer this question? How did you define *steady state*?
2. Describe the overall difference in mean annual temperature between the modern and the CO_2 doubling experiment, with an emphasis on high latitudes. Explain the spatial pattern you observe in that difference.
3. How does snow differ between the modern climate and the CO_2 doubling experiment? *This is a deceptively short question.*
4. How does minimum sea ice extent in the Arctic change in the CO_2 doubling experiment?

graduate students

5. The model generates many precipitation-related variables. Discuss how these variables can be used together to generate a complete understanding of snow in different climate conditions. To get started, think about the difference between snow fall and net snow accumulation. Looking at the units of the different variables will help here.
6. Theory predicts that high latitudes should warm relatively more than lower latitudes under greenhouse scenarios, with spatial variations due to the nature of the landscape. Such predictions are indeed borne out by observation. Use data produced by the CO_2 doubling experiment to examine at least one high-latitude climate feedback in the Arctic and Antarctic.

3.4 References

Thorpe, A.J., 2005, Climate change prediction: A challenging scientific problem, *Institute of Physics*, pp.15.