Chapter 17

3-D General Circulation Models

17.1 A History, in Brief:

General circulation modeling has its own subculture within the scientific community. Whether harmful or beneficial all subcultures have their own jargon and history. Sometimes it becomes very difficult for one of the uninitiated to converse with a member of this subculture unless they are ”up” on the lingo (kind of like an FBI agent trying to talk to a Berkeley student in the late 1960’s). So to help our students we begin this section of the course with a brief history of GCM modeling in the United States and introduce you to some of the legendary names of the period. It’s not important that you know the capabilities of the ol’ ”CDC stretch”, but it helps to know that in the late 1960’s it was considered the hottest box around. Based on your own experience with computers and this time index, you will be able to draw your own conclusions about its capabilities.

In 1969 Kirk Bryan published his seminal paper in J. of Computational Physics (Bryan, 1969, JCP, 4, 347-376) that laid out the primitive equations that 3-D general circulation modeling would be using for the next 30 (or more?) years. Then very shortly after, or actually in conjunction with, Mike Cox produced the first FORTRAN coding of Bryan’s primitive equations on the old CDC ”stretch” 7600. As time went on and computers became better suited for doing this type of computation Mike Cox continued to work at NOAA’s GFDL in Princeton, NJ eventually moving on up to the UNIVAC 1108. Then in the early 70’s Bert Semtner rewrote this code for the new CRAY ”super”computers (Semtner, 1974). Mike Cox continued to work on and improve his code and in the late 1970’s early 1980’s produced a vectorized version that ran on the first Texas Instruments ASC. Then in 1984 (Cox, 1984) Mike Cox adopted Bert Semtner’s code and optimized it for the CDC Cyber 205. Then in the early 1990’s Ron Pacanowski (Pacanowski et al., 1991) rewrote Mike Cox’s code in modular programming style and gives birth to MOM-1 with Dixon and Rosati. Later Pacanowski, Goldberg, Rosati, and Dixon generalized this code further to produce MOM-2 (see http://www.gfdl.gov and follow the links to the latest version MOM-2 v2.2).

The goal all along was to produce a flexible research tool sufficiently generalized to make it useful for ocean and coupled air-sea modeling over a wide range of time and space scales. The pursuit of this goal continues today. At the National Center for Atmospheric Research (NCAR) they are developing the NCAR Climate System Model (CSM). The Journal of Climate recently had a special issue dedicated to the release of version one (volume 11, June 1998) and a great deal of this climate system modeling code is available for not only the ocean, but also for the atmosphere and terrestrial systems at http://www.ucar.edu/ just follow the links.

17.2 General Circulation Model Description:

We will begin our discussion of general circulation models per se with a description of three very coarse parts of the model: the primitive equations, the grid, and the bathymetery underneath the model.

17.2.1 Primitive Equations

Primitive equations are a mathematical description of the local balance of heat and salt. They allow the simulation of wind driven and thermohaline (density) driven circulation as a response to forcing of heat, wind and freshwater at the surface of the ocean. The primitive equations are the following:

hydrostatic Boussinesq Navier-Stokes non-linear equation of state

The hydrostatic equation is written:

which can be used to give the pressure at any depth through the following integration:

where ps is the pressure at the surface (it is held constant). The Boussinesq approximation is accomplished by replacing in the Navier-Stokes equations with kg/m3 (depth averaged). Essentially the buoyancy term has the form of but the continuity equation is approximated by:

i.e. the fluid is incompressible.

Additional simplifications are made. The rigid lid approximation is made since the vertical range of motion of the free surface is much smaller than that of internal waves, hence the pressure effect of surface displacement can be approximated by the pressure exerted by a rigid lid. Put all of this together and you get:

where:

And that's, basically, the primitive equation(s) used to calculate the general circulation of the ocean.

17.2.2 The Grid

In this discussion of GCMs we are going to use the coarse resolution GCM used in Toggweiler et al. (1989a&b) as a basic example. In this case, we will talk about the grid used in these GCM simulations and give you an idea of what we mean when we say ”coarse”. In his model integrations Toggweiler used a grid that was 4.5o in latitude and 3.75o in longitude, with 12 vertical levels. This comes to only 46,080 grid points before land masking. Although Toggweiler learned a lot from this coarse grid, today finer and finer grids are being used with the current politically correct grid size goal for global long-term integrations appears to be about 1o x 1o. Investigators like Bert Semtner are pushing the grid resolution to scales as small as 1/16o (or even smaller) for limited ocean basin scale integrations or near-shore simulations.

Once the grid has been established temperature, salinity and chemical tracers are placed into the grid, but in different ways. Figure 23.2.1 shows, in plan view, how these components are placed on the underlying grid.

17.2.3 Bathymetry

Like the plan view grid, the ”levels” of the GCM also have to be adjusted to allow for some semblance to the real bathymetry. When the grid is coarse this can present some problems Fig. 23.2.2 shows Drake Passage in cross-section.

In Toggweiler’s coarse resolution model Iceland was eliminated and the Greenland-Scotland sill was deepened. The Straight of Gibraltar was left as it is, but no flow between the Mediterranean and the Atlantic was allowed. Additionally the horizontal viscosity of the water was increased to give rise to realistic western boundary currents (Gulf Stream, Kuroshio, etc.).

17.3 Model Numerics:

In this next section we will discuss some aspects of general circulation models. Some of these aspects they share with all modeling, but some are unique to GCMs.

17.3.1 Subgrid Scale Processes (”A terms”)

All models have a scale at which they are no longer able to resolve what’s going on. I suspect that unless someday we have the computational ability to model each and every molecule on an individual basis and their interactions with each other, subscale process parameterization will always be with us. In this particular case, the parameterization referred to deals with mixing at scales smaller than the scale of the grid the GCM is running on.

For example in the model run by Toggweiler et al. (1989a) the parameters Amh and Ahh are quite large due to the requirement for a smooth finite difference solution at this particular grid size. Toggweiler et al. assumed that Ahh would be larger in the upper ocean and used:

where

and no parameterization to allow along isopycnal surface mixing (instead of at ”level” surfaces) was used. In the vertical, they assumed that Ahv would be greater at depth and used the following parameterization to account for subgrid scale mixing in the vertical:

where:

17.3.2 Boundary Conditions

As always, the boundary conditions are very important. In this particular case we are dealing with the conditions at the surface and bottom of the ocean (as well as, by default, along the shores of the continents).

At the surface we have the following boundary conditions for wind stress: Hellerman and Rosenstein (1983) provide the monthly wind stresses turned into an annual mean and interpolated onto the Toggweiler et al. grid. This stress is applied as in the following:

For temperature and salinity they used anually averaged values of and S from Levitus (1982) at both the surface and in the interior of the model domain (in what they called their ”robust diagnostic mode” only). Values at the surface were the upper 50 m average from Levitus to get around the low salinity values found at some places in Levitus due to seasonal melt water.

Near the bottom Toggweiler et al. applied a simple linear drag to calculate:

17.3.3 The Restoring Parameter

The restoring parameter is well known to those that know it well. To the rest of the scientific community it sometimes comes as a bit of a shock. Essentially the restoring parameter is an adjustable parameter used in most general circulation models in an attempt to replicate the boundary fluxes of heat and freshwater at the air-sea interface. Rather than try to model the heat and freshwater fluxes at the surface explicitly, the modelers write:

where:

When the model was being run in ”prognostic” mode, the restoring term was applied to the surface only and was set to a value of 1/30 day-1 and when the model was run in ”diagnostic” mode it was applied tot he surface and the interior with value of 1/50 yr-1. Interestingly enough, these values are the recommended values used in MOM-2 v2.2 today. The effect of this parameter is to continuously push the model values of S and back towards the annual Levitus average with the attendant effect on circulation.

17.3.4 Model Runs

As already mentioned, Toggweiler et al. Ran their GCM in two different modes (as do most GCM operators do today still). In the ”prognostic mode” the surface values of and S are forced back to Levitus with a , in the interior is set to zero and thus the model is allowed to come into geostrophic balance. A GCM needs to run out some 3500 model years to achieve a steady state with a ”chemical tracer” like 14C, this is known as the ”spin-up” phase of running the model.

When run in the ”diagnostic mode”, the parameter, in effect, adds a small source of heat and salt artificially to the interior of the model. In this manner the model can reach ”equilibrium” in as short a run as 300 model years and then is run out an additional 450 model years. When being run in this mode Ahv = f(z) or Ahv = 1.0 cm2 s-1. Runs of the model were sampled every 5 model years to produce average flow field for the 14C experiments. Both modes continuously check for vertical density instabilities and mix convectively conserving , S and 14C.

17.4 Model Output:

When it comes to evaluating the results from a GCM run, this evaluation essentially comes down to a comparison of the output with what we think we know about how the real world ocean works. But because there are a lot of assumptions built into a model as complex as a GCM we don't always expect to get an exact match between the model output and observations. This is where a good understanding of the physics behind the model makeup is important in guiding the model experimenter in deciding what are significant and trivial similarities and differences.

17.4.1 Comparison to Levitus (Potential Temperature and Salinity)

In the model experiments conducted by Toggweiler et al. (1989a&b), and in general of most GCM runs, the following was observed. The prognostic model of operation did a superior job at reproducing the circulation, but the and S distributions compared more poorly to Levitus. In general the bottom salinities were too fresh (approximately 0.25and the temperature deviation at mid-depths were too warm by up to 4oC. There was no salinity minimum in the model output where the temperature deviation was the greatest.

The robust diagnostic version does a better job of matching Levitus (by almost a factor of two over the prognostic mode), but the weak restoring terms in the interior () suppress convection and other vertical motions causing major disruptions in deep sea ventilation. Diagnostic calculations with a constant Ahv = 1.0 cm2 s-1 are approximately 50higher in their deviations. Wereas diagnostic calculations done with Ahv = f (z) have temperature deviations approximately 50prognostic version. At great depth and S deviations are very small because yr-1 is particularly effective where velocities are small.

Typically coarse resolution models have the following well known deficiencies. Either they have weak thermohaline circulations or their thermoclines are too warm. Additionally the model isotherms are usually several 100 meters too deep. The deep salinities of the model are too fresh and smooth numerical solutions require high eddy diffusivity parameterizations. Finally, western boundary currents do not separate at the proper latitude accompanied by spurious upwelling landward of the western boundary current.

17.4.2 Adding 14C to the Model

In Toggweiler et al.'s model there was no chemical or biological transformations of 14C. The 14C values are usually reported in , i.e. in ppt deviation from a standard 14C/12C ratio in a standard reference material (in this case 19th century tree-rings). In the model the 14C values are reported in a n arbitrary scale and the atmosphere is held constant at 100 of these units. To convert between model to standard 14C scales use:

Keep in mind that is a ratio not a concentration, but this is one of those few cases where - because this model has no chemical or biological transformations of the 14C - the ratio can be treated as a concentration.

Toggweiler et al. performed five experiments on three different flow fields (prog, rdiag1, and rdiag2) with three different treatments of gas exchange. Experiment Flow Field Transfer Velocity Vertical Eddy Diffusivity A RDIAG1 20 mol C m-2 yr-1 Ahv = f (z) B RDIAG1 k = f (U10) Ahv = f (z) C RDIAG2 k = f (U10) Ahv = 1.0 P PROG k = f (U10) Ahv = f (z) P' PROG k = f (U10) x 1.2 Ahv = f (z)

The surface concentration of C was set at 2 mol-C m-3 and in experiment A:

where DZ1 is the depth of the surface box in meters and is the rate of change of 14C at the surface. This change takes place only at the surface grid cells and is propagated into the interior of the model by the primitive equations. In experiments B through P':

where U10 is wind speed in m/s measured at 10 m above the surface of the ocean.

17.4.3 Evaluating Output

One of the first things one should do after running a GCM and getting some output is look at the circulations patterns. As you can see in Fig. 23.4.1, there are some important differences between the prognostic and diagnostic experiments.

You can see by examining Fig. 23.4.1 that the two shallow overturning cells are straddling the equator due to Ekman divergence (most of this activity is in the Pacific). Note also the mid-latitude overturning cells have a marked difference between the prognostic and diagnostic experiments (weaker in the diagnostic because the interior restoring parameter dampens vertical convection). You will also note that there is "mid-depth" flow from the N to the S compensated by a return flow above 1000 m, due mostly to the N. Atlantic deep water. This raises a problem for the model's 14C because the NADW is mostly above 2500 m and the data show it deeper. In examining the flow field one finds that the prognostic integrations are about 50integrations in forming NADW. The abyssal northward flow, compensated by return flow above 3500 m (AABW), flows most strongly in the Pacific. Direct comparison to actual data is difficult due to problems with the time-mean meridional observations we mentioned in the last lecture.

When we look at the 14C profiles (globally averaged) at model steady state we observe the following in comparison to real data and between the experiments. The bottom 14C in the model is older than the 14C measured as part of GEOSECS, but the prognostic runs do a better than the diagnostic runs in this respect. The prognostic runs also have a minimum at mid-depth as was observed during the GEOSECS program, the diagnostic simulations do not. In experiment C (Ahv = 1.0 cm2 s-1) they found that vertical mixing has a strong effect on the deep water 14C values. One interesting outcome of all these experiments was that, apparently, global spatial variation of gas exchange has little effect on the deep 14C values (which is why using 14C from the deep to calibrate new gas exchange algorithms won't work, too insensitive). The prognostic experiment's and S deviations do not, apparently, degrade its ability to ventilate the interior (does a better job than the diagnostic runs). All of the experiments failed to produce enough NADW to fill the N. Atlantic basin and so AABW penetrates too far north.

If you restrict yourself to looking at just the bomb-14C, you begin to see some additional features. The model's (all runs) bomb-14C inventory at GEOSECS time is low by about 16exchange rates are responsible for this phenomena. The model's upper ocean vertical mixing rate, especially in the recirculation regions of the subtropical gyres and cooler temperate and subpolar areas, appears to be too weak. Upwelling inshore of the western boundary currents causes glaring deficiencies in bomb-14C inventory distributions. The model also moves bomb-14C into the deep N. Atlantic interior too slowly.

Many of these flows were not known until 14C distributions were compared to GCM output.