Transient Response to Greenhouse Gas Increases:

As a practical matter, it is important to know how the climate system will respond to gradually increasing greenhouse gases. The canonical experiment is to consider the response to a 1% per year increase in CO_2, which was felt to be a reasonable scenario for the combined effect of well-mixed greenhouse gases (but see Hansen, et al. 1988). In order to do such an experiment, you need a dynamical ocean, since you expect that ocean currents might affect things on a 100-year time scale, and this turns out to be the case.

The first, and still most informative studies of this nature were done by Manabe and collaborators at GFDL. They used a coarse-resolution climate model, including atmosphere, land surface, sea ice, snow cover, and dynamical ocean model components and incorporating a seasonal cycle.

- The atmosphere was an R15L9 model. This means the horizontal resolution was rhomboidal 15 and there were 9 levels in the vertical. This is equivalent to about 5˚ latitude-longitude resolution. Land topographic features are greatly smoothed. Clouds were predicted using a simple 99% relative humidity criterion with specified optical properties.
- The land surface model was of the bucket type.
- The ocean model had 4.5˚ longitude by 3.75˚ latitude resolution and 12 vertical levels. This resolution allows very crude, diffusive resolution of western boundary currents, but no ENSO-style variability. The Drake Passage has to be made rather wide to accommodate the right mass flux, and the Bering and Gibraltar Straits are closed. Other features are very blockish looking, and significant bathymetric features like the Mid-Atlantic Ridge are greatly smoothed. In order to tune in the current climate, salt and heat fluxes have to be added externally to the oceans to get the thermohaline circulation right. These flux adjustments are not changed as the experiments are done.
- The sea ice model is a thermodynamic one, except that the ice is allowed to flow with the surface currents, so long as the ice is less than 4m thick, at which point it locks into place.

With such a model Manabe and Stouffer(1988) showed that you can get two stable states of the climate, one with a thermohaline circulation in the North Atlantic, and one with no thermohaline circulation in the North Atlantic. Whether you get it or not depends on the initial conditions of the model. If you have one, it stays on, if it is off, it stays off (see figures in Chapter 10 of Hartmann, 1994).

In several papers, Manabe and collaborators did some transient CO_2 forcing experiments with this climate model, which showed the strong influence of the deep ocean circulation on transient climate response. Manabe, et al (1991) did a set of 100-year experiments, after spinning up the starting point, and discussed the response after about 70 years, which is the point at which carbon dioxide reaches twice its present value. They compared the transient runs at this point with an equilibrium calculation, in which the transient ocean effects are gone. They found large inter-hemispheric and regional differences caused by ocean heat capacity and transport effects. Specifically:

- The response at 70 years is greatly reduced, compared to the equilibrium response, in the circumpolar ocean of the Southern Hemisphere and in the northern North Atlantic, where sinking branches of the thermohaline circulation occur and where the effective heat capacity of the ocean is very large.

- Because the tropical water vapor content increases more than the polar water vapor content, the poleward flux of water vapor increases and this results in a positive precipitation minus evaporation (P-E) anomaly over the North Atlantic. The freshening of the surface water of the North Atlantic makes it less dense and this slows down the thermohaline circulation in the North Atlantic. The reduced northward heat flux causes the northern North Atlantic to be colder than it otherwise would.

- In the southern polar oceans the freshening of surface water decreases vertical mixing. Because, at least in winter, the deep waters are warmer than the surface waters, this results in further cooling. Later we will see that this has important implications for the carbon cycle, too.

- Because the tropics heat up more than the polar regions, the surface westerly winds over the southern ocean are strengthened in a greenhouse-warmed Earth. This increased surface wind stress increases the mixing and overturning of the southern ocean, enhancing the effects of deep circulation.

- Except for the high latitude oceans, the response of surface temperature is similar to that obtained with a mixed-layer model. Even with a dynamical ocean, the response is approximately linear, as suggested by experiments where CO_2 is decreased with time. The exception is the effect of surface salinity changes, which cause asymmetrical changes in ocean circulation that cannot be included in a simple mixed-layer formulation. Of course it must be remembered that the coarse and diffusive ocean model cannot resolve ENSO variability, and many would argue that ENSO is responding strongly to global warming.

Manabe et al.(1992) looked into the seasonal changes in these experiments. An interesting result is that the drying over land is increased. The oceans in high latitudes warm up less than the land. Near the center of the continents the summer climate warms up a lot, but the supply of moisture from the oceans is decreased because the SST does not warm up as much after 70 years as does the land. So during the transient warming, drought over land areas is more likely even than after the climate has equilibrated.

The same model was used by Manabe and Stouffer(1994) to look at longer 500-year runs with 2X and 4X CO_2 forcings. One run increased to doubled CO_2 in 70 years and then leveled off, and the other continued to 4X CO_2 at year 140 and then leveled off. These runs were compared with a 500 year control case. In these experiments they kept track of melting of Greenland and Antarctic ice sheets and their effect on sea level. In the 4X case the thermohaline circulation takes a linear decline to zero after about 200 years. In the 2X case the thermohaline circulation follows a similar trajectory for about 140 years and then slowly relaxes back to almost the initial circulation strength after 500 years. The gradual recover seems to be caused by storage of heat in the deep ocean, so that the deep ocean density increases enough for the fresher surface water to eventually sink. The collapse of the thermohaline circulation is mostly caused by the transient influx of fresh water to the polar oceans associated with the greenhouse warming.

Senior and Mitchell(2000) describe changes in the sensitivity of climate during an 800-year CO2 doubling experiment. Again, it is some what complicated, but because of the delay associated with the South Hemisphere Ocean dynamics, and its effect on cloud feedbacks, the sensitivity of the climate, as estimated at any time in the 800-year integration, increases about 40% from the beginning of the experiment to the end.

References:

Bryan, K., S. Manabe and M. J. Spelman, 1988: Interhemispheric asymmetry in the transient response of a coupled ocean-atmosphere model to a CO_2 forcing. *J. Phys. Ocean.*, **18**, 851-867.

Hansen, J. E., M. Sato, L. A., R. Ruedy, I. Tegen and E. Matthews, 1998: Climate forcings in the industrial era. *Proc. Natl. Acad. Sci.*, **95**, 12,753-58.

Hartmann, D. L., 1994: *Global Physical Climatology*. Academic Press, San Diego, 411.

Manabe, S. and R. J. Stouffer, 1988: Two stable equilibria of a coupled ocean-atmosphere model. *J. Climate*, **1**, 841-866.

Manabe, S. and R. J. Stouffer, 1993: Century-scale effects of increased atmospheric CO/sub 2/ on the ocean-atmosphere system. *Nature*, **364**, 215-18.

Manabe, S. and R. J. Stouffer, 1994: Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *Journal of Climate*, **7**, 5-23.

Manabe, S., R. J. Stouffer, M. J. Spelman and K. Bryan, 1991: Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO/sub 2/. I. Annual mean response. *Journal of Climate*, **4**, 785-818.

Manabe, S., M. J. Spelman and R. J. Stouffer, 1992: Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO/sub 2/. II. Seasonal response. *Journal of Climate*, **5**, 105-26.

Senior, C. A. and J. F. B. Mitchell, 2000: The time-dependence of climate sensitivity. *Geophys. Res. Lett.*, **27**, 2685-2688.

Stouffer, R. J., S. Manabe and K. Bryan, 1989: Interhemispheric asymmetry in climate response to a gradual increase of atmospheric carbon dioxide. *Nature*, **342**, 660-662.