Equilibrium Climate Sensitivity: Is It Accurate to Use a Slab Ocean Model?

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ABSTRACT
The equilibrium climate sensitivity of a climate model is usually defined as the globally averaged equi-
librium surface temperature response to a doubling of carbon dioxide. This is virtually always estimated in a
version with a slab model for the upper ocean. The question is whether this estimate is accurate for the full
climate model version, which includes a full-depth ocean component. This question has been answered for
the low-resolution version of the Community Climate System Model, version 3 (CCSM3). The answer is that
the equilibrium climate sensitivity using the full-depth ocean model is 0.14°C higher than that using the slab
ocean model, which is a small increase. In addition, these sensitivity estimates have a standard deviation of
nearly 0.1°C because of interannual variability. These results indicate that the standard practice of using a
slab ocean model does give a good estimate of the equilibrium climate sensitivity of the full CCSM3. Another
question addressed is whether the effective climate sensitivity is an accurate estimate of the equilibrium
climate sensitivity. Again the answer is yes, provided that at least 150 yr of data from the doubled carbon
dioxide run are used.

1. Introduction
Equilibrium climate sensitivity (ECS) is one of the
measures used to describe climate model temperature
sensitivity. It is defined as the equilibrium change in
global surface temperature following a doubling of the
atmospheric equivalent carbon dioxide (CO2) concen-
tration (e.g., Meehl et al. 2007). The ECS is usually
calculated using the climate model atmosphere and land
components, only the thermodynamic part of the sea ice
component, and a slab model for the upper ocean. The
reason to use a slab ocean model (SOM) is that this
configuration equilibrates in about 20 yr when CO2 is
doubled, and so only a 50-yr run is required to deter-
mine the ECS. We decided to test whether the ECS in
the slab ocean configuration is an accurate estimate for
the full climate model by using the low-resolution ver-
tion (T31x3) of the Community Climate System Model,
version 3 (CCSM3). This version has an atmosphere and
land horizontal resolution of T31 (3.75° × 3.75°), an
ocean and sea ice horizontal resolution of about 3°, and
its climate simulations are thoroughly documented in
Yeager et al. (2006).

Details of the slab ocean model are given in Kiehl
et al. (2006). The spatially varying depth is based on
observational estimates of annual-mean ocean mixed
layer and has a globally averaged value of 54 m. It also
uses a monthly varying heat flux transport, which ac-
counts for missing processes such as advection and
mixing. Two fully coupled integrations of the T31x3
CCSM3 have been completed. The first is a 1500-yr
control run using the 1990 CO2 value of 355 ppmv. The
second is a 3000-yr run in which the CO2 is instanta-
neously doubled to 710 ppmv. Both start from the same
initial conditions described in Yeager et al. (2006).

Have a pair of integrations like this been run to
equilibrium before? The only example we have found is
described in Stouffer and Manabe (1999), who used the
flux-corrected Geophysical Fluid Dynamics Laboratory
coupled model with R15 atmosphere and 4° ocean res-
olution. They analyzed a control run and a 1% yr⁻¹
increasing CO2 run in which the CO2 concentration was
kept constant after 70 yr (i.e., at doubled CO2 levels
from the control integration), and both were run for

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4000 yr. They found the ECS of the coupled model to be 4.5°C, whereas the ECS of their slab ocean version was 3.7°C. However, the control run had a slow drift over 2000 yr, such that the globally averaged surface temperature was 0.7°C colder than in the slab ocean version. Therefore, the authors say, “We are uncertain whether the equilibrium response of the coupled model with a more realistic control climate is significantly larger than that of the atmosphere-mixed layer ocean model.”

Senior and Mitchell (2000) used the flux-corrected Hadley Centre Coupled Model, version 2 (HadCM2) and ran a pair of integrations that were similar to that of Stouffer and Manabe (1999). However, the doubled CO₂ (2×CO₂) run was only integrated for a total of 900 yr. At the end of the run, the ocean was still taking up a significant amount of heat and the atmospheric surface temperature was still slowly rising. Thus, the authors say, “The true ECS of the coupled model remains unknown.” Gregory et al. (2004) analyzed integrations using the non-flux-corrected Hadley Centre Coupled Model, version 3 (HadCM3). However, the longest run out to 1200 yr has a quadrupled value of CO₂, and runs with doubled CO₂ were only integrated for 90 yr.

Gregory et al. (2004) proposed a method of diagnosing the effective climate sensitivity of a climate model without obtaining a steady-state solution. They suggested plotting the net radiative flux at the top of the atmosphere against the change in surface temperature during the initial stages of a 2×CO₂ run. Then, under the assumption that this effective climate sensitivity is independent of time, it can be used to estimate the ECS. Therefore, a second aim of the study presented here is to investigate whether this effective climate sensitivity method gives an accurate estimate of the ECS.

2. Results

a. Equilibrium climate sensitivity

Figure 1a shows the heat flux into the ocean, and Fig. 1b shows the volume-averaged ocean temperature, which is a measure of heat content, versus time from the control and 2×CO₂ runs. This confirms that the time scale for full adjustment of the deep ocean is about 3000 yr (e.g., Stouffer 2004; Danabasoglu 2004). It is set by the diffusive time scale estimated for the deep ocean using the very small model diapycnal diffusion coefficient below the thermocline. The temperatures at the end of the runs are 3.8°C and 5.8°C in the control and 2×CO₂ runs, respectively. However, very small secular trends remain in both runs; the surface heat fluxes are 0.015 and 0.078 W m⁻² in the control and 2×CO₂ runs, respectively, over the last 500 yr. Secular trends in ocean heat content are very common in climate models, and these present trends in the T31x3 CCSM3 are extremely small.

However, the surface temperature and upper-ocean heat content are much closer to equilibrium after 3000 yr. Figure 2a shows the globally averaged surface temperatures versus time from the control and 2×CO₂ runs, and Fig. 2b shows the difference between the surface temperatures from the 2×CO₂ run and the years 1001–1500 control run average. Taking the average of the curve in Fig. 2b over years 2501–3000 gives a value of 2.46°C, with an interannual standard deviation of 0.09°C. This is the ECS of the full-depth ocean, T31x3 CCSM3 version and is 0.14°C higher than the ECS of 2.32°C estimated using the slab ocean model (Kiehl et al. 2006). This difference is small, given the interannual standard deviations of 0.09°C and 0.07°C in the full-depth and slab ocean models, respectively. Note also that a comparable increase in the ECS—computed using the slab ocean model—occurs between the T42 and T31 versions of the CCSM3 (Kiehl et al. 2006). In addition, this difference is smaller than the change in ECS found by Bender (2008). She tuned the T42 atmosphere component of the CCSM3
in two ways such that the top-of-the-atmosphere (TOA) radiative balance agreed with two different satellite estimates and found that the ECS differed by 0.24°C when estimated in the usual way using the slab ocean model. Figures 3c and 3d show the spatial distribution of the change in surface temperature resulting from doubling CO₂ in the slab ocean and full-depth ocean runs, respectively. Again, the two fields are very close over much of the globe. The largest differences are in the high-latitude Southern Ocean and North Atlantic Ocean and are associated with more extensive reductions in sea ice area in the full-depth ocean run than in the slab ocean run.

b. Effective climate sensitivity

Here, we have followed the effective climate sensitivity method described in Gregory et al. (2004) but have used data from the entire 3000-yr 2×CO₂ run. Figure 4a shows the TOA radiative flux plotted against the change in surface temperature. The black, dark gray, and light gray dots represent annual values from the first, second, and third thousand years, respectively. The mean of the light gray dots is very close to zero, indicating that the model has very nearly equilibrated. The least squares straight line fit to the data intersects the x-axis at 1.928/0.791, which gives an effective climate sensitivity of 2.44°C, which is very close to the ECS of 2.46°C. We have also replotted Fig. 4a using decadal values (not shown), as is done in Fig. 2 of Gregory et al. (2004). The least squares fit is very close to that shown in Fig. 4a and is a good representation of all of the data after the first 20 yr. There is no change in slope of the data for the entire 3000 yr, in contrast with the quadrupled CO₂ (4×CO₂) run using HadCM3 shown in Fig. 2 of Gregory et al. (2004), and we do not expect that there should be a change in slope.

Thus, this method to estimate the ECS works well using all of the 3000-yr run, but the question is whether it works using data from only the initial part of the run. Figure 4b shows the effective climate sensitivity based on the same regression technique as a function of years of data used. If only 20 yr are used, the estimate is 6.25°C, but it very quickly drops to near 4°C. However, it does not reduce to 2.6°C until about 150 yr of data are used. Thus, in the low-resolution CCSM3, the effective climate sensitivity has a larger than 5% error in estimating the ECS if a 2×CO₂ run shorter than 150 yr is used.

3. Discussion

The main result of this work is that the ECS of the low-resolution CCSM3 estimated using the full-depth ocean component is 0.14°C higher than using the slab ocean model and that all estimates of ECS have an interannual standard deviation of about 0.1°C. Another result, not shown, is that the ECS was also estimated using a modified version of the slab ocean model. The
mixed layer depth was multiplied by a factor of 0.37, so that the globally averaged depth is 20 m rather than the 54 m of the standard slab ocean model. The ECS using the two slab ocean models is virtually the same. Are these results true just for this particular climate model, or are they true in general?

When CO$_2$ is doubled in the atmosphere, the heat flux into the ocean is increased. If this increase is accurately estimated by the intercept on the $y$ axis in Fig. 4a, then it is nearly 2 W m$^{-2}$ for the T31x3 CCSM3. The reason for the increase is that the extra longwave flux reflected back to the ocean surface is larger than the reduced solar flux reaching the surface. In response, the SST rises, which increases the latent and longwave heat flux losses, and it equilibrates when the heat flux at the surface rebalances to zero. Note that the only ocean quantity involved in this rebalancing is the SST through the heat flux laws. Technically, the CCSM3 flux laws depend on the difference between the atmosphere surface wind and the ocean surface current, but this ocean surface current dependence is extremely weak. Thus, the ECS depends upon the atmosphere component and the SST but is independent of the ocean model formulation. The ocean only provides the required SST increase, and it does this in 8 yr using the modified slab ocean, 18 yr using the standard slab ocean, and 2000 yr using the full-depth ocean.

We think there are some necessary conditions for the slab ocean and full-depth ocean estimates of the ECS.
to be close. The first is that the reduction in sea ice area resulting from doubled CO₂ is comparable in the two runs. This need not be the case, because the sea ice component is used differently in the slab ocean and full-depth ocean formulations. For the low-resolution CCSM3, the control run sea ice area is a little below the observational estimate using the slab ocean and is considerably above this estimate using the full-depth ocean (Yeager et al. 2006). The reduction in sea ice area using the slab ocean is 4.9
5 1012 m², whereas it reduces by 8.6
5 1012 m² using the full-depth ocean. This additional area of open water can then warm considerably, and we believe it is responsible for the 0.14°C higher ECS in the full-depth ocean run. The second condition was suggested by R. Stouffer (2008, personal communication) and results from the fact that the slab ocean heat flux transport is the same in both the control and 2×CO₂ runs. Thus, another necessary condition is that the meridional overturning circulation (MOC) and the northward heat transport do not change much between the two full-depth ocean runs. Figure 5a shows time series of the North Atlantic MOC maximum from the two runs. The average values over the last 500 yr are 15.4 and 13.2 Sv (1 Sv = 10⁶ m³ s⁻¹) in the control and 2×CO₂ runs, respectively, which is a reduction of 14%. This results in a 0.1 PW smaller Atlantic heat transport in the 2×CO₂ case (Fig. 5b). The change in the global MOC maximum transports is even smaller than in the Atlantic (not shown): the average values over the last 500 yr are 21.1 and 20.6 Sv, respectively, in the control and 2×CO₂ cases. Thus, the global heat transports are comparable, with the maxima reduced by the 0.1 PW from the Atlantic in the 2×CO₂ run. We think a third necessary condition is that the full-depth ocean control run is very well balanced. Otherwise, the control run drift can cause problems, such as those of Stouffer and Manabe (1999) discussed in the introduction. We believe that if other climate models satisfy these three conditions then their ECS estimated using a slab ocean model will also be close to the ECS of the full climate model.

Another important, and perhaps more practically useful, result is that the effective climate sensitivity estimated using all the data from the 2×CO₂ run does give an accurate estimate of the ECS. However, Fig. 4b
shows that this estimate needs to be based on at least a 150-yr-long \(2\times CO_2\) run to give an estimate within 5% of the true ECS. Again, we think a necessary condition to ensure that this technique gives an accurate estimate is to have a very well-balanced control run, with a TOA balance smaller than 0.1 W m\(^{-2}\). Then, the early changes in the \(2\times CO_2\) run will really reflect the changes resulting from forcing, and not drift in the model control run.

We set out on this project thinking that we would show that the ECS using a slab ocean and the full-depth ocean would be somewhat different. However, we now think that if the three necessary conditions outlined above are met then they will be close. If the sea ice extent does reduce significantly more in the full-depth ocean run than in the slab ocean run, then the ECS using the full climate model will be larger. However, in the low-resolution CCSM3 this increase in ECS is small, especially given that all of these sensitivity estimates have an interannual standard deviation of 0.1°C. Thus, the standard practice of using a slab ocean model should give a good estimate of full climate model ECS. It also has the very real advantage of using far less computational resources.

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