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 equilibrium 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 (CO_2) concentration (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 CO_2 is doubled, and so only a 50-yr run is required to determine 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 version (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 accounts 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 CO_2 value of 355 ppmv. The second is a 3000-yr run in which the CO_2 is instantaneously 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 resolution. They analyzed a control run and a 1% yr^{-1} increasing CO_2 run in which the CO_2 concentration was kept constant after 70 yr (i.e., at doubled CO_2 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 CO_2 ($2\times CO_2$) 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 CO_2, and runs with doubled CO_2 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 $2\times CO_2$ 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 $2\times CO_2$ 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 3.80° and 5.85°C in the control and $2\times CO_2$ 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 $2\times CO_2$ 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.

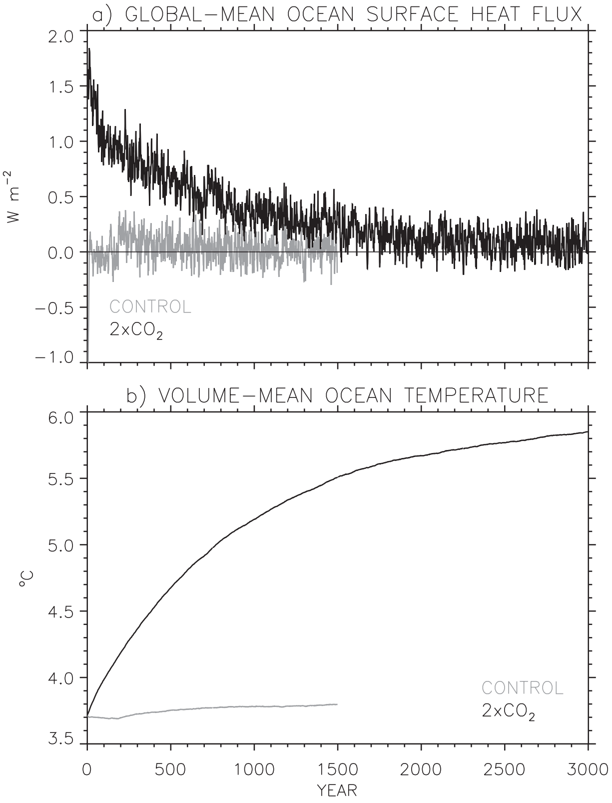

FIG. 1. (a) Annual-mean, globally averaged surface heat flux into the ocean, and (b) annual-mean, volume-averaged ocean temperature vs time from the $2 \times CO_2$ (black lines) and control (gray lines) runs.

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 $2\times CO_2$ runs, and Fig. 2b shows the difference between the surface temperatures from the $2\times CO_2$ 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° 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

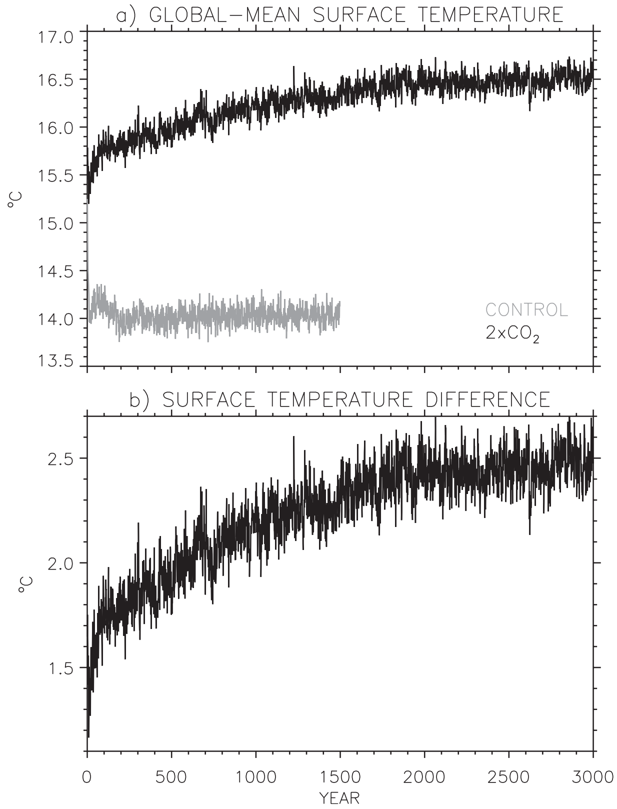

FIG. 2. (a) Annual-mean, globally averaged surface temperature vs time from the 2 × CO_2 (black line) and control (gray line) runs, and (b) the difference between the annual-mean surface temperature in the 2 × CO_2 run and the years 1001–1500 control run average.

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.

Figure 3 shows the surface temperature from the end of the slab ocean (25-yr average) and full-depth ocean (250-yr average) control runs and the change between the 2×CO_2 and control runs. The slab ocean model heat flux transport is constructed to produce a realistic sea surface temperature (SST) field (Fig. 3a) compared to observations. However, both SSTs and land surface temperatures are higher than observed, giving a 0.6°C positive bias for the globally averaged surface temperature in comparison with the National Centers for Environmental Prediction (NCEP) observational estimate. Figure 3b shows the CCSM3 warm SST biases in the upwelling regions and the cold bias in the northwest North Atlantic Ocean. Spatially averaged surface temperatures indicate that CCSM3 has cold biases over both land and oceans, so that its globally averaged surface temperature is about 0.5°C below the NCEP value and more than 1°C colder than the value using the slab ocean model. Figures 3c and 3d show the spatial distribution of the change in surface temperature resulting from doubling CO_2 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×CO_2 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 CO_2 (4×CO_2) 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×CO_2 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

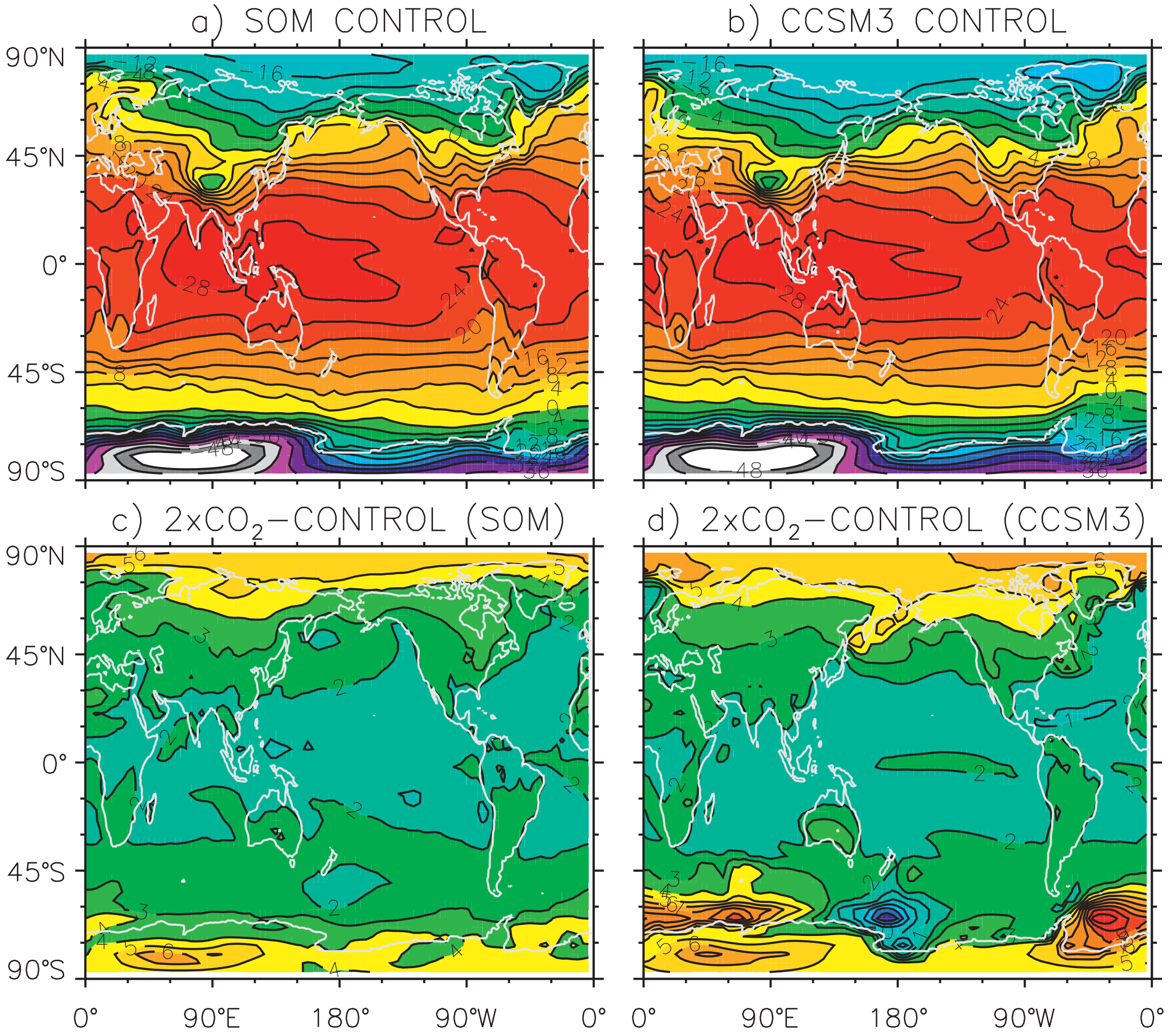

FIG. 3. Surface temperature from the end of runs for (a) SOM control and (b) full-depth ocean control, and difference in surface temperature for (c) SOM 2 × CO$_2$ − control and (d) full-depth ocean 2 × CO$_2$ − control.

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

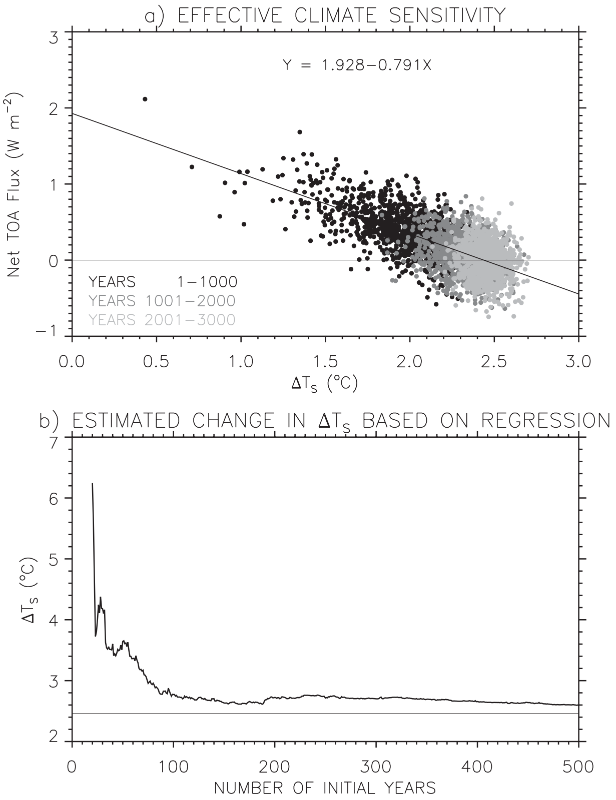

FIG. 4. (a) TOA radiative flux against the change in surface temperature from the 2 × CO_2 run. The black, dark gray, and light gray dots represent annual-mean data for years 1–1000, 1001–2000, and 2001–3000, respectively. (b) Effective climate sensitivity against years of data (annual mean) used from the 2 × CO_2 run.

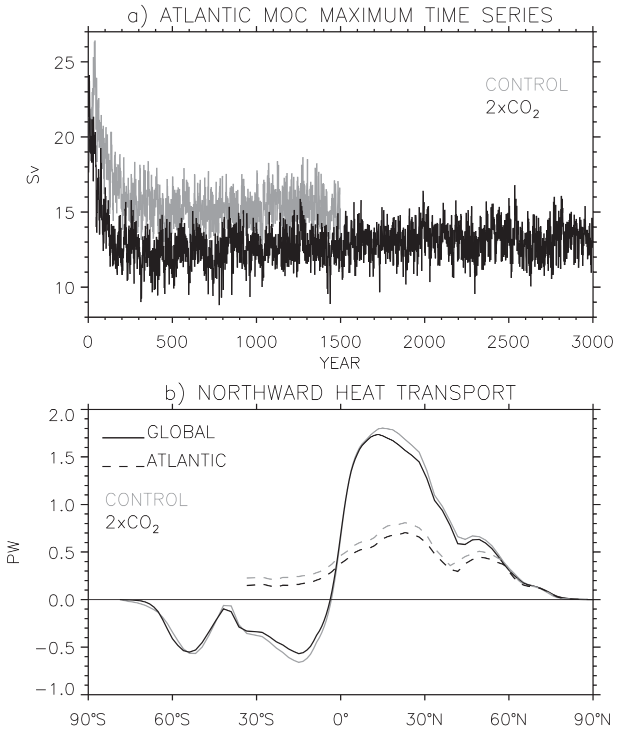

FIG. 5. (a) Annual-mean maximum of the Atlantic MOC vs time (control is upper gray line and 2 × CO_2 is lower black line), and (b) northward heat transport in the global (solid lines) and Atlantic (dashed lines) oceans from the 2 × CO_2 (black lines) and control (gray lines) runs. In (b), the heat transports are computed for the last 500 yr.

to be close. The first is that the reduction in sea ice area resulting from doubled CO_2 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 4.9×10^{12} m^2, whereas it reduces by 8.6×10^{12} m^2 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 $2\times CO_2$ 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 ≡ 10^6 m^3 s^{-1}) in the control and $2\times CO_2$ runs, respectively, which is a reduction of 14%. This results in a 0.1 PW smaller Atlantic heat transport in the $2\times CO_2$ 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 $2\times CO_2$ cases. Thus, the global heat transports are comparable, with the maxima reduced by the 0.1 PW from the Atlantic in the $2\times CO_2$ 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 $2\times CO_2$ 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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