Equilibrium Climate Sensitivity:

is it accurate to use a slab ocean model?

by

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Abstract

The equilibrium climate sensitivity of a climate model is defined as the globally-averaged surface temperature response to a doubling of carbon dioxide. This is virtually always calculated by using a slab model for the upper ocean. The question is whether this is an accurate assessment for the climate model as a whole, 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. The answer is that the equilibrium climate sensitivity using the full depth ocean model is 0.15°C higher than using the slab ocean model, which is a rather small increase. Given that these sensitivity calculations have a standard deviation of 0.1°C due to inter-annual variability, this implies that the standard practice of using a slab ocean model does give a good estimate of the true equilibrium climate sensitivity.

1. Introduction

Equilibrium climate sensitivity (ECS) is one of the measures used to describe climate model 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 calculated using the climate model atmosphere and land components, the thermodynamic part of the sea ice component, and a slab model for the upper ocean. The reason to use a slab upper ocean model is that this configuration equilibrates in about 20 years when CO_2 is doubled, and so only a 50 year run is required to determine the ECS. We decided to test whether the ECS is an accurate measure for the climate model as a whole using the low-resolution version (T31x3) of the Community Climate System Model version 3 (CCSM3). This version has an atmosphere and land resolution of T31 (3.75°x 3.75°), an ocean and sea ice resolution of about 3°, and its solutions characteristics are thoroughly documented in Yeager et al. (2006).

Two fully-coupled integrations of the T31x3 CCSM3 have been completed. The first is a 1500 year control run using the 1990 value for CO_2 of 355 ppmv. This is a clean repeat of the 880 year control run described in Yeager et al. (2006), that had a couple of changes made during the early part of the run. The second is a 2000 year run where the CO_2 is set to 710 ppmv, which starts from the same initial conditions as the first, control run.

Have a pair of integrations like this been run to equilibrium before? We believe not, especially in the last decade when climate models have become much more computationally expensive because of increased resolution and complexity. The closest work we have found is described in Senior and Mitchell (2000), who used the flux-corrected HadCM2 model. They used a 1800 year control run, and a 1% per year increasing CO_2 run that then kept the CO_2 concentration constant after 70 years, and ran for a further 830 years. However, even after this long a 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 that, "The true ECS of the coupled model remains unknown".

2. Results

Figure 1a shows the heat flux into the ocean, and Fig. 1b shows the volume-averaged ocean temperature (a measure of heat content) versus time from the 2xCO_2 and control runs. It is clear that the ocean has not fully equilibrated even after 2000 years, as it is still taking up heat from the other components. The control surface heat flux is 0.02 W/m^2 over the last 500 years, which is a secular trend, and the 2xCO_2 run flux is 0.10 W/m^2 over the last 100 years. This just confirms that the timescale for full adjustment of the deep ocean is about 3000 years (e.g. Danabasoglu 2004). It is set by the diffusive timescale estimated for the deep ocean using the very small model cross-isopycnal diffusion

coefficient below the thermocline. Using an exponential fit to the last 500 years of the curves in Fig. 1b gives equilibrium temperatures of 3.82°C and 5.78°C in the control and 2xCO_2 runs, respectively. This means that the CCSM3 estimate is that the equilibrium ocean heat content in response to a doubling of the CO_2 level to 710 ppmv increases by 51% measured in °C, or by 35% with respect to the freezing temperature of sea water taken to be -1.8°C.

The upper ocean heat content and surface temperature are much nearer to equilibrium after 2000 years. Figure 2a shows the surface temperatures versus time from the 2xCO_2 and control runs, and Fig. 2b shows the difference between the surface temperature from the 2xCO_2 run and the $< 1001-1500 >$ control run average, representing the time series of climate sensitivity. Taking the average of the curve in Fig. 2b over $< 1751-2000 >$ gives a value of 2.42°C, with a standard deviation of 0.10°C. If the last 500 years are smoothed with a 50 year time filter, then an exponential fit to the curve in Fig. 2b gives an equilibrium value of 2.47°C. This is the ECS of the full depth ocean, T31x3 CCSM3 version, and is 0.15°C higher than the ECS of 2.32°C calculated using a slab ocean model (Kiehl et al. 2006). This increase is rather small, given the standard deviation of 0.1°C. Note that this change is the same as the difference in ECS between the T42 and T31 versions of the CCSM3 atmosphere component and slab ocean model (Kiehl et al. 2006). It is smaller than the change in ECS found by Bender (2008). He tuned the T42 atmosphere component of the CCSM3 in two ways such that the top of the atmosphere radiative balance agreed with two different satellite estimates, and found the ECS differed by 0.24°C when calculated in the usual way using a slab ocean model.

Figure 3 shows the surface temperature from the end of slab ocean (25 year average) and full depth ocean (250 year average) control runs and the change between the 2xCO_2 and control runs. Comparing the control runs in Figs. 3 a,b shows that the slab ocean reproduces the full model surface temperature rather well. Thus, the heat flux transport used in the slab ocean model, which accounts for missing processes such as advection and mixing, has done its job to give a good sea surface temperature (SST) field. Close inspection shows there are differences in the area of the warm pool >28°C and in the northwest North Atlantic Ocean, for example. Figures 3 c,d show the spatial distribution of the change in surface temperature due to doubling CO_2 in the slab ocean and full depth ocean runs, respectively. Again the two fields are quite close over much of the globe. The largest differences are in the high latitude Southern Ocean and North Atlantic Ocean, and are associated with substantial reductions in the area of sea ice in the full depth ocean run. The reduction in sea ice (run in thermodynamic mode only) is much smaller in the slab ocean run.

3. **Discussion**

The two main results of this work are that the ECS of the low-resolution CCSM3 calculated using the full-depth ocean component is 0.15°C higher than using a slab ocean model, and that all calculations of ECS have a standard deviation of about 0.1°C. A third result, not shown, is that the ECS was also calculated using a modified version of the slab ocean model. The mixed layer depth was reduced 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. Kiehl et al. (2006) estimate this as 3.5 W/m^2 for the T42 CCSM3. The reason 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 flux laws do depend on the ocean surface current, but this 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 years using the modified slab ocean, 18 years using the standard slab ocean, and 3000 years using the full depth ocean.

The sea ice component is also used differently in the slab ocean and full depth ocean formulations. The control run sea ice area is a little below the observational estimate using the slab ocean, and considerably above this estimate using the full depth ocean (Yeager et al. 2006). We think a requirement that different ocean models give the same ECS is that the reduction in sea ice area due to doubled CO_2 is comparable. The two slab ocean model formulations both have a reduction in sea ice area of 4.9 x 10^{12} m^2, whereas the sea ice area reduces by 8.55 x 10^{12} m^2 using the full depth CCSM3. This additional area of open water can then warm considerably, and is probably responsible for the 0.15°C higher ECS in the full depth ocean run. We think this increased sea ice loss would also occur if other complete climate models were run to equilibrium under CO_2 doubling, so we believe our results are true in general.

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 sea ice extent changes are comparable, then they will be rather close. If the sea ice extent does reduce significantly, then the ECS using the full climate model can increase. However, in the CCSM3 this increase is rather small, given that these sensitivity calculations have a standard deviation of 0.1°C. This implies that the standard practice of using a slab ocean model does give a good estimate of the true equilibrium climate sensitivity. It also has the advantage of using far less computational resource.

Acknowledgment

We thank Jeffrey Kiehl and Christine Shields for information and help with the model codes used in this project. The NCAR is sponsored by the National Science Foundation.

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Figure Captions

1. a) Globally-averaged heat flux into the ocean and b) volume-averaged ocean temperature versus time from the $2xCO_2$ and control runs.

2. a) Globally-averaged surface temperature versus time from the $2xCO_2$ and control runs, and b) the difference between the surface temperature in the $2xCO_2$ run and the $< 1001 - 1500 >$ control run average.

3. Surface temperature from the end of runs a) slab ocean model (SOM) control, b) full depth ocean control, c) slab ocean model $2xCO_2-$ control, and d) full depth ocean $2xCO_2-$ control.

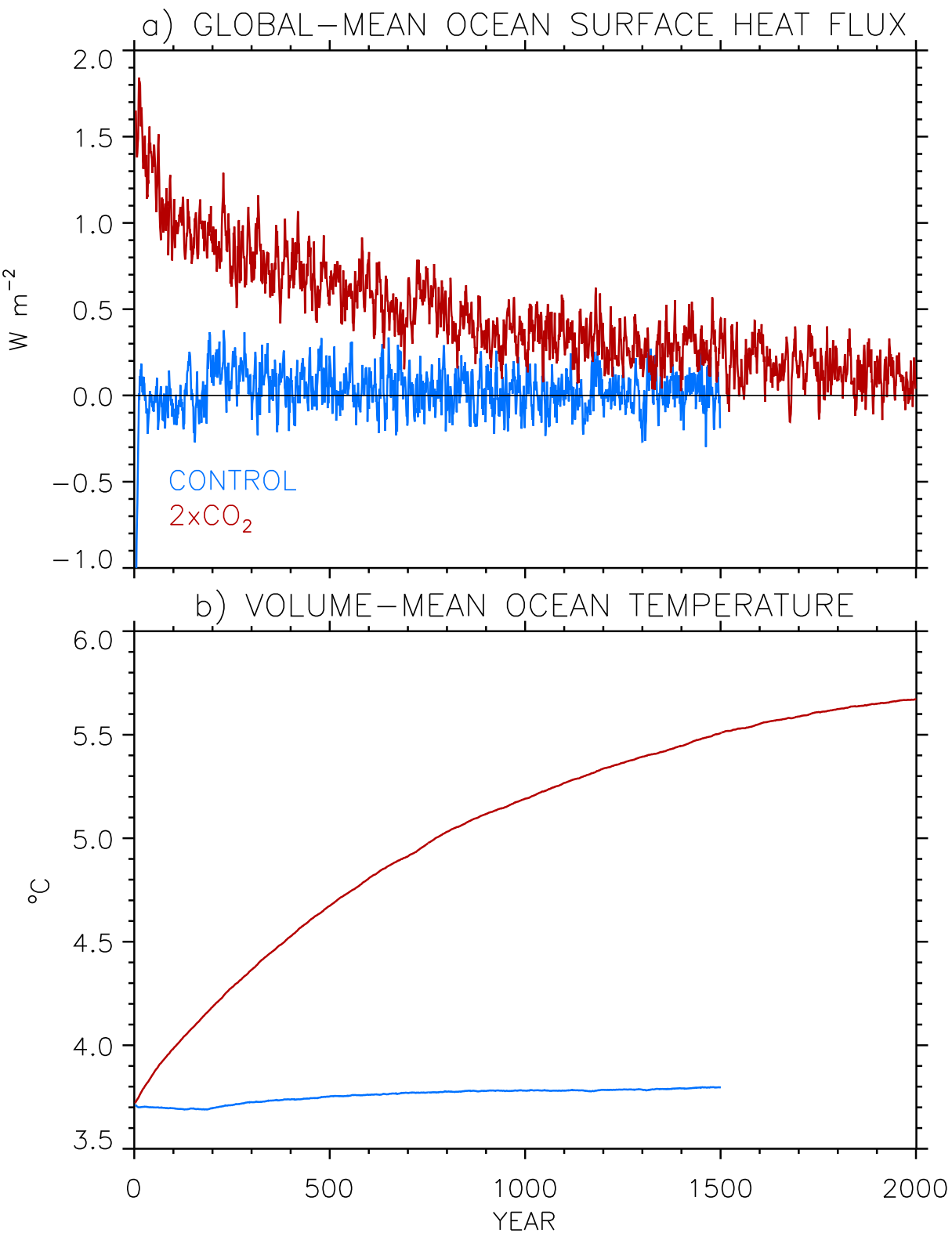

Figure 1. a) Globally-averaged heat flux into the ocean and b) volume-averaged ocean temperature versus time from the 2xCO$_2$ and control runs.

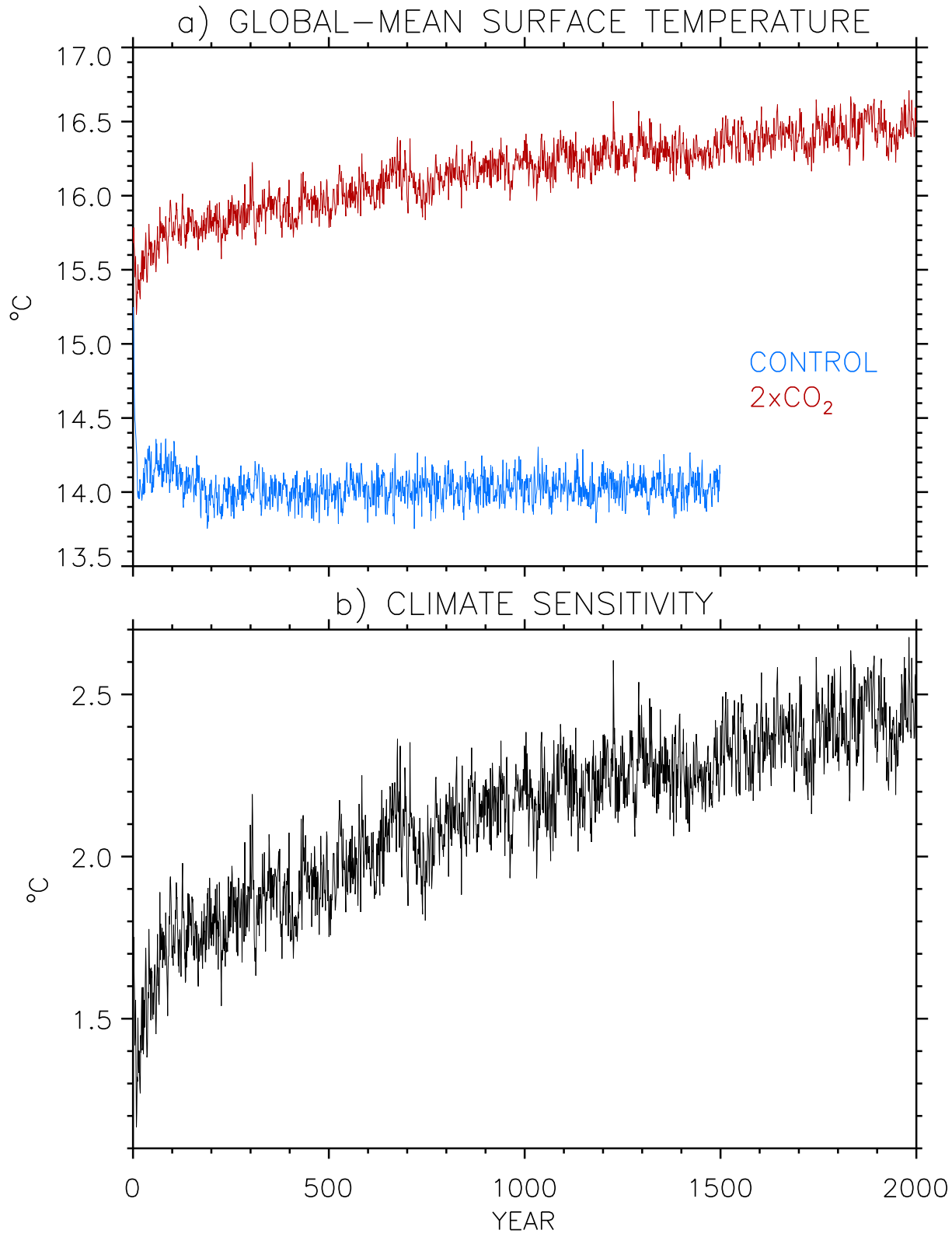

Figure 2. a) Globally-averaged surface temperature versus time from the 2xCO_2 and control runs, and b) the difference between the surface temperature in the 2xCO_2 run and the $< 1001 - 1500 >$ control run average.

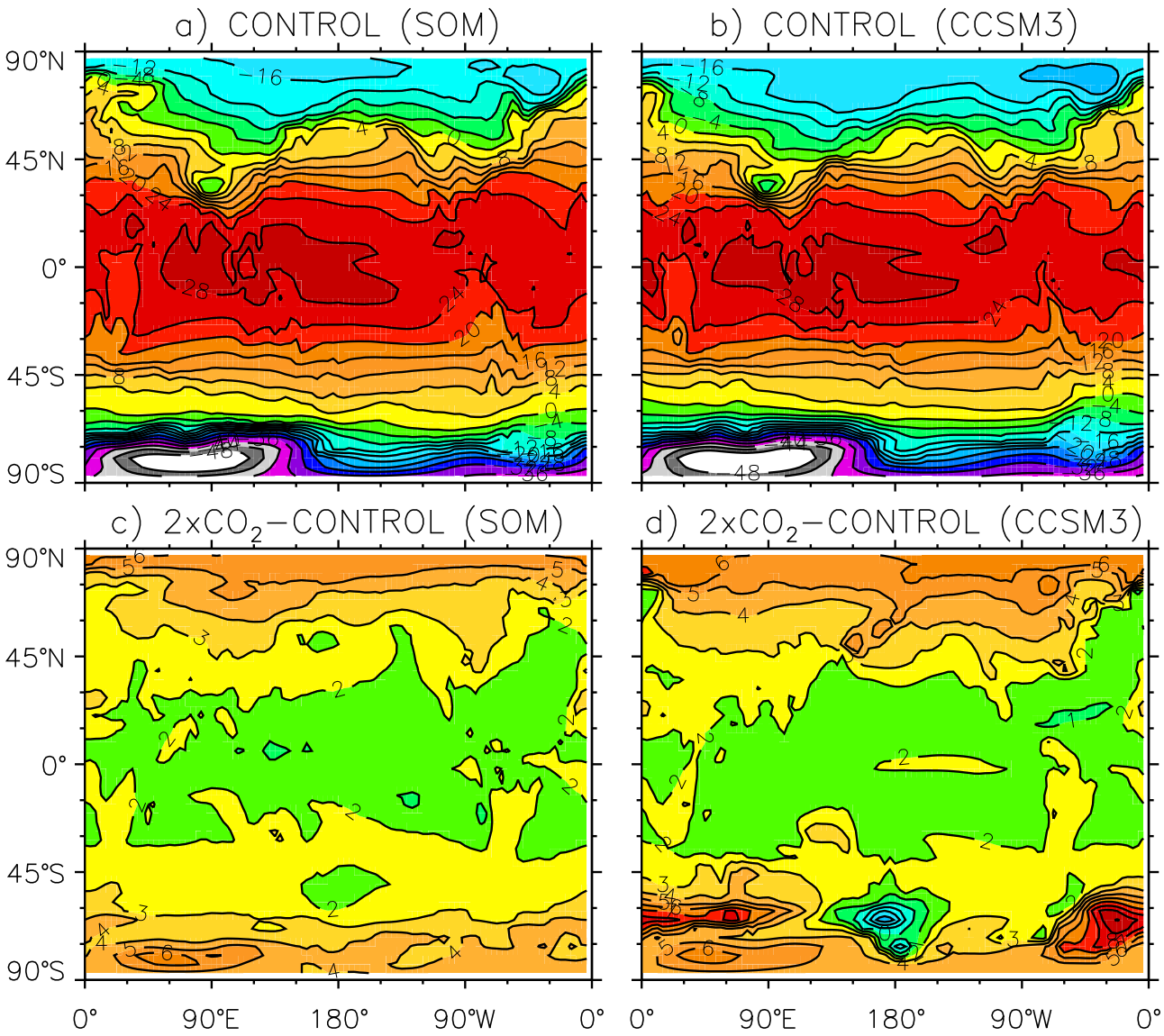

Figure 3. Surface temperature from the end of runs a) slab ocean model (SOM) control, b) full depth ocean control, c) slab ocean model 2xCO_2− control, and d) full depth ocean 2xCO_2− control.