

Effects of stabilizing atmospheric CO₂ on global climate in the next two centuries

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Abstract. Previous coupled ocean-atmosphere model simulations showed that the reduction in global warming is only moderate by year 2100 under CO₂ stabilization (STA) scenarios compared with that under business-as-usual (BAU) scenarios. To further illustrate the long-term effect of stabilizing CO₂ on global climate, we integrated a coupled ocean-atmosphere model from 1870 to 2200 forced by historical and projected CO₂, SO₂ and other greenhouse gases under newly updated BAU and STA scenarios. Our results show that the reduction in global warming resulting from CO₂ stabilization could be large ($\sim 1.5^{\circ}\text{C}$ globally, and up to 12°C in DJF at northern high-latitudes) by the later part of the 22nd century. Stabilizing the CO₂ level also results in reduced changes in precipitation, soil moisture and diurnal temperature range. BAU and STA patterns of change are similar for all variables examined.

1. Introduction

Given strong evidence that increases in atmospheric CO₂ and other greenhouse gases can produce substantial warming and other climate changes [e.g., Cubasch *et al.*, 2001], attention has turned to stabilizing greenhouse gas concentrations in order to limit future climate change [Wigley *et al.*, 1996]. Simulations using coupled ocean-atmosphere general circulation models (GCMs) suggest that spatial patterns of temperature and precipitation changes are similar under business-as-usual (BAU, i.e., no policies to limit greenhouse gas emissions) and CO₂ stabilization (STA) scenarios [Mitchell *et al.*, 2000; Dai *et al.*, 2001a,b].

The magnitudes of change depend, of course, on the chosen BAU scenario and the stabilization level; and on the climate sensitivity. For the Dai *et al.* [2001a,b] cases, the differences between BAU and (550 ppm) stabilization are still small by 2100. We therefore chose to extend the scenarios and simulation lengths to investigate both the long-term benefits of stabilizing CO₂ concentrations, and possible non-linear responses as the greenhouse gas forcing becomes increasingly large under a BAU scenario. These simulations employ extended projections of CO₂, CH₄, SO₂, N₂O, O₃ and CFCs for

the 22nd century under a BAU and a 550 ppm STA scenario. We recognize that projections of distant-future emissions have very large uncertainties and the magnitudes of change reported here are scenario- and model-dependent. We shall focus on the change patterns and the simulated differences between the BAU and STA scenarios, which are likely to be more reliable.

2. Model, scenarios and simulations

We used the Parallel Climate Model (PCM) [Washington *et al.*, 2000]. It consists of an atmospheric GCM ($\sim 2.8^{\circ}$ lat/lon resolution, 18 layers, 2.1°C warming for $2\times\text{CO}_2$ when coupled to a slab ocean), an ocean GCM ($\sim 2/3^{\circ}$ mean resolution, 32 layers), a land-surface model, and a sea-ice model. The PCM does not use flux adjustments. It produces a stable climate under current conditions that is comparable to observations [Washington *et al.*, 2000; Dai *et al.*, 2001c] and has near-observed El Niño amplitudes [Meehl *et al.*, 2001]. The model simulates fairly well the geographical, seasonal, and interannual variations in global surface air temperature and precipitation.

Greenhouse gas (CO₂, CH₄, N₂O, O₃, and CFCs) concentrations and SO₂ emissions were derived based on observations for 1870–1996. For 1997–2099, they were estimated using an energy-economics model driven by regionally-specific assumptions with regard to population growth, economic growth, energy use per capita, technology development, etc. The only difference between the BAU and STA scenarios is in CO₂: atmospheric CO₂ is projected to stabilize at 550 ppmv in 2150 [Wigley *et al.*, 1996] (Fig. 1). Details of the 1870–2099 scenarios are given in Dai *et al.* [2001a]. Our BAU scenario is similar to the average of all projections under the latest IPCC emissions scenarios [Nakićenović and Swart, 2000], which have a large spread.

The BAU scenario was extended to 2200 by assuming constant emissions for CO₂, N₂O, SO₂, and all halocarbons (CO₂ and N₂O levels in 2200 are 1114 ppm and 465 ppb, respectively). For CH₄, it stabilizes at 2500 ppb in 2100 in the original BAU scenario, and constant concentrations were assumed thereafter. For tropospheric and stratospheric ozone, constant 2100 concentrations were assumed. For the STA case, the only difference (as previously) is for CO₂ which continues along the original stabilization pathway to 550 ppm in 2150. Fig. 1 illustrates some of these details. We emphasize that

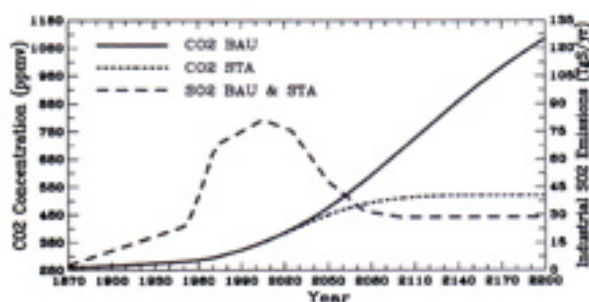


Figure 1. Atmospheric-mean CO₂ concentrations and global industrial SO₂ emissions under the BAU and STA scenarios from 1870 to 2200.

these future scenarios were designed for illustrating the effect of CO₂ stabilization. They represent only two of many possible future scenarios.

An ensemble of ten runs was completed for 1870–1999 and two ensembles of five runs were done for 2000–2099 [Dai et al., 2001b]. For 2100–2199, we completed only one run for each scenario. Analyses using the ensemble runs of 1870–2099 showed that for the averaged results shown here there are only small differences between ensemble mean and individual runs. For consistency, here we used only the runs extending to 2199.

3. Results

Fig. 2 shows that global-mean temperature and precipitation rise steadily in the BAU case after ~1980, in accord with the CO₂ increase (Fig. 1). Under the BAU scenario, global-mean temperature (precipitation) increases by ~2.0°C (3.3%) from the 1990s to the 2090s and by 1.4°C (2.4%) from the 2090s to the 2190s (Fig. 2), while the CO₂ concentration rises from 362 ppm in 1995

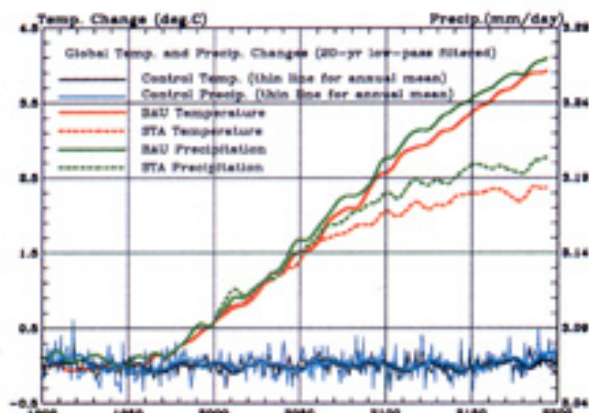


Figure 2. Global-mean temperature (red) and precipitation (green) changes simulated by the PCM under the BAU (solid) and STA (dashed) scenarios. Also shown are data from a control run.

to 688 ppm in 2095 and to 1097 ppm in 2195. Under the STA scenario, global-mean temperature and precipitation increase at a much slower pace than in the BAU case after about 2060 (Fig. 2), as the CO₂ difference becomes increasingly large (Fig. 1). Stabilizing CO₂ reduces the 1990s-to-2090s warming by ~0.5°C (relative to the BAU case) and the 2090s-to-2190s warming by a further 1.0°C. Note, however, that global-mean temperature in the STA case is still rising (slowly) in 2200. This is mainly a result of oceanic thermal inertia.

For the BAU case, the warming patterns during the 21st and 22nd centuries are similar ($r = 0.78$), although the warming during the 22nd century is slightly less than during the 21st century (Fig. 3a-b). This is especially true at high latitudes, where sea-ice area and snow cover decrease steadily (not shown) as the surface

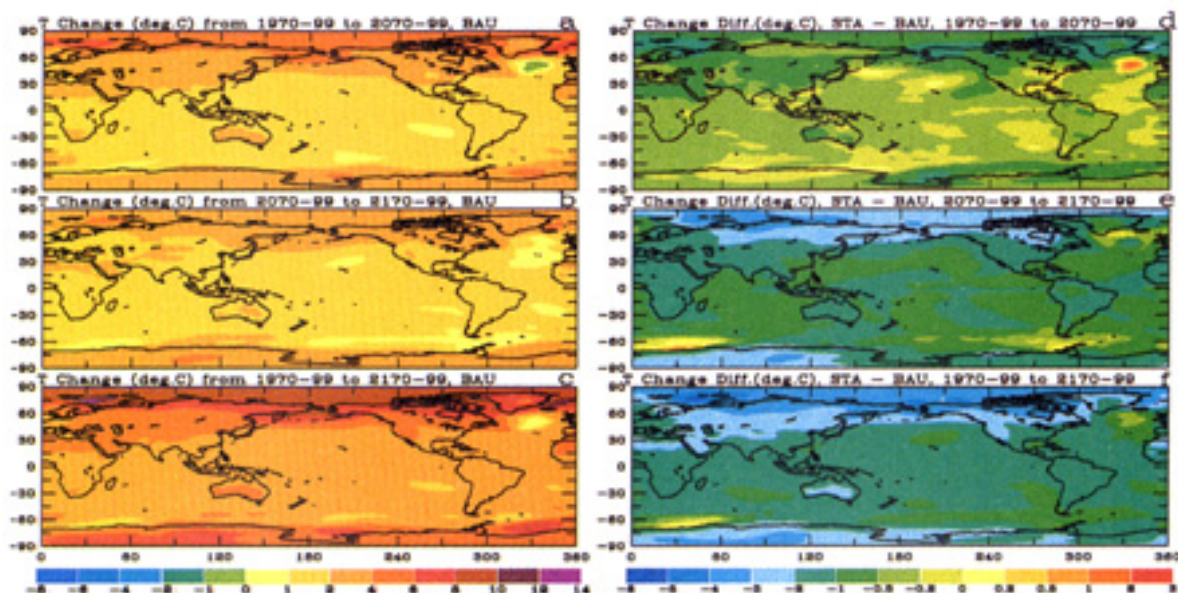


Figure 3. Left: Annual-mean surface air temperature changes (°C) simulated by the PCM under the BAU scenario from 1970–1999 to 2070–2099 (a), 2070–2099 to 2170–2199 (b), and 1970–1999 to 2170–2199 (c). Right: Temperature change differences under the two scenarios (STA minus BAU) for the three periods.

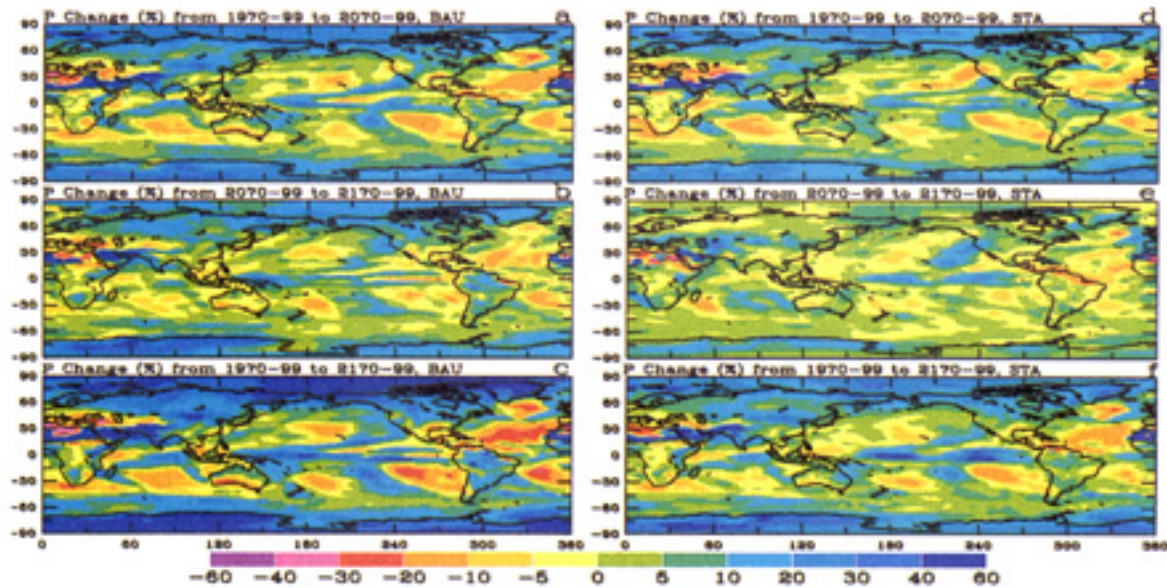


Figure 4. *Left:* Same as Fig. 3a–c but for precipitation. *Right:* Same as a–c but for the STA scenario.

temperature increases. Reduced sea-ice area and snow cover provide less potential for positive feedback at high latitudes [e.g., Hansen *et al.*, 1984].

Under the BAU scenario, the warming from 1970–1999 to 2170–2199 reaches 6–12°C at northern high latitudes (12–20°C in Dec.–Feb. or DJF) and 4–8°C at northern midlatitudes (5–12°C in DJF), whereas the warming is 2–4°C over most oceans and low-latitude land (similar in DJF) (Fig. 3c). In the STA case, the warming during 2070–2099 is reduced by 0.5–2.0°C (compared with the BAU case) over northern mid- and high-latitudes and only by 0.2–0.5°C over most oceans and low-latitude land (Fig. 3d). As the CO₂ level stabilizes in the 22nd century under the STA scenario, the reduction in the warming becomes much larger (2–4°C at high latitudes and 1–2°C at low latitudes by 2170–2199, Fig. 3e). From 1970–1999 to 2170–2199, the STA scenario reduces the warming by 2–6°C (up to 12°C in DJF) at northern high latitudes and 1–2°C at low latitudes (Fig. 3f).

Precipitation change patterns during the 21st and 22nd centuries are comparable ($r=0.42$) in the BAU case (Fig. 4a–b). In the STA case, precipitation changes are similar ($r=0.86$) to those in the BAU case during the 21st century and become small during the 22nd century (Fig. 4d–e). By 2170–2199, precipitation increases in the BAU case are large (40–60%, larger in DJF) at high latitudes and over the equatorial western and central Pacific, India and the Middle East, while the decreases over many subtropical oceans reach 20–30% (Fig. 4c).

In the BAU case, the increase in nighttime minimum temperature continues to exceed the increase in daytime maximum temperature in the 22nd century, resulting in substantial (0.5–2.5°C) decreases in diurnal temperature range (DTR) over most land areas (except southern Europe, the southern United States and southern Australia) (Fig. 5a). Changes in total cloud cover are

generally within $\pm 5\%$ (of the sky) and only have a weak correlation ($r=-0.28$) with the DTR change (Fig. 5b). Root-zone soil moisture generally increases over most Asia, North and South Americas, but decreases over southern Europe, the southern United States and southern Australia (Fig. 5c). The changes in soil moisture correlate significantly ($r=-0.56$) with the DTR change, suggesting that increased surface latent heat flux (not shown) slows down the increase in daytime maximum temperature and contributes to the DTR decrease, a process identified previously [e.g., Dai *et al.*, 1999].

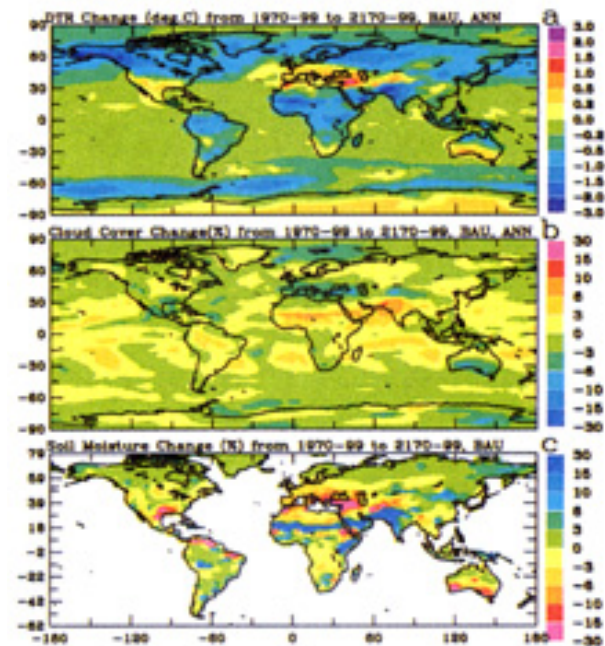


Figure 5. PCM-simulated changes from 1970–1999 to 2170–2199 in the BAU case in annual diurnal temperature range (a, °C), cloud cover (b, % of the sky), and soil (top 70 cm) moisture content (c, % change).

Under the STA scenario, the changes in DTR, cloud cover and soil moisture exhibit patterns similar to BAU, but with reduced magnitudes.

4. Concluding remarks

We investigated the long-term effect of stabilizing atmospheric CO₂ concentrations on global climate by integrating a coupled GCM from 1870 to 2199 under two newly updated future emissions scenarios: a no-climate-intervention-policy or BAU scenario and a CO₂ stabilization or STA scenario. Under the BAU scenario, the atmospheric CO₂ concentration increases from 362 ppm in 1995 to 688 ppm in 2095 and to 1097 ppm in 2195, whereas under the STA scenario the CO₂ level rises to 536 ppm in 2095 and then stabilizes at 550 ppm by 2150. The model results show that under the STA scenario global-mean temperature increases only slightly ($\sim 0.3^{\circ}\text{C}$) in the 22nd century, while precipitation changes are small. *As a result, global warming is reduced by $\sim 1.5^{\circ}\text{C}$ under the STA scenario compared with that under the BAU scenario by the later part of the 22nd century. This reduction in surface warming is about three times larger than the reduction by the later part of the 21st century and is much larger (up to 12°C in DJF) at northern high-latitudes.* Increases in mid- and high-latitude precipitation are also ($\sim 10\text{--}15\%$) lower in the STA case than the BAU case by 2170–2199. This leads to smaller changes in soil moisture and diurnal temperature range under the STA scenario. Patterns of change over the 21st century are similar under the BAU and STA scenarios. For BAU, patterns of temperature change over the 22nd century differ from those in the 21st century over high latitudes because of reduced sea-ice area and snow cover.

Our model results are qualitatively consistent with those of Mitchell *et al.* [2000], who examined the effect of CO₂ stabilization using a coupled GCM with higher climate sensitivity and simpler scenarios. For example, in the two models the warming patterns are comparable and differ only slightly under the baseline or BAU and STA scenarios, although our results show greater similarity under the two scenarios. Since the PCM's sensitivity (2.1°C for $2\times\text{CO}_2$) is in the lower half of the range ($1.5\text{--}4.5^{\circ}\text{C}$) of current GCMs, the effect of the CO₂ stabilization could be larger in many other GCMs.

The reduction in surface warming and other associated changes resulting from the CO₂ stabilization is very large compared with past climate changes [e.g., Folland *et al.*, 2001]. This suggests that the associated reductions in impacts on the environment and human society could be substantial. Since the rate of climate change in our STA simulation is small over the 22nd century, the immediate impacts might also be small. However, it is likely that these systems will still be suffering from the rapid climate changes that occur in the 21st century even in the STA case.

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