THE ACPI CLIMATE CHANGE SIMULATIONS

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Abstract. The Parallel Climate Model (PCM) has been used in the Accelerated Climate Prediction Initiative (ACPI) Program to simulate the global climate response to projected CO_2, sulfate, and other greenhouse gas forcing under a business-as-usual emissions scenario during the 21st century. In these runs, the oceans were initialized to 1995 conditions by a group from the Scripps Institution of Oceanography and other institutions. An ensemble of three model runs was then carried out to the year 2099 using the projected forcing. Atmospheric data from these runs were saved at 6-hourly intervals (hourly for certain critical fields) to support the ACPI objective of accurately modeling hydrological cycles over the western U.S. It is shown that the initialization to 1995 conditions partly removes the un-forced oceanic temperature and salinity drifts that occurred in the standard 20th century integration. The ACPI runs show a global surface temperature increase of 3–8 °C over northern high-latitudes by the end of the 21st century, and 1–2 °C over the oceans. This is generally within ± 0.1 °C of model runs without the 1995 ocean initialization. The exception is in the Antarctic circumpolar ocean where surface air temperature is cooler in the ACPI run; however the ensemble scatter is large in this region. Although the difference in climate at the end of the 21st century is minimal between the ACPI runs and traditionally spun up runs, it might be larger for CGCMs with higher climate sensitivity or larger ocean drifts. Our results suggest that the effect of small errors in the oceans (such as those associated with climate drifts) on CGCM-simulated climate changes for the next 50–100 years may be negligible.

1. Introduction

Specifying initial conditions (i.e., initialization) for coupled general circulation models (CGCMs) has long been recognized as an important and formidable task in global climate simulations (Stouffer and Dixon, 1998; McAvaney et al., 2001). This problem arises because the top-of-atmospheric radiative fluxes and the interfacial fluxes of heat, mass and momentum among the component (atmosphere, ocean, land and sea-ice) models need to be in balance at the beginning of an integration so that there will be negligible trends or drifts in global surface temperature and other fields. Initialization of the component models is designed to achieve these balances. In practice, however, this has been proven to be difficult, partly because we do not have the perfect observations of the states of the atmosphere, oceans, and land, and partly because we do not have perfect component models. The observed climate, especially the oceans, is unlikely in equilibrium. This further complicates the model initialization (Weaver et al., 2000). As a result, sizable drifts often occur in

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un-forced or control integrations of CGCMs. Since many parts of the deep oceans takes hundreds to thousands of years to reach an equilibrium, these drifts could persist for many centuries (albeit at decreasing magnitudes) and thus contaminate the climate response to given forcing.

Initialization of the atmospheric and land models is easier than for the ocean. This is mainly because the atmosphere and land have a relatively small heat capacity compared to the ocean so that errors or imbalances in the initial conditions will persist for only a few years to a few decades. Also, we have better observations of the atmosphere than for the ocean. The atmospheric models are often initialized either using observational data sets or using the output from an earlier integration (Stouffer and Dixon, 1998).

Initializing the ocean model in a CGCM is difficult because observations of the ocean states are limited and errors in oceanic initial conditions will have lasting effects on the simulated climate by CGCMs. There have been two main types of ocean model initialization (Stouffer and Dixon, 1998). The first is to use the observed state of the ocean, such as that compiled by Levitus and collaborators (Levitus, 1982; Levitus et al., 1994; Levitus and Boyer, 1994), to initialize the model's temperature and salinity fields. This is probably the simplest and most cost effective method, but the Levitus climatology is not an equilibrium solution and has many other caveats (Stouffer and Dixon, 1998) that could result in drifts in coupled integrations. The second method is to integrate the ocean model toward equilibrium using various means of forcing on the ocean surface. Because of the long adjustment time in the deep oceans, techniques have been developed to accelerate the convergence to equilibrium of ocean models (e.g., Bryan, 1984; Danabasoglu et al., 1996). This approach is often complicated to implement (Boville and Gent, 1998) and may require more computer resources than the first method.

Climate change simulations using CGCMs done during the last several years often start from a pre-industrial (e.g., 1870) condition. They are integrated over the 20th century using observation-based CO_2 and other natural and anthropogenic forcings. These simulations are often extended to the 21st century under projected CO_2 and other trace gas emissions (see Cubasch et al., 2001 and references therein). From the standpoint of solely predicting near-future (e.g., the next 50 yr) climate changes due to projected CO_2 and other anthropogenic forcing, this approach (of starting from pre-industrial conditions) is not only inefficient (i.e., the 1870–present simulation is not really needed for this purpose), but also may induce errors due to inaccurate representation of current (i.e., the 1990s) climate conditions by the CGCMs. It has been shown that the climate response to a given forcing is dependent on the starting mean state of the climate (Spelman and Manabe, 1984), thus starting the CGCMs from present climate conditions is important for simulating future climate changes.

To address these two problems in current simulations of future climate changes, the U.S. Department of Energy (DOE) sponsored a pilot project, under the Accelerated Climate Prediction Initiative (ACPI), to initialize a CGCM, namely the

Parallel Climate Model (PCM) (Washington et al., 2000), with observed conditions for current climate, integrated the CGCM over the next 50–100 years under a 'business as usual' (BAU) emissions scenario, and downscale the CGCM results for regional climate change assessment. This initialization method, which is described by Pierce et al. (2004), is more cost effective in terms of computer resources than the conventional techniques discussed above. In theory, it should also improve future climate projections as a result of the improved starting conditions. The method represents a new approach for initializing CGCMs for future climate change simulations. Therefore, its effects on the projected climate changes are of interest. In this short article, we briefly describe the PCM simulations employing this ocean initialization method and examine the effects of the initialization by comparing with other standard (i.e., without initialization to current conditions) BAU runs. The PCM simulations have been used in other studies included in this special issue, thus this paper also provides background information for the other papers.

2. The Parallel Climate Model

The CGCM used here is the Parallel Climate Model (PCM) version 1 (Washington et al., 2000). The PCM is a coupled climate system model consisting of an atmospheric general circulation model (GCM), an ocean GCM, a land model, and a sea-ice model. These component models are coupled through a flux coupler which computes the interfacial fluxes among the component models. The PCM does not use flux adjustments (Boville and Gent, 1988). It produces a stable climate (except for the deep oceans where there is a small cooling with time) under current conditions that is comparable to observations (Washington et al., 2000; Dai et al., 2001a) and has near-observed El Niño amplitude and spatial patterns (Meehl et al., 2001). The PCM has been used to simulate the climates of the 20th century forced with observation-based greenhouse gas, sulfate aerosol, solar, and volcanic forcings (Dai et al., 2001b; Meehl et al., 2002; Ammann et al., 2003) and of the 21st century under projected emissions scenarios (Dai et al., 2001a–c).

The atmospheric GCM is the Community Climate Model version 3 (CCM3) (Kiehl et al., 1998). It is a spectral model, with a truncation at T42 ($\sim$2.8° lat./lon.) resolution and 18 vertical layers (3 in the planetary boundary layer, on a hybrid sigma coordinate). The CCM3 has an equilibrium climate sensitivity of about 2.1 °C global warming for doubling atmospheric CO_2 content (Meehl et al., 2000a) (the coupled PCM has a transient climate sensitivity of 1.7 °C (Raper et al., 2002)), which is relatively low compared with most other GCMs (Cubasch et al., 2001).

The PCM ocean component uses the Los Alamos National Laboratory Parallel Ocean Program (POP) with a displaced North Pole over North America (Smith et al., 1992; Dukowicz and Smith, 1994). The ocean grid has an average resolution of 2/3° latitude and longitude with increased latitude resolution near the equator of $\sim$1/2°. In the vertical, the grid has 32 layers (2 in the top 50 meters) on a z-coordinate. The vertical diffusion parameterization of Pacanowski and Philander (1981) is used in this version of the POP. The displacement of the North Pole greatly improves the Arctic Ocean flow patterns (Washington et al., 2000).

The PCM includes a comprehensive land surface biophysics model (Bonan, 1998) which runs on the T42 grid. The sea-ice component consists of a dynamic-thermodynamic sea-ice model based on Zhang and Hibler (1997) that has a grid spacing of approximately 27 km. Note that the PCM does not simulate continental river discharge explicitly. Instead, it distributes the river discharge over the oceans by scaling up oceanic precipitation.

3. Model Initialization

In our 'standard' climate change simulations, the initialization is similar to that described by Washington et al. (2000). Specifically, the atmospheric model, with 1870 greenhouse gas forcing, was run 10 years from a standard September 1 initial data set using Levitus sea surface temperature (SST) climatology as the lower boundary condition. The last 5 years were used to generate the forcing data for the ocean model, which was run 80 years with an initial ocean state from Levitus climatology and sea-ice deduced from Levitus SST (Boville and Gent, 1998). During this integration, deep oceans were accelerated toward equilibrium (Bryan, 1984; Danabasoglu et al., 1996). Using a state from the 10th year of the atmospheric run and a consistent ocean state from year 80, the PCM was run in a fully-coupled mode for many centuries (without the deep ocean acceleration). As expected, large drifts occurred during the early stage of the coupled integration (within the first $\sim$100 years). The model conditions (at different times) after this initial period were taken as the starting point for ensemble historical runs for the period 1870–1999. CO_2 and other forcing for this period were temporally varying, and were specified based on available data (see Dai et al. (2001d) for details). Solar and volcanic forcing was not included in these historical runs. Five of the historical runs were extended into the 21st century under a BAU emissions scenario without any modifications to the model conditions of the 1990s (besides the changes in atmospheric trace gases and sulfate aerosols).

The simulations used here differ from the above standard climate change runs in that the ocean component model was initialized to observation-based 1995 conditions derived from assimilated ocean data before the PCM was integrated into the 21st century. This ocean initialization to the 1995 condition (hereafter referred to as the 1995 ocean initialization) was done by Pierce et al. (2004). The initialization to current conditions was motivated by the notion that a more realistic starting state may result in a better prediction of future climate change. Also, if this approach is proven to be valid, then one can start from present conditions (instead of starting from pre-industrial conditions) for simulating future climate changes, thereby reducing the required computer resources.

Experimental runs showed that the 1995 ocean initialization, which employed an anomaly coupling scheme (Pierce et al., 2004), did not induce any noticeable jumps in the global-mean surface temperature (Pierce et al., 2004), while the oceanic temperature (T) (below the sea surface) and salinity (S) were adjusted to the 1995 conditions.

4. Forcing Scenario, Simulations, and Data Output

The BAU scenario of greenhouse gas (CO_2, CH_4, N_2O, O_3, and CFCs) concentrations and SO_2 emissions for the 21st century is described in Dai et al. (2001d). Internally consistent emissions for the two most important gases, CO_2 and SO_2, were generated using energy economics models (Edmonds et al., 1997) driven by regionally specific assumptions with regard to population growth, economic growth, energy use per capita, technology developments, etc. The CO_2 level in year 2000 and 2100 is $\sim$371 ppm and 710 ppm, respectively. Global SO_2 emissions peak around 2005 (at 81 Tg S/yr, 1 Tg $= 10^{12}$ g) and then decline steadily (as a result of reducing air pollution) until 2080 when they stabilize at $\sim$30 Tg S/yr. Atmospheric sulfate loadings under the SO_2 emissions were taken from earlier simulations using the NCAR Climate System Model (CSM) (Dai et al., 2001d). Tropospheric ozone was kept constant at the 1990 level, while stratospheric ozone was predicted (to recover in the 21st century) externally using a two-dimensional chemical transport model (Garcia and Solomon, 1994) driven by harlocarbon projections consistent with the Montreal Protocol and its recent amendments and adjustments. The treatment of the other trace gases were described in Dai et al. (2001d). Our BAU scenario, which was developed before the IPCC SRES scenarios (Nakićenović and Swart, 2000) were available, is close to the mean of all SRES scenarios.

Three ensemble runs were carried out for the 1995–2099 period (cases B06.44, B06.46, and B06.47, referred to as the ACPI runs). These runs started from the same atmospheric, land, and sea-ice conditions for 1995 obtained from one of the historical runs (case B06.28), but used slightly different ocean conditions for 1995 that were derived from the assimilated ocean data (see the previous section and Pierce et al., 2004). In addition to monthly data for standard fields, daily, 6-hourly averaged and 6-hourly instantaneous data for selected atmospheric fields were saved for the 1995–2099 period for all the three runs. In addition, hourly data for a number of 2-dimensional fields were saved for the 2047–2052 period (through case B06.63). The monthly and daily data are archived at PCMDI (http://www-pcmdi.llnl.gov/modeldata/PCM_Data/pcgdahome.html), while the 6-hourly data ($\sim$1 terabyte for each case) are still on Oak Ridge National Laboratory storage devices. Here we used the ensemble mean of the three ACPI runs.

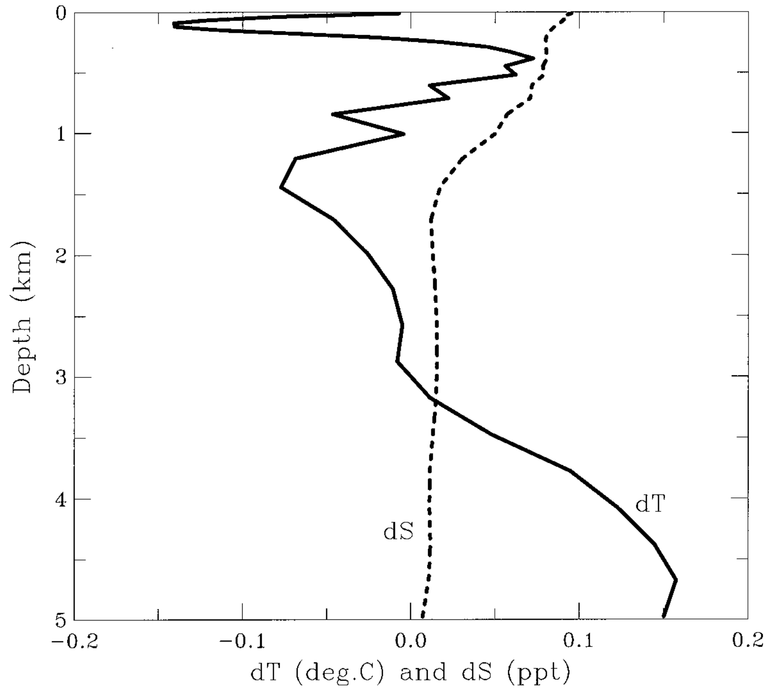

Figure 1. Profiles of ocean temperature (°C, solid line) and salinity (ppt, dashed line) differences (averaged over 1995–1999) between the runs with and without the 1995 ocean initialization. Three ensemble members were used for each line.

5. Effects of the Ocean Initialization

The ocean temperature and salinity adjustments induced by the 1995 ocean initialization vary with depth (Figure 1). The temperature adjustment (dT) is positive (i.e., to raise the original model ocean temperature) below about 3.0 km, while it is mostly negative above 3.0 km (except for the depth of 1.5–2.5 km). The dT was ramped to zero at the surface to reduce the 'shock effect' on the atmosphere (Pierce et al., 2004). The salinity correction (dS) was positive at all depths and largest ($\sim$0.09 parts per thousand or ppt) at the surface (Figure 1).

Figures 2 and 3 show, respectively, spatial distributions of the mean temperature and salinity differences (averaged over different depths) between the ensemble-mean of the ACPI runs and the standard historical run (case B06.28) for 1995–1999 (i.e., right after the ocean initialization). Consistent with Figure 1, the (ACPI minus standard) temperature difference averaged over the top 2000 m depth is negative (0.0 $\sim$ $-$0.3 °C) over most oceans such as the North Atlantic, the Southern Ocean, and the tropical Pacific. At depths of 2000–3500 m, the temperature difference is small (within $\pm$0.1 °C) over most oceans. In the deep oceans below 3500 m, the temperature difference is positive (0.0 $\sim$ 0.2 °C) over most oceans such as the Pacifc and Inidian Oceans, as implied by Figure 1. Figure 3 shows that the 1995

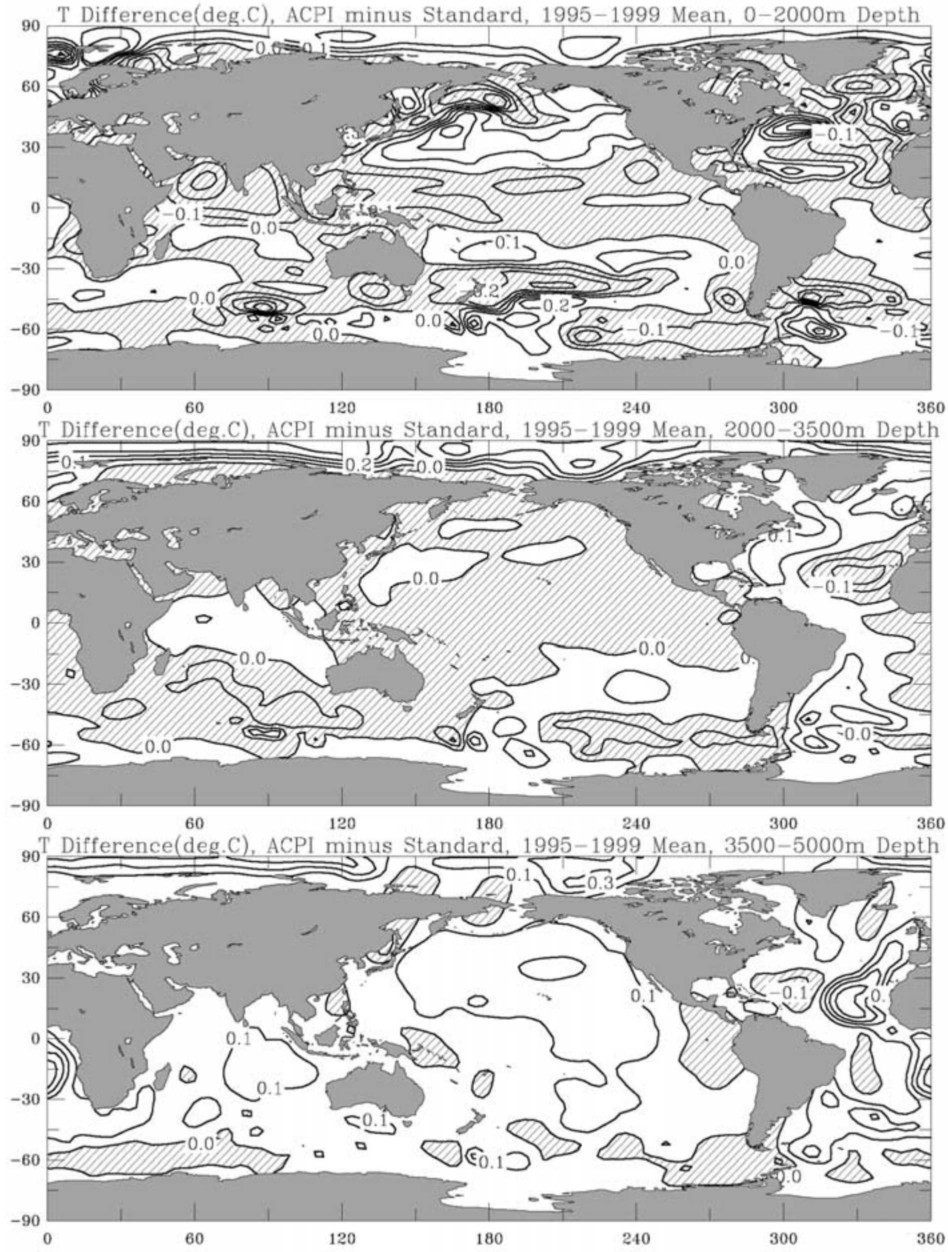

Figure 2. Geographical distributions of the temperature difference (°C) shown in Figure 1 averaged over (top) 0–2000, (middle) 2000–3500 m, and (bottom) 3500–5000 m depth.

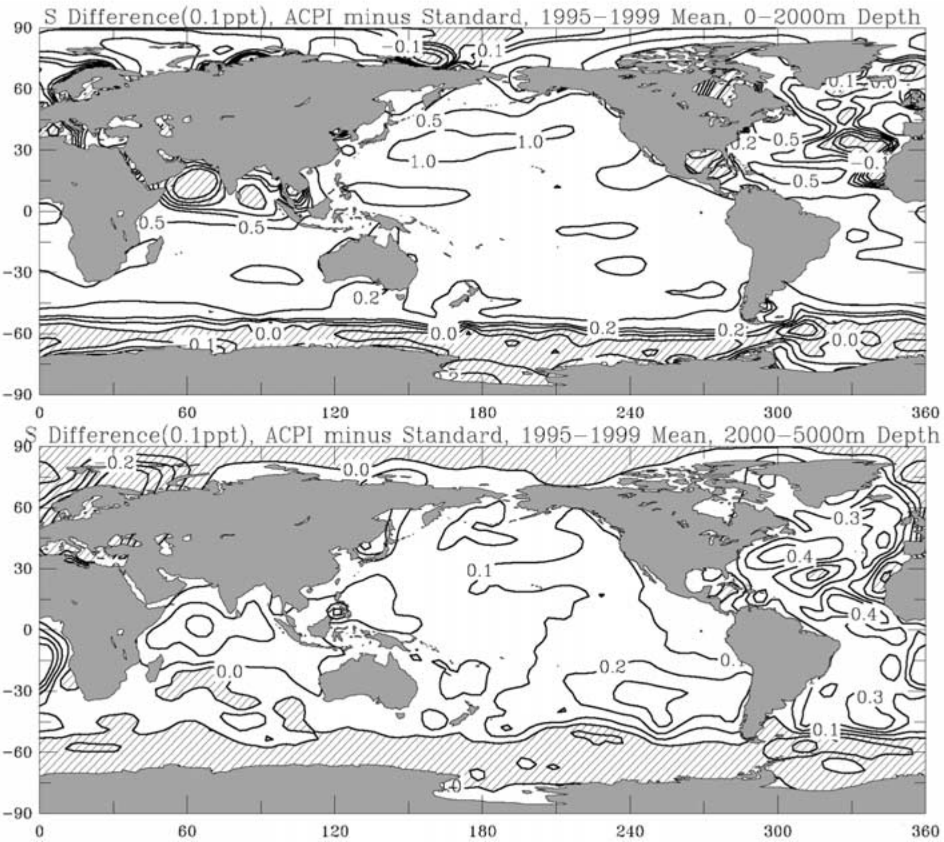

Figure 3. Same as Figure 2 except for salinity (in 0.1 ppt) for (top) 0–2000 m and (bottom) 2000–5000 m depth.

ocean initialization increases salinity over most oceans (by about 0.02 $\sim$ 0.1 ppt in the upper oceans and by 0.0 $\sim$ 0.03 ppt in the deep ocean below 2000 m), except for the the Antarctic circumpolar ocean and a few other regions, where salinity decreases.

As pointed out in Section 2, the PCM has a small cooling trend ($\sim$0.9 °C cooling in a 1000 yr integration at 3.5 km) in deep oceans in the control run. The deep oceans also get slightly saltier while the upper oceans become slightly fresher in the control run. Figure 4 shows the temperature and salinity differences between the decades centered at 1995 and 1870 in the un-forced 1870 control run. Thus Figure 4 represents the temperature and salinity drifts that would occur if no CO_2 and other forcings were added in the historical run that was used for the 1995 ocean initialization and the ACPI runs. It can be seen that the oceans at depths of 0.5–1.2 km and 2.0–4.2 km cool by about 0.05–0.15 °C from 1870 to 1995, while the top 1.0 km become fresher by 0.5–0.6 ppt and the oceans below $\sim$4.0 km is saltier by 0.5–0.7 ppt by 1995.

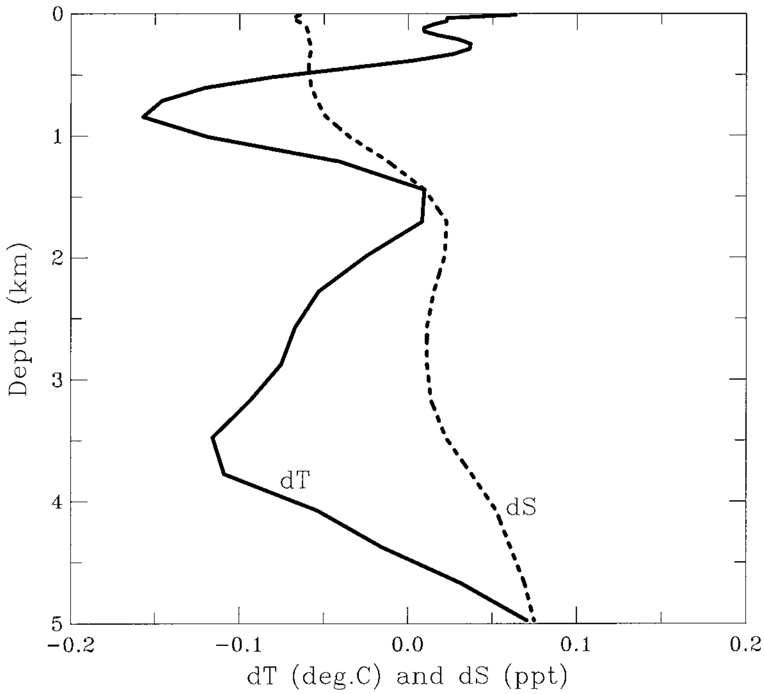

Figure 4. Profiles of ocean temperature (°C, solid line) and salinity (ppt, dashed line) differences between the decades centered at model years equivalent to calendar year 1995 and 1870 in the un-forced control run (with trace gas levels set to 1870 conditions).

The dT and dS of Figure 1 represents the model drifts during the 1870–1995 period plus the differences between the observed and model simulated T and S changes during this period (e.g., due to deficiencies in the forcing and the model response). A comparison of Figures 1 and 4 suggests that the 1995 ocean initialization partly removes the model drifts. This is especially true for the upper ocean salinity, although the dT and dS curves in Figures 1 and 4 do not cancel each other at most depths.

Pierce et al. (2004) compared several surface climate fields for the 2000–2050 period from the runs with and without the 1995 ocean initialization. They found insignificant differences between these two types of runs in global-mean surface temperature, precipitation, total cloud cover, sea level pressure, and snow depth. They concluded that this null effect of the assimilated initial conditions is a reflection of the similarity between the PCM-simulated and assimilated ocean fields for 1995.

Figure 5 shows time series of the globally-averaged surface temperature for 1980–2099 under the BAU emissions scenario. The solid curve is a 3-member ensemble average from BAU runs without the 1995 ocean initialization while the dashed curve is the mean of the three BAU runs with the ocean initialization (data

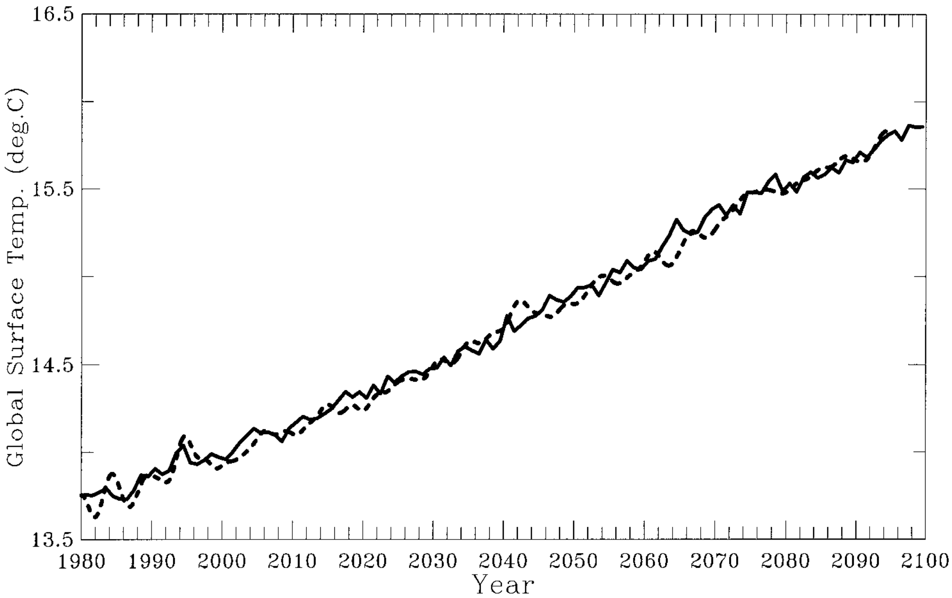

Figure 5. The 1980–2099 time series of global mean surface temperature under the BAU scenario simulated with (dashed line) and without (solid line) the 1995 ocean intialization.

before 1995 are from historical runs). It can be seen that there is essentially no differences in global surface temperature during the entire 21st century between the two types of runs.

Spatial distributions of the ensemble-mean annual surface air temperature changes from 1961–1990 to 2070–2099 under the BAU scenario with (top panel) and without (middle panel) the 1995 ocean initialization are shown in Figure 6. It is clear that the warming patterns are very similar, with 3–8 °C warming over northern high-latitudes and Antarctica, and 1–2 °C over most oceans. The differences (bottom panel) are within about ± 0.1 °C over most areas, which are insignificant (note that the ensemble range of this temperature change is about 0.2–0.5 °C over most oceans and low-latitude land and >0.5 °C over mid- and high-latitude land based on a 5-member ensemble). One exception might be the Antarctic circumpolar ocean where the surface air temperature is generally cooler (by up to 0.5 °C) in the 1995 ocean initialization case than in the standard BAU runs. However, these differences are not very significant as the ensemble range (or intra-ensemble variability) is very large (0.5–2.0 °C) over these regions.

We also did not find significant differences in precipitation and other surface fields over most of the globe. Therefore, the 1995 ocean initialization appears to have very small effects on the surface climate even by the late 21st century, consistent with Pierce et al. (2004).

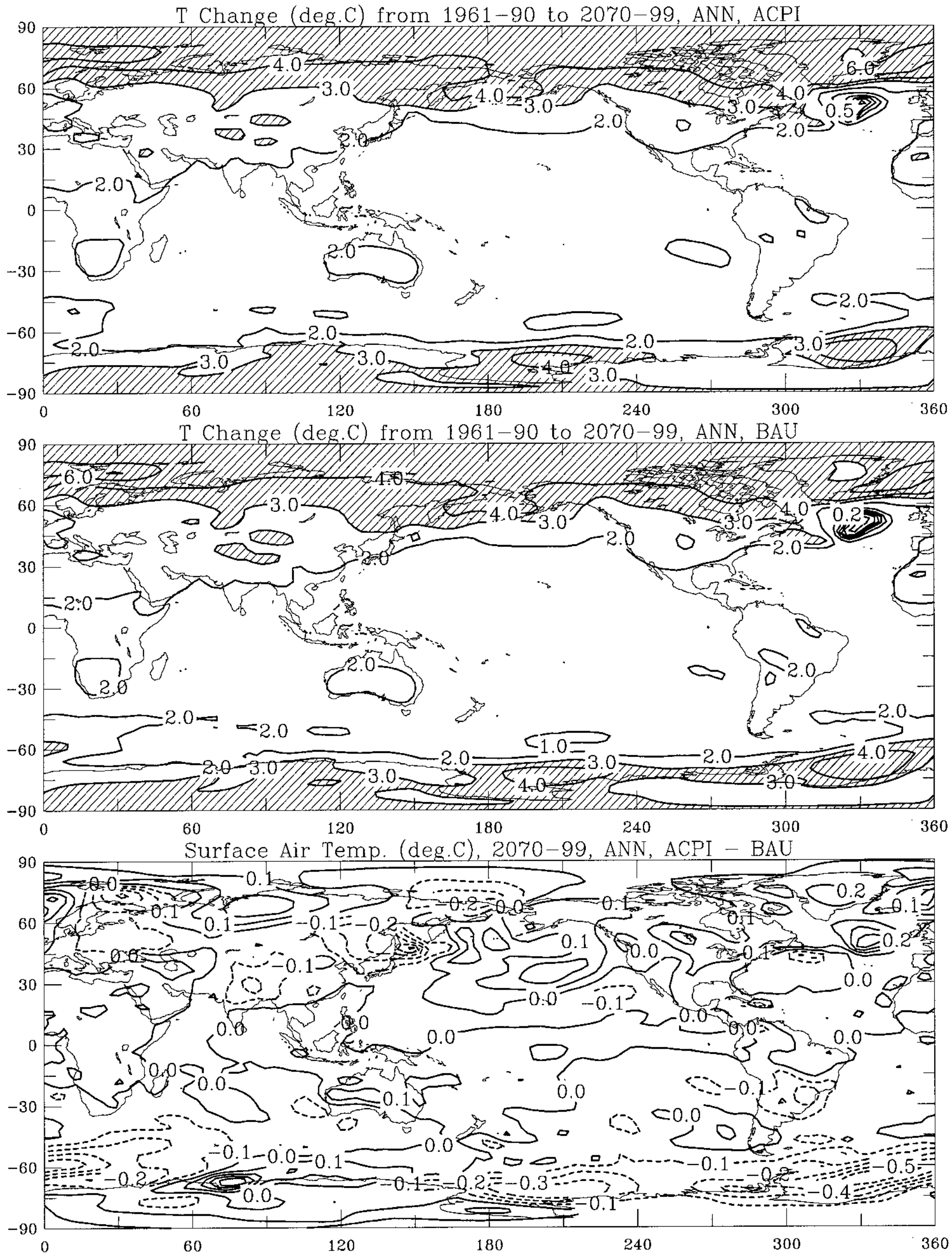

Figure 6. Annual surface air temperature change (°C) from 1961–1990 to 2070–2099 under the BAU scenario simulated (top) with and (middle) without the 1995 ocean initialization, and (bottom) the difference of the top minus the middle panel. Values over 3 °C are hatched in top two panels. Three ensemble members were used for each panel.

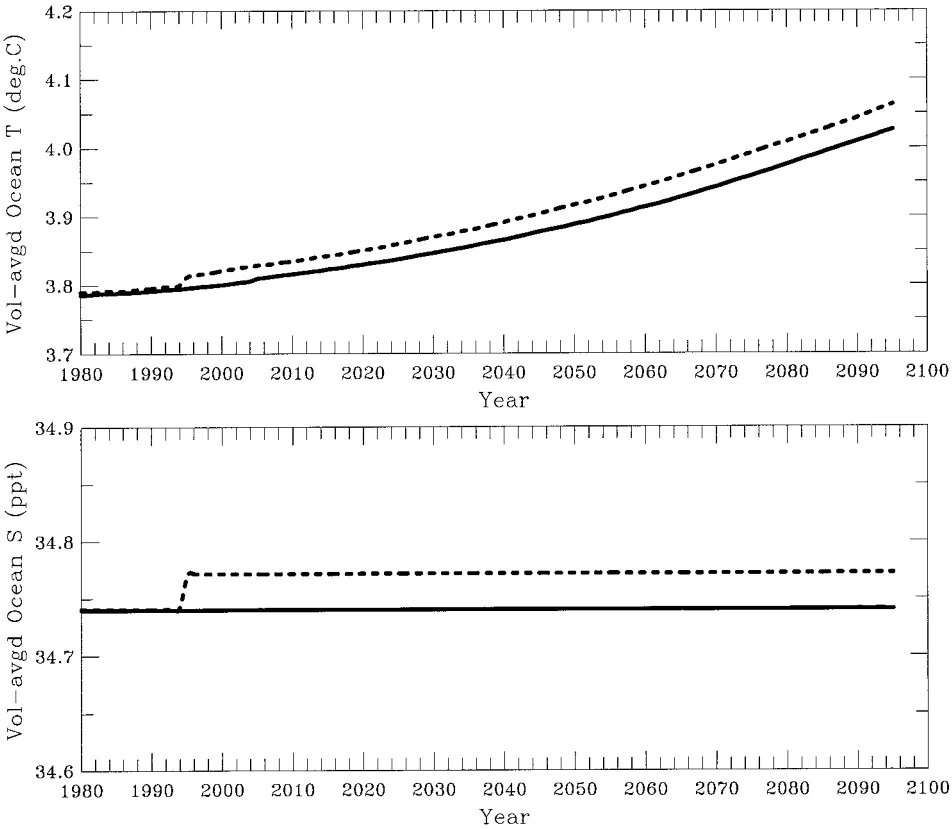

Figure 7. Ocean temperature (top) and salinity (bottom) averaged over the entire ocean volume under the BAU scenario simulated with (dashed line) and without (solid line) the 1995 ocean initialization.

We did, however, find that the 1995 ocean initialization does induce noticeable changes in ocean temperature and salinity fields. For example, Figure 7 (same line patterns and runs as in Figure 5) shows the 1980–2095 smoothed time series of temperature and salinity averaged over the entire global ocean volume. It is clear that the initialization at 1995 induces a jump of about 0.02 °C in volume-averaged temperature and an increase of about 0.03 ppt in volume-averaged salinity. The temperature difference increases to ~0.03 °C by the late 21st century, while the salinity difference is fairly constant over the 100 year period.

6. Discussion and Summary

Because the temperature correction induced by the 1995 ocean initialization was reduced to zero at the sea surface (see Pierce et al., 2004), the immediate effect of this initialization on the atmosphere should be negligible. After a few decades, some of the T and S adjustments within the oceans (cf. Figures 1–3) should be felt at the sea surface (through mixing and advection) and thus by the atmosphere. However, a temperature change of $\leq 0.1\,°C$ is very small compared with atmospheric and surface temperature variability. Therefore, it is not surprising that there are negligible differences in most of the surface and atmospheric fields between the runs with and without the 1995 ocean initialization.

It is possible, however, that the dT and dS corrections could be larger in some other coupled models than in the PCM if the model-simulated 1995 ocean conditions differ substantially from the assimilated (e.g., due to larger model drifts or larger oceanic response to historical forcing). Given the fact that the PCM has relatively low climate sensitivity and that there are higher heat fluxes into the oceans in models with higher climate sensitivity (Raper et al., 2002), larger oceanic warming is likely in some other CGCMs. This could lead to larger oceanic temperature corrections at 1995 than that in the PCM, and thus potentially bigger effects on surface and atmospheric fields in later decades.

In summary, we found that the initialization of the oceans to the 1995 condition as done by Pierce et al. (2004) has relatively small effects on oceanic temperature and salinity ($<0.15\,°C$ and <0.10 ppt), which is a reflection of the similarity of the PCM-simulated and assimilated ocean conditions for 1995. This confirms the similar finding by Pierce et al. (2004). The adjustments partly remove the un-forced drifts in oceanic temperature and salinity in the PCM. Comparisons with runs without the 1995 ocean initialization showed that there are insignificant differences in global surface temperature and other surface climate fields over the 21st century under the BAU emissions scenario.

Our results suggest that small differences in ocean temperature ($\sim 0.1\,°C$) and salinity (≤ 0.1 ppt) have negligible effects on surface and atmospheric fields simulated by CGCMs for the 21st century under projected emissions scenarios. If this is confirmed by other CGCMs, it would provide evidence suggesting that small drifts within the oceans in CGCMs do not affect surface climates simulated by the CGCMs for the next 50–100 years. This would be an important conclusion since most current CGCMs, whether they use surface flux adjustments or not, have drifts of varying magnitudes within the oceans in their un-forced control runs (Meehl et al., 2000b).

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