

A lowering effect of Holocene changes in sea surface temperatures  
on the atmospheric CO<sub>2</sub> concentration

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## ABSTRACT

One of mechanisms proposed to explain about 20 ppmv increase in atmospheric CO<sub>2</sub> concentration from the early to late Holocene is a warming of the surface ocean that reduces CO<sub>2</sub> solubility [*Indermühle et al.*, 1999]. Here we show that this hypothesis is not supported by both reconstructed and simulated changes in sea surface temperatures (SSTs). The reason is an inhomogeneous distribution of the SST changes across the globe during the course of Holocene. While alkenone-based SST reconstructions compiled in the GHOST database [*Kim et al.*, 2004; *Kim and Schneider*, 2004] suggest a net warming of the surface ocean on a global scale by  $0.2\pm 0.2^{\circ}\text{C}$ , both data and model results support significant cooling trend for the North Atlantic during the last 8,000 years. In response to reconstructed cooling of the North Atlantic by  $1.1\pm 0.2^{\circ}\text{C}$ , zonally-averaged model of oceanic biogeochemistry simulates a drawdown of atmospheric CO<sub>2</sub> by  $7\pm 0.8$  ppmv, while reconstructed warming of Pacific Ocean by  $0.6\pm 0.4^{\circ}\text{C}$  counterbalances this effect by about 1 ppmv. On a global scale, this model simulates a lowering of atmospheric CO<sub>2</sub> from the Holocene to pre-industrial by  $6\pm 2$  ppmv due to changes in SSTs, while more complex, three-dimensional biogeochemistry model indicates a moderate decrease by 1 ppmv after 300 years of the model integration. Our study suggests that changes in SSTs had altered atmospheric CO<sub>2</sub> in a direction opposite to the observed trend and that the other mechanisms were responsible for the CO<sub>2</sub> growth during the Holocene.

## Introduction

Understanding of carbon cycle in the past is a key for successful projection of atmospheric CO<sub>2</sub> dynamics in the future. What mechanisms have caused about 20 parts per million by volume (ppmv) increase in atmospheric CO<sub>2</sub> during the Holocene recorded in the Taylor Dome ice core [*Indermühle et al.*, 1999]? An interest to this question is heated up by *Ruddiman's* [2003; 2005; 2006] hypothesis that this CO<sub>2</sub> growth manifests a beginning of profound influence of humans on climate. There are no doubts that anthropogenic land cover changes have started long before industrial era, but the magnitude of these changes and their climatic consequences is quite uncertain [*Houghton et al.*, 1983; *Klein Goldewijk*, 2001; *Brovkin et al.*, 2004; *Olofsson and Hickler*, in press]. Meanwhile, there is a rationale to check a need to invoke anthropogenic hypothesis by firstly testing hypotheses about natural forcings in the Holocene, especially ones that might be tested against available proxy data [*Claussen et al.*, 2005; *Crucifix et al.*, 2005; *Broecker and Stocker*, 2006; *Schurgers et al.*, in press]. Several natural explanations for the Holocene CO<sub>2</sub> trend have been suggested, including release of terrestrial carbon and changes in SSTs [*Indermühle et al.*, 1999], carbonate compensation in the ocean [*Broecker et al.*, 1999a; *Broecker and Clark*, 2003], and coral reef growth [*Ridgwell et al.*, 2003].

Here we focus on the effect of changes in SSTs on the atmospheric CO<sub>2</sub>. *Indermühle et al.* [1999] applied inverse modeling and estimated an effect on global SST increase of 0.5°C on atmospheric CO<sub>2</sub> in 10 ppmv. *Brovkin et al.* [2002] have found no substantial effect of SSTs on the CO<sub>2</sub> in the Holocene simulations, while model results by *Joos et al.* [2004] suggest that up to one third of CO<sub>2</sub> growth during the Holocene could be caused by increasing SSTs. *Wang et al.* [2005] suggested some increase in CO<sub>2</sub> due to small increase in SSTs (0.2°C on a global scale) during the Holocene simulated by their climate model. The uncertainty in SSTs effect on CO<sub>2</sub> in simulations discussed above was caused by differences in physical and biogeochemical models, as well as boundary conditions. For example, *Brovkin et al.* [2002] have not accounted for cooling effect of Laurentide ice sheet on climate that completely disappeared only around 7,000 yr BP, while this factor was included in simulations by *Joos et al.* [2004] and *Wang et al.* [2005]. At the same time, an impulse response model of biogeochemistry applied by *Joos et al.* [2004] is driven by globally-averaged SSTs changes, while CLIMBER-2 model used by *Brovkin et al.* [2002] includes zonally-averaged model with 2.5° latitudinal resolution. The latter

model accounts for difference in precessional forcing between tropical and extratropical regions that is pronounced for the Holocene [Berger and Loutre, 2004].

Recently, Kim *et al.* [2004] reconstructed changes in SSTs during the Holocene based on alkenone biomarker. This analysis reveals a rather complex pattern of SSTs changes during the Holocene. North Atlantic sites have a pronounced trend towards cooling, while North Pacific and northern subtropical and tropical sites indicate warming trend. For the North Atlantic, their conclusions are in line with results by Marchal *et al.* [2002] on long-term cooling of the sea surface in the northeast Atlantic and Mediterranean during the Holocene. The assemblage of alkenone SST data in GHOST dataset [Kim and Schneider, 2004] provides globally-average changes in  $0.2\pm 0.2^\circ\text{C}$  for the last 8,000 years (Fig. 1).

## Methods

Are opposite trends in the North Atlantic and the tropics revealed in the proxy data supported by model simulations? If so, what is their effect on atmospheric CO<sub>2</sub> concentration? To address these questions, we have used two Earth system models developed in PIK. CLIMBER-2 model that includes interactive atmospheric and land surface modules, zonally-averaged model of ocean dynamics, and oceanic biogeochemistry [Petoukhov *et al.*, 2000; Ganopolski *et al.*, 2001; Brovkin *et al.*, 2002] has been used for transient simulations through the Holocene and in the sensitivity analysis. More sophisticated model, CLIMBER-3 $\alpha$ , consisting of interactive atmosphere, land surface, and 3-dimensional ocean model [Montoya *et al.*, 2005] has been applied in sensitivity experiments to evaluate effect of reconstructed SSTs on atmospheric CO<sub>2</sub>. CLIMBER-3 $\alpha$  was coupled with the same type of NPZD model [Six and Maier-Reimer, 1996] as CLIMBER-2, however, in contrast to the latter, air-sea gas-exchange of CO<sub>2</sub> was treated as a quadratic function of the 10m height wind speed [Wanninkhof, 1992] provided by the NCEP climatology [Kalnay *et al.*, 1996]. Since the CLIMBER-3 $\alpha$  ocean model employs an advection scheme which is nearly free of numerical diffusion, it was used with low diapycnal background diffusivities of the order of  $0.1\text{ cm}^2\text{s}^{-1}$ , notably within the permanent thermocline [Hofmann and Maqueda, 2006].

## Results

### *CLIMBER-2 transient simulation*

In the transient simulation TRAN of climate from 8,000 yr BP to pre-industrial, CLIMBER-2 model has been driven by changes in orbital forcing [Berger and Loutre, 1991], ice sheet [Peltier, 1994; Joos *et al.*, 2004], and observed atmospheric CO<sub>2</sub> concentration [Indermühle *et al.*, 1999]. Initial state was achieved after 10,000 years of the model integration with boundary conditions for 8,000 yr BP. On a global scale, simulated SST increased from 8,000 yr BP to pre-industrial period by 0.1°C, most of this warming occurred from 8,000 to 7,000 yr BP in response to decay of the Laurentide ice sheet. During the later period, warming effect of increasing atmospheric CO<sub>2</sub> concentration counteracts cooling due to declining summer insolation in the northern high latitudes. In the high latitude regions, the biomarkers such as alkenones are proxies for temperature during the summer when organic production is taking place. In general, CLIMBER-2 shows changes in SSTs of a smaller scale than in the alkenone SST reconstructions. In the North Atlantic, simulated temperatures in August (mid-summer) in 70-80°N region declines by 1°C, the most changes occurs during the period from 8,000 to 3,000 yr BP (Fig. 2, a). In latitudes 50-70°N, a cooling trend is visible but amplitude of changes is smaller (from 0.2°C at 8,000 yr BP to -0.1°C at 3,000 yr BP). Data for marine core MD952015 (59°N, 26°W) from the open ocean support an SSTs decrease by about 1.2°C from 8,000 to 3,500 yr BP and some tendency for later warming (Fig. 2a). In the tropical region of 0-10°N, the model simulates a warming trend in SST by about 0.1°C and 0.2°C for the Atlantic and the Pacific, respectively (Fig. 2b). In the other latitudes in zone 30°S to 30°N, SSTs behavior is similar (not shown). A marine core M35003-4 (12°N, 61°W) from the Caribbean basin demonstrates warming of 0.7°C that is stronger than changes simulated by the model but goes in the same direction.

Simulated SSTs in the North Atlantic decline during the Holocene, and this cooling trend is reversed towards warming in the tropical region. As already discussed by Marchal *et al.* [2002] and Lorenz *et al.* [2004] these trends could be explained by the orbital forcing, and an increase in atmospheric CO<sub>2</sub> concentration may play additional role that counterbalanced orbital forcing in the North Atlantic and amplified in the tropics. In the North Pacific, CLIMBER-2 simulations doesn't show a warming trend reconstructed from alkenone records by Kim *et al.* [2004]. This could be explained by both model and data limitation. First, CLIMBER-2 model doesn't simulate planetary waves and zonal oscillation patterns that might be responsible for Northeast Atlantic - Northeast Pacific dipole (see discussion below). Second, alkenone records analyzed by Kim *et al.* [2004] were collected for coastal regions that might be not fully representative for the open ocean areas.

*Kim et al.* [2004] suggested that a dipole in temperature changes between the Northeast Atlantic (cooling) and the Northeast Pacific (warming) could be caused by an interaction between positive Pacific North American (PNA) and negative North Atlantic Oscillation (NAO) phases of the atmospheric circulation. This hypothesis was supported by simulation of the ECHO-G model [*Lorenz and Lohmann*, 2004]. ECHO-G is a general circulation model that in particular simulates atmospheric planetary waves responsible for oscillation patterns and teleconnections, while CLIMBER-2 has a statistical-dynamical atmospheric module that simulates average atmospheric dynamics and neglects planetary waves. Therefore, the hypothesis on the suggested mechanism of teleconnection cannot be tested with CLIMBER-2 that simulates a cooling trend in the North Pacific similar to the North Atlantic.

#### *CLIMBER-2 simulations with SST forcing*

The SST changes presented on Fig. 1 are site-dependent while for using as a forcing in numerical experiments, they should be spatially and temporally aggregated. To account for the coarse resolution of the CLIMBER-2 model, the values were averaged over 10°-latitudinal belts for Atlantic, Indian, and Pacific basins. Arctic region and Southern Ocean to the south of 30°S were excluded from the analysis because of the lack of data. The values for the other areas with absent data, e.g. the tropical Pacific, were taken from the adjusted neighboring sectors for the same basin. To correct for the seasonality in sensitivity simulations, we reduced a magnitude of SST changes for the Atlantic region 50-80°N in accordance with ratio of summer to annual temperature changes in the transient simulation TRAN. Due to this seasonality adjustment, we assume that estimates of SST changes for the region and their effect on SST are conservative. Resulting SST changes with 95% confidence interval are listed in the Table 1.

What is a consequence of reconstructed SSTs changes for the atmospheric CO<sub>2</sub>? In the global simulation GLOB, changes in SSTs reported in the Table 1 were applied to the oceanic surface within CLIMBER-2 oceanic biogeochemical model while physical climate model components were driven by pre-industrial initial condition so that neither changes in SSTs nor CO<sub>2</sub> influence the climate. Atmospheric CO<sub>2</sub> was interactive between ocean and atmosphere and the model has been integrated for 2,000 years to achieve a new steady state. As a result, atmospheric CO<sub>2</sub> concentration was lowered by 6±2 ppmv. Assuming that circulation patterns and marine biology has not been changed substantially during the Holocene, this CO<sub>2</sub> decrease could be interpreted as an effect of

reconstructed SST trend on atmospheric CO<sub>2</sub> during the Holocene. To get deeper insight into effect of regional SSTs changes on CO<sub>2</sub>, additional simulations have been performed in which SSTs were changed only in North Atlantic (30°-80°N), North Pacific (30°-60°N), Tropical Atlantic (30°S-30°N), and Tropical Pacific (30°S-30°N) realms. A spatial distribution of SST forcing averaged over realms and atmospheric CO<sub>2</sub> response is presented on Fig. 3 in schematic form. The model driven by SST changes for the North Atlantic realm reveals a decrease in atmospheric CO<sub>2</sub> by 7±0.8 ppmv. The SST changes in the other oceanic realms had much less pronounced effect on atmospheric CO<sub>2</sub>: the later has been increased by 0.3±0.2 and 0.4±0.2 ppmv in simulations for the North Pacific and the North Atlantic, respectively. An effect of SST changes in tropical Atlantic was insignificant (0±0.2 ppmv). This suggests that regarding effect on atmospheric CO<sub>2</sub>, the cooling in the North Atlantic dominates over the warming in the other oceanic realms. Note that SSTs in the Southern Ocean were unchanged in the sensitivity simulations since data for this region are not available.

#### *CLIMBER-3α simulations with SST forcing*

CLIMBER-2 model possesses simplified, zonally-averaged oceanic module. How different its results are from a response of three-dimensional model? We performed simulation GLOB with CLIMBER-3α model. For comparison with CLIMBER-2, the SST forcing was kept in the same basin-averaged zonal form and mean SST values from the Table 1 were applied simultaneously to the all oceanic realms. After 1500 year spinup of the ocean physics, the oceanic biogeochemistry was switched on in CLIMBER-3α and integrated for the further 500 years. During this spinup, the atmospheric *p*CO<sub>2</sub> rose to a level of 288.7 ppmv, with an upward trend of about 0.25 ppmv per decade. The carbon cycle spinup was followed by a further integration over 300 years using the SST forcing applied in the carbon cycle model at the year 20 of the simulation. To account for the *p*CO<sub>2</sub> drift, a 300 years control simulation without Holocene SST forcing was performed as well. A dynamics of difference in atmospheric CO<sub>2</sub> between the experiment and control is shown in Fig. 4. In response to the SST changes, the atmospheric CO<sub>2</sub> difference rose abruptly by 0.3 ppmv, presumably in response to a warming in the large Pacific and Indian basins, and then started to decline due to cooling in Atlantic. By the end of the experiment, the atmospheric CO<sub>2</sub> difference was 1 ppmv and continued to grow indicating a further possible decrease in the SST experiment. A spatial distribution of annual mean sea-surface CO<sub>2</sub> difference between sensitivity and control simulations at the end of integration (year 300) is shown in Fig. 5. While CO<sub>2</sub> in Pacific and Indian basins was increased by 5 to 15 ppmv, it has been decreased by 10 to 20 ppmv in the

North Atlantic, in particular in the regions where North Atlantic Deep Waters (NADW) are formed. The later explains why, although regions with CO<sub>2</sub> increase have larger area than areas with CO<sub>2</sub> decrease, the model reveals an averaged decrease in atmospheric CO<sub>2</sub>, in line with CLIMBER-2 simulations. Although the amplitude of the increase of the annual mean sea-surface *p*CO<sub>2</sub> over the Pacific- and Indian basin is much higher in the simulation using CLIMBER-3 $\alpha$  than in CLIMBER-2, the global net effect in applying reconstructed SST anomalies is very small and tends in the same direction.

## Discussion and conclusions

We have performed several additional tests with CLIMBER-2. The biogeochemistry model of CLIMBER-2 has a sensitivity of atmospheric CO<sub>2</sub> in 11 ppmv/°C for present-day circulation (neglecting changes in land carbon and carbonate compensation). This is close to the 9-10 ppmv/°C equilibrium sensitivity suggested by *Bacastow* [1996] and *Archer et al.* [2004]. A Harvardton-Bear Equilibration Index (HBEI) has been suggested to measure an effect of low latitudes on atmospheric CO<sub>2</sub>. The index is a ratio of equilibrium changes to instantaneous changes in CO<sub>2</sub> after perturbation of the warm low-latitude surface ocean. *Broecker et al.* [1999b] have showed that box models typically possess low values of HBEI (0.1-0.2) that corresponds to a low significance of warm ocean for atmospheric CO<sub>2</sub> while three-dimensional models reveal higher values of the index (0.2-0.4) that suggests a greater exchange between warm and cold waters than in the box model. To evaluate the HBEI, the CLIMBER-2 model performed 2,000 yrs simulation of a 6°C cooling of the surface ocean between 40°S and 40°N and calculating changes in the surface CO<sub>2</sub>. The resulting HBEI value of 0.33 suggests that the CLIMBER-2 model, as a 2-dimensional model that explicitly simulated thermohaline circulation, is more similar to the 3-dimensional ocean general circulation models than to the box models. *Broecker et al.* [1999b] reported that Bern 2-D model that is similar to CLIMBER-2 has a HBEI value of 0.14, while *Ridgwell* [2001] has found a HBEI value of 0.39 for the similar 2-D model. As suggested by *Ridgwell* [2001], the representation of convective mixing is a primary factor responsible for the variability in values reported by *Broecker et al.* [1999b].

Transient Holocene simulations with CLIMBER-2 model suggested that the SSTs in the North Atlantic realm declined during the Holocene, and that this cooling trend was reversed towards warming in the tropical region. These results support the view by *Marchal et al.* [2002] and *Kim et al.* [2004] that the Holocene SST dynamics could be

explained by the orbital forcing changes, and an increase in atmospheric CO<sub>2</sub> concentration may play additional role that counterbalanced orbital forcing in northern temperate and subtropical latitudes (see comments above). In the North Pacific, CLIMBER-2 simulations do not reveal a warming trend observed in alkenone records. Presumably, a simplicity of atmospheric dynamics module prevents the model from simulation of a dipole in temperature changes between Atlantic and Pacific basins due to an interaction between positive PNA and negative NAO phases of the atmospheric circulation [Kim *et al.*, 2004; Lorenz and Lohmann, 2004]. [Lorenz *et al.*, 2006] argued that the warming in the tropics is due to the winter insolation increase in the tropics while the cooling in the North Atlantic is due to the summer insolation decrease. The increase of CO<sub>2</sub> might have increased SST everywhere. Therefore, a CO<sub>2</sub>-induced warming in the North Atlantic is overprinted by a stronger cooling by orbital forcing but amplified a warming in the tropics.

The CO<sub>2</sub> lowering by 1 ppmv in CLIMBER-3 $\alpha$  is much less than a decrease by 6 $\pm$ 2 ppmv obtained in CLIMBER-2 simulations. One of the reasons for this difference is that 300 yrs simulation with CLIMBER-3 $\alpha$  is not long enough to come to equilibrium with the new boundary conditions. In CLIMBER-2 simulations, the decrease in CO<sub>2</sub> after 300 years (3 ppmv) is only about a half of the equilibrium response after 2,000 years. The same temporal dynamics could be valid for CLIMBER-3 $\alpha$ . As opposed to CLIMBER-2, CLIMBER-3 $\alpha$  uses a variable air-sea gas-exchange parameterization [Wanninkhof, 1992] and low vertical diffusivities [Hofmann and Maqueda, 2006], which might also lead to a less sensitive model behaviour.

Simulations of oceanic biogeochemistry with CLIMBER-2 and CLIMBER-3 $\alpha$  models suggested that the Holocene SST changes reconstructed by Kim and Schneider [2004] led to a decrease in atmospheric CO<sub>2</sub>. A difference in the magnitude of CO<sub>2</sub> decrease, 6 $\pm$ 2 ppmv and 1 ppmv for CLIMBER-2 and CLIMBER-3 $\alpha$  models respectively, could be explained by differences in model parameterization and simulation length. Our study suggests that changes in SSTs had altered atmospheric CO<sub>2</sub> in a direction opposite to the observed trend and that the other mechanisms, presumably related to the changes in carbonate chemistry, were responsible for the CO<sub>2</sub> increase during the Holocene.

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Table 1. Changes in SSTs used to force the biogeochemistry models. GHOST data [Kim and Schneider, 2004], shown in Fig. 1, are seasonally adjusted for latitudes 50-80°N in the Atlantic and substituted with nearest basin data in case no data is available for the latitudinal belt. SSTs changes in the Arctic basin and to the south of 30°S were neglected. The measurement error is for 95% confidence interval.

Latitude	$\Delta$ SST, °C		
	Atlantic	Indian	Pacific
70-80°N	-1.3±0.1		
60-70°N	-1.5±0.1		
50-60°N	-1.4±0.1		0.7±0.4
40-50°N	-0.9±0.5		0.7±0.4
30-40°N	-0.8±0.2		0.6±0.7
20-30°N	-0.9±0.1	0.6±0.2	0.4±0.2
10-20°N	0.2±0.2	0.3±0.1	0.7±1.0
0-10°N	0.2±0.2	0.3±0.1	0.9±0.1
0-10°S	0.2±0.2	0.3±0.1	0.9±0.1
10-20°S	-0.2±0.1	0.3±0.1	0.9±0.1
20-30°S	-0.2±0.1	-0.1±0.3	0.9±0.1

## Figure captions

Fig. 1. The spatial distribution of linear trend in SST ( $^{\circ}\text{C}/8,000$  yr) reconstructed from the alkenone data [Kim and Schneider, 2004]. Blue and red color of labels indicates cooling and warming trends from 8,000 yr BP to pre-industrial, respectively.

Fig. 2. Model-data comparison of SST changes ( $^{\circ}\text{C}$ ) through the Holocene relative to the pre-industrial period. Model results are from the transient CLIMBER-2 simulation: a) North Atlantic and b) Tropical Ocean.

Fig. 3. A sketch showing an effect of SST changes in Table 1 on atmospheric  $\text{CO}_2$  for different oceanic realms during the last 8,000 years obtained in CLIMBER-2 sensitivity simulations (see text for details).

Fig. 4. A dynamics of difference in annual mean sea-surface  $\text{CO}_2$  difference (ppmv) simulated by CLIMBER-3 $\alpha$  in response to the SST changes. Shown is a difference between sensitivity and control simulations, the SST forcing was applied after first 20 simulation years.

Fig. 5. Annual mean sea-surface  $\text{CO}_2$  difference (ppmv) simulated by CLIMBER-3 $\alpha$  in response to the SST changes in Table 1. Shown is a difference between sensitivity and control simulations after 300-yr integration.

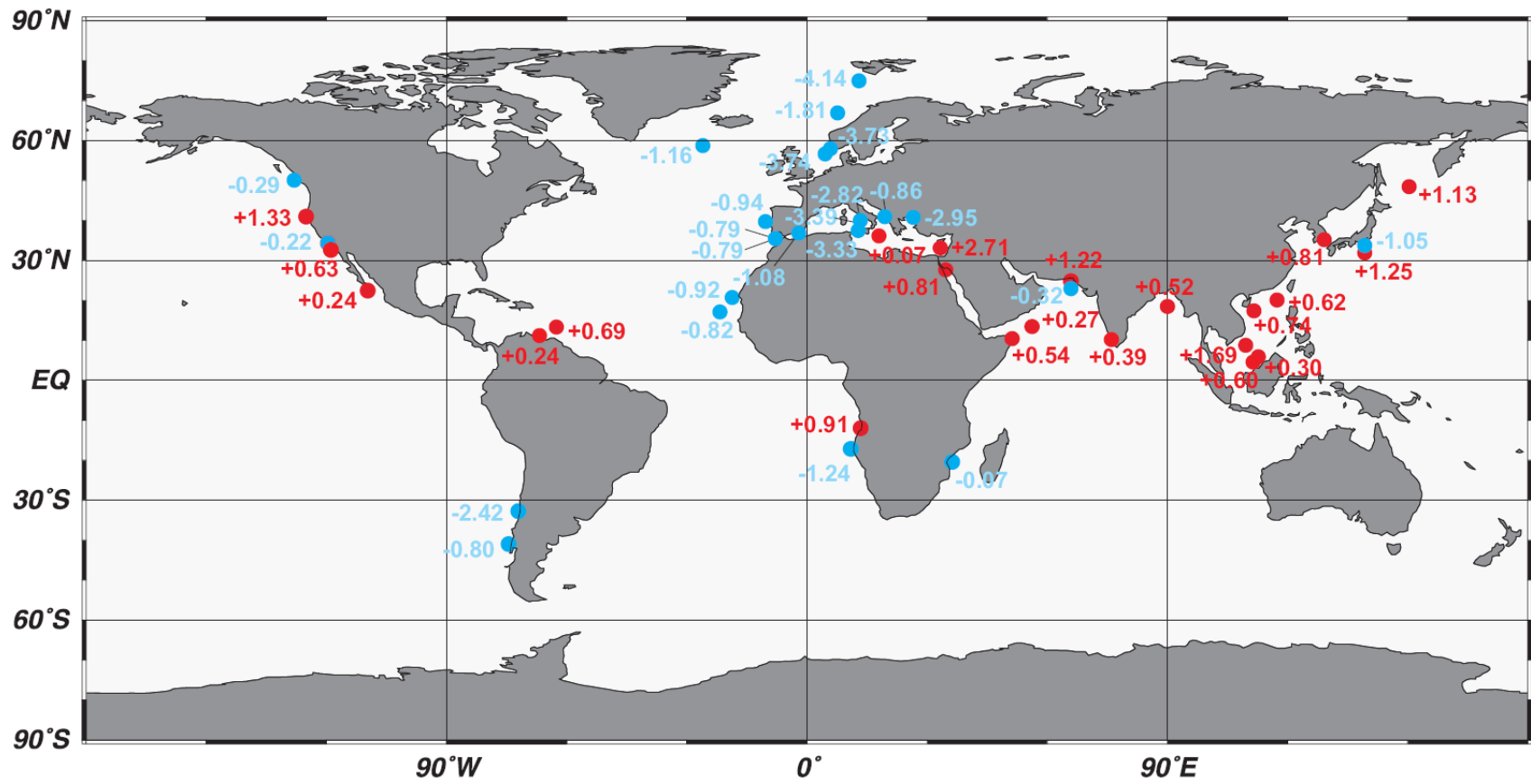


Figure 1

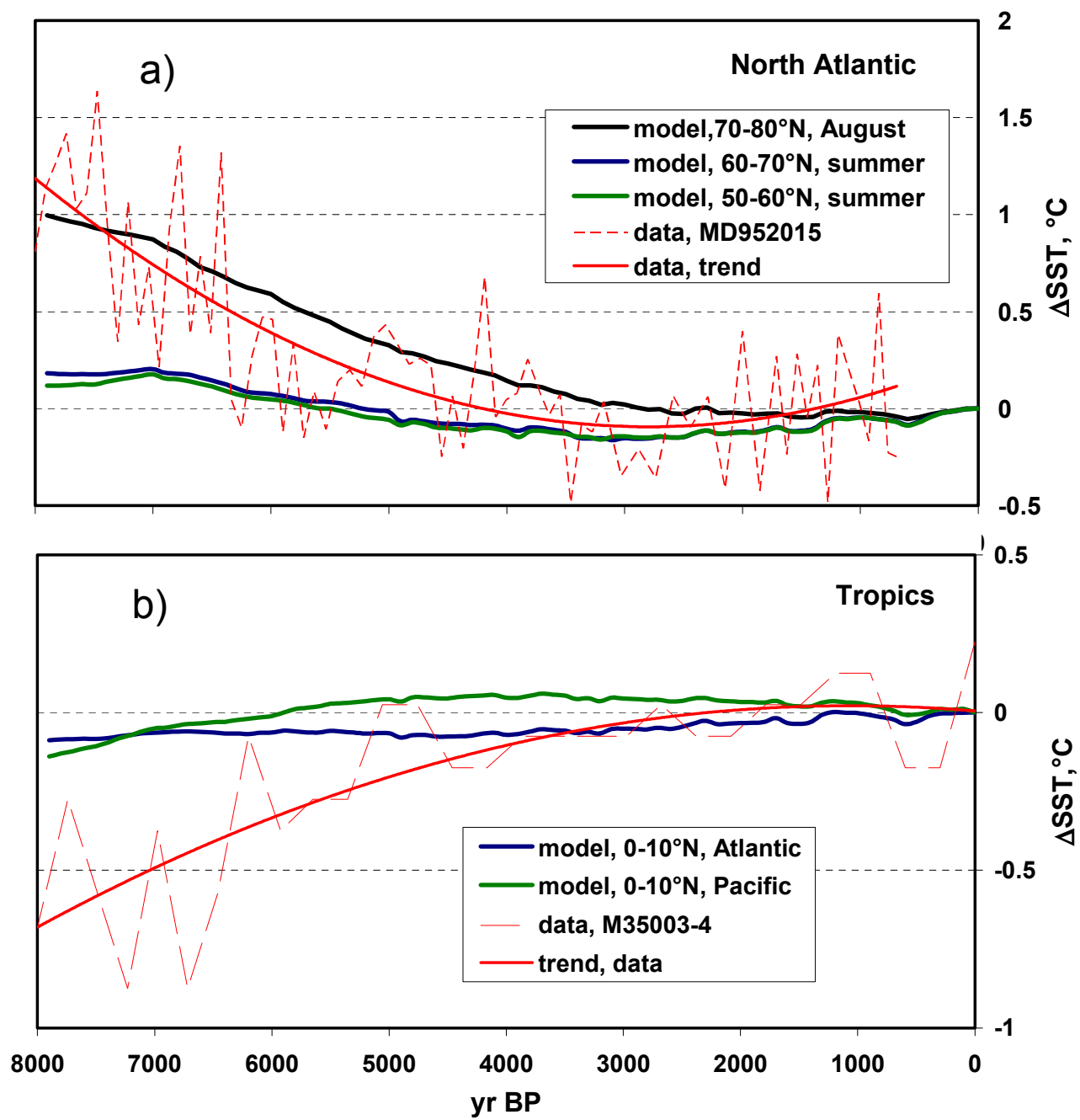


Figure 2

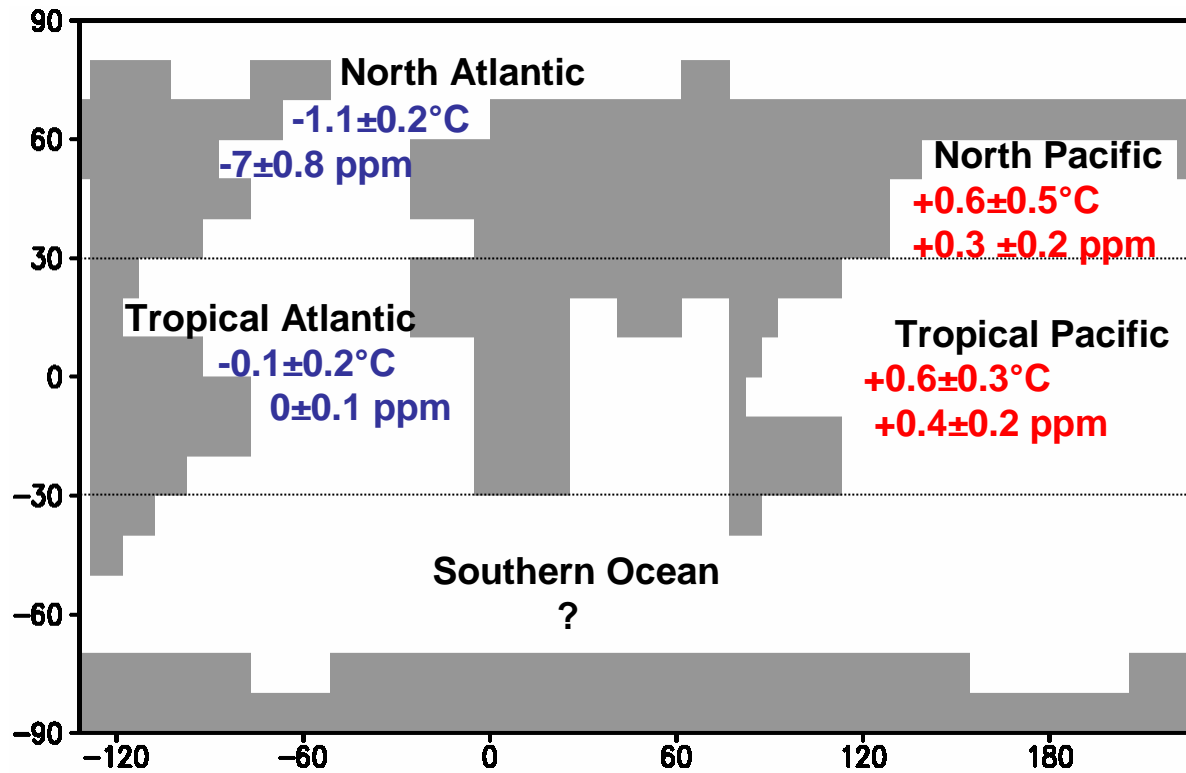


Figure 3

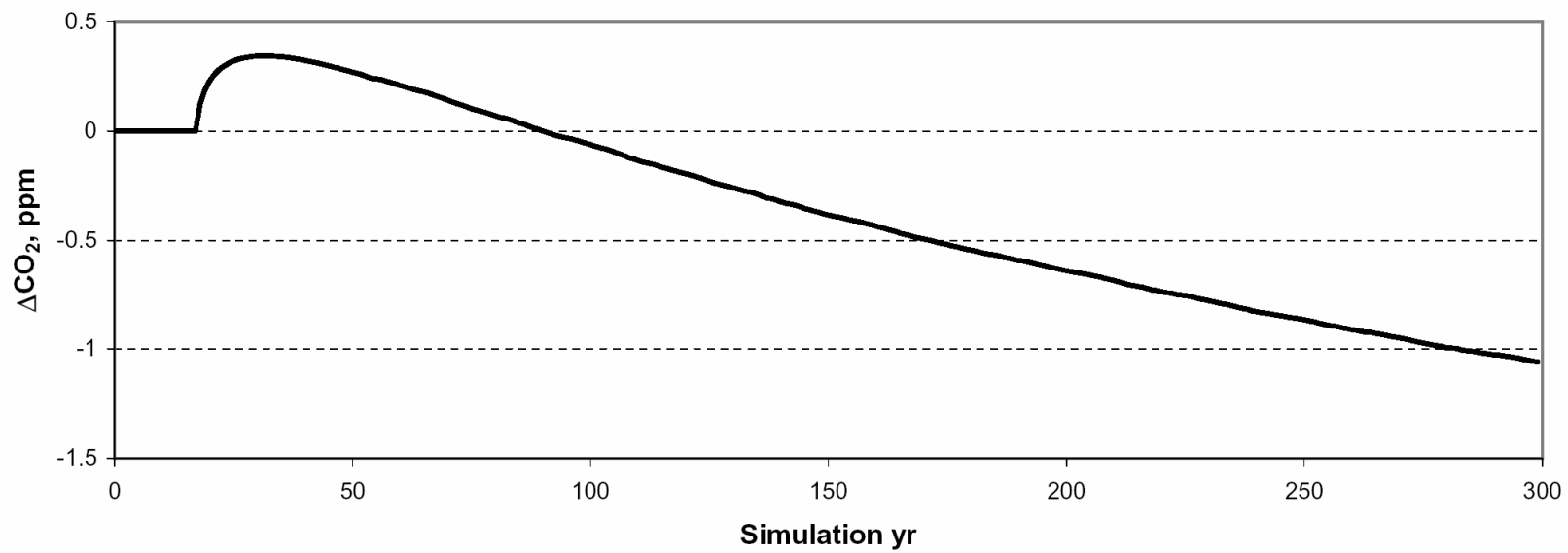


Figure 4

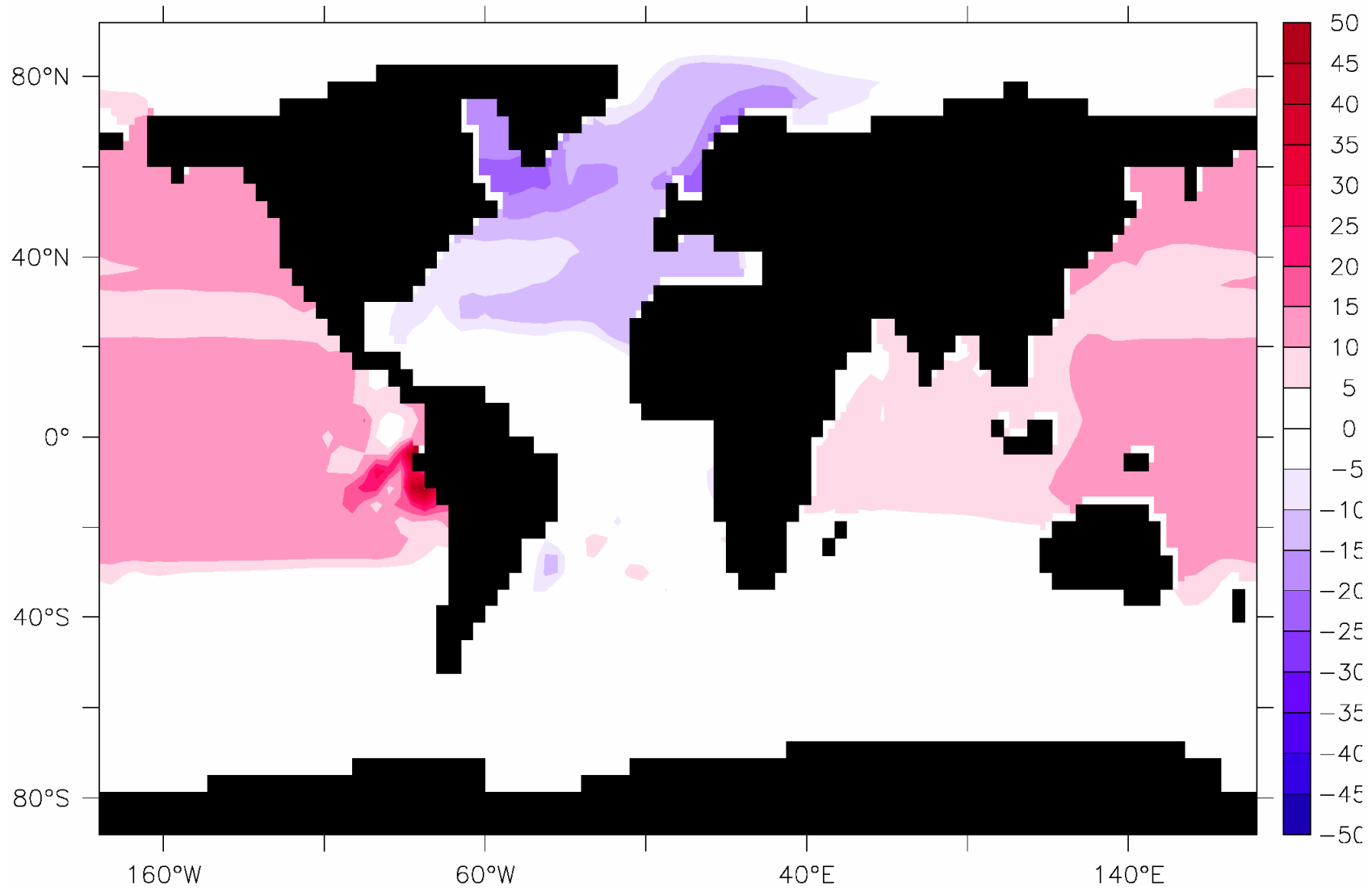


Figure 5