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HIGH-RESOLUTION GLOBAL SIMULATION OF THE CLIMATIC EFFECTS OF INCREASED GREENHOUSE GASES

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1. INTRODUCTION

Typical state of the art Atmospheric General Circulation Models (AGCMs) used in climate change studies have approximately 300 km resolution in the horizontal. As computing power increases, many climate modeling groups are exploring the possibility of enhancing the resolution of AGCMs. In principle, high-resolution models have several advantages. Dynamics, topography and the land sea mask are better resolved compared to their coarse resolution counterparts. More physical processes can be explicitly represented reducing dependence on semi-empirical parameterizations. With a high-resolution model, regional spatial scale details are simulated and hence prediction of regional climate change becomes more credible. Because high-resolution models simulate a wider spectrum of spatial scales and their nonlinear interactions, in principle, even the larger scale features should be better simulated by them. This was found to be the case by Williamson (1999) and Duffy et al. (2002). Higher resolution *global* models have the added advantage over regional models that they avoid the numerical problems associated with lateral boundary conditions. They also avoid the scale separation issues that are faced by regional models driven by coarse resolution global models.

In this paper, we report on the simulation of global climate change using the highest resolution (T170) yet performed for the global domain with an AGCM. Here, our primary motivation is to investigate if climate sensitivity on both global and regional scales depends on the resolution of the model. This is an important issue in global climate models whenever their resolution is changed. Because of the high cost of computing, we compare only two resolutions in this study, T42 and T170.

Caution should be exercised in interpreting our results because we have performed climate simulations using a *single* atmospheric general circulation model driven by prescribed sea surface temperatures and sea ice. It lacks the feedbacks associated with a fully dynamically coupled ocean, and those associated with ocean and land carbon cycles. Traditional estimates of climate model sensitivity use AGCMs coupled to a mixed layer ocean. Instead, we have used a simplified model formulation for our estimate of climate sensitivity. Therefore, it is possible that other atmospheric GCMs coupled to ocean and carbon cycle models would yield qualitatively and quantitatively different results (Hansen *et al*., 1999).

2. THE MODEL

We use National Center for Atmospheric Research (NCAR) CCM3 (Kiehl *et al*., 1996). CCM3 is a spectral model with a specified number of spherical harmonics to represent the horizontal structure of prognostic variables. In the vertical, a hybrid sigma-pressure coordinate system is used. For our experiments we used 42 and 170 waves in the horizontal: the horizontal resolution is ~2.8° (grid spacing of 300 km) in latitude and longitude for T42 and 0.7^0 (~ 75 km) for T170. The model has 18 levels in the vertical. The model has been extensively "tuned" to optimize results at T42. In part as a result of this tuning, the standard configuration (T42) has now very little systematic bias in the top-of-atmosphere and surface energy budgets. We adopted a version of CCM3 that uses

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prescribed sea surface temperature and sea ice as lower boundary condition.

3. EXPERIMENTS

Two simulations are performed at each resolution (T42 and T170): 1) a control simulation with present day climatological SSTs and sea ice extent, 2) a "2100 AD" simulation with SST and sea ice extent corresponding to 2100 AD. The greenhouse gas concentrations for these simulations are listed in Table 1. The mixing ratios for the 2100 AD simulation are the average values for the years 2090-2099 of the Business As Usual (BAU) 21st century simulation (Dai *et al*., 2001) of the NCAR Climate System Model (CSM).

Table 1: Concentrations of greenhouse gases used in the simulations

Gases	Present (control)	2100 AD
CO_2 (ppmv)	355	710
CH_4 (ppbv)	1714	2538
N_2O (ppbv)	311	412
CFC-11 (pptv)	280	938
CFC-12 (pptv)	503	230

The monthly mean SST differences between the 2100 AD and control simulations are obtained from the average values for the years 2090-2099 of the BAU 21st century CSM simulation minus values for 1990-1999 of IPCC A1 scenario 21st simulation of CSM. These monthly mean SST differences are added to monthly mean SST used in the control simulations to obtain the monthly mean SST and sea ice extent used in the 2100 AD simulations.

4. RESULTS

4.1 Global climate sensitivity

It can be noted from Table 2 that the global climate sensitivity differs between the two model resolutions by 13 %. The clear sky sensitivity is nearly the same at both resolutions. The implication is that cloud feedbacks are responsible for the slightly decreased sensitivity at the high resolution. The change in shortwave and longwave cloud forcings, listed in Table 2, can qualitatively explain the difference in global climate sensitivity: At both resolutions, changes in cloud radiative forcing (cloud feedback) tend to reduce the warming due to increased greenhouse gases. On a global basis, this negative cloud feedback at T170 is slightly larger (by 0.14 Wm^{-2}) than at T42. This difference 0.14 Wm^{-2} in cloud forcing change largely explains the lower climate sensitivity of T170. Our results are in agreement with May and Roeckner (2001) who also found weaker climate sensitivity at higher resolution (T106 vs T42).

4.2 Large scale changes in Climate

Fig. 1 shows the annual mean surface temperature change (difference between 2100 AD and control simulations) at T42 and T170. The patterns of surface temperature change are similar in both the cases. Over ocean, the temperature change is the same in both cases

Table 2: Global- and annual-mean net forcing, surface temperature change (ΔTs), climate sensitivity (λ), shortwave and longwave cloud feedback for T42 and T170 climate change experiments

Resolution	Radiative forcing ($W\ m^{-2}$)	ΔTs (K)	λ (K/Wm^{-2})	SW Cloud feedback ($W\ m^{-2}$)	LW cloud feedback ($W\ m^{-2}$)	Net cloud feedback ($W\ m^{-2}$)
Clear sky values						
T42	1.43	1.78	1.24	-	-	-
T170	1.35	1.72	1.27	-	-	-
All sky values						
T42	2.60	1.78	0.68	-1.44	-0.62	-2.06
T170	2.91	1.72	0.59	-1.67	-0.53	-2.20

because SST is prescribed in our experiments. The mean warming is slightly more over land areas in the T42 case because the global sensitivity is slightly higher at T42. The zonal mean changes of annual mean surface temperature are also similar in T170 and T42 (Figure not shown). As noted in previous studies, there is enhanced warming in the high latitudes near the sea ice boundaries (~ 70^0 lat.) due to ice -albedo feedback. T170 shows less warming over Antarctic than T42. We speculate that differences in cloud feedback are responsible for this.

The large scale patterns of change in precipitation are generally similar (Fig. 2) at T42 and T170. However, regional scale differences are apparent over Africa, South America, Tropical Indian Ocean, and elsewhere. The zonal mean of the precipitation change has very similar patterns in T42 and T170 (Figure not shown). In general, there is increased precipitation in the tropics and mid latitudes. In the annual mean, precipitation decreases between 10N and 20N and between 10S and 20S. The tropical convection is stronger at higher resolutions (Williamson et al., 1995; Duffy et al., 2002) and the tropical response to greenhouse gas forcing is also is stronger in T170. The precipitation increases over the high latitudes are associated with the large warming at these latitudes at the surface and in the lower troposphere (Fig. 1). The warming increases the water vapor content and results in increased large scale precipitation.

The large scale patterns of change in other fields such as surface pressure, cloud cover, zonally averaged atmospheric temperature, water vapor, cloudiness and zonal wind, are generally similar at T42 and T170.

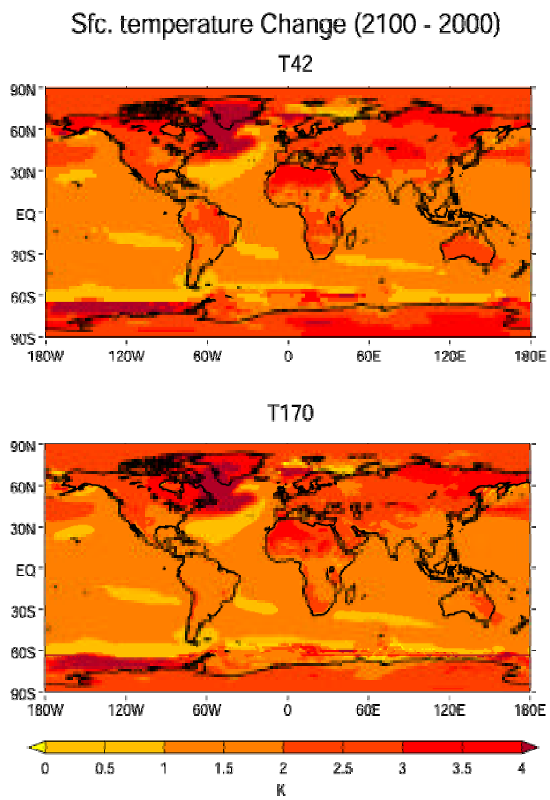

Fig. 1 a) Simulated annual mean surface temperature change (K) between "2100 AD" and present day by T42 (top) and T170 (bottom) models. The patterns of changes are similar at both resolutions.

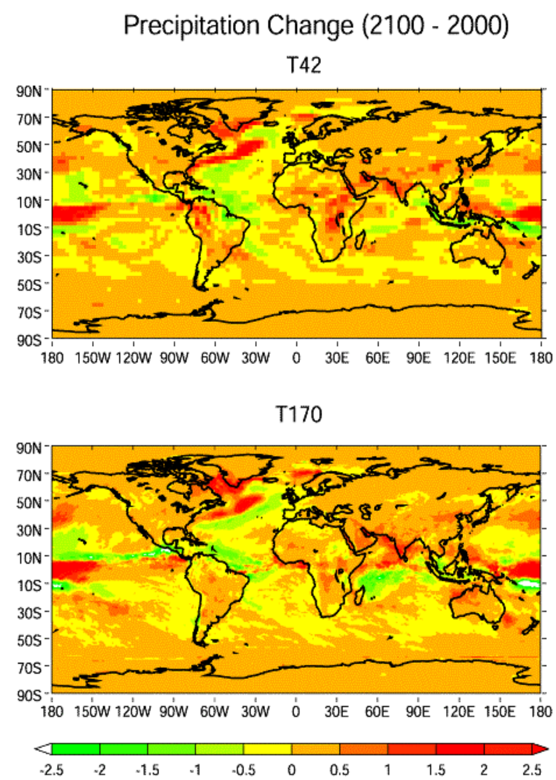

Fig. 2 Simulated annual mean precipitation change (mm day^{-1}) between "2100 AD" and present day by T42 (top) and T170 (bottom) models.

4.3 Regional climate change over US

In order to illustrate regional differences, we will be confining our discussion to climate change over the US. Table 3 lists the mean changes in DJF and JJA over the domain (30N to 50N and 70W to 125W) that encompasses the US. T170 predicts more DJF mean warming over this domain and less warming in JJA in comparison to T42. The warming in DJF is less than in JJA for T42 while the opposite is true for T170. Therefore, T42 predicts an increase in amplitude of the seasonal cycle while T170 predicts a decrease in the cycle over US. The larger warming in DJF for T170 is associated with larger increases in precipitation, precipitable water, latent heat flux, snow melt and cloudiness, and larger decrease in sea level pressure (Table 3). In fact, changes in all listed quantities are larger at T170 than T42 in DJF. In JJA, cloudiness shows an increase in T170, in comparison to T42, over the US, that leads to a decrease in surface solar insolation, and hence a smaller increase in surface temperature, sensible and latent heat fluxes, and precipitation and, a larger increase in sea level pressure.

Fig. 3 shows the DJF and JJA surface temperature change in the two cases. In DJF, there are large differences over the Rocky Mountains and Northeast US and Eastern Canada. T170 simulates larger temperature change over the Rocky Mountains because of snow albedo feedback. The amount of high cloudiness increases by 2-5 % over the northeast corner of the region in T170 while T42 shows no change in that region. This contributes to the larger warming in T170 over the Northeast US and Eastern Canada. In JJA, the simulated warming is in general smaller over US in T170 case compared to the T42 case. The warming is significantly smaller over the Central US, Rocky Mountains and Northeastern US in the T170 simulation in the summer. We found that changes in total cloudiness contribute (Figure not shown) to this difference.

Large differences in snow depth change are simulated by the two cases (Fig. 4). At T170, the DJF water equivalent snow

Table 3. Climate Statistics: Simulated change in key climate variables between "2100 AD" and present day over a domain covering US (70W to 125W and 30N to 50N) in DJF and JJA.

Climate variable	DJF		JJA	
	T42	T170	T42	T170
Ts (K)	1.96	2.36	2.44	2.17
Precipitation (mm/day)	0.15	0.38	0.24	0.18
Precipitable H_20 (mm)	1.75	1.90	3.17	3.31
Cloudiness (%)	2.29	4.68	-0.47	1.05
Snow depth (mm of H_20)	-4.17	-5.50	0.003	-0.063
Sfc. Solar insolation (Wm^{-2})	-2.95	-4.45	3.85	-3.23
Latent heat flux (Wm^{-2})	2.65	4.20	5.13	5.00
Sensible heat flux (Wm^{-2})	0.35	-1.25	0.66	-2.65
Sfc. net longwave (Wm^{-2})	-5.57	-8.40	-2.68	-5.52
SLP (pascals)	-57.0	-70.6	54.9	79.28

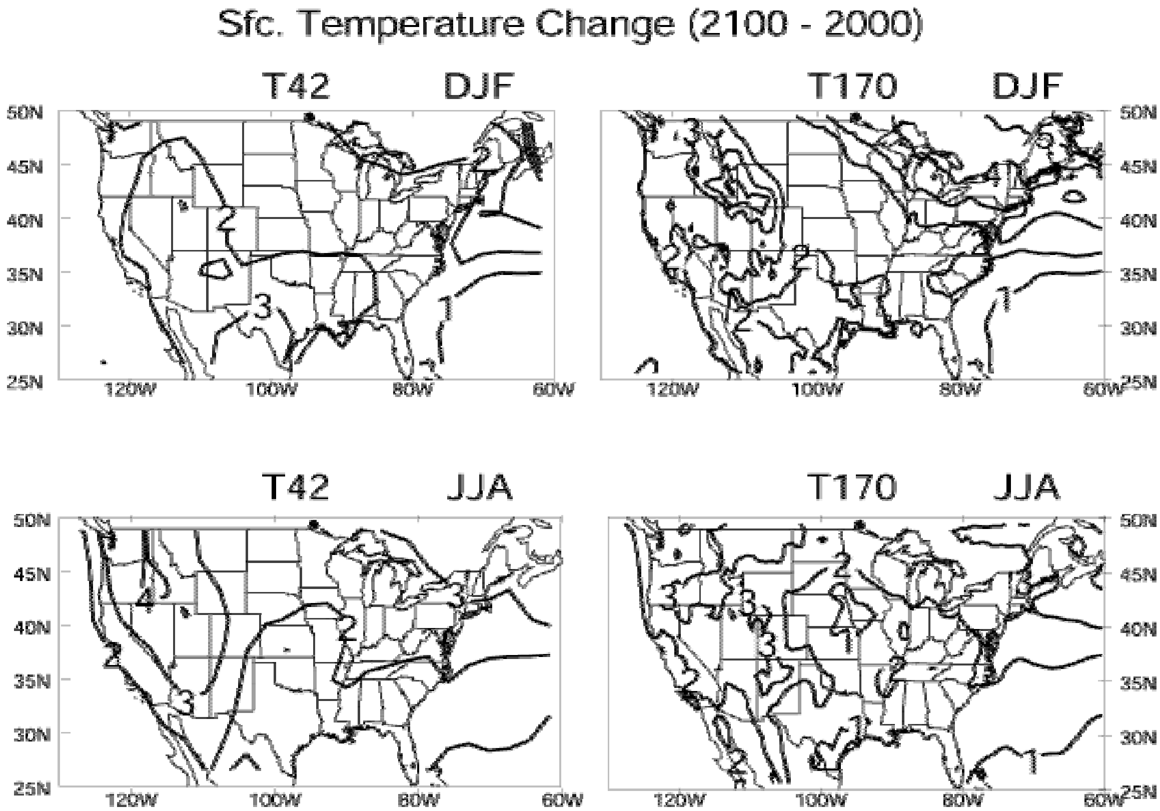

Fig. 3 Simulated surface temperature change (K) over US in DJF (top) and in JJA (bottom) between "2100 AD" and present day by T42 (left) and T170 (right) models. The contour interval is 1 K.

depth change over the Rocky Mountains is around 20 cm. This is an order of magnitude more than the change simulated in T42 case. This difference occurs because in the present climate simulation, there is more snow in T170 than T42 due to better resolution of topography. This produces higher elevations and colder surface temperatures at T170. It can be noticed that the resolution of topography at neither T42 nor T170 is not adequate to simulate the snowfall over the Sierra Nevada Mountains. Therefore, we do not see any snow depth change in either case there. Neither model simulates any significant snow depth changes in JJA.

5. Discussion

In this paper, we discuss results from by far the highest-resolution simulations of global warming yet performed with a state-of-the-art global Atmospheric General Circulation Model (AGCM). We find that the global climate sensitivity and large scale patterns of climate change at both resolutions are similar. This is consistent with the findings by an earlier study (May and Roeckner, 2001). However, there are important regional scale differences, like the snow pack changes over the Rocky Mountains, that arise due to better representation of topography at high resolutions. Other significant differences, e.g. in the response of cloudiness to increased greenhouse gases, are also observed.

In this study, we have not investigated the resolution dependence of simulated variability, severe weather events, and extreme-value statistics. Our simulations do not represent land use change, nor do they represent the changes in aerosols, solar and volcanic variability, and the transient effects of climate change. Our model lacks sophisticated dynamical ocean and sea ice components. Nor were feedbacks in the carbon cycle considered in this study. Nonetheless, there is no reason to think that inclusion of these factors would change our conclusions.

We have performed climate simulations using an atmospheric general circulation model driven by prescribed sea

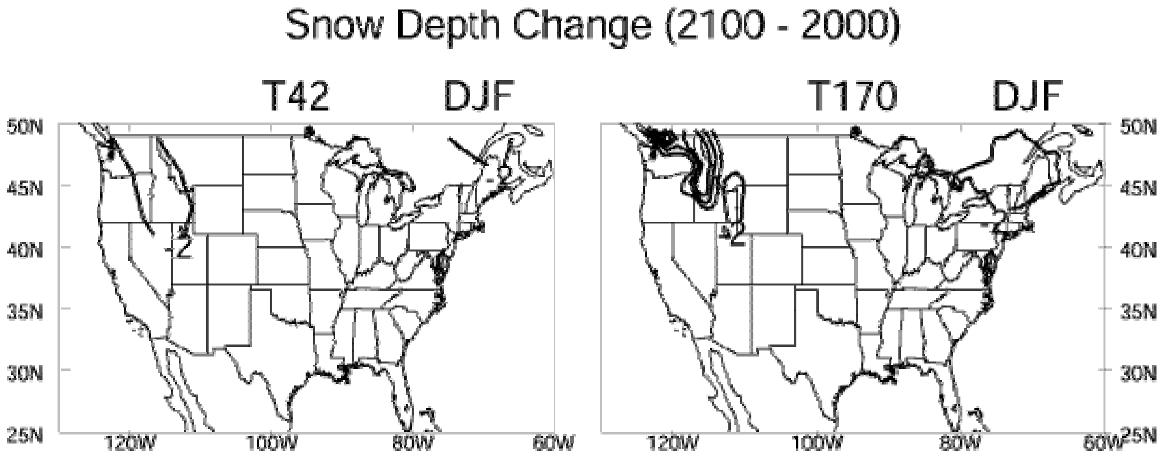

Fig. 4 Simulated snow depth change (cm of water) over US in DJF between "2100 AD" and present day by T42 (left) and T170 (right) models. The plotted contours are -2, -6, -10, -14, -18, -22 cm of water equivalent snow depth.

surface temperature, sea ice extent and sea ice thickness (Kiehl *et al*., 1996). Simulations using a coupled atmosphere, dynamic sea ice, ocean general circulation model and carbon cycle model would include dynamical feedbacks that might amplify or diminish the regional or global climate change. It is possible that other GCMs would yield quantitatively different results (Hansen *et al*., 1997), because the results may be highly sensitive to the formulation of the model and the parameterization of various physical processes.

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