Chinese Science Bulletin 2006 Vol. 51 No. 21 2651—2656

DOI: 10.1007/s11434-006-2161-6

Analyses of the predicted changes of the global oceans under the increased greenhouse gases scenarios

MU Lin[1,3], WU Dexing[1], CHEN Xue'en[1,2] & J Jungclaus[3]

1. Physical Oceanography Laboratory, Ocean University of China, Qingdao 266003, China;
2. Institute of Oceanography, Hamburg University, Hamburg 20146, Germany;
3. Max-Planck Institute for Meteorology, Hamburg 20146, Germany

Correspondence should be addressed to Mu Lin (email: lin.mu@dkrz.de)

Received April 3, 2006; accepted July 7, 2006

Abstract A new climate model (ECHAM5/MPI-OM1) developed for the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) at Max-Planck Institute for Meteorology is used to study the climate changes under the different increased CO_2 scenarios (B1, A1B and A2). Based on the corresponding model results, the sea surface temperature and salinity structure, the variations of the thermohaline circulation (THC) and the changes of sea ice in the northern hemisphere are analyzed. It is concluded that from the year of 2000 to 2100, under the B1, A1B and A2 scenarios, the global mean sea surface temperatures (SST) would increase by 2.5℃, 3.5℃ and 4.0℃ respectively, especially in the region of the Arctic, the increase of SST would be even above 10.0℃; the maximal negative value of the variation of the fresh water flux is located in the subtropical oceans, while the precipitation in the eastern tropical Pacific increases. The strength of THC decreases under the B1, A1B and A2 scenarios, and the reductions would be about 20%, 25% and 25.1% of the present THC strength respectively. In the northern hemisphere, the area of the sea ice cover would decrease by about 50% under the A1B scenario.

Keywords: greenhouse gases, THC, IPCC.

Due to the anthropogenic discharge, the greenhouse gases concentrations (mainly CO_2) continually increase after industrialization. The greenhouse gases absorb less short wave radiation from the sun, so the Earth's surface is heated which radiates longer wave energy. Most of terrestrial long wave radiation energy is absorbed by the greenhouse gases in the atmosphere, and the atmosphere is heated which also radiates longer wave radiation mostly going back to the Earth's surface. This leads to the temperature increase of the Earth's surface and lower layer atmosphere, and results in greenhouse effect. As we know, the increases of the greenhouse gases concentrations will reduce the efficiency with which the Earth's surface radiates to space. This results in a positive radiative forcing that tends to warm the lower atmosphere and the Earth's surface. The coupled system will become warmer. Because less heat escapes to space, this is the enhanced greenhouse effect[1]. The atmospheric concentration of CO_2 has increased from 280 ppm in 1750 to 367 ppm in 1999 with fossil-fuel combustion and deforestation during the Industrial Era. With the greenhouse gases concentrations increasing, the global average surface temperature has increased by 0.6 ± 0.2℃ since the late 19th century[1].

The greenhouse effect leads to a series of changes of the Earth climate system: sea level rise; changes in snow cover and land- and sea-ice extent; changes in atmospheric circulation patterns; variation of ocean circulation patterns. The climate change is a large challenge to the sustainable development. Thus to forecast the variation of the climate system under the greenhouse gases increasing scenario has very important scientific, social and economic meanings; it also has profound influences on international policies making (for example, Kyoto Protocol).

In consequence of climate changes due to greenhouse effect, changes of the thermohaline circulation (THC) are very remarkable. The present THC is characterized by the Atlantic conveyor belt, and there is no THC in the Pacific Ocean[2,3]. The THC is normally defined as the density-driven global-scale oceanic circulation which in the Atlantic Ocean sinks at high latitudes and upwells at low latitudes. The meridional transport of THC is about 90% of the total global ocean meridional transport[4]. The THC in the Atlantic flows northward in the upper layer and southward in the deeper layer. It plays an important role in the global meridional heat and freshwater transport.

The strength of THC is very important for the meridional heat transport in the Atlantic Ocean and the climate of Europe. The surface buoyancy flux perturbation can lead to the variations of the THC. With human-induced global warming due to increased atmospheric CO_2 and other greenhouse gases, there is more moisture in the atmosphere, so the meridional moisture transport is expected to be strengthened[5]. The sea surface freshwater flux is changed: there is more freshwater taken out of the subtropical oceans, and there is more freshwater added to the subpolar oceans. The salinity of the subtropical oceans increases and salinity of the subpolar oceans decreases. As a result of this salinity change, the seawater density difference between high latitudes and low latitudes in Atlantic decreases. The THC strength will thus decrease. This variation of THC will influence the climate of Europe[6].

Since the pioneering work of Manabe *et al*.[7], the variation of THC with global warming becomes a focus for oceanography scientists. Especially after Intergovernmental Panel on Climate Change project (IPCC) started, many climate models simulate the evolution of THC with increased atmospheric CO_2. Although the results of most models show that the THC will be weakened, the discrepancies of different model results are fairly large[1]. Therefore the numerical simulation about the variation of THC should be improved. A series of studies about variation of THC have been done earlier by Laboratory of Atmospheric Science and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences. For example, Zhou[8] used the atmosphere-ocean coupled model of LASG——GOALS (GOALS has been involved in the third assessment report of the IPCC[1]), to study the variation of THC with global warming. Due to computation capacity limit, however, the resolution of this model is not very high and sea ice module is fairly simple. The Max-Planck Institute for Meteorology's global atmosphere-ocean-sea ice model ——ECHAM5/MPI-OM1 is a member model of the Coupled Model Intercomparison Project (CMIP), whose results of global warming are also included in the third assessment report of the IPCC[1].

In this paper, based on the Max-Planck Institute for Meteorology's global atmosphere-ocean-sea ice model ——ECHAM5/MPI-OM1 with high resolution, the Earth system climate in the future and the variation of the THC under the greenhouse gases increasing scenarios are intensively studied.

1 Introduction of model and design of experiments

The model used here is the Max-Planck Institute for Meteorology's global atmosphere-ocean sea ice model ——ECHAM5/MPI-OM1. The Max-Planck Institute Ocean Model (MPI-OM) is a global general ocean circulation model based on an orthogonal curvilinear Arakawa C-grid. The model contains a free surface and a state of the art sea ice model with viscous-plastic rheology and snow. An orthogonal curvilinear grid allows for an arbitrary placement of the grid poles. In the current set-up, the model's north pole is shifted to Greenland and the south pole is moved toward the center of the Antarctic continent. This approach not only removes the numerical singularity associated with the convergence of meridians at the geographical poles but also produces higher resolution in the North Atlantic deep water (NADW) formation regions near Greenland (Greenland Sea, Labrador Sea) and in the Weddell Sea. In fact, the grid spacing has a minimum of about 15km around Greenland and a maximum of 184 km in the Pacific. The ocean has a 1.5° × 1.5° average horizontal grid spacing with 40 unevenly spaced vertical levels. The Max-Planck Institute Atmosphere Model (ECHAM) has its original roots in global forecast models developed at European Centre for Medium-Range Weather Forecasts (ECMWF). This model has been modified for climate research, and its development continued to the current version ECHAM5. The atmosphere model uses version 5.2 of the ECHAM model family and is run at T63 resolution (1.875° × 1.875°) with 31 vertical (hybrid) levels. There is no flux adjustment in ECHAM5/MPI-OM1, which is an advantage of this coupled model. Compared to extensively used ECHAM4, there are some modifications in ECHAM5. The aerosol module of ECHAM5 has been improved, and a new cloud cover parameterization is employed. At the same time, separate treatment has been used to cloud water and cloud ice, which improves the simulation of precipitation. A new set of land surface data (vegetation ratio, leaf area index and forest ratio) has been updated in the ECHAM5[9]. The changes of MPI-OM1 compared to MPI-OM are the improvement of sea surface wind stress calculation considering the influence of local current makes the ocean upper layer dynamics more accurate, and the modification of the sea ice module, describing the growing, melting and transport of sea ice more exactly[10].

The coupled model is run under different increased atmospheric CO_2 scenarios, which belong to the scenarios (Fig. 1) that are listed in the IPCC assessment report. From 1860 to 2000, the CO_2 forcing used is of observed values. From 2000, the coupled model is run under three scenarios of IPCC (B1, A1B and A2). The A2 scenario describes such a world in the future: the global economies develop very quickly, the global population also increases very quickly, and new energy resources and technologies will not be used, CO_2 concentrations will thus increase rapidly. In the A1B scenario, the global population and economies develop very quickly, and make a balance across all energy sources, where balance is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supplies and end use technologies. In the B1 scenario, the global population will peak in middle of the 21st century and decline thereafter, and there is rapid change in economic structures toward a service and information economy with reduction in material intensity and the introduction of clean and efficient technologies. Here, CO_2 concentration will increase gradually slowly and reach stabilization, and this scenario is an optimistic assumption.

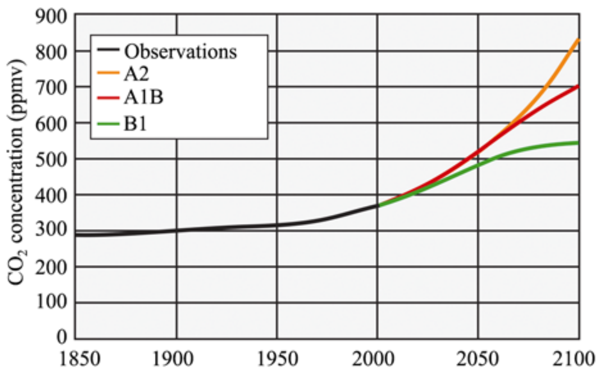

Fig. 1. CO_2 concentrations of scenarios of IPCC assessment report (data from ref. [1]).

Based on the model configured above, we run the coupled model under different greenhouse gases increasing scenarios on the super computer of German Climate Center. Firstly the coupled model spins up for 500 years with the fixed CO_2 concentration –280 ppmv which is the CO_2 concentration before industrialization. Secondly the coupled model is run from 1860 to 2000 with the observed CO_2 concentration. Finally drive the model under the B1, A1B and A2 scenarios after 2000. Because the computation is very huge, only one test is run for each scenario. Output result is of yearly mean format.

2 Analyses of results

2.1 Variation of global temperature and salinity field

Extensive evaluation on the performance of a model system is the precondition of using the model as useful tool in projecting possible future climate change. The widely used evaluation criteria are from CMIP[1)]. The precipitation, sea surface pressure and temperature simulated by ECHAM5/MPI-OM1 closely resemble observation, and the correlation coefficients are 0.51, 0.8 and 0.95 respectively. The standard deviations of precipitation, sea surface pressure and temperature are less than ±25% of the observation. The performance of this model in simulating the climate state such as the zonal mean condition, the seasonal cycle and especially the precipitation is better than that of ECHAM4/MPI-OM[9].

As a result of greenhouse effect, under increased atmospheric CO_2 scenarios, global warming will happen. Fig. 2 (a) shows time series of global mean sea surface temperature (SST) under the different scenarios. From 2000 to 2100, under the B1, A1B and A2 scenarios, global mean SST increases by 2.5 °C, 3.5 °C and 4.0 °C respectively (green line indicates the global mean SST from 1860 to 2000 under the observed CO_2 concentration forcing, and that after 2000 with the fixed CO_2 concentration in 2000). Annual mean linear trends of global mean SST are 0.025 $°C \cdot a^{-1}$, 0.035 $°C \cdot a^{-1}$ and 0.04 $°C \cdot a^{-1}$ under the B1, A1B and A2 scenarios, and the correlations all exceed 95% confidence level. The temperature increase simulated by ECHAM5/MPI-OM1 is weaker than that of GFDL Model[11], and is stronger than that of Hadley Center Model[12].

Fig. 3(a) shows the differences in the SST between the 20th century and the 21st century under the A1B scenario. The SST globally increases with greenhouse gases increasing, especially in the Arctic Ocean where the increase of SST is about 10°C. The Arctic Ocean is mainly covered by the sea ice. When the Earth system globally becomes warmer, the sea ice in the Arctic Ocean melts in large scale especially in the summer. As we know, the sea ice has high reflectivity to radiation. When the sea ice area decreases, the albedo of the Arctic Ocean will decrease. The Arctic Ocean will then absorb more radiation, and the temperature will increase more quickly, thus this would lead to a positive feedback. As a result of this positive feedback, more

1) http://www.pcmdi.llnl.gov/cmip/

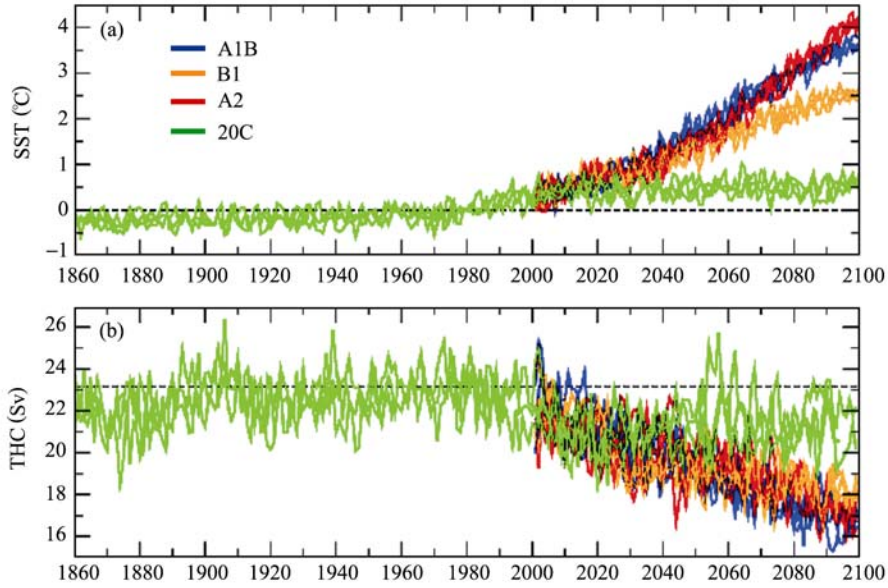

Fig. 2. Time series of (a) global mean sea surface temperature (SST) and (b) the maximum value of the annual mean THC strength with global warming under different scenarios. Green line indicates the global mean SST from 1860 to 2000 under the observed CO_2 concentration forcing, and that after 2000 with the fixed CO_2 concentration in 2000.

sea ice will be melted in the Arctic Ocean. Therefore the sea ice area becomes smaller. However the temperature increase by the Antarctic is not very large compared with that in the Arctic Ocean, because the sea ice around the Antarctic is very thick, at the same time, because of the Antarctic continent, the sea ice area will not decrease much with global warming, and the positive feedback will not be formed.

The increase of SST in the North Atlantic is not so noticeable. With global warming, the meridional THC fairly weakens, so the meridional heat transport by THC also decreases. This is why the increase of SST in the North Atlantic is not so noticeable.

Fig. 3(b) shows the differences in fresh water flux between the 20th century and the 21st century under the A1B scenario. Positive value means fresh water entering the oceans. With global warming, there is more freshwater taken out of the subtropical oceans, while more freshwater is added to the subpolar oceans. With global warming, there is more moisture in the atmosphere, so the meridional moisture transport is expected to be strengthened. Thus the evaporation of subtropical oceans increases and the precipitation of subpolar oceans is strengthened[13]. On the other hand, the zonal interbasin moisture transport is also strengthened with global warming. There is zonal interbasin fresh water transport between the Pacific Ocean and the Atlantic Ocean. And fresh water is transported by atmosphere from the Atlantic Ocean to the low latitude district of the Pacific Ocean. This transport is about 0.3Sv (1 Sv = 10^6 $m^3 \cdot s^{-1}$) at present[14]. With global warming, this transport is strengthened, leading to the increase of the precipitation in the eastern tropics in the Pacific Ocean[15,16].

Fig. 3(c) shows the differences in the sea surface salinity (SSS) between the 20th century and the 21st century under the A1B scenario. The changing pattern of SSS is similar to that of fresh water flux.

2.2 Variation of the THC

Zonally integrate the meridional current field in the Atlantic, and get the meridional streamfunction. Select the maximal value of this streamfunction as the THC strength index. Fig. 2(b) shows the time evolution of the maximum values of the annual mean THC strength under global warming. From 2000 to 2100, the strength of THC would decrease by 4 Sv, 5.1Sv and 5.2 Sv under the B1, A1B and A2 scenarios respectively, approximating 20%, 25% and 25.1% of the present THC strength. The deep water formation of the THC is highly localized in Labrador Sea and Greenland Sea which are in North Atlantic subpolar area. With global warming, there is more freshwater added to the subpolar oceans, and the temperature of these areas increases. As a result of these salinity and temperature changes, the seawater density difference between high latitudes and

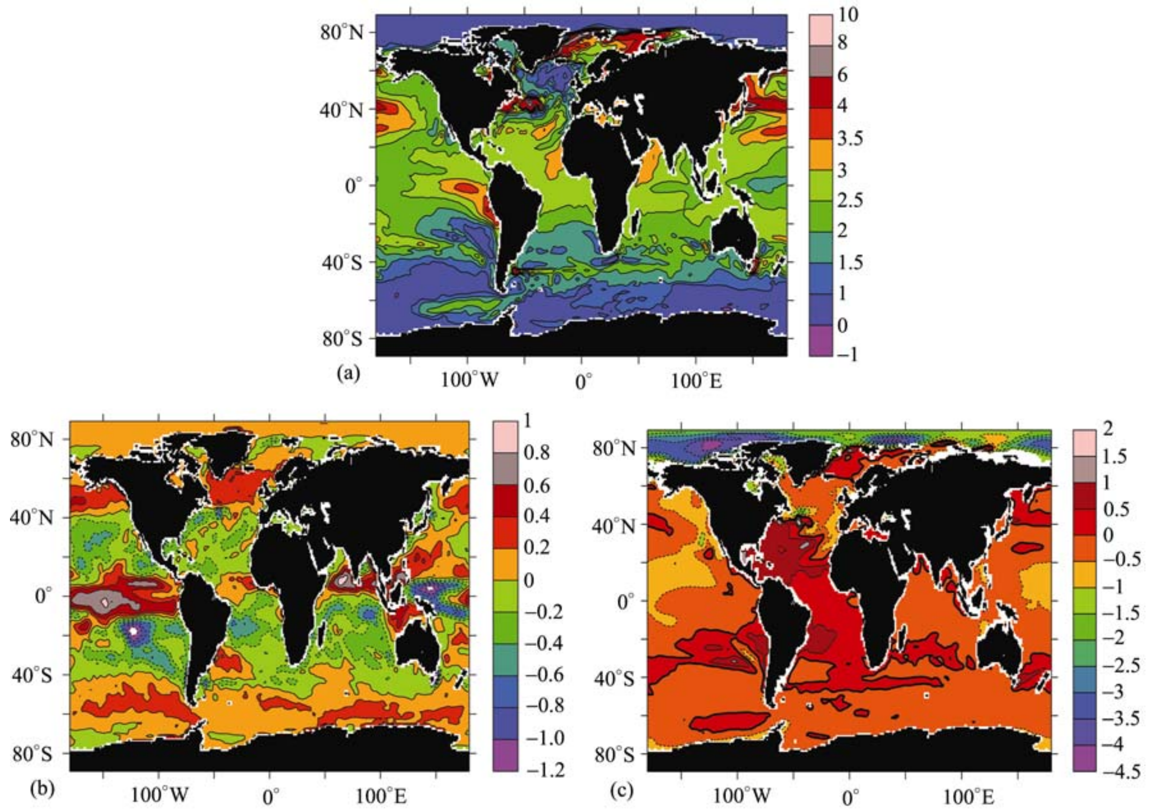

Fig. 3 The differences in (a) sea surface temperature (°C), (b) fresh water flux (m·a^{-1}), and (c) sea surface salinity (psu) between 20th century and 21st century under the A1B scenario. Solid line denotes positive value; dash line denotes negative value.

low latitudes in Atlantic decreases. Thus the deep water formation rate will decrease and the THC strength will also decrease. This THC strength weakening is a kind of total basin-wide weakening, different from the result of GOALS in IAP/LASG which shows that the weakening of THC is only located in the North Atlantic[8].

2.3 *Variation of the sea ice in the Northern Hemisphere*

According to the observation, the annual mean Northern Hemispheric sea ice area is about 12×10^6 km^2 in 1978—1998, and the yearly variation is about 1×10^6 km^2 [17]. The simulated result of GFDL Model closely resembles the observation[11]. And the output of Hadley Center Model is fairly smaller, about 10×10^6 km^2 in 1978—1998[12]. The northern hemispheric sea ice area in 1978 to 1998 simulated by ECHAM5/MPI-OM1 is similar to that of Hadley Center Model. Fig. 4 shows time series of annual mean Northern Hemispheric sea ice area with global warming under different scenarios. From 2000 to 2100, the Northern Hemispheric sea ice area would decrease by approximately 20%, 25% and 25.1% of the present sea ice area respectively, under the B1, A1B and A2 scenarios. At the end of 21st century, with global warming, the sea ice and snow of the Northern Hemisphere will melt in large scale under the greenhouse gases increasing scenario. Especially in the summer, the sea ice in the Arctic Ocean will almost totally melt. Due to the melting of sea ice, the Arctic Ocean absorbs more radiation, and sea temperature in-

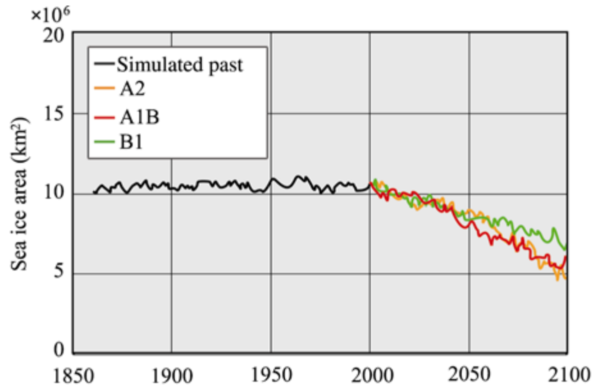

Fig. 4 Time series of annual mean Northern Hemispheric sea ice area with global warming under different scenarios.

creases rapidly; at the same time a lot of fresh water is set out to the ocean, leading to the decrease of salinity of the Arctic Ocean.

3 Conclusions

A new climate model (ECHAM5/MPI-OM1) developed for the fourth assessment report of the IPCC at Max-Planck Institute for Meteorology is used to simulate the climate changes under different increased CO_2 scenarios (B1, A1B and A2). Based on the corresponding model results, the sea surface temperature and salinity structure, the variations of the THC and the changes of sea ice in the Northern Hemisphere were analyzed. It is concluded that from 2000 to 2100, under the B1, A1B and A2 scenarios, the global mean sea surface temperatures (SST) would increase by 2.5°C, 3.5°C and 4.0°C respectively, especially in Arctic Regions, the increase of SST is even above 10.0°C; the maximal negative value of the variation of the fresh water flux is located in the subtropical oceans, while the precipitation in the eastern tropical Pacific increases. The strength of THC decreases under the B1, A1B and A2 scenarios, and the reductions are approximately 20%, 25% and 25.1% of the present THC strength respectively. In the Northern Hemisphere, the area of the sea ice cover decreases by about 50% under the A1B scenario.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 90411010), the National Basic Research Program (Grant No. 2005CB422302) and German Academic Exchange Service (DAAD), and technically supported by German Climate Center.

References

1 Houghton J T, Ding Y, Griggs D J, et al. Intergovernmental Panel on Climate Change (IPCC), 2001: The scientific basis. Contributions of Working Group I to the Third Assessment Report of the IPCC. Cambridge: Cambridge University Press, 2001. 525—583

2 Broecker W S. The great ocean conveyor. Oceanography, 1991, 4: 79—89

3 Schmitz Jr W J. On the interbasin-scale thermohaline circulation. Rev Geophys, 1995, 33:151—173[DOI]

4 Zhou T J, Wang S W. Preliminary evaluation on the decadal scale variability of the North Atlantic Thermohaline Circulation during 20th Century. Clim Environ Res (in Chinese), 2001, 6(3): 294—304

5 Manabe S, Wetherald R T. The effect of doubling CO_2 concentrtion on the climate of the general circulation model. J Atmos Sci, 1975, 32:3—15

6 Marotzke J. Abrupt Climate Change and Thermohaline Circulation: Mechanisms and Predictablity. Proc Nat Acad Sci USA, 2000, 97: 1347—1350[DOI]

7 Manabe S, Bryan Jr K. CO_2-induced change in a coupled ocean-atmosphere model and its paleoclimatic implications. J Geophys Res, 1985, 90 (C11):11689—11707

8 Zhou T J, Yu R C, Liu X Y, et al. Weak response of the Atlantic thermohaline circulation to an increase of atmospheric carbon dioxide in IAP/LASG Climate System Model. Chin Sci Bull, 2005, 50(6): 592—598

9 Roeckner E G, Bäuml L, Bonaventura R, et al. The atmospheric general circulation model ECHAM5, part I: Model description. Max-Planck-Institut für Meteorologie—Report, 2003, No. 349

10 Jungclaus J H, Botzet M, Maak H, et al. Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. J Climate, 2006, 19: 3952—3972[DOI]

11 Dixon K W, Delworth T L, Knutson T R, et al. A comparison of climate change simulations produced by two GFDL coupled climate models. Global & Planetary Change, 2003, 37(1-2): 81—102

12 Johns T C, Gregory J M, Ingram W J, et al. Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios. Hadley Centre Technical Note, 2001, No. 22

13 Yang F, Kumar A, Schlesinger M E, et al. Intensity of hydrological cycles in warmer climates. J Climate, 2003, 16: 2419—2423[DOI]

14 Baumgartner A, Reichel E. The World Water Balance. London: Elsevier, 1975. 98—112

15 Thorpe R B, Gregory J M, Johns T C, et al. Mechanisms determining the Atlantic thermohaline circulation response to greenhouse gas forcing in a non-flux-adjusted coupled climate model. J Climate, 2001, 14: 3102—3116[DOI]

16 Held I, Soden B. Robust responses of the hydrological cycle to global warming. J Climate, in press

17 Vinnikov K Y, Robock A, Stouffer R J, et al. Global warming and Northern Hemisphere sea ice extent. Science, 1999, 286:1934—1937