Numerical simulation of the sensitivity of the Pacific subtropical-tropical meridional cell to global warming*

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Abstract Sensitivity of the Pacific subtropical-tropical meridional cell to global warming is examined by using a global ocean-atmosphere coupled model developed at LASG/IAP. Results indicate that associated with the increasing of atmospheric carbon dioxide, the most prominent signals of global warming locate at high latitudes, and the change of middle and low latitudes, in particular the surface wind, is relatively weak, which leads to a weak response of the Pacific subtropical-tropical meridional cell. At the time of atmospheric carbon dioxide doubling, the change of the meridional cell strength is smaller than the amplitude of natural variability.

Keywords: **Pacific subtropical-tropical meridional cell, global warming, ocean-atmosphere coupled model.**

The north Pacific subtropical-tropical meridional cell (STC) is a shallow meridional overturning circulation that transports water subducted in the subtropics during the winter season to the tropics, where it is upwelled to the surface. The upwelled water is modified by air-sea heat exchange and then advected back to the subtropics by poleward Ekman flows in the surface layer to complete the STC. The STC is climatically important because it carries cool subsurface water into the equatorial region, and hence is an essential part of the equatorial heat balance. However, compared with the Atlantic meridional overturning circulation or thermohaline circulation, which has been the object of numerous investigations during the last decade[1], much less attention has been given to observational and modeling studies of the shallow subtropical/tropical overturning cells that can act as a mechanism for transferring mass, heat, salt and tracers between the subtropical and equatorial gyres.

Several recent studies suggest that as one important component of the ocean-atmosphere coupled system, the STC may play a role in regulating the climate variability involving tropical Pacific SST from seasonal to interannual and decadal scales. Recent observational evidence indicated that the STC has been slowing down since the 1970s, causing a decrease in upwelling of about 25% in an equatorial strip between 9°S and 9°N, and this reduction in equatorial upwelling of relatively cool water is associated with a rise in equatorial sea surface temperatures of about 0.8°C. The onset of this change occurred at about the same time as the pronounced shift in the Pacific Decadal Oscillation, which occurred in 1976—1977[2]. It had already been noticed that the temperature of the sea surface at the equatorial Pacific has risen by 0.8°C over the past 30 years[3]. This phenomenon puzzled researchers, because cloudy skies in this area have become more frequent over the past 50 years, providing cooling shade[4]. The finding of STC slowing down explains the warming: the supply of cool subtropical water has dropped. Even more importantly, the warming that sluggish circulation has brought to the equatorial Pacific may have something to do with the shift in the mid-1970s towards stronger, longer, and more frequent El Nino events. The relation between decade-long circulation changes and shifts in the three- to seven-year El Nino cycles needs further investigation. The mechanism responsible for this slowing down of the STC remains to be determined, although there are suggestions that it may have been influenced either by global warming or by natural variability[2]. The brief motivation of this paper is to examine the evolution of the STC under the global warming situation through numerical simulations using a global ocean-atmosphere coupled model.

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1 Model and experiments

The fourth version of the global ocean-atmosphere-land system model (GOALS) developed at LASG/IAP is used[5,6]. Two sets of model simulations have been performed. The first is the control run, in which the concentration of atmospheric CO_2 is set to be 345 ppm and the 80 years coupled run is finished. The second is the sensitivity experiment, in which the control run is repeated. However, the atmospheric CO_2 is now transiently increasing at a rate of 1% per year, and the concentration of atmospheric CO_2 is doubled around the 70th model year. In the following analysis on the climate change resulting from CO_2 increasing, the anomalies are calculated as the "sensitivity run" relative to the "control run". The natural variability inside the coupled system is therefore removed.

The atmospheric component of the GOALS model is a global spectral AGCM, which is rhomboidally truncated at the zonal wavenumber of 15 and there are nine unevenly spaced levels in the vertical coordinate (L9R15). The land system model SSiB includes one vegetation layer, three soil layers and eleven types of vegetation. The oceanic component of GOALS is a free surface OGCM with 20 unevenly spaced layers in the vertical coordinate. The horizontal resolution is 4° in latitude by 5° in longitude on a B-grid. A simple thermodynamic sea-ice model is incorporated into the ocean model to predict the polar sea ice concentration and thickness[5,6]. The fourth version of GOALS[7,8] has been involved in the second phase of coupled model inter-comparison project (CMIP2). The time series of global mean precipitation and surface air temperature associated with gradual increase of the atmospheric CO_2 concentration are comparable to many models worldwide[9,10]. The time evolutions of the global mean surface air temperature and the North Atlantic thermohaline circulation in both the control run and sensitivity experiment can be found in Refs. [9—11]. Relatively good performance of the model provides a solid footstone for this work.

2 Results and discussion

The meridional overturning circulation is usually expressed using the zonal mean meridional streamfunction. The annual mean Pacific STC in the control run is shown in Fig. 1. The down-welling of STC occurs mainly along the strip between 15°N and 25°N of the North Pacific. It then flows equator-ward at the depth of 150—300 m. Near 5°N—10°N, the returning flows rise to the surface, bringing cooler water with them, and flows northward as warm waters to complete the cell. The climate mean state of the North Pacific STC has a maximum value of 20.0 Sv[1)], locating at the depth of 120 m. The intensity is about 5.0 Sv weaker and the depth with maximum intensity is slightly deeper than some model results reported[2)]. These differences could be attributed to the low resolution of the ocean model. Inspections on the zonal mean sea temperature associated with the STC reveal the importance of the STC in modulating the heat balance of the equatorial and low latitude Pacific Ocean.

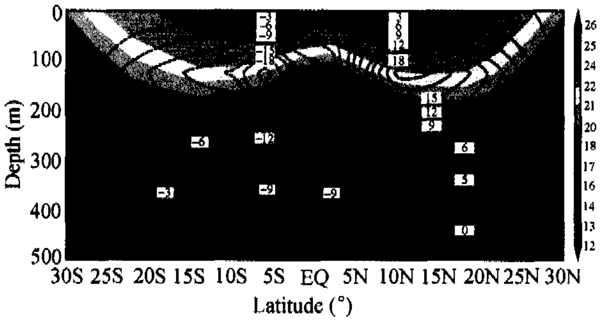

Fig. 1. Climate mean state of the Pacific STC in the control run. The zonal mean meridional streamfunction is shown in contours (in unit of Sv), and the zonal mean temperature is shown as coloring background (in unit of ℃). The vertical axis indicates the ocean depth in unit of m.

To describe the variability of the STC, an index is defined as the maximum value of the meridional stream-function of the North Pacific. The time evolutions of the STC index in the control run and the sensitivity run with increasing CO_2 are shown in Fig. 2. There exist robust oscillations on interannual and decadal scales in the control run, with the magnitude of the STC index ranging from 19.0 Sv to 27.0 Sv. Following the gradual increase of atmospheric CO_2 concentration, both the phase and amplitude of STC index have changed. However, there is clearly no significant linear trend. The global warming associated with the increasing atmospheric CO_2 does not result in

1) 1 Sv = 1 Sverdrup = 1.0×10^6 $m^3\cdot s^{-1}$

2) Lohmann K. and Latif M. 2004, Tropical Pacific variability and the Subtropical-Tropical Cells, International Conference on Earth System Modelling, Hamburg, Germany, 2003.

significant influences on the strength of the North Pacific STC. The difference of STC time series between sensitivity and control experiments is shown in Fig. 2(b). Following the gradual warming of global climate, the North Pacific STC has experienced a weakening at the preliminary stage, and then goes back to the original intensity within 10 years. After that, the STC oscillates around the climate mean states. When the atmospheric CO_2 concentration is doubled in the 70-model year, the STC has the largest magnitude.

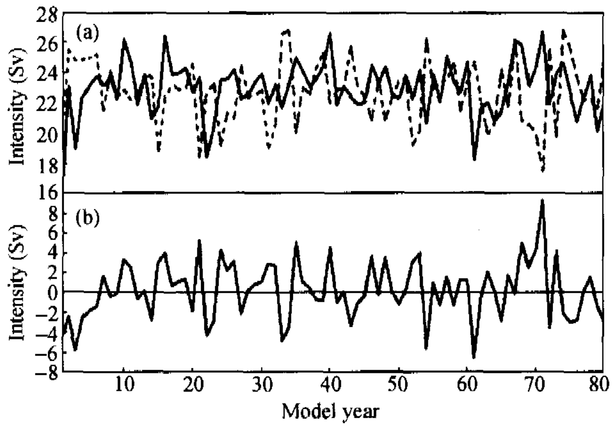

Fig. 2. Time series of North Pacific STC index in GOALS model. (a) Sensitivity experiment (solid) and the control run (dashed); (b) anomalies of the STC index in sensitivity experiment relative to the control run. Unit for the vertical axis is Sv, and the abscissa indicates the model year.

To quantitatively address the impact of global warming on the STC, anomalies of North Pacific meridional stream function are regressed upon the time series of global mean surface air temperature. The result is given in Fig. 3. Associated with the gradual warming of global climate, the North Pacific STC only experienced a weak enhancement with a strength of 0.2—0.3 Sv/K, that is, if the global mean surface air temperature increases 1℃, the North Pacific STC will become 0.2—0.3 Sv stronger. Previous studies found that when the atmospheric CO_2 concentration is doubled in the GOALS model, the global mean surface air temperature would increase by 1.65℃[9,10], and the associated increase of the STC intensity would be 0.33—0.50 Sv, which is about 1.7%—2.5% of its climate mean value. This response is far less than the amplitude of natural variability. Note the standard deviation of annual mean STC intensity in the control run is 2.1 Sv, which equals 10.5% of the climate mean value. Hence, sensitivity of the North Pacific STC to global warming is weak in the GOALS model.

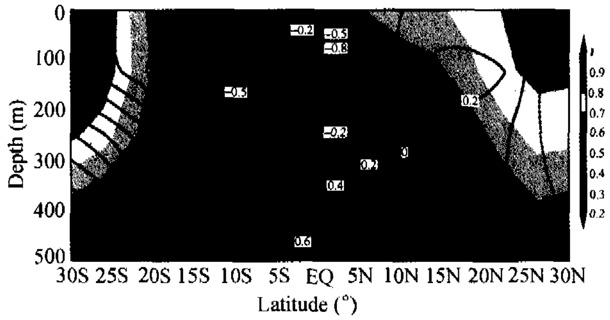

Fig. 3. Anomalies of Pacific zonal mean meridional streamfunction (Contours in unit of Sv) and zonal mean sea temperature (coloring background in unit of K) associated with 1 K warming of global mean surface air temperature in the GOALS model. The vertical axis indicates the ocean depth in unit of m.

One open question for the results mentioned above is whether the simulated ocean circulation change is model-dependent. In comparison with the simulation of ocean currents, climate models usually have better performances in simulating the sea temperature. The performance of the coupled model in simulating the ocean warming should be examined. For this purpose, evolutions of the global mean sea surface and subsurface (125 m) temperature anomalies associated with the increasing of atmospheric CO_2 concentration are shown in Fig. 4(a). Both the sea surface and subsurface temperature closely resemble the surface air temperature in having a warming linear trend, indicating an acceptable performance of the model in producing the ocean response. Similar results of the North Pacific (120°E—90°W, 0°—30°N) are presented in Fig. 4(b). This domain corresponds to the region controlled by the STC. Both the surface

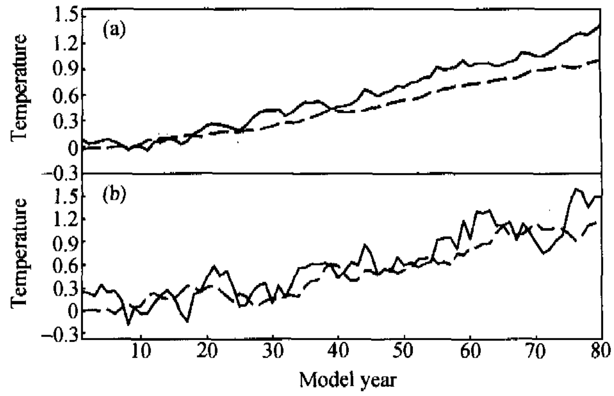

Fig. 4. (a) Anomalies of global mean surface (solid) and subsurface (125 m) sea temperature (dotted) in the sensitivity experiment with the atmospheric CO_2 increasing 1% per year; (b) Anomalies of tropical North Pacific average surface (solid) and subsurface (125 m) sea temperature (dotted) in the sensitivity experiment with the atmospheric CO_2 increasing 1% per year. The abscissa indicates the model year.

and subsurface temperature over this domain have experienced a linear warming trend. Nevertheless, there are still meridional differences in the warming trend of the ocean. The latitude-depth cross section of the zonal mean sea temperature anomalies in the Pacific basin associated with the warming of global mean surface air temperature is shown in Fig. 3. The most typical feature is that the magnitude of the warming trend in higher latitudes is stronger than that in lower latitudes. Corresponding change of the sea level pressure is also examined, stronger change is found over higher latitudes in comparison with that over lower latitudes. Not surprisingly, the situation of the surface wind field is also similar. In the control run, when the North Pacific STC is stronger, anomalous east wind at 850 hPa appears over the tropical Pacific west to 140°W (see the shaded region in Fig. 5(a)), which indicates an intensified Ekman drift. Associated with the global warming, the wind anomalies over this domain also appear as east wind (see the shaded region in Fig. 5(b)). However, the intensity is very weak, and this only leads to a small change of the Ekman drift, and accordingly the weak response of the STC. Since the STC is actually a wind-driven circulation, the weak response of the low latitudes atmosphere, especially the surface wind field, results in the weak response of the shallow ocean circulation.

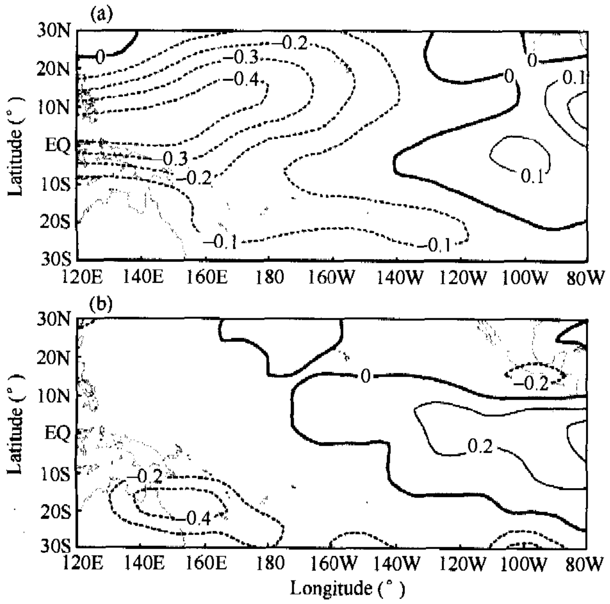

Fig. 5. (a) Anomalies of the zonal wind at 850 hPa associated with one standard deviation change of the STC index; (b) anomalies of the zonal wind at 850 hPa associated with 1 K warming of global mean surface air temperature in the sensitivity experiment. The unit is m/s. The shaded regions indicate the east wind anomalies.

As mentioned above, recent observational evidence found weakening of the Pacific STC since the 1970s. McPhaden and Zhang suggested that the global warming and natural variability might be responsible for this weakening[2]. According to the results presented above, the impact of global warming on the STC is weak in the GOALS model. In addition, there is no decadal scale intensifying or weakening of the STC in the control run of the GAOLS model, indicating that the natural variability might not be a candidate mechanism. Hence, the mechanism responsible for the slowing down of the STC is more complex than speculations and remains to be an open problem. It should be noted that the model we used here has a low resolution, which might influence the results. The control run is only 80 years, and this is not long enough to discuss the decadal scale variability of the STC. It is interesting to note that the weak response of the Pacific circulation to global warming has also been reported in many models, for example, Gordon et al.[12] discussed the response of the Atlantic and the Pacific meridional circulation to the increasing of atmospheric CO_2. Although no special attention has been paid to the Pacific STC, the circulation change around 40° N of the Pacific is not obvious. This response unfavourably contrasts with that of the Atlantic and Southern ocean bottom waters.

3 Conclusion

Impact of global warming on the North Pacific STC has been examined by using a global ocean-atmosphere coupled model. The results prove that responses of the atmosphere to the increasing of atmospheric CO_2 concentration are more robust at middle and high latitudes, and the change of wind over the tropical Pacific is very weak. This leads to a weak response of the STC. Sensitivity of the Pacific STC to global warming is only 0.2—0.3 Sv/K, which locates within the amplitudes of natural variability. According to the model results given here, the global warming might not serve as a dominant mechanism responsible for the observed slowing down of the Pacific STC since the 1970s.

It should be noted that the current state-of-the-art model is still waiting for improvement to reasonably well reproduce the nature. This study has presented the results of GOALS model. However, whether these results are model dependent remains to be determined. For example, impacts of the low model resolution and the flux correction technique need to be discussed. Future work should combine the outputs of international models and make multi-models inter-comparisons, which is one of the targets of the Coupled Model Inter-comparison Project (CMIP)[13]. In addition, the new version of LASG/IAP coupled climate system model, called FGOALS, which employs high resolution in both the oceanic and the atmospheric components, is under developing[14]. The model results presented here will be examined by using the new models.

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