ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 24, NO. 6, 2007, 1109–1120

Progress in the Development and Application of Climate Ocean Models and Ocean-Atmosphere Coupled Models in China

ZHOU Tianjun* (周天军), YU Yongqiang (俞永强), LIU Hailong (刘海龙), LI Wei (李 薇), YOU Xiaobao (游小宝), and ZHOU Guangqing (周广庆)

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics,

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

(Received 30 January 2007; revised 3 August 2007)

ABSTRACT

A review is presented about the development and application of climate ocean models and ocean-atmosphere coupled models developed in China as well as a review of climate variability and climate change studies performed with these models. While the history of model development is briefly reviewed, emphasis has been put on the achievements made in the last five years. Advances in model development are described along with a summary on scientific issues addressed by using these models. The focus of the review is the climate ocean models and the associated coupled models, including both global and regional models, developed at the Institute of Atmospheric Physics, Chinese Academy of Sciences. The progress of either coupled model development made by other institutions or climate modeling using internationally developed models also is reviewed.

Key words: climate ocean model, ocean-atmosphere coupled model, climate modeling

DOI: 10.1007/s00376-007-1109-3

1. Introduction

The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere. Internal variation of the climate involves a complex interplay of physical, chemical, and biological processes of the atmosphere, ocean, sea ice, and land surface. This system is influenced by various external forcing mechanisms. Any change, whether natural or anthropogenic, in the components of the climate system and their interactions, or in the external forcing, may result in climate variations (IPCC, 2001; Blackmon et al., 2001). Addressing the interplay among different components or establishing the climate system's response to changes in anthropogenic emissions of greenhouse gases requires a coupled climate-system approach. The most complex climate models, termed coupled climate system models, involve coupling comprehensive three-dimensional atmospheric general circulation models (AGCMs), with ocean general circulation models (OGCMs), with sea-ice models, and with models of land-surface processes (see IPCC SAR and TAR for an extensive review, IPCC, 1995, 2001). Climate system models, as grand geophysical laboratories, are among the most powerful tools to both enhance our understanding of the fundamental mechanisms of the climate system and make scenario projections of future climate change.

Recognizing the central importance of climate models in climate studies, the Institute of Atmospheric of Physics of Chinese Academy of Sciences (hereinafter IAP) has put much effort into GCM development. The development and usage of numerical models for the study of climate have been a central focus of the Sate Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics's (hereinafter LASG) research activities since the establishment of the laboratory in 1985. Many pioneering Chinese models have been developed at LASG/IAP, including the IAP Atmospheric General Circulation Model, Oceanic General Circulation Model, global coupled ocean-atmosphere models, and global atmosphere-tropical Pacific coupled models for

*Corresponding author: ZHOU Tianjun, zhoutj@lasg.iap.ac.cn

research and seasonal forecasting (Wu et al., 1997; Zhou and Zeng, 1998; Zhang et al., 1999, 2000; Yu et al., 2004a; Wang, 2005).

In recent years, more and more Chinese institutions have been involved in the development and application of climate ocean models and coupled climate system models. For example, the China Meteorological Administration has set up a plan to develop a new coupled climate system model for operational seasonal forecasts and climate change studies (Wu, 2006). In the meantime, many internationally developed climate ocean models such as the Modular Ocean Model (Pacanowski, 1995), coupled climate system models such as the Community Climate System Model (hereinafter CCSM) (Boville and Gent, 1998; Collins et al., 2006), the Bergen Climate Model (hereinafter BCM) (Furevik et al., 2003), and the Fast Ocean-Atmosphere Model (hereinafter FOAM) (Jacob, 1997) have been set up and used in many Chinese institutions. In addition to global ocean or coupled ocean-atmosphere models, regional climate ocean models (Li et al., 2002) and regional ocean-atmosphere coupled models (Ren and Qian, 2000; Yao and Zhang, 2007) have also been developed in China. Here we summarize the achievements to date and outline our current state of the development and performance of the recent versions of the global climate ocean model and coupled climate system model in use at the IAP. We also provide a brief summary of the climate variability and climate change experiments carried out by Chinese scientists who have used some internationally developed models.

To clearly document the progress of the Chinese climate modeling community in the development and application of climate ocean models and ocean-atmosphere coupled models, this paper is mainly historically organized. While this provides a clear picture of the history of different model versions, it does not facilitate a clear picture of the scientific focus of each study. Hence we emphasize the scientific achievements of modeling studies at the end of each section. The outline of the paper is as following: The development and applications of LASG/IAP global climate ocean model are described in section 2. The evolution and applications of LASG/IAP global ocean-atmosphere coupled models are described in section 3. A review of the development and application of regional ocean models and the regional ocean-atmosphere coupled model is made in section 4, while in Section 5 the use of other climate ocean models and ocean-atmosphere coupled models is described, along with some key scientific results. A concluding discussion is presented in section 6.

2. Development and applications of LASG/IAP climate ocean model

2.1 *Early achievements*

The family of LASG/IAP climate ocean models has been developing in succession during the past twenty years. The primary features of the model include a free surface, an energy conserving numerical differential scheme, and the η-coordinate in the vertical direction. LASG/IAP initiated its baroclinic OGCM from a 4-layer model in 1980s (Zhang and Liang, 1989). The first version has a horizontal resolution of $4^\circ \times 5^\circ$, covering the region between 60°S–60°N. The second version is the same as the first one except that the vertical layer was increased to 20-levels (ML20) and the model domain extends to the entire globe except the North Pole (Chen, 1994). The simulation of thermohaline circulation was improved in ML20 relative to the previous 4-layer model (Zhang et al., 1996).

The third generation of LASG/IAP OGCM was developed by Jin et al. (1999). It has 30 layers in the vertical direction and the horizontal discretization is conducted based on a triangular spectral truncation with a zonal wave number of 63 (approximately $1.875^\circ \times 1.875^\circ$) (hereinafter L30T63). The physical processes have been improved in L30T63, including the parameterization of mesoscale eddies (Gent and McWilliams, 1990) and the inclusion of the vertical diffusion scheme dependent upon the Richardson number (Pacanowski and Philander, 1981). The permanent thermocline, the thermohaline circulation, as well as the meridional heat transport were significantly improved in L30T63 (Jin et al., 1999; Zhang et al., 2003).

The development of the LASG/IAP climate ocean model was initiated for climate variability and climate change studies as well as large-scale ocean circulation simulations. Zhou et al. (2000a) discussed the ocean circulation response to surface freshwater forcing and found that the stability of the thermohaline circulation in ML20 was highly sensitive to the surface flux condition of salinity. Disturbance of the surface freshwater forcing might cause a collapse of the Atlantic thermohaline circulation. The stand-alone ocean model has also been used in the understanding of tropical ocean dynamics. Yu et al. (2001) drove the L30T63 model by observational monthly wind stress covering 1980–1989 and got a reasonable interannual variability in the tropical Pacific, proving a good performance of L30T63. The El Niño events are generally better simulated than La Niña events in L30T63. Liu et al. (2002) forced the L30T63 by daily wind stress and heat flux to address ocean's responses to the western wind burst (WWB) during the Tropical Ocean Global Atmosphere Intensive Observation Period (September to December of 1992). They found that the L30T63 successfully reproduced the deepening of the mixed layer and the weakening of surface current over the warm pool during WWB event. The L30T63 model was also employed in paleo-climate simulations. Yu et al. (2004b) performed a set of experiments with the oceanic bathymeter at present, 6Ma BP and 14MA BP, respectively, to investigate the effect of the north shift of the Australian continent on the tropical ocean. They found a closure of Indonesian passage would result in a warming in tropical Pacific and a cooling in tropical Indian Ocean.

2.2 *Recent progress*

The development of the L30T63 has been an important milestone. However, later evaluations revealed some limitations, which could be attributed to its coarse meridional resolution (Jin et al., 1999). These limitations include a weaker North Equatorial Countercurrent (NECC) and Equatorial Undercurrent (EUC), as well as a stronger South Equatorial Current (SEC) relative to observations. Recently, Liu et al. (2004a,b) established an eddy-permitting version with a uniform grid of 0.5° by 0.5°. This improved version was named as LICOM (LASG/IAP Climate Ocean Model). The 0.5° by 0.5° grids are marginal resolutions to resolve the equatorial Rossby radius of deformation. The complicated topographies surrounding the Indonesian seas, including the channels connecting the Pacific and Indian Oceans, are well represented in LICOM. The horizontal viscosity and diffusivity schemes were also updated in LICOM. Evaluations on LICOM reveal many improvements, including better western boundary currents, stronger EUC and NECC, and an intensified meridional heat transport. The Ekman cells around the equator and the Deacon Cell of the Antarctic Circulation Current were also improved (Liu et al., 2004a,b).

To improve the simulation of tropical thermocline, Wu et al. (2005) has increased the vertical resolution of LICOM within the upper 150 m and a more realistic cold tongue extending from the coast of Peru to the equator is found. Recently, the chlorophyll related solar radiation penetration scheme of Ohlmann et al. (2003) was incorporated into LICOM by Lin Pengfei (2006, personal communication). Efforts in improving the equatorial Pacific simulation have also been devoted to the advection treatment, and the two-step shape-preserving advection scheme of Yu (1994) was incorporated into LICOM by Xiao (2006). The excessively westward extension of the eastern Pacific cold tongue was reduced relative to the former version by employing a two-order central differential scheme.

The LICOM has been the ocean component of LASG/IAP coupled climate system model (e.g., Yu et al., 2004a; Yu, 2005; Zhou et al., 2005a,b; Wang, 2005). In addition to global ocean circulation simulations, the LICOM has also been used in regional sea studies. Li et al. (2004b) and Liu et al. (2005a) drove the LICOM by observational surface wind and finished 44-year integration. The Indonesian Throughflow (ITF) transport from 1958 to 2001 was estimated. The LICOM represents a reasonable pathway of the ITF with the Makassar Strait serving as the major passage transferring the North Pacific water southward. The simulated annual mean ITF transport is 14.5 Sv[a], with 13.2 Sv in the upper 700 m. Both the annual mean and seasonal cycles of the ITF agree well with the observations. Analyses suggest that the ENSO-related interannual variability of the Pacific is dominant in controlling the ITF transport. Cai et al. (2005) presents a quantitative estimate of the water exchange of the South China Sea with its adjacent ocean through five straits by using a 900-year integration of LICOM. They found that the annual transport is the largest in the Luzon Strait, then in the Taiwan Strait, and then in the Sunda Shelf, in the Balabac Strait, and in the Mindoro Strait. The largest monthly transport variation appears in the Luzon Strait and Sunda Shelf. The ITF dominates the mass and heat exchanges between the Pacific and Indian Ocean. In addition, some ongoing work using LICOM includes the investigations of meridional heat transport in the Indian Ocean (Wu et al., 2007).

3. Development and application of the LASG/IAP global ocean-atmosphere coupled models

3.1 *Early achievements*

The development of global ocean-atmosphere coupled models in the LASG/IAP dates back to early 1990s. A four-layer OGCM was successfully coupled with the two-level AGCM by using a prediction-correction Monthly Flux Anomaly coupling scheme (referred to as MFA) (Zhang et al., 1992). This is the first ocean-atmosphere coupled model developed in China. With the MFA scheme, the twenty-layer OGCM of LASG/IAP was also coupled with the two-level AGCM (Guo et al., 1996) and a multi-level AGCM, i.e., the nine-level and R15 spectral AGCM (L9R15) (Wu et al., 1996; Liu et al., 1996). Since both of these coupled models have climate drifts, much effort has been devoted to the improvements of the coupling scheme, and a modified MFA scheme (referred to

[a] 1 Sv=10^6 m^3 s^{-1}

as MMFA) was presented (Yu and Zhang, 1998). By using the MMFA scheme, the twenty-layer OGCM of LASG/IAP has been successfully coupled with L9R15 AGCM to build up an ocean-atmosphere-land system model, i.e. the LASG/IAP Global Ocean Atmosphere Land System (GOALS) model (Wu et al., 1997). Four versions of the GOALS model have been developed and all of them have been integrated for 100-200 years without serious climate drift. Relative to the preliminary version of GOALS (Wu et al., 1997), version 2 employed a daily coupling scheme instead of the original monthly coupling (Yu and Zhang, 1998), version 3 improved the atmospheric solar radiation by including its daily variation (Shao et al., 1998), and version 4 improved the coupling processes by including the ocean-atmospheric freshwater exchange (Zhou et al., 2000a, 2001a). For details of these early achievements, readers are referred to Zhang et al. (1999) and Yu et al. (2004a) for a review.

The GOALS model has been widely used in the climate variability and climate change studies. It has been a useful tool in global ocean circulation studies. By using the long term integration of version 2 of GOALS, Zhou et al. (2000b) studied the relationship between the North Atlantic thermohaline circulation (THC) and atmospheric circulation and they found a significant negative correlation between the THC and the North Atlantic Oscillation. Zhou (2003a) identified the multi-spatial variability modes of the Atlantic THC in version 4 of GOALS, the THC either oscillates at decadal scales with strong cross-equatorial flow or fluctuates locally at interannual scales with weaker cross-equatorial flow. Recently, response of THC to global warming is examined by using version 4 of GOALS (Zhou et al., 2005c). The evidence indicates that the gradually warming climate associated with increased atmospheric carbon dioxide leads to warmer and fresher surface water at the high latitudes of the North Atlantic, which prevents the down-welling of the surface water. The succedent reduction of the pole-to-equator meridional potential density gradient finally results in the decrease of the THC in intensity. In response to the doubling of the atmospheric carbon dioxide, the maximum value of the Atlantic THC decreases by approximately 8%. The associated poleward oceanic heat transport also becomes weaker. This kind of THC weakening centralizes mainly in the northern part of the North Atlantic basin, indicating briefly a local scale adjustment rather than a loop oscillation with the whole Atlantic "conveyor belt" decelerating. Similar basin or local scale adjustment of the THC were found in BCM (Bentsen et al., 2004; Zhou and Drange, 2005).

The discussion of ocean circulation in GOALS model is not limited to the Atlantic Ocean. Recently, sensitivity of the Pacific subtropical-tropical meridional cell (STC) to global warming is examined by using version 4 of GOALS. A weak response of the STC to the increasing of atmospheric carbon dioxide is found. Associated with the doubling of the atmospheric carbon dioxide, the change of the STC strength is smaller than the amplitude of natural variability (Zhou et al., 2006a).

The GOALS model has played active roles in monsoon studies, e.g. the relationship between ENSO and East Asian monsoon is addressed by Wang (2000). Both data diagnoses and model analyses reveal that there exists a time-dependence in the relationship between the East Asian monsoon and SST. The anomalous winter monsoon may have significant correlations with the succeeding summer monsoon, but this relationship may disappear in a different time period. The GOALS model has also been a useful tool in climate change studies. Ma et al. (2004) drove the GOALS model by using historical greenhouse gases concentrations, the mass mixing ratio of sulfate aerosols, and reconstructed solar variations spanning 1900–1997. The model reproduced reasonable temporal and spatial distributions of the temperature change. The global warming during the 20th century is caused mainly by increasing greenhouse gas concentration especially since the late 1980s; sulfate aerosols offset a portion of the global warming.

3.2 *Recent progress*

Enlightened by NCAR in developing the Community Climate System Model (Boville and Gent, 1998) and Geophysical Fluid Dynamics Laboratory in developing its Flexible Modeling System[b], in the late 1990s, LASG/IAP made a decision to consolidate and modernize the numerical modeling activities through the development of a new coupled system employing coupler structure. A preliminary experimental version was carried out in 2002 (Yu et al., 2002), which is temporarily called Flexible General Circulation Model (FGCM). Version 0 of FGCM (hereinafter FGCM0) is the same as NCAR CSM (Boville and Gent, 1998) except that the ocean component has been replaced with the fourth generation of LASG/IAP climate ocean model L30T63 (Jin et al., 1999).

The FGCM0 shows many improvements relative to the GOALS model (Yu et al., 2002; Liu, 2001). For example, Zhou et al. (2001b) compared the atmospheric moisture transport and air-sea freshwater exchange in GOALS and FGCM0 and found that the latter performs better. Similar to many other "none flux adjust-

[b]http://www.gfdl.noaa.gov/~fms/

ment" coupled models; however, the FGCM0 also suffers from the spurious "Double ITCZ" problem. Great efforts have been devoted to the improvement of this tropical bias. Based on the relationship between the low-level cloud cover and the bulk stability of the low troposphere, Dai et al. (2003) modified the parameterization scheme of low-level cloud in CCM3, which is the AGCM component of FGCM0, and found an improved simulation of the low-level cloud over the cold oceans, which then effectively reduces the SST warm biases in ITCZ north of the equator. Li et al. (2004a) showed that the double ITCZ in FGCM0 is a result of non-local and nonlinear adjustment processes of the coupled system. The zonal gradient of the equatorial SST is too large in the ocean component and the amount of low-level stratus over the Peruvian coast is too low in the atmospheric component. Both of them contribute to the formation of the "double ITCZ". Zhang et al. (2007) analyzed structures of the double ITCZ in the central equatorial Pacific simulated by three coupled ocean-atmosphere general circulation models. It is shown that the surface wind convergence, associated with the zonally oriented double rain bands on both sides of the equator, also correspond to surface wind curls that are favorable to Ekman pumping immediately poleward of the rain bands. The pumping results in a thermocline ridge south of the equator in the central equatorial Pacific, causing a significant overestimation of the eastward South Equatorial Counter Current. A positive feedback mechanism is then described for the amplification of the double ITCZ in the coupled models from initial biases in stand-alone atmospheric models through the following chain of interactions: precipitation (atmospheric latent heating), surface wind convergence, surface wind curls, Ekman pumping, South Equatorial Counter Current, and eastward advection of ocean temperature. This pathology provides a possible means to address the longstanding double ITCZ problem in coupled models.

Improvements in wave-induced mixing also have significant impacts on the coupled model. Insufficient vertical mixing of OGCM would cause an overestimated SST and underestimated mixed layer depth in summer (Qiao et al., 2004, 2006). The wave-induced vertical viscosity/diffusivity can be expressed as a function of wave number spectrum (Qiao et al., 2004; Yuan and Qiao, 2006) (hereinafter Qiao-Yuan scheme). By employing the Qiao-Yuan scheme into the ocean component of FGCM0, Song et al (2006) has reduced the tropical SST bias more than 0.8 K with a maximum value of 1.2 K nearing 0°–3°N, 160°–180°E.

Benefitting from the freely available NCAR CCSM2 (Kiehl and Gent, 2004), version 1 of FGCM was developed by changing the ocean component of CCSM2 to LICOM (Yu et al., 2002). This version was improved in 2005 by employing a new atmospheric component, i.e., the Grid Atmospheric Model of IAP/LASG (GAMIL) (Wang et al., 2004a). The new version of the coupled model was nominally named as FGOALS_g1.0 (Flexible Global Ocean Atmosphere Land Sea-ice model) by LASG (Wang, 2005; Yu, 2005). A twin version of FGOALS_g was developed by changing its atmospheric component to another AGCM developed at LASG/IAP, i.e., the Spectral Atmospheric Model of IAP/LASG (SAMIL) (Wu et al., 1996; Wang et al., 2004c). This version of the FGOALS model employing SAMIL as its atmospheric component was nominally named as FGOALS_s (Zhou et al., 2005a,b). Preliminary analyses on the land surface variables indicate an improvement in FGOALS_s (Bao et al., 2006; Chen et al., 2007). Due to the bias in cloud-radiation process, however, there exists apparent cold bias in the tropical ocean (Zhou et al., 2005b), which in turn influences the strength of the mean meridional circulation and the westerly jets (Wang et al., 2007).

The FGOALS_g1.0 model has been used in many international model inter-comparison projects such as IPCC AR4 and PMIP (Yu, 2005; Masson-Delmotte et al., 2006). In a multi-model ensemble discussion on the El Niño mean state-seasonal cycle interactions, Guilyardi (2006) noted that the pre-industrial control El Niño amplitude of FGOALS_g1.0 is larger than observation, along with a too regular frequency. Saji et al. (2006) shows that the tropical Indian Ocean response to ENSO is stronger than observation in FGOALS_g.1.0. In the meantime, however, the ENSO amplitude in FGOALS_s, which shares the same ocean component of FGOALS_g1.0, is weaker than observation (Zhou et al., 2005b), indicating the impact of the atmosphere on the ENSO intensity of the coupled system. The outputs of the FGOALS_g1.0 experiments for IPCC AR4 have been widely used in climate change and climate variability studies, e.g., the South Asian High (Zhou et al., 2006d), the mechanism of 20th century surface air temperature evolution over China and the globe (Zhou and Yu, 2006), the polar sea ice simulation (Zhang and Walsh, 2006), Indian Ocean variability (Saji et al., 2006), and soil moisture studies (Zhang, 2006), among many others.

In addition to the improvements of the FGOALS_g and FGOALS_s models, efforts in LASG/IAP have also been devoted to the development of a low resolution fast ocean-atmosphere coupled model, which will be used in the millennial scale climate simulations (Zhou et al., 2007; Wen et al., 2007). By combining different versions together, LASG/IAP aims to create a common modeling infrastructure, which will be receptive to components of varying complexity and of varying resolutions, and which will balance scientific needs with resource availability. This model system would support diverse research activities, from seasonal monsoon evolution to anthropogenic climate change, and from millennial climate evolution to paleo-climate simulation.

Besides the global ocean-atmosphere coupled models, IAP also developed a global atmosphere-tropical Pacific Ocean coupled model for ENSO-prediction purposes (Zhou and Zeng, 1998, 2001). The tropical Pacific Ocean model has a horizontal resolution of 2° longitude by 1° latitude and 14 layers in the vertical, and the global atmospheric model is the IAP 2L AGCM (Zeng et al., 1989). This model has shown good performance in ENSO predictions (Zhou et al., 1999). Recently, Fu (2005) improved this model by increasing the horizontal resolution of the ocean model to be 0.5° by 0.5°. The atmospheric component was changed to IAP 9 layer AGCM, which is the new version of IAP 2L AGCM (Bi, 1993). This new coupled model shows great improvements in the simulations of the equatorial Pacific Ocean circulation and the East Asian monsoon (Fu, 2005).

4. Development and application of regional ocean models and ocean atmosphere coupled models

Besides the global OGCM, a regional Oceanic General Circulation Model (Hereinafter IAP-ROCM) with η coordinate and free surface has been developed in IAP (Li et al., 2002; Li and You, 2003; You et al., 2003). The IAP-ROCM has been applied to simulate the circulation in the South China Sea (SCS), and the influence of the Kuroshio is considered through open boundaries (You et al., 2001; Li et al., 2003a,b). The IAP-ROCM successfully produced the anticyclonic meandering path of the Kuroshio, which appears west of the Luzon Strait, and a tongue with relatively high temperature and salinity, which spreads into SCS through the Luzon Strait and represents an intrusion of the Kuroshio in winter. In summer, the anticyclonic circulation in the southern SCS is mainly driven by the southwest monsoon. The cyclonic eddy in the northern SCS is formed due to the joint actions of Kuroshio, bottom topography effect and baroclinic effect. You et al. (2001) developed a 24-level tri-nested regional ocean model with a horizontal resolution of $0.25° \times 0.25°$. The current system in the China Seas, such as the Kuroshio, Mindanao Current, South China Sea Warm Current, Taiwan Warm Current, Yellow Sea Warm Current, Tsushima Warm Current and some mesoscale eddies, has been well reproduced.

Efforts have also been devoted to the development of regional air-sea coupled models in China. Ren and Qian (2001) developed a regional air-sea coupled model by using the Nanjing University regional climate model (P-σ RCM) and a regional ocean model (POM). A case study on the 1998 monsoon season (from May to August) suggests that the model has a reasonable performance. This model, however, still has a cold bias, which was caused by the disagreement of the surface heat fluxes produced by the P-Sigma RCM with those required by the POM (Ren and Qian, 2005). This model has been used in discussing the evolution of the South China Sea branch of the Kuroshio current in the monsoon season (Ren and Qian, 2000; Ren et al., 2000).

Recently, Yao and Zhang (2007) coupled the regional climate model RegCM3 with the regional oceanic model POM. They found that the air-sea coupled model (henceforth RegCM3-POM) has good performance in simulating summer precipitation. The distribution of rain bands in the coupled model is more reasonable than the results of the uncoupled model. The improvement of rainfall simulation is remarkable in the Yangtze River Valley and south China. This improvement is observed in both the climate mean state and the interannual variability. Further analysis suggests that this is due to the inclusion of air-sea interactions over the neighboring oceans.

5. The application of other ocean or ocean-atmosphere coupled models and model inter-comparisons

In addition to the climate models developed by Chinese institutions, some internationally-developed general circulation models have also been used in China. Applications include studies of climate variability from interannual to interdecadal time scales, simulations of paleo-climate regimes, and projections of future anthropogenic climate change (Pu et al., 2004). The interannual variabilities of the tropical Pacific as well as the controlling mechanisms of ENSO evolution are investigated by using the GFDL MOM2 model forced with monthly mean data of COADS covering 1945–1993, and the delayed oscillator mechanism is found to be active (Rong and Yang, 2004). In the tropical Indian Ocean, the ENSO-related basin-wide warming/cooling mode and the dipole mode are successfully simulated. The model also successfully simulates an ENSO-like mode of the SST variations in the tropical Atlantic. Rong and Yang (2005) discussed the MOM2 response to surface forcing and found that the model successfully captures the dominant mode of the SST anomalies on the decadal-to-interdecadal timescales, as well as the major feature of SST anomalies in the 1976/77 regime shift. Examination of the upper ocean heat budget in three key regions [central North Pacific, coast of California and Kuoshio-Oyashio Extension (KOE) region] reveals that the 1976/77 regime shift was caused by both the sustained heat flux input anomalies and the strong horizontal advection anomalies in the central North Pacific. In the California coastal region, only the heat flux input anomalies were found dominant, and the effect of the horizontal advection anomalies is negligible. In the KOE region, the vertical advection, heat flux, and horizontal advection anomalies are important in producing the regime shift.

Rong and Yang (2003) discussed the sensitivity of ENSO characteristics in GFDL coupled model to change of climatological background state. They found that the ENSO characters including the frequency and the amplitude and its controlling mechanism strongly depend on the climatological background states. Two different ENSO modes were identified for the two different background states. One is the “delayed oscillator” mode, corresponding to a background state close to the observations; and the other is a stationary mode, corresponding to a background state with a decreased zonal thermal gradient and a flat thermocline structure along the equatorial Pacific.

Climate variability involves complex processes of ocean-atmosphere feedbacks and tele-connection; our means of diagnosing these processes in a climate model are very limited. Recently, the modeling group at the Physical Oceanography Laboratory of the Ocean University of China is taking a novel modeling approach, referred to as ”Modeling Surgery” (Wu et al., 2003), to address these issues. This new modeling strategy is specifically to diagnose ocean-atmosphere feedbacks and teleconnections through systematically modifying the coupling configuration and telconnective pathways in a climate model. Using “Modeling surgery”, this group has been investigating the origins of the mid-70s' North Pacific climate regime shift (Wu et al., 2005a). By constraining the wind stress forcing of the North Pacific in a coupled model, they were able to find that the adjustment of the subtropical ocean circulation in response to the persistent wind stress prior to the climate shift can induce SST first in the western subtropical North Pacific. It can further induce a shift of the atmospheric circulation, leading a change of SST in the central Pacific and then in the KOE region (Wu et al., 2005b). This new hypothesis is further tested in a coupled model initial-value approach. They further proposed that the KOE region can be an important source of global decadal climate variability, which can induce SST in the tropical Indian Ocean, South Pacific, and north and tropical Atlantic through the Asian winter monsoon and Artic Oscillation/North Atlantic Oscillation (NAO) (Wu et al., 2005c).

Mid-latitude air-sea interaction was discussed by Zhou et al. (2006b) with a focus on the North Atlantic. The North Atlantic inter-annual variability associated with the NAO is examined over 300-year integration of BCM. The dominant mode of the North Atlantic wintertime SST variability exhibits a meridional tri-polar pattern, with a colder sub-polar region, warmer mid-latitude, and a colder region between the equator and 30°N. The atmospheric circulation change associated with the tri-polar SST anomalies exhibits as NAO and has a barotropic structure. The tri-polar structure SST anomalies over the North Atlantic mainly result from the barotropic driving of the NAO-like atmospheric forcing, and the thermal process plays a dominant role in this process. Similar result was reported in Zhou et al. (2000c). The feedback of the tri-polar SST anomalies on the atmosphere is weak. Zhou et al. (2006c) addressed the contribution of the tropical Pacific forcing to the North Atlantic interannual time scale variability in BCM and found that the dominant mode of the interannual time scale SST variability of the North Atlantic is partly forced by the atmospheric tele-connections originating from the middle and eastern equatorial Pacific. Positive phase of the tri-polar North Atlantic SST mode corresponds to a cold event in the equatorial Pacific. The response of the North Atlantic SST to the equatorial Pacific forcing has a lag time of 2–3 months.

Studies on the mid-latitude air-sea interaction have been extended to address the atmospheric forcing on the ocean circulation. Zhou (2003b) discussed the adjustment of the thermohaline circulation (THC) to the forcing of NAO and found that a positive phase NAO and thereby intensified westerlies enhance the net heat flux loss of the Labrador Sea, in conjunction with the positive salinity anomaly over there, water at the surface then becomes denser, and deep convection occurs. Three months after the NAO reaches its maximum state, the Labrador Sea convection reaches its largest depth. Response of the North Atlantic thermohaline circulation to the Labrador Sea convection lags 3 years in the model. The oceanic poleward heat transport has a maximum simultaneous correlation with the THC.

Tropical inter-basin interaction has been studied by using a coupled model. Wu et al. (2005c) discussed the influence of the tropical Atlantic on the tropical Pacific. Using so-called “partial-coupling” strategy, they were able to find that a north Atlantic SST anomaly can induce a meridional SST dipole in the eastern equatorial Pacific in spring, which can subsequently evolve into an ENSO-like pattern. This finding may help interpret the global climatic impacts of THC collapse (Wu et al., 2005c).

During El Niño events, the warm anomalies in the eastern tropical Pacific are seen to occur in conjunction with prominent warm anomalies in the North Pacific SSTs off the west coast of North America as well as with cold anomalies in the central North Pacific. By analyzing the long term integration of IPSL (Institute Pierre-Simon-Laplace des Sciences de l'Environnement Global, France) coupled model, Zhou et al. (2002) demonstrate that the North Pacific response to ENSO is achieved via an atmospheric bridge, i.e., the atmospheric response to ENSO in turn forces the extra-tropical SST anomalies associated with the El Niño event, thereby serving as a bridge between the tropical and extra-tropical Pacific. Zhou et al. (2004) demonstrate that this mechanism is also active in resulting in the warming of the Indian Ocean associated with ENSO events.

Chinese scientists have also benefited from the international modeling group in paleo-climate simulations. Liu et al. (2005b) compared the reconstructed temperature anomalies in the eastern China with the output from a 1000-year ECHO-G simulation in an attempt to understand the causes of climate change in China over the last millennium. The Medieval Warm Period during 1000–1300 A.D., the Little Ice Age during 1300–1850 A.D., and the modern warming period after 1900 A.D. are all recognizable from both the simulated and reconstructed temperatures. Diagnosis of the model results indicates that, during the last millennium, variations in solar radiation and volcanic activity are the main controlling factors on regional temperature change, while in the most recent 100 years, the change of the concentration of greenhouse gases plays the most important role in explaining the rapid temperature rising.

6. Summary

Climate system models play an instrumental role in understanding and simulating past, present, and future climate. Both global and regional climate ocean models and their associated coupled system models have been created to represent the principal components of the climate system and their interactions. The development and application of these models are carried out by the Chinese climate research community. This paper mainly reviewed the history, current capabilities, and applications of the climate ocean model and the associated ocean-atmosphere model developed at IAP, with the goals of providing a summary useful to present and future users. The development of regional ocean models and regional ocean-atmosphere coupled models in China, and applications of several internationally-developed climate ocean and ocean-atmosphere coupled models are also reviewed. Emphasis has been put on the achievements gained in the last five years. Although the authors attempt to outline the main contributions of Chinese scientists in this field, clearly it is beyond the authors' ability to summarize such a large amount of literature into this short paper.

The performance of both global climate ocean models and ocean-atmosphere coupled models developed at the IAP has been significantly improved. The involvement of IAP model in many international climate model inter-comparison projects has greatly promoted the development and improvement of these models. Relative to global models, the history of regional Ocean and ocean-atmosphere coupled models is shorter. However, great achievements have been made in recent years, which greatly facilitated our understandings of marginal sea ocean-atmosphere interactions. The application of some internationally developed coupled climate models in China has made great contributions to our understanding of climate physics. The results of multi-model inter-comparison have been serving as guides for the improvement of Chinese models.

We are living in a world facing many scientific challenges of the climate problem. To address these challenges, we need to upgrade our model from a climate system model, which consists of four components for the atmosphere, ocean, sea ice, and land surface, to an earth system model through the incorporation of an integrated chemistry model and the inclusion of global prognostic biogeochemical components for land, ocean, and atmosphere (Wang et al., 2004b). In order to make such developments possible, wide intellectual participation is needed, such as what NCAR has done in its development of the Community Climate System Model (Blackmon et al., 2001). In addition to the inclusion of new component models, development efforts should also focus on the incorporation and improvement of new representations of physical processes.

Acknowledgements. We acknowledge Profs. Wu Lixin, Qiao Fangli, Ren Xuejuan and Zhang Yaocun for providing relevant literatures. This work was jointly supported by the National Natural Science Foundation of China (Grant Nos. 40523001, 40221503, 40675050), the Major State Basic Research Development Program of China under Grant Nos. 2005CB321703, 2006CB403603, and the International Partnership Creative Group entitled "The Climate System Model Development and Application Studies".

REFERENCES

Bao, Q., Y. Liu, T. Zhou, Z. Wang, G. Wu, and P. Wang, 2006: The sensitivity of the new atmospheric general circulation model SAMIL-R42L26 of LASG/IAP to the land-atmosphere flux. *Chinese J. Atmos. Sci.*, **30**, 1077–1090 (in Chinese).

Bentsen, M., H. Drange, T. Furevik, and T. Zhou, 2004: Simulated variability of the Atlantic Meridional Overturning circulation. *Climate Dyn.*, **22**, 701–720.

Bi, X., 1993: IAP nine-level AGCM and its simulation of climate. Ph.D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 210pp. (in Chinese)

Blackmon, M. B., and Coauthors, 2001: The Community Climate System Model. *Bull. Amer. Meteor. Soc.*, **82**(11), 2357–2376.

Boville, B. A., and P. R. Gent, 1998: The NCAR climate system model, Version One. *J. Climate*, **11**, 115–1130.

Cai, S., H. Liu, W. Li, and X. Long, 2005: Application of LICOM model to the numerical study of the water exchange between the South China Sea and its adjacent oceans. *Acta Oceanologica Sinica*, **24**, 10–19.

Chen, K., 1994: Improvements of IAP coupled global ocean-atmosphere general circulation model and its simulation of climate change induced by increasing greenhouse gases. Ph.D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 145pp. (in Chinese)

Chen, H. M., T. J. Zhou, R. C. Yu, and Q. Bao, 2007: The East Asian summer monsoon simulated by LASG/IAP coupled model FGOALS_s. *Chinese J. Atmos. Sci.*, in press. (in Chinese)

Collins, W. D., and Coauthors, 2006: The Community Climate System Model: CCSM3. *J. Climate*, **19**(11), 2122–2143.

Dai, F., R. Yu, X. Zhang, Y. Yu, and J. Li, 2003: The impact of low-level cloud over the eastern subtropical Pacific in the "Double ITCZ" in LASG FGCM-0. *Adv. Atmos. Sci.*, **20**(3), 461–474.

Fu, W., 2005: A high resolution tropical Pacific OGCM and its coupling to a global AGCM. Ph.D. dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 169pp. (in Chinese)

Furevik, T., M. Bentsen, H. Drange, I. K. T. Kindem, N. G. Kvamsto, and A. Sorteberg, 2003: Description and evaluation of the Bergen climate model: ARPEGE coupled with MICOM. *Climate Dyn.*, **21**(1), 27–51.

Gent, P. R., and J. C. McWilliams, 1990: Isopycnal mixing in ocean circulation models. *J. Phys. Oceanogr.*, **20**, 150–155.

Guilyardi, E., 2006: El Niño-mean state-seasonal cycle interactions in a multi-model ensemble. *Climate Dyn.*, **26**(4), 329–348

Guo, Y., Y. Yu, K. Chen, X. Jin, and X. Zhang, 1996: Mean climate state simulated by a coupled ocean-atmosphere general circulation model. *Theor. Appl. Climatol.*, **55**, 99–112.

IPCC, 1995: *Climate Change 1995: The Science of Climate Change*. Houghton et al., Eds., Cambridge University Press, UK, 572pp.

IPCC, 2001: *Climate Change 2001: The Scientific Basis*. Houghton et al., Eds., Cambridge University Press, 892pp.

Jacob, R., 1997: Low frequency variability in a simulated atmosphere ocean system. Ph.D dissertation, University of Wisconsin, 155pp.

Jin, X., X. Zhang, and T. Zhou, 1999: Fundamental framework and experiments of the third generation of IAP/LASG world ocean general circulation model. *Adv. Atmos. Sci.*, **16**, 197–215.

Kiehl, J. T., and P. R. Gent, 2004: The Community Climate System Model, Version 2. *J. Climate*, **17**, 3666–3682.

Li, D., X. You, and M. Zhang, 2003a: Numerical simulation of every monthly mean ocean currents in the South China Sea. *Scientia Meteorologica Sinica*, **23**(1), 22–38. (in Chinese)

Li, D., X. You, and M. Zhang, 2003b: A study on the circulation mechanism of the South China Sea in summer by numerical experiments. *Journal of Tropical Oceanography*, **22**(6), 54–63. (in Chinese)

Li, J. L., X. Zhang, Y. Yu, and F. Dai, 2004a: Primary reasoning behind the double ITCZ phenomenon in a coupled ocean-atmosphere general circulation model. *Adv. Atmos. Sci.*, **21**(6), 857–867.

Li, R., and X. You，2003: The development and application of the oceanic general circulation models. Part II. The regional oceanic general circulation models. *Chinese J. Atmos. Sci.*, **27**, 729–739. (in Chinese)

Li, R., X. You, and P. Wongwises, 2002: *A Three-dimensional Coastal Ocean Circulation Model*. King Mongkut's University of Technology Thonburi Press, Bangkok, Thailand, 1–59.

Li, W., H. Liu, and X. Zhang, 2004b: Indonesian throughflow in an eddy-permitting oceanic GCM. *Chinese Science Bulletin*, **49**(21), 2305–2310.

Liu, H., X. Jin, X. Zhang, and G. Wu, 1996: A coupling experiment of an atmosphere and ocean model with a monthly anomaly exchange scheme. *Adv. Atmos. Sci.*, **13**, 133–146.

Liu, H. L., W. Li, X. Zhang, and Y. Yu, 2002: Simulated response of SST to west wind bursts in the western equatorial Pacific warm pool. *Chinese J. Atmos. Sci.*, **26**, 172–184. (in Chinese)

Liu, H. L., Y. Yu, W. Li, and X. Zhang, 2004a: Reference Manual of LASG/IAP Climate System Ocean Model (LICOM1.0). Special technical report of State Key Laboratory of Numerical Modelling forAtmospheric Sciences and Geophysical Fluid Dynamics, Science Press, Beijing, 107pp. (in Chinese)

Liu, H. L., X. Zhang, W. Li, Y. Yu, and R. Yu, 2004b: An eddy-permitting oceanic general circulation model and its preliminary evaluations. *Adv. Atmos. Sci.*, **21**, 675–690.

Liu, H. L., W. Li, and X. Zhang, 2005a: Climatology and Variability of the Indonesian Throughflow in an Eddy-permitting Oceanic GCM. *Adv. Atmos. Sci.*, **22**, 496–508.

Liu, J., H. Storch, X. Chen, E. Zorita, J. Zheng, and S. Wang, 2005b: Simulated and reconstructed winter temperature in the eastern China during the last millennium. *Chinese Science Bulletin*, **50**, 2872–2877.

Liu, X. Y., 2001: The simulation and study of sea-ice-air interaction in the northern high latitude region. Ph.D. dissertation, Graduate School of the Chinese Academy of Sciences, 136pp. (in Chinese)

Ma, X., Y. Guo, G. Shi, and Y. Yu, 2004: Numerical simulation of global temperature change during the 20th century with the IAP/LASG GOALS model. *Adv. Atmos. Sci.*, **21**, 227–235.

Masson-Delmotte, V., and Coauthors, 2006: Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. *Climate Dyn.*, **26**, 513–529.

Ohlmann, J. C., 2003: Ocean radiant heating in climate models. *J. Climate*, **16**, 1337–1351.

Pacanowski, R. C., 1995: MOM2 documentation users guide and reference manual. GFDL Ocean Technical Report No. 3, Princeton, USA, 232pp.

Pacanowski, R. C., and G. Philander, 1981: Parameterization of vertical mixing in numerical models of the tropical ocean. *J. Phys. Oceanogr.*, **11**, 1442–1451.

Pu, S., J. Zhao, W. Yu, Y. Zhao, and B. Yang, 2004: Progress of large-scale air-sea interaction studies in China. *Adv. Atmos. Sci.*, **21**(3), 383–398.

Qiao, F., Y. Yuan, Y. Yang, Q. Zheng, C. Xia, and J. Ma, 2004: Wave-induced mixing in the upper ocean: Distribution and application in a global ocean circulation model. *Geophys. Res. Lett.*, **31**, L11303, doi:10.1029/2004GL019824.

Qiao, F., Y. Yuan, T. Ezer, C. Xia, Y. Yang, and Z. Song, 2006: A three-dimensional surface wave-ocean circulation coupled model: System description and initial testing. *Ocean Modelling.* (in press)

Ren, X., and Y. Qian, 2000: Numerical simulation of oceanic elements at East Asian coastal oceans from May to August in 1998 by using a coupled regional ocean-atmosphere model. *Climatic and Environmental Research*, **5**(4), 482–485. (in Chinese)

Ren, X., and Y. Qian, 2001: Development of a coupled regional air-sea model and its numerical simulation for summer monsoon in 1998. *Acta Meteorologica Sinica*, **15**(4), 385–396.

Ren, X., and Y. Qian, 2005: A coupled regional air-sea model, its performance and climate drift in simulation of the East Asian summer monsoon in 1998. *International Journal of Climatology*, **25**, 679–692.

Ren, X., Y. Qian, and Y. Zhang, 2000: Numerical simulations of oceanic elements in the South China Sea and its neighboring sea regions from January to August in 1998. *Journal of Tropical Meteorology*, **16**(2), 139–147. (in Chinese).

Rong, X., and X. Yang, 2003: Sensitivity of ENSO characteristics in a coupled ocean-atmosphere GCM to change of climatological background state. *Acta Meteorologica Sinica*, **61**(1), 52–65. (in Chinese)

Rong, X., and X. Yang, 2004: The upper-ocean response and adjustment to surface forcing in an oceanic general circulation model: I. Interannual variability. *Acta Oceanologica Sinica*, **26**(2), 20–36. (in Chinese)

Rong, X., and X. Yang, 2005: The upper-ocean response and adjustment to surface forcing in an oceanic general circulation model: II Decadal-to-interdecadal variability. *Acta Oceanologica Sinica*, **27**(3), 20–31. (in Chinese)

Saji, N. H., S.-P. Xie , and T. Yamagata, 2006: Tropical Indian Ocean variability in the IPCC 20th-century climate simulations. *J. Climate*, **19**(17), 4397–4417.

Shao, H., Y. Qian, and Q. Wang, 1998: Impact of solar radiation diurnal cycle on the simulation results of R15L9. *Plateau Meteorology*, **17**, 158–168. (in Chinese)

Song, Z., F. Qiao, Y. Yang, and Y. Yuan, 2006: An improvement of the too cold tongue in the tropical Pacific with the development of an ocean-wave-atmosphere coupled numerical model. *Progress in Natural Sciences*, **17**(5), 576–583.

Wang, B., 2005: Introduction of the 4th generation of LASG/IAP climate system model FGOALS and its numerical experiments. *The 2004 Annual Academic Conference of the Institute of Atmospheric Physics*, Chinese Academy of Sciences, 22 Feb. 2005, Beijing.

Wang, B., and Coauthors, 2004a: Design of a new dynamical core for global atmospheric models based on some efficient numerical methods. *Science in China (A)*, **47**(Suppl), 4–21.

Wang, H. J., 2000: The interannual variability of East Asian monsoon and its relationship with SST in a coupled Ocean-Atmosphere-Land climate model. *Adv. Atmos. Sci.*, **17**, 31–47.

Wang, H., Y. F. Xu, T. J. Zhou, H. B. Chen, S. T. Gao, P. C. Wang, R. Y. Lu, and M. G. Zhang, 2004b: Atmospheric Science: A vigorous frontier science. *Advances in Earth Sciences*, **19**(4), 31–38. (in Chinese)

Wang, Z., G. Wu., and T. Wu, 2004c: User's Guide and Reference Manual of the ALGCM (R42), Technical Report of LASG/IAP, No.14, 73pp.

Wang, Z., R. Yu, Q. Bao, T. Zhou, G. Wu, Y. Liu, and P. Wang, 2007: A comparison of the atmospheric circulations simulated by the FGOALS-s and SAMIL. *Chinese J. Atmos. Sci.*, **31**(2), 202–213.(in Chinese)

Wen, X., T. Zhou, S. Wang, B. Wang, H. Wan, and J. Li, 2007: Performance of a reconfigured atmospheric general circulation model at low resolution. *Adv. Atmos. Sci.*, **24**(4), 712–728.

Wu, F., H. Liu, W. Li, and X. Zhang, 2005: Effect of adjusting vertical resolution on the eastern equatorial Pacific cold tongue. *Acta Oceanologica Sinica*, **24**(3), 1–12 .

Wu, F., W. Li, H. L. Liu, and X. Zhang, 2007: Evaluation on seasonal circulation and heat transport simulated by LICOM in the Northern Indian Ocean. *Chinese*

J. Atmos. Sci., (in press). (in Chinese)
Wu, G., H. Liu, Y. C. Zhao, and W. P. Li, 1996: A nine-layer atmospheric general circulation model and its performance. *Adv. Atmos. Sci.*, **13**, 1–18.
Wu, G., and Coauthors, 1997: Global ocean-atmosphere-land system model of LASG (GOALS/LASG) and its performance in simulation study. *Quarterly Journal of Applied Meteorology*, **8**(Suppl.), 15–28. (in Chinese)
Wu, L., Z. Liu, R. Gallimore, R. Jacob, D. Lee, and Y. Zhong, 2003: Pacific decadal variability: The Tropical Pacific mode and the North Pacific mode. *J. Climate*, **16**, 1101–1120.
Wu, L., D. Lee, and Z. Liu, 2005a: The 1976/77 North Pacific climate shift: The role of subtropical ocean adjustment and coupled ocean-atmosphere feedbacks. *J. Climate*, **18**, 5125–5140.
Wu, L., Z. Liu, Y. Liu, Q. Liu, and X. Liu, 2005b: Potential global climatic impacts of the North Pacific Ocean. *Geophys. Res. Lett.*, **32**, L24710, 10.1029/2005GL024812.
Wu, L., F. He, and Z. Liu, 2005c: Coupled ocean-atmosphere response to north tropical Atlantic SST: Tropical Atlantic dipole and ENSO. *Geophys. Res. Lett.*, **32**, L21712, 10.1029/2005GL024222.
Wu, T. W., 2006: The coupled climate system model development plan of China Meteorological Administration and its recent progress. The East Asian Climate (EAC) Workshop, 31 March–1 April, 2006, Sun Moon Lake, Nantou, Taiwan, China.
Xiao, C., 2006: Adoption of a two-step shape-preserving advection scheme in an OGCM and its coupled experiment. M.S. thesis, Institute of Atmospheric Physics, Chinese Academy of Sciences, 89pp. (in Chinese)
Yao, S., and Y. Zhang, 2007: Regional air-sea coupled model simulation of China summer precipitation. *Acta Meteorologica Sinica*, in press. (in Chinese)
You, X., R. Li, M. Zhang, and Q. Zeng, 2001: Numerical calculation of the wintertime circulation in the South China Sea by using a baroclinic model. *Acta Oceanologia Sinica*, **23**(6), 1–10. (in Chinese)
You, X., G. Zhou, J. Zhu, and R. Li, 2003: A sea temperature data assimilation system for the China Sea and adjacent areas. *Chinese Science Bulletin*, **48**(Suppl. II), 70–76. (in Chinese)
Yu, R. C., 1994: A two-step shape-preserving advection scheme. *Adv. Atmos. Sci.*, **11**(4), 479–490.
Yu, Y., 2005: IAP Global Coupled Climate Model FGOALS and its application in climate change. *MOST-DOE Science Team Meeting*, 9–11 June 2005, Beijing.
Yu, Y., and X. Zhang, 1998: A modified air-sea flux anomaly coupling scheme. *Chinese Science Bulletin*, **43**, 866–870. (in Chinese)
Yu, Y., A. Izard, Y. Guo, and X. Zhang, 2001: A response of IAP/LASG Oceanic General Circulation Model to the observed wind stress. *Chinese J. Atmos. Sci.*, **25**, 305–324. (in Chinese)
Yu, Y., R. Yu, X. Zhang, and H. Liu, 2002: A flexible global coupled climate model. *Adv. Atmos. Sci.*, **19**, 169–190.
Yu, Y., X. Zhang, and Y. Guo, 2004a: Global coupled ocean-atmosphere general circulation models in LASG/IAP. *Adv. Atmos. Sci.*, **21**, 444–455.
Yu, Y., Z. Zhou, and X. Zhang, 2004b: Impact of the closure of Indonesian seaway on climate: A numerical modeling study. *Chinese Science Bulletin*, **48**(Suppl. II), 88–93.
Yuan, Y. and F. Qiao, 2006: Ocean dynamic system and MASNUM marine numerical models. *Progress in Natural Sciences*, **16**(10), 1257–1267. (in Chinese)
Zeng, Q., X. Zhang, X. Liang, C. Yuan, and S. Chen, 1989: Documentation of IAP Two-Level Atmospheric General Circulation Model. TRO44, DOE/ER/60314-HI, 383pp.
Zhang, W. J., 2006: Spatial distribution and temporal variation of the observed and simulated soil moisture over China. M.S. thesis, Institute of Atmospheric Physics, Chinese Academy of Sciences, 119pp. (in Chinese)
Zhang, X., and X. Liang, 1989: A numerical world ocean general circulation model. *Adv. Atmos. Sci.*, **6**, 43–61.
Zhang, X., and J. E. Walsh, 2006: Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 model simulations. *J. Climate*, **19**, 1730–1747.
Zhang, X., N. Bao, R. C. Yu, and W. Wang, 1992: Coupling scheme experiments based on an atmospheric and an oceanic GCM. *Chinese J. Atmos. Sci.*, **16**, 129–144. (in Chinese)
Zhang, X., K. Chen, X. Jin, W. Lin, and Y. Yu, 1996: Simulation of thermohaline circulation with a twenty-layer oceanic general circulation model. *Theoretical and Applied Climatology*, **55**, 65–87.
Zhang, X., Y. Guo, C. Yuan, G. Shi, and G. Wu, 1999: Achievements in GCM studies at IAP. *Greenhouse Effect and Climate Change*, Tao et al., Eds., China Ocean Press, Beijing, 96–107. (in Chinese)
Zhang, X., G. Shi, H. Liu, and Y. Yu, Eds., 2000: *IAP Global Ocean-Atmosphere-Land System Model*. Science Press, Beijing, 251pp.
Zhang, X., Y. Yu, and H. Liu, 2003: The development and application of the oceanic circulation models, Part I: The global oceanic general circulation models. *Chinese J. Atmos. Sci.*, **27**, 607–617. (in Chinese)
Zhang, X., W. Lin, and M. Zhang, 2007: Toward understanding the double Intertropical Convergence Zone pathology in coupled ocean-atmosphere general circulation models. *J. Geophys. Res.*, **112**, D12102, doi:10.1029/2006JD007878.
Zhou, G. Q., and Q. Zeng, 1998: A coupled ocean-atmosphere general circulation model for ENSO prediction and 1997/1998 ENSO forecast. *Climatic and Environmental Research*, **3**(4), 349–357. (in Chinese)
Zhou, G. Q., and Q. Zeng, 2001: Prediction of ENSO with a coupled atmosphere-ocean general circulation model. *Adv. Atmos. Sci.*, **18**(4), 1587–1603.

Zhou, G. Q., Q. Zeng, and R. Zhang, 1999: An improved coupled ocean-atmosphere general circulation model and its numerical simulation. *Progress in Natural Science*, **9**(5), 374–381.

Zhou, N., Y. Yu, and Y. Qian, 2006d: Simulations of the 100 hPa South Asia High and Precipitation over the East Asia with IPCC Coupled GCMs. *Adv. Atmos. Sci.*, **23**(3), 375–390.

Zhou, T., X. Zhang, Y. Yu, R. Yu, and S. Wang, 2000a: Response of IAP/LASG GOALS model to the coupling of air-sea freshwater exchange. *Adv. Atmos. Sci.*, **17**(3), 473–486.

Zhou, T., X. Zhang, and S. Wang, 2000b: The relationship between the thermohaline circulation and climate variability. *Chinese Science Bulletin*, **45**(11), 1052–1056.

Zhou, T., X. Zhang, R. Yu, Y. Yu, and S. Wang, 2000c: The North Atlantic Oscillation simulated by Version 2 and 4 of IAP/LASG GOALS Model. *Adv. Atmos. Sci.*, **17**(4), 601–616

Zhou, T., X. Zhang, and Y. Yu, 2001a: On the coupling procedure of air-sea freshwater exchange in climate system models. *Chinese Science Bulletin*, **46**(1), 83–85.

Zhou, T., R. Yu, X. Zhang, Y. Yu, W. Li, H. Li, and X. Liu, 2001b: The features of atmospheric moisture transport, convergence and air-sea freshwater flux on coupled climate models. *Chinese J. Atmos. Sci.*, **25**(5), 598–608. (in Chinese).

Zhou, T., R. Yu, and Z. Li, 2002: ENSO-dependent and ENSO-independent variability over the midlatitude North Pacific: Observation and air-sea coupled model simulation. *Adv. Atmos. Sci.*, **19**, 1127–1147.

Zhou, T., 2003a: Multi-spatial variability modes of the Atlantic meridional overturning circulation. *Chinese Science Bulletin*, **48**(Suppl. II), 30–35.

Zhou, T., 2003b: Adjustment of the North Atlantic thermohaline circulation to the atmospheric forcing in a global air-sea coupled model. *Acta Meteorologica Sinica*, **61**(2), 164–179. (in Chinese)

Zhou, T., and R. Yu, 2006: Twentieth century surface air temperature over China and the globe simulated by coupled climate models. *J. Climate*, **19**(22), 5843–5858.

Zhou, T., Z. Li, Y. Yu, R. Yu, and X. Zhang, 2004: Indian Ocean response to ENSO in IPSL air-sea coupled model. *Chinese J. Atmos. Sci.*, **28**(4), 313–330. (in Chinese)

Zhou, T., and Coauthors, 2005a: The climate system model FGOALS_s using LASG/IAP spectral AGCM SAMIL at its atmospheric component. *Acta Meteorologica Sinica*, **63**(5), 702–715. (in Chinese).

Zhou, T., R. Yu, Z. Wang, and T. Wu, 2005b: *The Atmospheric General Circulation Model SAMIL and the Associated Coupled Model FGOALS_s*. China Meteorological Press, Beijing, 288pp. (in Chinese).

Zhou, T., and H. Drange, 2005: Climate impacts of the decadal and interannual variability of the Atlantic Thermohaline circulation in Bergen Climate Model. *Chinese J. Atmos. Sci.*, **29**(2), 167–177. (in Chinese)

Zhou, T., R. Yu, X. Liu, Y. Guo, Y. Yu, and X. Zhang, 2005c: Weak response of the Atlantic thermohaline circulation to an increase of atmospheric carbon dioxide in IAP/LASG Climate System Model. *Chinese Science Bulletin*, **50**(6), 592–598.

Zhou, T., Y. Yu, H. Liu, W. Li, and R. Yu, 2006a: Numerical simulation of the sensitivity of the Pacific subtropical-tropical meridional cell to global warming. *Progress in Natural Science*, **16**(5), 507–511.

Zhou, T., R. Yu, Y. Gao, and H. Drange, 2006b: Ocean-atmosphere coupled model simulation of North Atlantic interannual variability (I): Local air-sea interaction. *Acta Meteorologica Sinica*, **64**(1), 1–17. (in Chinese)

Zhou, T., R. Yu, Y. Gao, and H. Drange, 2006c: Ocean-atmosphere coupled model simulation of North Atlantic interannual variability (II): Tropical teleconnection. *Acta Meteorologica Sinica*, **64**(1), 18–30. (in Chinese)

Zhou, T., and Coauthors, 2007: A fast version of LASG/IAP climate system model and its 1000-year control integration. *Adv. Atmos. Sci.*. (in press)