Global Coupled Ocean-Atmosphere General Circulation Models in LASG/IAP

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(Received 6 March 2003; revised 24 November 2003)

ABSTRACT

Coupled ocean-atmospheric general circulation models are the only tools to quantitatively simulate the climate system. Since the end of the 1980s, a group of scientists in the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), have been working to develop a global OGCM and a global coupled ocean-atmosphere general circulation model (CGCM). From the original flux anomaly-coupling model developed in the beginning of the 1990s to the latest directly-coupling model, LASG scientists have developed four global coupled GCMs. This study summarizes the development history of these models and describes the third and fourth coupled GCMs and selected applications. Strengths and weaknesses of these models are highlighted.

Key words: coupled GCM, climate change, OGCM

1. Introduction

In order to simulate the Earth's climate and its variations on intra-seasonal to decadal timescales, a hierarchy of comprehensive climate system models is needed. The most important components in such models are the atmosphere, the oceans, sea ice, and the land and its features. The development of such models has been undergoing a step-by-step process: from stand-alone atmosphere models to coupled ocean-atmosphere models, and later to multi-sphere interactive models. The process is far from finished for climate modeling communities. The global coupled GCMs described in this study may represent an early stage toward the development of more complete climate system models. During the past decade, climate-modeling activities in the world underwent an important transition from using atmosphere-alone models to interactive ocean-atmosphere models. Rapid progress in the development of coupled ocean-atmosphere general circulation models (CGCMs) has been made since the late 1980s. The impetus for such rapid progress comes from the recognition as best summarized in the project of Climate Variability and Predictability (CLIVAR): "The major tools used in simulating, understanding, and predicting climate variations on all timescales will increasingly be computer models of the global coupled ocean-atmosphere-land system".

The effort in developing numerical climate models in the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), was initiated in the mid 1980s. The first global coupled GCM was developed in LASG based on a two-layer atmospheric general circulation model (AGCM) and a four-layer oceanic general circulation model (OGCM) by Zhang et al. (1992). The model was integrated for forty years and showed some ENSO-like interannual variability dominated by a westward propagating coupled mode.

Since the early 1990s, much effort has been put into developing multi-layer AGCMs and OGCMs at LASG. A twenty-layer 4°(Lat)×5°(Lon) OGCM with an incorporated thermodynamic sea ice model was developed first (Hereafter referred to as ML20; Zhang et al., 1996; Chen et al., 1997a). With the enhanced vertical resolution, the model is capable of not only reproducing some large-scale features of the upper ocean circulation but also depicting an acceptable configuration of

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the thermohaline circulation. The ML20 was coupled with the two-level AGCM to study the mean climate of the coupled system (Guo and Yu, 1996) and the time-dependent climate change due to increasing atmospheric CO_2 concentration (Chen et al., 1996; Chen et al., 1997b; IPCC, 1996). Meanwhile, a version of the nine-level spectral AGCM with a rhomboidal truncated wave number of 15 originating from Simmonds (1995) was introduced and reconstructed by Wu et al. (1996, hereafter referred to as L9R15). On the basis of such efforts, a new CGCM with its component OGCM of ML20 and AGCM of L9R15 was preliminarily presented in 1995 (Liu et al., 1996). This may be regarded as the original version of the IAP/LASG global ocean-atmosphere-land system model (GOALS) (Wu et al., 1997). Six versions of the IAP GOALS model have been successively presented based on the above mentioned versions of the AGCM and OGCM (Liu et al., 1996; Yu and Zhang, 1998; Liu and Wu, 1997; Liu et al., 1998; Zhang et al., 2002; Wu et al., 2003). All these versions of the GOALS model (except the GOALS-0) were integrated for 200 years or longer without finding serious climate drift. The data have been used in evaluating the model's ability in climate simulation and in studying some selected aspects of climate diagnoses and analyses (Liu et al., 1998; Zhang et al., 1998; Yu et al., 2000; Meng and Wu, 2000).

Due to the coarse resolution of GOALS models, it is very difficult to accurately represent many important air-sea interaction processes such as ENSO events. Thus a medium resolution OGCM with thirty layers and the approximately $1.875^\circ \times 1.875^\circ$ horizontal resolution was developed in LASG by Jin et al. (1999) (Hereafter referred to as "L30T63"). Then, based on the ocean model L30T63, a primary version of a Flexible General Circulation Model for climate system was finished (referred to as FGCM-0) (Yu et al., 2002). The FGCM-0 is formulated based on the NCAR Climate System Model Version1.2 (CSM-1.2) (Boville and Gent, 1998,) by replacing the CSM-1.2's ocean component, NCOM (the NCAR CSM Ocean Model), with the L30T63 in virtue of the CSM-1.2's flux coupler. The flux coupler is also responsible for interpolating and averaging between the different grid system of component models while conserving local and integral properties. The coupling strategy (based on the flux coupler) allows component models to be exchanged relatively easily. In fact, it provides an efficient way to formulate a new climate system model and to test the sensitivity of the model to any of its component models. The atmosphere and land surface components are the CCM3 (the Community Climate Model, Version Three, see Kiehl et al., 1998) and the Land System Model (Bonan, 1998), respectively. Since the geography of the FGCM-0 is identical with that of the L30T63, the land-sea marks and surface types of the CCM3 have been modified to match the OGCM. Also, the horizontal grid of the sea ice model of Weatherly et al. (1998) has been modified to replace the original thermodynamic sea ice model of L30T63. The atmospheric, land, and sea ice models communicate with the flux coupler every model hour, while the oceanic model does so every model day.

In summary, LASG scientists have devoted themselves to developing atmosphere, ocean, and climate system models since the end of the 1980s. Up to now, they have finished four global coupled GCMs, and these have been used in many ways to understand the atmosphere and oceans. In this study, we describe the latest two global coupled GCMs—GOALS and FGCM-0.

2. GOALS model

2.1 *Atmospheric and land component models*

The atmospheric component model is a nine-layer spectral model that is rhomboidally truncated at zonal wave number 15 (hereafter referred to as L9R15), which was originally from a version by Simmonds (1985). In order to make the model perform much better, some improvements are implemented as follows.

(1) The standard stratification of temperature is introduced into the dynamical framework, and the scheme of reduction of a standard atmosphere, an idea proposed by Zeng (1963) and Phillips (1973), is used to improve the model performance. As a result, the deviation of temperature becomes a prognostic variable (Wu et al., 1996).

(2) A new K-distribution radiation scheme is implemented into the model. This radiation scheme can easily take the effects of trace gases, such as CO_2, CH_4, N_2O, and CFCs into account. Cloud processes are treated more reasonably in this scheme (Shi, 1981; Wang, 1996).

(3) A simplified biosphere and soil/snow model (Xue et al., 1991) is implemented into the model (Liu and Wu, 1997).

(4) The diagnosed cloud cover and liquid water path scheme is introduced into the model (Liu et al., 1998).

(5) The drag coefficient for momentum surface stress over ocean is calculated according to Hellerman and Rosenstein (1983), instead of Simmonds (1985). The reason is that the Simmonds (1985) scheme greatly underestimates the drag coefficient over the eastern equatorial Pacific, only about 50% of that from observation.

(6) The diurnal variation of shortwave and longwave radiation is introduced into the model (Shao et al., 1998).

(7) Wu et al. (2003) enhanced the horizontal resolution of the AGCM L9R15 from R15 to R42, and found that the simulated precipitation is greatly improved by the high resolution version.

2.2 *Oceanic and sea ice component models of GOALS*

Based on a four-layer OGCM by Zhang and Liang (1989), the oceanic component model of GOALS has been developed since 1994. It is a twenty-layer model with the same horizontal resolution as that of the previous four-layer model but covers from the Antarctic coastline to 70°N in its original version (Chen, 1994; Zhang et al., 1996; hereafter referred to as ML20-0) and the global scope except the North Pole in its revised version (Yu, 1997). Another important difference between the ML20-0 and the ML20-1 is that the former uses the "upwind" finite-difference scheme for calculating the advections of temperature and salinity (Maier-Reimer et al., 1993) thereby ignoring the explicit diffusion terms in the temperature and salinity equations, whereas the latter uses central finite-difference schemes for the advections and has conventional second-order diffusion terms. With the enhanced vertical resolution, both the ML20-0 and the ML20-1 are capable of reproducing some large-scale features of the upper ocean circulation and depicting an acceptable configuration of the thermohaline circulation (THC), while forced by observational atmospheric wind stress and thermal forcing as well as observational sea surface salinity (Zhang et al., 2000). The oceanic model ML20-0 was adopted in the original version of GOLAS (GOALS-0), and ML20-1 was adopted in the later five versions of GOALS.

A simple thermodynamic sea-ice model formulated based on Parkinson and Washington (1979) is incorporated into the ocean model. In the present ocean-sea ice coupling model, no attempt was made to parameterize the leads and brine-rejection processes. As a surrogate of the brine-rejection effect on the ocean thermohaline circulation (especially on the formation of Antarctic Bottom Water (AABW)), an enhanced salinity forcing similar to England (1993) is imposed at the three rows adjacent to Antarctica throughout the model's integration without considering its seasonal variation.

2.3 *Air-sea coupling scheme*

With observed boundary conditions, AGCMs and OGCMs can reproduce, to certain extents, reasonable large-scale circulation patterns in the atmosphere and ocean. However, when an AGCM and an OGCM are directly coupled to each other, the basic climate simulated by the coupled model usually drifts away from the observed one. This is the problem known as climate drift. In general, climate drift occurs due to errors in the fluxes at the air-sea interface, which may be amplified by some positive feedback processes in a CGCM.

In order to reduce the flux errors in CGCMs, additional terms are often required to correct the simulated fluxes at the air-sea interface, that is the so-called "flux correction" (Sausen et al., 1988). The "flux-correction" (or "flux-adjustment") technique has been widely used in the existing CGCMs (see Meehl, 1990; Neelin et al., 1992; Murphy, 1995) before 1995.

After some coupling experiments based on a two-level AGCM (Zeng et al., 1989) and a four-layer OGCM (Zhang and Liang, 1989), Zhang et al. (1992) developed a prediction-correction monthly flux anomaly (MFA) coupling scheme. With the MFA scheme, the coupled model (referred to as M2+4) was integrated for forty years without significant climate drift (Zhang et al., 1992). Afterwards, the MFA scheme was employed in the two successive CGCMs. One is based on the 2-L AGCM and a twenty-layer OGCM (ML20), and the coupled model is referred to as M2+20 in this study. The other is based on a nine-layer and R15 spectral AGCM and the ML20-0. It is the original version of the GOALS/LASG model, i.e., the GOALS-0. However, the performances of the MFA scheme in these two models were not fully successful. The M2+20 suffered from a considerable cooling trend in its 130-year control run (Chen, 1994) and the GOALS-0 showed a one-degree (Celsius) warming in its forty-year integration (Liu et al., 1996). In other words, the MFA coupling scheme is not "robust" in controlling the climate drift.

Yu (1997) analyzed the performance of the GOALS-0 and developed a modified MFA coupling scheme (MMFA) (Yu, 1997; Yu and Zhang, 1998). The MMFA scheme has been successfully used in three successive versions of the GOALS model. The coupling scheme used in the subsequent version, GOALS-3, is essentially the MMFA but slightly different from those used before. All of these GOALS versions were integrated for long time periods without noticeable climate drift.

Until the GOALS-4, the coupling time step was one month so that the "prediction-correction" method (Zhang et al., 1992) was necessary for keeping the synchronization between the AGCM and OGCM. In the GOALS-4, the coupling time step was set to one day and a daily flux anomaly-coupling scheme (referred to as DFA) was used so that the prediction-correction

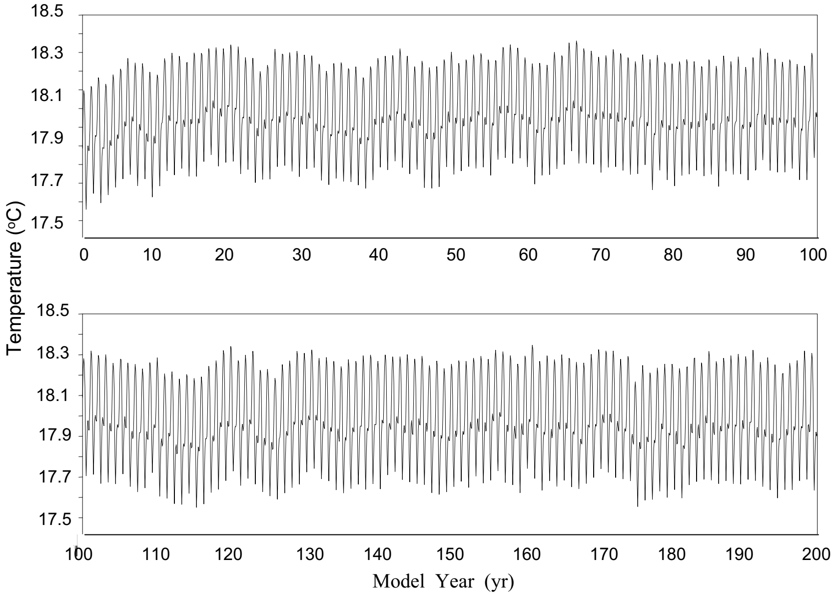

Fig. 1. The monthly global mean SST (°C) simulated by GOALS-4 from the 1st to 200th model year.

procedure was dropped. Preliminary results of the GOALS-4 show a good performance of the DFA scheme (Fig. 1). Recently Zhang et al. (2002) and Wu (Personal communication) carried out another two versions of GOALS (GOALS-5 and GOALS-6 respectively); the oceanic component model of both versions of GOLAS is L30T63 rather than ML20.

2.4 *Mean climatology state by GOALS*

The evaluations show that, in general, four versions of the GOALS model are all able to reasonably reproduce the basic characteristics of current observed climate in many aspects, especially for the large-scale features and seasonal cycle (Yu, 1997; Guo et al., 2000). However, it is more important to remember that there are many weaknesses in the coupled modelling. Some weaknesses may be common to most coupled models, and some weaknesses may be related to the parameterizations of some physical processes of the GOALS model. We notice that the introductions of the SSiB land model and diurnal cycle of shortwave radiation to the model obviously improve the simulation of surface air temperature. The diagnostic cloud parameterization scheme, which leads to the absence of cloudiness and the anomalous high temperature in middle latitudes in Northern summer, need to be improved in the future. All six versions of the GOALS model simulate lower amounts of global mean precipitation. Particularly, the much less precipitation simulated in summer and the more precipitation in winter in the Northern Hemisphere middle latitudes suggest that modification to the precipitation parameterization scheme is necessary. The GOALS model is able to reproduce the annual cycle of SST and the El Niño timescale variability at the equatorial Pacific, although the simulated amplitude is weaker and the position of maximum SST anomaly is located further west when compared with the observed values (Fig. 2).

2.5 *Simulations of Global Climate Change for the Past and the Next 100 years*

The six versions of GOALS have been widely applied in studies of climate variabilities, air-sea interaction, monsoon, etc. (Liu et al., 1998; Yu et al., 2000; Meng and Wu, 2000; Zhang et al., 1998). In this paper, we will mainly describe simulations of global climate change by human activities with the GOALS model.

Although the GOALS model shows reasonably good simulations of the present climate, this does not necessarily guarantee that the response to a perturbation remains credible. Therefore, many works first assess the performance of the model in simulating the climate over the 20th century. Especially since the pioneer experiments conducted at the Hadley Centre for Climate Prediction and Research (Mitchell et al., 1995) and at the Deutsche Klimarechenzentrum (DKRZ) (Hasselmann et al., 1995), the simulations of the global climate change during the past 100 years have become a standard experiment for coupled models (Boer et al., 2000; Emori et al., 1999; Haywood et al., 1997). Ma et al. (2004) carried out simulations of

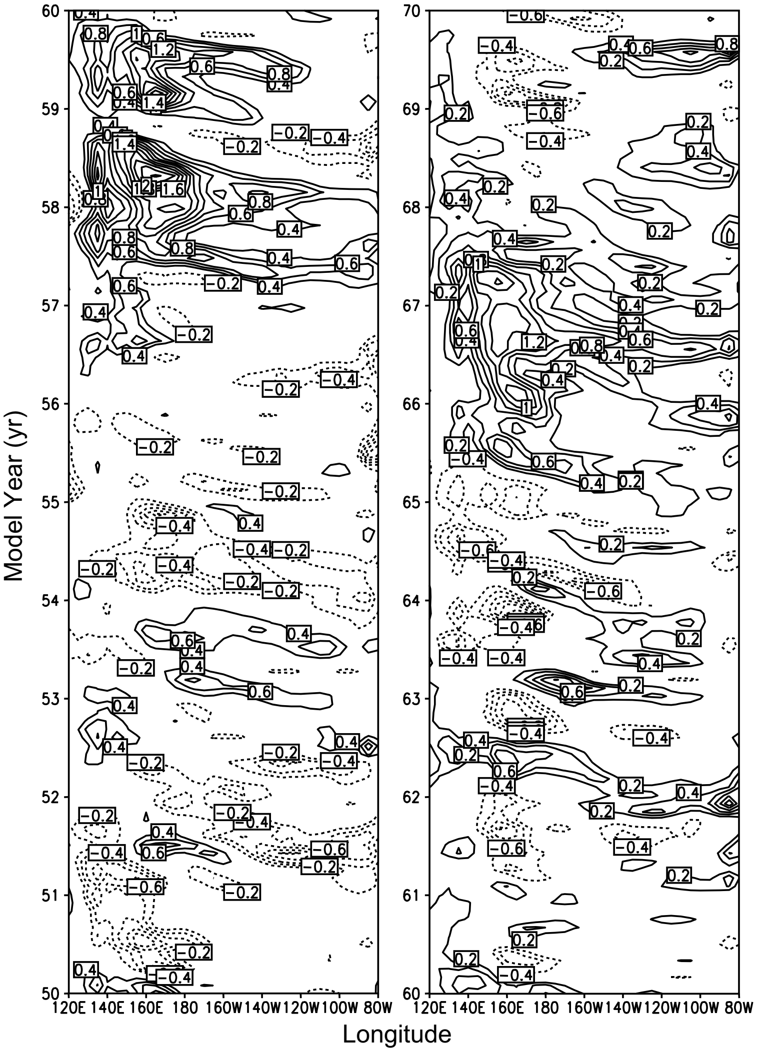

Fig. 2. The simulated SST (°C) anomaly averaged from 2°S to 2°N by GOALS-4 as a function of longitude (X-axis) and time (Y-axis) from the 50th to 70th model year.

the 20th century with GOALS including four experiments: control run, sensitivity run forced by greenhouse gases only, sensitivity run forced by greenhouse gases and solar radiation, and sensitivity run forced by greenhouse gases, solar radiation, and sulphate aerosols. The simulated global mean surface air temperature anomaly (Fig. 3) suggested that the observed global warming 0.6°C should be mainly attributed to greenhouse gases during the past 100 years, but the effects of solar radiation and, sulphate aerosols cannot be ignored. When all forcings including greenhouse gases, solar radiation, and sulphate aerosols are considered in the coupled model, the simulated global warming is 0.65°C during the 20th century, which agrees well with the observed value.

Based on the simulations of the 20th century, Guo et al. (2001) finished two simulations, one for the control run and another for the perturbation run with GOALS-4 to investigate the global warming, with much detailed emphasis on East Asia. Results indicate that there is no climate drift in the control run and at the time of CO_2 doubling the global temperature increases about 1.65°C (Fig. 4). The GOALS model is able to simulate the observed spatial distribution and annual cycles of temperature and precipitation for East Asia quite well. But, in general, the model underestimates temperature and overestimates rainfall amount for the regional annual average. For the climate change in East Asia, the temperature and precipitation in East Asia increase 2.1°C and 5% respectively, and the maximum warming occurs at middle-latitude continent and the maximum precipitation increase oc-

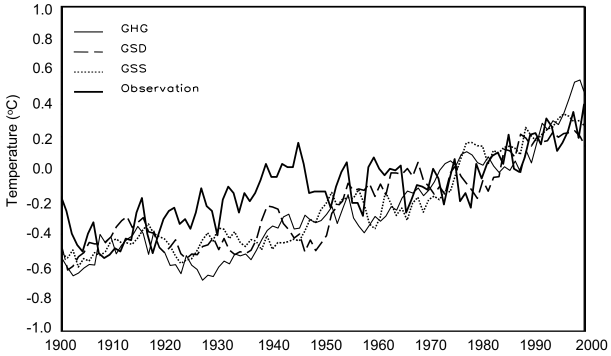

Fig. 3. The global mean SST anomaly (relative to the 1960–1990 mean value) during the 20th century. GHG denotes the experiment considering greenhouse gases only, GSD denotes the experiment considering greenhouse gases and sulphate aerosols, and GSS denotes the experiment considering greenhouse gases, sulphate aerosols, and solar radiation.

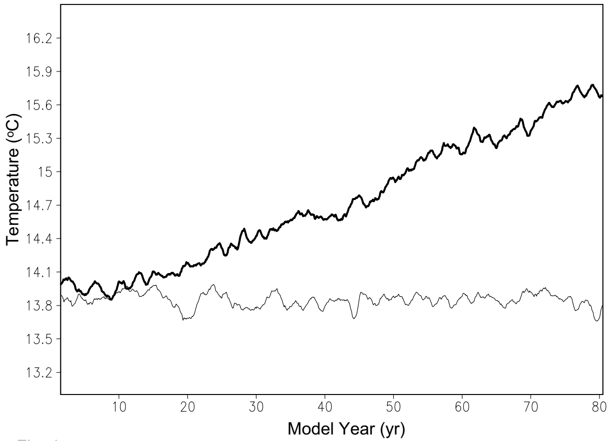

Fig. 4. The global mean surface air temperature simulated by GOALS-4 for the control run (thick line) and CO_2 doubling run (thin line).

curs around 25°N with reduced precipitation in the tropical western Pacific.

3. The Flexible Global Coupled GCM Version 0—FGCM-0

3.1 *Basic configuration of FGCM-0*

The coupled ocean-atmosphere general circulation model (CGCM) used in this study is the primary version of a Flexible General Circulation Model for climate systems (referred to as FGCM-0). The FGCM-0 is formulated based on the NCAR CSM-1 (Boville and Gent, 1998) by replacing the CSM-1.2's ocean component, NCOM (the NCAR CSM Ocean Model), with the L30T63 in virtue of the CSM's flux coupler. The functions of the flux coupler are: (1) controlling the time coordination of all the component models of the climate system model; (2) calculating most of the interfacial fluxes; (3) communicating with component models for exchanging fluxes and some control parameters (Fig. 5). The flux coupler is also responsible for interpolating and averaging between the different grid system of component models while conserving local and integral properties. As pointed out already in Boville and Gent (1998), the coupling strategy (based on the flux coupler) allows component models to be exchanged relatively easily. In fact, it provides an efficient way to formulate a new climate system model and to test the sensitivity of the model to any of its component models. The FGCM-0 represents just the first step towards a fully developed FGCM, of which the oceanic component is the OGCM, L30T63 (without using its thermodynamic sea-ice component), and the others are almost the same as those in the CSM-1. The atmosphere and land surface components are the CCM3 (Kiehl et al., 1998) and the LSM1 (Bonan, 1998), respectively. Since the geography of the FGCM-0 is identical with that of the L30T63, the land-sea marks and surface types of the CCM3 have been modified to match the OGCM. Also, the horizontal grid of the sea ice model of Weatherly et al. (1998) has been modified to replace that in the original L30T63. The atmospheric, land, and sea ice models communicate with the flux coupler every model hour, and the oceanic model does this every model day. To diminish the initial shock in the coupling process, a spin-up procedure is adopted before running the FGCM-0.

Firstly, the AGCM, CCM3, and the land surface model, LSM1, are integrated for five years by using the observed climatological SST, sea-ice distributions based on Shea et al. (1990), and the same land-sea mask as the ocean component model L30T63. This five-year integration is referred to as "Run 1" in this study. Daily data from the last four years of Run 1 are archived for state variables and for radiation flux

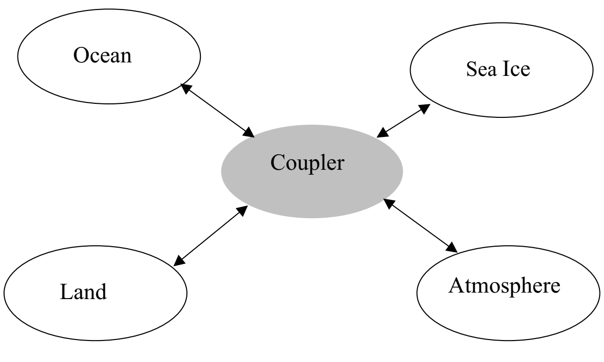

Fig. 5. The FGCM-0 component models configurations.

at the lowest model level.

Secondly, the OGCM, L30T63, in association with the thermodynamic sea ice model of Weatherly et al. (1998) is integrated for seventy years, starting from the year 1160 of the ocean model's basic run mentioned above. In the course of the integration, the surface wind stress and thermal forcing were taken from the daily state variables and radiation flux for the last four years of the aforementioned CCM3 run. For the surface salinity, the restoring condition is still used, without considering the fresh water flux calculated based on the AGCM and OGCM themselves. This seventy-year integration of the ocean model will be referred to as "Run 2" or the "Spinup Run".

Following the spinup step, the fully coupled model, FGCM-0, is integrated for sixty years. The initial conditions for atmosphere, land surface, ocean, and sea ice models are taken from the end of Run 1 and Run 2, respectively. As in the CSM-1.2, the atmosphere and ocean-sea ice models in the FGCM-0 are directly coupled by exchanging the heat and momentum fluxes themselves, rather than the flux-anomalies as in the previous IAP/LASG CGCMs. Different from the CSM-1, the fresh water exchange is not included; instead, the relaxation condition of salinity is still used in the FGCM-0. Also in order to diminish the initial shock, the dynamic processes of sea ice are not included until the end of the first seven years of the coupled integration.

3.2 *Oceanic Component Model of FGCM-0*

The oceanic component model used in the coupled model is the third-generation global OGCM developed at IAP by Jin et al. (1999). Its horizontal grid is just the same as that of a T63 AGCM with a grid size of about 1.875°×1.875°. There are thirty layers in the vertical, of which twelve equal depth layers are placed in the upper 300 m to better depict the equatorial thermocline. For short, the model is often called "L30T63". Some fairly mature parameterizations are adapted to the model, including the penetration of solar radiation (Rosati et al., 1988), the "PP" scheme for the upper ocean vertical mixing (Pacanowski et al., 1981), and the isopycnal mixing scheme proposed by Gent and MacWilliams (1990). A thermodynamic sea-ice model based on Parkinson and Washington (1979) is also incorporated into the ocean model. The model was first integrated for 1160 years with the wind stress forcing of Hellerman and Rosenstein (1983) and the thermal forcing required in a Haney-type formula for heat-flux (Haney, 1971), taken from the COADS (Comprehensive Ocean-Atmosphere Data Set) (da Silva et al., 1994). The model's surface salinity was simply relaxed to the climatological annual cycle of Levitus et al. (1994). By the end of the integration, the model reaches a quasi-equilibrium state, of which both the wind-driven circulation and the thermohaline circulation are reasonably simulated (Jin et al., 1999). This may be seen as the L30T63's basic run that provides initial conditions for the coupled model spinup run. Forced by the month-by-month wind stress over the tropical Pacific Ocean from the European Center for Medium Weather Forecast (ECMWF) reanalysis data for the time period from 1980 to 1989, the OGCM reproduces the reasonable interannual variability in the tropical Pacific Ocean (Yu et al., 2001).

3.3 *Mean Climatology by FGCM-0*

The model FGCM-0 has been integrated 60 years successfully. Although the flux correction is not employed in the coupled model FGCM-0, the model does not show obvious climate drift. This is because all the component models, NCAR CCM3, the land model, the sea ice model, as well as IAP OGCM, show good ability to depict dynamical and physical processes in the climate system. In the meantime, the flux coupler, which assures the conservation of energy and mass at the interfaces of model components, also plays a very important role in controlling the climate drift.

Compared to the observed climatology, although the model FGCM-0 reproduces the east-west gradient of SST in the equatorial Pacific, the model's major errors are the simulated double ITCZ and the associated SST pattern (Fig. 6). As described by many other studies (Mechoso et al., 1995; Boville and Gent, 1998), they are common features for the coupled models without flux correction. The equatorial warm pool simulated by the FGCM-0 differs substantially from observation, with the temperature averaged over the upper 100 m being about three degrees colder than observation. With the exaggerated role of ocean dynamics in the thermal equilibrium, the "warm pool" simulated by the FGCM-0 resembles, to a certain extent, the cold tongue. Moreover, the FGCM-0-simulated thermocline in most of the tropical South Pacific is tens-to-hundred meters shallower than observation. As a consequence, the thermocline tends to be latitudinally symmetrical about the equator. This may represent an image of the "double ITCZ" mode in the ocean component of a coupled ocean-atmosphere model. The severe biases in the simulated thermocline may be attributed to the systematic errors in the surface wind stress, and to the sharp decrease of the vertical mixing with depth (Li et al., 2003; Dai et al., 2003). It is found that the meridional overturning circulation related to the unrealistic cold water in the middle- and high-latitudes North Pacific Ocean may be favorable to maintain the

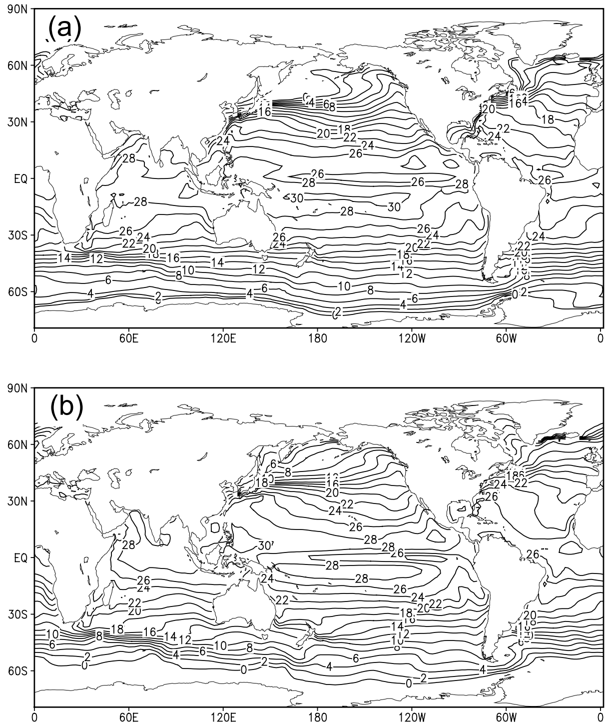

Fig. 6. Simulated sea surface temperatures (°C) by FGCM-0 averaged from the 11th to 60th model year for (a) March and (b) September.

cold biases in the tropical thermocline. For further diagnoses of mean climatology by FGCM-0, see Zhang et al. (2003a, b).

3.4 *ENSO and Indian Ocean dipole (IOD) modes by FGCM-0*

Forced with the observed wind stress, the oceanic component model has shown good ability in reproducing El Niño and La Niña events during the 1980s (Yu et al., 2001). When the oceanic model is coupled to the atmospheric, land, and sea ice models through the flux coupler, the interannual variation of the averaged SST over the Niño-3.4 region (5°S–5°N, 170°W–120°W) is produced automatically without any external forcing except for solar radiation, implying that the coupled model can simulate the “ENSO-like” phenomena (Fig. 7). The coupled model produces a very similar amplitude of the Niño index to the observational one, but shows a quasi-biennial oscillation only instead of one with considerably wide period from 2 to 7 years as in the real world. Further analyses indicate that the physical mechanism for the simulated ENSO-like events is very similar to the so-called a “Delayed Oscillator” mechanism proposed by Schopf and Suares (1988) and Battisti and Hirst (1989).

In the tropical Indian Ocean, the coupled model FGCM-0 shows a similar dipole mode pattern to the observational one (Fig. 8). Figure 8a shows the simu-

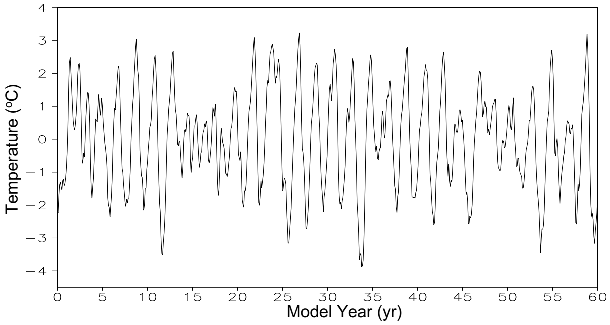

Fig. 7. Simulated sea surface temperature anomalies (°C) by FGCM-0 averaged over the Niño-3.4 region (5°S–5°N, 170°W– 120°W).

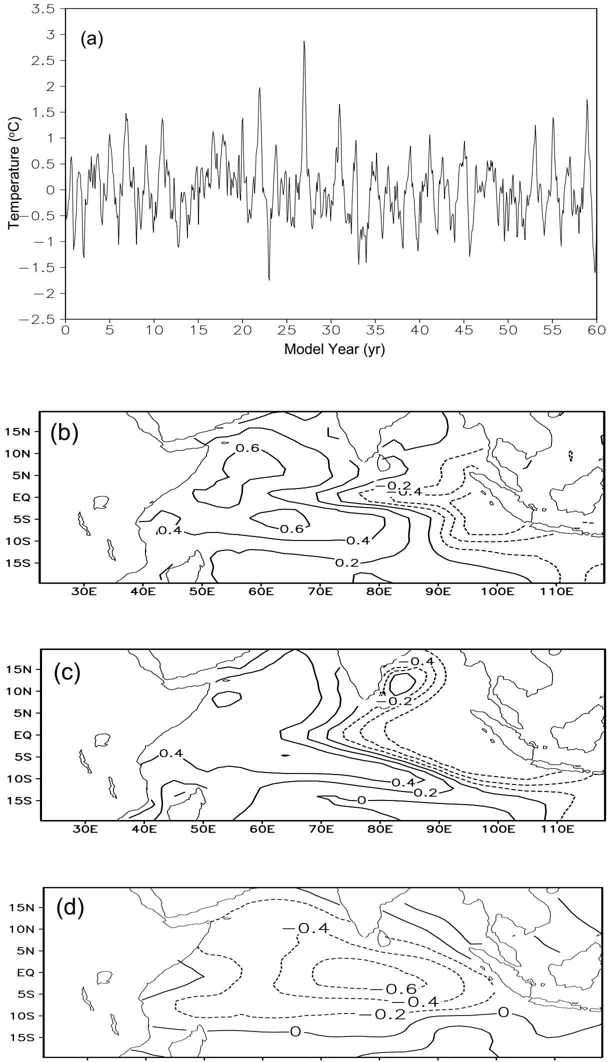

Fig. 8. (a) The simulated dipole mode index in the Indian Ocean, correlation coefficients of DMI with (b) SST, (c) vertically averaged temperatures in the upper 300 m, and (d) zonal wind stress.

lated dipole mode index (DMI), which is defined in Saji et al. (1999). The correlation coefficient between the DMI and the Niño-3.4 index is 0.44, which is not very strong but still significant. This implies that the simulated dipole mode in tropical Indian Ocean is associated with the ENSO event in the coupled model. Figures 8b–d are the correlations between DMI and SST, zonal wind stress, and upper ocean heat content, respectively. Thus, the simulated dipole mode pattern is not only in SST, but also in VAT, and in particular, there is a close correlation between the dipole mode index and the zonal wind stress in the central Indian Ocean, which implies that the dipole mode pattern is a coupled mode resulting from the air-sea interaction in the tropical Indian Ocean.

3.5 *Paleo-climate modeling by FGCM-0*

In order to investigate the paleoclimate effect of the opening of the Isthmus of Panama and Indonesian passage on the oceanic and atmospheric circulation, the ocean model topography are derived from study by Zhou et al. (2004) for various geological times including those at the present, 6 million years before present (6 Ma BP), and 14 million years before present (14 Ma BP), respectively, then a series of numerical experiments are implemented with the individual OGCM and the coupled model FGCM-0. The numerical experiments of the individual OGCM forced by the modern atmospheric circulation and coupled ocean-atmosphere model all show that the closing of the Indonesian passage results in a warming in the Pacific Ocean and a cooling in the Indian Ocean; furthermore, the Indonesian Through Flow (ITF) mainly originates from the southern Pacific at 14 Ma BP, while it mainly originates from the northern Pacific now. Meanwhile, the closing of the Isthmus of Panama causes strong upwelling in the eastern equatorial Pacific and isolates heat exchange between the Pacific and Atlantic Oceans, and eventually results in a cooling in SST and an uplift of the thermocline in the eastern Pacific and increases the contrast of heat content between the western and eastern Pacific (Fig. 9).

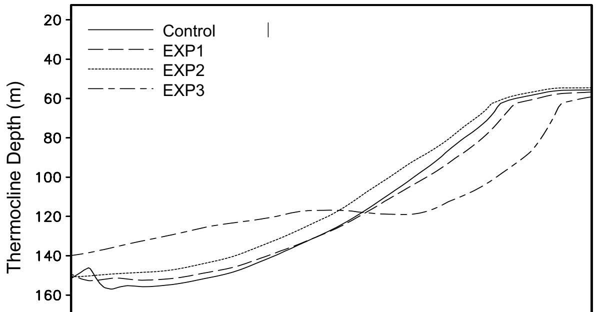

Fig. 9. Simulated thermocline depth defined as the isotherm line of 18°C, averaged from 2°S–2°N as a function of longitude (X-axis) and depth (Y-axis, units: m), for the control experiment (using modern topography), sensitivity experiment 1 (using paleo-topography at 6 Ma BP in the Indonesian Ocean), sensitivity experiment 2 (using paleo-topography at 14 Ma BP in the Indonesian Ocean), and experiment 3 (as experiment 2 except for the opening of the Isthmus of Panama).

4. Summary

Two global coupled GCMs, GOALS and FGCM-0 have been developed in LASG in the past five years, and they have been employed in simulating natural climate variability from seasonal to decadal timescales and anthropogenic climate change. Although there are many uncertainties in all state-of-the-art coupled GCMs including GOALS and FGCM-0, scientists in LASG have expended much effort during the past decades in the development and validation of climate models, and considerable progresses have been made, as given follows.

Based on the individual ocean, atmosphere, land, and sea ice models, LASG has put forward the MMFA and DFA coupling schemes and developed a coupled GCM GOALS model. In fact, the GOALS model was the first physical climate system model from LASG.

Four versions of the GOALS model have been integrated at least 200 years for their control runs, and in particular, several additional extended integrations have been carried out for investigating climate change induced by human activities. Almost all model output data have been analyzed for evaluating the model, and investigating the physical processes of the climate system, etc. In particular, the second and the fourth versions of GOALS (GOALS-2 and GOALS-4) joined the Coupled Model Intercomparisons Project phase 1 and phase 2 (CMIP1 and CMIP2), and simulations of global climate change have been used to estimate future climate change (IPCC, 1996; 2001)

Although many shortcomings still remain in GOALS and the other earlier coupled models developed in LASG, LASG scientists acquired the most important knowledge and experiences through developing and improving them so that the latest coupled model FGCM-0 reaches a higher level than other earlier coupled models. For example, FGCM-0 is a flexible GCM, where the word "flexible" implies that it is very easy to replace any parts of FGCM-0 including physical parameterization schemes or component models. Thus it is possible to compare individual GCMs or parameterization schemes under the same framework of the climate system model, making it easy to improve and develop the model.

Besides FGCM-0 and GOALS, another coupled GCM–LASG/NCC (National Climate Cneter) T63AOGCM was developed in 2000 through coupling IAP/LASG L30T63 OGCM and NCC T63 AGCM with the DFA coupling scheme for short-range climate prediction (Liu et al., 2003). The model T63AOGCM's ocean component is the same as FGCM-0, but its atmospheric model was developed based on a medium-range weather forecast model from ECMWF by Ye et al. (2000) at the NCC. Yu (personal communication) indicated that FGCM-0 and T63AOGCM show very large differences in the simulated mean climatological state and ENSO events, which implies that the AGCM plays a key role in the coupled model. The model T63AOGCM has shown some skill in short-range climate prediction during the past three years (Ding et al., 2002).

Acknowledgments. This study was jointly supported by the Chinese Academy of Sciences (CAS) "Innovation Program" (ZKCX2-SW-210), State Key Project (G2000078502), and the National Natural Science Foundation of China (Nos. 40231004, 40221503, and 40023001). Research activities on the LASG coupled GCMs are not possible without the support from LASG. We appreciate all the scientists who participated in the development, evaluation, and application of LASG coupled models, especially Dr. Zhou Tianjun, Dr. Li Wei, Dr. Liu Hui, Dr. Jin Xiangze, Dr. Chen Keming, Dr. Liu Hailong, Dr. Wang Zaizhi, Dr. Wang Biao, and Dr. Shi Guangyu.

REFERENCES

Battisti, D. S., and A. C. Hisrt, 1989: Interannual variability in a tropical atmosphere-ocean model: Influence of the basic state, ocean geometry and nonlinearity. *J. Atmos. Sci.*, **46**, 1687–1712.

Boer, G. J., G. Flato, M. C. Reader, and D. Ramsden, 2000: A transient climate change simulation with greenhouse gas and aerosol forcing: Experimental design and comparison with the instrumental record for the 20th century. *Climate Dyn.*, **16**, 405–426.

Bonan, G. B., 1998: The Land surface climatology of the NCAR land surface model coupled to the NCAR community climate model. *J. Climate*, **11**, 1307–1326.

Boville, B. A., and P. R. Gent, 1998: The NCAR climate system model, Version One. *J. Climate*, **11**, 1115–1130.

Chen Qiying, Yu Yongqiang, Guo Yufu, and Zhang Xuehong, 1996: Climatic change in East Asia induced by greenhouse effect. *Climatic and Environmental Research*, **1**, 113–123.(in Chinese)

Chen Keming, Zhang Xuehong, and Jin Xingze, 1997a: A coupled ocean-atmosphere general circulation model for studies of global climate changes, I. Formulation and performance of the model. *Acta Oceanologia Sinica*, **19**(3), 21–32. (in Chinese)

Chen Keming, Zhang Xuehong, Jin Xiangze, Yu Yongqiang, and Guo Yufu, 1997b: A coupled ocean-atmosphere general circulation model for studies of global climate changes: II. Preliminary analyses on climate drift and enhanced greenhouse effect. *Acta Oceanologia Sinica*, **19**(4), 26–40. (in Chinese)

Dai Fushan, Yu Rucong, Zhang Xuehong, and Yu Yongqiang, 2003: The impact of low-level cloud over the eastern subtropical Pacific on the "Double ITCZ" in LASG FGCM-0. *Adv. Atmos. Sci.*, **20**, 461–474.

Da Silva, A. M., A. C. Young, and S. Levitus, 1994: *Algorithms and Procedures.* Vol. 1, *Atlas of Surface Marine Data 1994,* NOAA Atlas NESDIS 6, U.S. Dept. of Commerce, Washington D.C., 83pp.

Ding Yihui, Liu Yimin, and Song Yongjia, 2002: Research and experiments of dynamical model system for short-term climate predication. *Climatic and Environmental Research,* **7**, 236–246. (in Chinese)

Emori, S., T. Nozawa, A. Abe-Ouchi, A. Numaguti, M. Kimoto, and T. Nakajima, 1999: Coupled ocean-atmosphere model experiments of future climate change with an explicit representation of sulfate aerosol scattering. *J. Meteor. Soc. Japan*, **77**, 1299–1307.

England, M. H., 1993: Representing the global-scale water masses in ocean circulation models. *J. Phys. Oceanogr.*, **23**, 1523–1552.

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

Guo Yufu, Yu Yongqiang, Chen Keming, Jin Xiangze, and Zhang Xuehong, 1996: Mean climate state simulated by a coupled ocean-atmosphere general circulation model. *Theor. Appl. Climatol.*, **55**(1–4), 99–112.

Guo Yufu, Yu Yongqiang, and Zhang Tao, 2000: Evaluation of IAP/LASG GOALS model. *IAP Global Ocean-Atmosphere-Land System Model.* Zhang et al. Eds., Science Press, Beijing, New York, 252pp.

Guo Yufu, Yu Yongqiang, Liu Xiying, and Zhang Xuehong, 2001：Simulation of climate change induced by CO_2 increasing for East Asia with IAP/LASG GOALS model. *Adv. Atmos. Sci.*, **18**, 53–66.

Haney, R. L., 1971: Surface thermal boundary condition for ocean circulation models. *J. Phys. Oceanogr.* , **1**, 241–248.

Hasselmann, K., and Coauthors, 1995: Detection of anthropogenic climate change using a fingerprint method. *Proceedings of "Modern Dynamical Meteorology", Symposium in honor of Aksel Wiin-Nielsen*, P. Ditlevsen, Ed., ECMWF Press, 203–221.

Haywood, J. M., R. J. Stouffer, R. T. Wetherald, S. Manabe, and V. Ramaswamy, 1997: Transient response of a coupled model to estimated changes in greenhouse gas and sulfate concentrations. *Geophys. Res. Lett.*, **24**, 1335–1338.

Hellerman, S., and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates, *J. Phys. Oceanogr.*, **13**, 1093–1104.

IPCC, 1996: *Climate Change 1996: The Science of Climate Change.* T. J. Houghton et al., Eds., Cambridge University Press, Cambridge, U. K., 572pp.

IPCC, 2001, *Climate Change 2001: The Scientific Basis.* R. Watson, T. J. Houghton, and Y. Ding Eds., Cambridge University Press, Cambridge, U. K., 882pp.

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

Jin Xiangze, Zhang Xuehong, and Yu Yongqiang, 2000: Oceanic general circulation and sea-ice model. *IAP Global Ocean-Atmosphere-Land System Model*, Zhang et al., Eds., Science Press, Beijing, New York, 252pp.

Kiehl, J. F., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Pasch, 1998: The National Center for Atmospheric Research community climate model: CCM3. *J. Climate*, **11**, 1131–1149.

Levitus, S., R. Burgett, and T.P. Boyer, 1994: W*orld Ocean Atlas 1994. Vol. 3: Salinity.* NOAA Atlas NESDIS 3, U.S. Department of Commerce, Washington D.C., 99pp.

Li Jianglong, Zhang Xuehong, Yu Yongqiang, and Dai Fushan, 2003: Double ITCZ phenomenon and analysis of its heat budget in a coupled ocean-atmosphere general circulation model. *Acta Meteorological Sinica,* **61**, 39–51. (in Chinese)

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

Liu Hui, and Wu Guoxing, 1997: Impacts of land surface on climate of July and onset of summer monsoon: A study with an AGCM plus SSiB. *Adv. Atmos. Sci.*, **14**, 289–308.

Liu Hui, Zhang Xuehong, and Wu Guoxiong, 1998: Cloud feedback on SST variability in western equatorial Pacific in a CGCM. *Adv. Atmos. Sci.* **15**(3), 410–423.

Liu Xiying, Zhang Xuehong, and Yu Yongqiang, 2003: Simulated major climatic features of sea ice in the northern high latitude region in a global sea-sea ice-air coupled model. *Earth Science Frontier*, **10**, 419–426. (in Chinese)

Ma Xiaoyan, Guo Yufu, Shi Guangyu, and Yu Yongqiang, 2004: Numerical simulation of global temperature change over the 20th century with IAP/LASG GOALS model. *Adv. Atmos. Sci.*, **21**, 234–242.

Maier-Reimer, E., U. Mikolajewicz, and K. Hasselmann, 1993: On the sensitivity of the global ocean circulation to changes in the surface heat flux forcing. *J. Phys. Oceanogr.*, **23**, 731–757.

Mechoso, C. R., and Coauthors, 1995: The seasonal cycle over the tropical Pacific in coupled ocean-atmosphere general circulation models. *Mon. Wea. Rev.*, **123**, 2825–2838.

Meehl, G. A., 1990: Seasonal cycle forcing of El Niño-Southern Oscillation in a global coupled ocean-atmosphere GCM. *J. Climate*, **3**, 72–98.

Meng Wen, and Wu Guoxiong, 2000: Gearing between the Indo-Monsoon circulation and the Pacific Walker circulation and ENSO as simulated by GOALS/LASG model. *IAP Global Ocean-Atmosphere-Land System Model*, Zhang et al., Eds., Science Press, Beijing, New York, 252pp.

Mitchell, J. F. B., T. C. Johns, J. M. Gregory, and S. F. B. Tett, 1995: Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Natur*e, **376**, 501–504.

Murphy, J. M., 1995: Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part 1. Control climate and flux correction. *J. Climate*, **8**, 36–80.

Neelin, J. D., and Coauthors, 1992: Tropical air-sea interaction in general circulation models. *Climate Dyn.*, **7**, 73–104.

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

Parkinson, C. L., and W. M. Washington, 1979: A large-scale numerical model of sea ice. *J. Geophys. Res.*, **84**, 311–337.

Phillips, N. A., 1973: Principles of large scale numerical weather prediction. *Dynamic Meteorology*, P. Morel, Ed., D. Reidel Publishing Comp, 3–96.

Rosati, A., and K. Miyakoda, 1988: A general circulation model for upper ocean circulation. *J. Phys. Oceanogr.*, **18**, 1601–1626.

Saji, N. N., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature*, **401**, 360–363.

Sausen, R., K. Barthel, and K. Hasselmann, 1988: Coupled ocean-atmosphere models with flux correction. *Climate Dyn.*, **2**, 145–163.

Schopf, P. S., and M. J. Suares, 1988: Vacillations in a coupled ocean-atmosphere model. *J. Atmos. Sci.*, **45**, 549–566.

Shao Hui, Qiang Yongfu, and Wang Qianqian, 1998: The effects of the diurnal variation of solar radiation on climate modeling of R15L9. *Plateau Meteorology,* **17,** 158–169. (in Chinese)

Shea, D. J., K. E. Trenberth, and R. W. Reynolds, 1990: A global monthly mean sea surface temperature climatology. NCAR Tech. Note NCAR/TN-345, 167pp.

Shi Guangyu, 1981: An accurate calculation and representation of the infrared transmissions function of the atmospheric constitutions. Ph. D. Dissertation, Dept. of Sci., Tokoku University of Japan.

Simmonds, I., 1985: Analysis of the "spinning" of a global circulation model. *J. Geophys. Res.*, **90,** 5637–5660.

Wang Biao, 1996: On the radiation transfer models for climate simulation, Ph. D. Dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 92pp. (in Chinese)

Weatherly, J. W., B. P. Briegleb, W. G. Large, and J. A. Maslanik, 1998, Sea ice and polar climate in the NCAR CSM. *J. Climate*, **11**, 1472–1486.

Wu Guoxiong, Liu Hui, Zhao Yuheng, and Li Weiping, 1996: A nine-layer atmospheric general circulation model and its performance. *Adv. Atmos. Sci.*, **13**(1), 1–18.

Wu Guoxiong, and Coauthors, 1997: Global ocean-atmosphere-land system model of LASG (GOALS/LASG) and its performance in simulation study. *Quart. J. Appl. Meteor.* (Suppl.), 15–28. (in Chinese)

Wu Tongwen, Liu Ping, Wang Zaizhi, Liu Yimin, Yu Rucong, and Wu Guoxiong, 2003: The Performance of Atmospheric Component Model (R42L9.0) of LASG GOALS. *Adv. Atmos. Sci.*, **20,** 726–742.

Xue, Y.-K., P. J. Sellers, J. L. Kinter II, and J. Shukla, 1991: A simplified biosphere model for use within general circulation models. *J. Climate*, **4**, 345–364.

Ye Zhengqing, Dong Min, and Chen Jiabin, 2000: Simulated climate by National Climate Center GCM with the observed SST. *Development of Dynamical Model System for Short-Term Climate Prediction in China*, Ding et al., Eds., China Meteorological Press, 70–89. (in Chinese).

Yu Yongqiang, 1997: Design of ocean-atmosphere-sea ice coupling scheme and simulation of interdecadal oscillation of climate. Ph. D. Dissertation, Institute of Atmospheric Physics, Chinese Academy of Sciences, 130pp. (in Chinese)

Yu Yongqiang, and Zhang Xuehong, 1998: A modified monthly flux anomaly scheme for coupling an AGCM and an OGCM. *Chinese Sci. Bull.*, **43**, 866–870. (in Chinese)

Yu Yongqiang, Guo Yufu, and Zhang Xuehong, 2000: Interdecadal climate variability. *IAP Global Ocean-Atmosphere-Land System Model*, Zhang et al., Eds., Science Press, Beijing, New York, 252pp.

Yu Yongqiang, A. Izard, Guo Yufu, and Zhang Xuehong, 2001: A response of IAP/LASG oceanic general circulation model to the observed wind stress. *Chinese J. Atmos. Sci.*, **25**, 305–324.

Yu Yongqiang, Yu Rucong, Zhang Xuehong, and Liu Hailong, 2002: A flexible global coupled climate model. *Adv. Atmos. Sci.,* **19**, 169–190.

Zeng Qingcun, 1963: Characteristic parameter and dynamical equation of atmospheric motions. *Acta Meteor. Sinica*, **33**, 472–483. (in Chinese)

Zeng Qingcun, Zhang Xuehong, Liang Xinzhong, and Chen Shengfang, 1989: Documentation of IAP two-level atmospheric general circulation model. DOE/ER/60314-H1, TR044, 383pp.

Zhang Tao, Guo Yufu, and Wu Guoxiong, 2002: A coupled ocean-atmosphere model with high resolution oceanic component. *Quart. J. Appl. Meteor.,* **13**, 688–695. (in Chinese)

Zhang Xuehong, and Liang Xinzhong, 1989: A numerical world ocean general circulation model. *Adv. Atmos. Sci.*, **6**, 43–61.

Zhang Xuehong, Bao Ning, Yu Rucong, and Wang Wanqiu, 1992: Coupling scheme experiments based on an atmospheric and an oceanic GCM. *Chinese J. Atmos. Sci.*, **16**(2), 129–144. (in Chinese)

Zhang Xuehong, Chen Keming, Jin Xiangze, Lin Wuyin, and Yu Yongqiang, 1996: Simulation of thermohaline circulation with a twenty-layer oceanic general circulation model. *Theore. and Appl. Clim.*, **55**(1–4), 65–87.

Zhang Xuehong, Yu Yongqiang, and Liu Hui, 1998: Wintertime North Pacific surface heat flux anomaly and air-sea interaction in a coupled ocean-atmosphere model. *Chinese J. Atmos. Sci.,* **22**, 511–521. (in Chinese)

Zhang Xuehong, Shi Guangyu, Liu Hui, and Yu Yongqiang, 2000: *IAP Global Ocean-Atmosphere-Land System Model.* Science Press, Beijing, New York, 252pp.

Zhang Xuehong, Yu Yongqiang, Yu Rucong, Liu Hailong, Zhou Tianjun, and Li Wei, 2003a: Assessments of an OGCM and the relevant CGCM Part I: Annual mean simulations in the tropical ocean. *Chinese J. Atmos. Sci.*, **27**, 649–970. (in Chinese)

Zhang Xuehong, Yu Yongqiang, and Liu Hailong, 2003b: 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)

Zhou Zuyi, Jin Xinduan, Wang Liaoling, Jian Zhimin, and Xu Changhai, 2004: Twice closure of the Indonesian Seaway and its relationship to the formation and evolution of the western Pacific Warmpool. *Marine Geology and Quaternary Geology*, **24**, 7–14.