Indian Ocean warming during 1958–2004 simulated by a climate system model and its mechanism

Lu Dong · Tianjun Zhou · Bo Wu

Received: 6 August 2012 / Accepted: 4 March 2013 / Published online: 15 March 2013
© The Author(s) 2013. This article is published with open access at Springerlink.com

Abstract The mechanism responsible for Indian Ocean Sea surface temperature (SST) basin-wide warming trend during 1958–2004 is studied based on both observational data analysis and numerical experiments with a climate system model FGOALS-g1. To quantitatively estimate the relative contributions of external forcing (anthropogenic and natural forcing) and internal variability, three sets of numerical experiments are conducted, viz. an all forcing run forced by both anthropogenic forcing (greenhouse gases and sulfate aerosols) and natural forcing (solar constant and volcanic aerosols), a natural forcing run driven by only natural forcing, and a pre-industrial control run. The model results are compared to the observations. The results show that the observed warming trend during 1958–2004 ($0.5\text{ K (47-year)}^{-1}$) is largely attributed to the external forcing (more than 90 % of the total trend), while the residual is attributed to the internal variability. Model results indicate that the anthropogenic forcing accounts for approximately 98.8 % contribution of the external forcing trend. Heat budget analysis shows that the surface latent heat flux due to atmosphere and surface longwave radiation, which are mainly associated with anthropogenic

forcing, are in favor of the basin-wide warming trend. The basin-wide warming is not spatially uniform, but with an equatorial IOD-like pattern in climate model. The atmospheric processes, oceanic processes and climatological latent heat flux together form an equatorial IOD-like warming pattern, and the oceanic process is the most important in forming the zonal dipole pattern. Both the anthropogenic forcing and natural forcing result in easterly wind anomalies over the equator, which reduce the wind speed, thereby lead to less evaporation and warmer SST in the equatorial western basin. Based on Bjerknes feedback, the easterly wind anomalies uplift the thermocline, which is unfavorable to SST warming in the eastern basin, and contribute to SST warming via deeper thermocline in the western basin. The easterly anomalies also drive westward anomalous equatorial currents, against the eastward climatology currents, which is in favor of the SST warming in the western basin via anomalous warm advection. Therefore, both the atmospheric and oceanic processes are in favor of the IOD-like warming pattern formation over the equator.

Keywords Indian Ocean · SST warming · External forcing · Internal variability · Climate system model

L. Dong · T. Zhou (✉) · B. Wu
State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics (LASG), Chinese Academy of Sciences, Beijing 100029, China
e-mail: zhoutj@lasg.iap.ac.cn

L. Dong
University of Chinese Academy of Sciences,
Beijing 100049, China

T. Zhou
Climate Change Research Center, Chinese Academy of Sciences, Beijing 100029, China

1 Introduction

Oceans play a key role in the climate system as they absorb most of the excess solar heating trapped by the greenhouse gases (GHGs) due to their large heat capacity (Levitus et al. 2005). A warming trend has been revealed in the global ocean in recent decades by a wide-range of observations (e.g., Intergovernmental Panel on Climate Change 2001; Levitus et al. 2001, 2005). During the second half of

the twentieth century, the sea surface temperature (SST) in the Indian Ocean exhibits a strong basin-scale warming, which is the strongest and most robust warming signal around the global oceans based on a signal-to-noise ratio measure (Lau and Weng 1999; Hoerling et al. 2004; Du and Xie 2008).

The Indian Ocean SST has a great effect on the global climate change. Its warming trend is likely to influence internal modes of interannual variability such as Indian Ocean dipole (IOD) (Saji et al. 1999). The Indian Ocean SST affects the southwest monsoon circulation in South Asia monsoon regime (Krishnan et al. 2006) and Australian rainfall (Ashok et al. 2003; Cai et al. 2005). Atmospheric model simulations suggest that the Indian Ocean warming is related to the droughts in African Sahel (Giannini et al. 2003), and also influences the northern middle latitudes (Lu et al. 2004; Hoerling et al. 2004) and the extratropical teleconnections of ENSO (Lau et al. 2006). Tropical Indian Ocean (TIO) SST anomalies are interactive with the atmosphere and Pacific SST via atmospheric bridge (Schott et al. 2009; Alexander et al. 2002; Lau and Nath 2003). Observations and model results show that the TIO teleconnection to the northwestern Pacific strengthens after the mid-1970s, most likely as a result of enhanced variability in summer TIO SST (Huang et al. 2010; Xie et al. 2010b). The interdecadal transition of the East Asian climate, especially the East Asian summer monsoon circulation and rainfall is partly due to the atmospheric response to the Indian Ocean-western Pacific warming (Zhou et al. 2009; Li et al. 2010). Therefore, understanding the mechanism of Indian Ocean warming is of a crucial importance to the climate change studies.

The Indian Ocean warming shows a complex horizontal pattern. It has been implied that an important tropical SST fingerprint to global warming is a stronger equatorial warming than the subtropical warming (Liu et al. 2005). The heat storage shows an enhanced increase in the southern part relative to the northern part of the Indian Ocean (Levitus et al. 2005), although this result may be controversial due to the sparse data coverage, especially in the southern hemisphere (Harrison and Carson 2007). In the east–west direction, the warming trend is also asymmetric. Many climate models show an positive IOD-like warming pattern under projection simulations, that is, the warming trend in the equatorial western Indian Ocean is stronger than that in the east (Vecchi and Soden 2007; Du and Xie 2008; Stowasser et al. 2009; Zheng et al. 2010; Xie et al. 2010a). On the other hand, the Indian Ocean warming trend presents a complex vertical structure (Han et al. 2006). The warming is limited to the upper 125 m in both the observations (Pierce et al. 2006) and general circulation models (GCMs) (Du and Xie 2008). In contrast to the surface warming, Alory et al. (2007) found a subsurface

cooling trend of the main thermocline over the Indonesian Throughflow (ITF) region. Both local forcing, which shoals the thermocline, and the remote forcing from the Pacific via the ITF have contributions to the subsurface cooling (Trenary and Han 2008).

The mechanism responsible for the Indian Ocean warming is a subject of ongoing investigation. The increasing GHGs responsible for the warming of the global ocean was first recognized by Revelle et al. (1965). The basin-wide Indian Ocean shows substantial warming after the 1976/1977 climate regime shift over the Pacific Ocean (Terray and Dominiak 2005). These changes may in some degree be internal variability, or the local exhibition of the global scale warming owing to the anthropogenic GHGs and aerosols (Ihara et al. 2008). Yu et al. (2007) investigated six heat flux products and argued that the surface warming may be not directly caused by surface heating, because all the heat flux products did not show obvious increase during the latest decade in the TIO.

The warming trend over the TIO can be reproduced by coupled ocean–atmosphere GCMs forced by increased GHG concentrations (Barnett et al. 2005; Pierce et al. 2006; Knutson et al. 2006; Alory et al. 2007). But the processes dominating the warming trend are model-dependent. For example, Barnett et al. (2005) indicated that advection was the dominant process for the increase of the northern Indian Ocean heat content, while in other areas of the Indian Ocean basin the surface heat fluxes prevailed. The warming is triggered by the increase in downward longwave radiation induced by GHGs, and then amplified by the water vapor feedback and atmospheric adjustments in models. The weakened winds can suppress surface latent heat flux from the ocean via less evaporation so that further amplify the warming (Du and Xie 2008). By comparing the twentieth century historical and control simulations, Alory and Meyers (2009) stated that the main cause of the Indian Ocean surface warming was a decrease in the upwelling related to a slowdown of the wind-driven Ekman pumping. Global warming projections in many models feature an IOD-like pattern with reduced warming in the eastern Indian Ocean and easterly wind anomalies in the equatorial Indian Ocean (Vecchi and Soden 2007; Du and Xie 2008; Stowasser et al. 2009; Zheng et al. 2010; Xie et al. 2010a). However, the mechanism for the Indian Ocean response to the GHG forcing remains unclear in climate models (Du and Xie 2008).

The main motivation of the present study is to understand the mechanism responsible for the Indian Ocean basin-wide warming trend. Three sets of numerical experiments, viz. all forcing run, natural forcing run and control run, were done by a global climate system model FGOALS-gl. The model results are compared to the observations. The relative contributions of external forcing

(anthropogenic and natural forcing) and internal variability to the warming are estimated quantitatively. We show evidences that the external forcing, mainly the anthropogenic forcing, dominates the Indian Ocean warming trend. The surface latent heat flux due to atmospheric forcing and longwave radiation, mainly associated with the anthropogenic forcing, are in favor of the basin-wide warming trend. Heat budget analysis also shows that the atmospheric processes, oceanic processes and climatological latent heat flux together form the equatorial IOD-like warming pattern, and the oceanic process is the most important in forming the zonal dipole pattern. The easterly wind anomalies over the equatorial Indian Ocean, induced by both anthropogenic forcing and natural forcing, contribute to the IOD-like warming pattern.

The remainder of the paper is organized as follows. In Sect. 2, we describe the model, data and analysis methods. Section 3 presents results of the mechanism responsible for the Indian Ocean warming. Finally, a summary is presented in Sect. 4.

2 Model, data and analysis methods

2.1 Model and experiments

The model used in the study is FGOALS-gl (Zhou et al. 2008), which is a fast-coupled version of LASG/IAP “Flexible-Global-Ocean–Atmosphere–Land Surface–Sea Ice” coupled model FGOALS (Yu et al. 2002, 2004; Zhou et al. 2005a, b, 2007; Yu et al. 2008). The strategy adopted for developing this model follows that of the Hadley Centre for Climate Prediction and Research, Met Office (Rayner et al. 2003), and the National Centers for Atmospheric Research (NCAR) (Yeager et al. 2006). The physical package of its atmospheric component is the same as CAM2 (Wen et al. 2007). The left parts of the coupled model are identical to the standard version of FGOALS-g, which was used in CMIP3 (the third Coupled Model Intercomparison Project) simulations (Zhou et al. 2007; Yu et al. 2008). Its atmospheric component is the Grid Atmospheric Model of LASG/IAP (GAMIL), with a horizontal resolution of $4^\circ\text{latitude} \times 5^\circ\text{longitude}$ (Wen et al. 2007). The model employs a sigma-pressure coordinate in the vertical direction and has 26 vertical levels. The oceanic component of FGOALS-gl is LASG/IAP climate ocean model (LICOM), with the horizontal resolution of $1^\circ\text{latitude} \times 1^\circ\text{longitude}$, and 30 levels in the vertical direction (Jin et al. 1999; Liu et al. 2004). The land surface and sea ice components are NCAR CLM (Bonan et al. 2002) and CSIM (Briegleb et al. 2004), respectively. The above four components are coupled together through the NCAR CCSM2 coupler (Kiehl and Gent 2004).

The coupled model does not employ flux correction techniques (Zhou et al. 2011). More details of the model are described in Zhou et al. (2008) and Wen et al. (2007). Previous studies found that the model has a reasonable performance in simulating atmospheric temperature evolution in the 20th century (Man et al. 2011), tropical air-sea interaction (Man et al. 2010), cloud-radiation feedback (Liu et al. 2011), climate change over the past millennium (Zhang et al. 2009; Zhou et al. 2011), North Pacific decadal variability (Zhu et al. 2008), and CMIP5 interdecadal prediction (Wu and Zhou 2012).

Three sets of numerical simulations are conducted in this study (Table 1). The details are described below:

1. “The 20th century Climate in Coupled Models” (20C3 M), here simply called *all forcing run*. The forcing data is from the CMIP3 for the 4th assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The forcing fields include natural (solar constant and volcanic aerosols) and anthropogenic (GHGs and sulfate aerosols) forcing agents (Zhou and Yu 2006).
2. Twentieth century natural forcing run. The natural forcing agents are the same as those used in the all forcing run, but the anthropogenic forcing agents are fixed at the pre-industrial level.
3. Pre-industrial control run. The natural and anthropogenic forcing agents keep constant at the pre-industrial level.

2.2 Data description

The observed datasets used in this study include: (1) the monthly observed SST data from the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) analysis dataset (Rayner et al. 2003) from 1958 to 2004. It is a reconstruction of SST based on combined satellite and in situ observations, with a spatial resolution of $1^\circ\text{latitude} \times 1^\circ\text{longitude}$; (2) the monthly SST from Kaplan Extended SST version 2 (Kaplan_V2) for the period 1958–2004 (Kaplan et al. 1998), with a spatial resolution of

Table 1 Basic information of the three numerical simulations of FGOALS-gl

External forcing	Anthropogenic agents (greenhouse gases and sulfate aerosols)	Natural agents (solar constant and volcanic aerosols)
<i>Numerical simulation</i>		
All forcing run	CMIP3	CMIP3
Natural forcing run	Pre-industrial level	CMIP3
Control run	Pre-industrial level	Pre-industrial level

5°latitude $\times$ 5°longitude; (3) the monthly surface air temperature data from the third Met Office Hadley Centre and Climatic Research Unit Global Land and Sea Surface Temperature Data Set (HadCRUT3) (Brohan et al. 2006), with a spatial resolution of 5°latitude $\times$ 5°longitude.

2.3 Analysis methods

To quantify the contributions of external forcing and internal variability to the warming trend, we separate the two distinctive signals (external forcing and internal variability) from observed SST following Ting et al. (2009). The details of the three methods applied in the study will be introduced in Sect. 3.2.

The changes of SST can be diagnosed by a mixed layer heat budget analysis. The SST tendency equation is written as:

$$C \frac{\partial T'}{\partial t} = D'_o + Q'_{net}, \quad (1)$$

where T' is SST change (here we assume SST equals to mixed-layer mean temperature), $C = c_p^o \rho_o H$ is the heat capacity of the mixed layer, c_p^o and ρ_o are the specific heat at constant pressure and density of seawater, H is the mixed layer depth, Q'_{net} represents the change in the net surface heat flux into the ocean (positive downward), and D'_o denotes the ocean heat transport effect due to three-dimensional advection and mixing.

At the interdecadal and longer time scales, the SST tendency is one order smaller than the changes of net surface heat flux and ocean heat transport (Xie et al. 2010a; Schneider and Fan 2012). To verify this hypothesis in our model, the SST tendency is calculated by the SST change pattern divided by the number of years between the midpoint of the two periods used in our study (1958–1978 and 1979–2004). By comparing SST tendency pattern with the net heat flux change pattern, we find that the SST tendency term is one order smaller than the net surface heat flux term in FGOALS-gl (figure not shown here). Therefore, the net surface heat flux balances the ocean heat transport effect to the first order,

$$D'_o = -Q'_{net}. \quad (2)$$

In the view of this convenient diagnostic relationship, we can infer the ocean heat transport effect without explicitly calculating all of the advection and mixing terms.

To obtain the SST changes, the surface latent heat flux (Q'_E) is treated as a mixture of ocean response (Q'_E) and atmospheric forcing (Q'_a) (de Szoeke et al. 2007; Xie et al. 2010a; Du and Xie 2008). The former part is written as:

$$Q'_E = \frac{\partial Q_E}{\partial T} T' = \alpha \overline{Q_E} T', \quad (3)$$

where Q'_E represents the Newtonian cooling effect, $\overline{Q_E}$ is the climatological latent heat flux and α is a coefficient. The latter part is calculated as a residual,

$$Q'^a_E = Q'_E - Q'_E. \quad (4)$$

As a result, for SST changes pattern formation (T'), we obtain the following equation,

$$0 = (D'_o + Q'_a) - \alpha \overline{Q_E} T'. \quad (5)$$

Then SST changes (T') may arise from ocean forcing (D'_o), atmospheric forcing via radiative and turbulent fluxes (Q'_a), and climatological latent heat flux ($\overline{Q_E}$). In Eqs. (3) and (5), the coefficient α is $LR_v^{-1} T^{-2}$ based on the Clausius-Clapeyron equation. For the temperature near the sea surface, T is 297 K, and the latent heat of evaporation, L , is 2.44×10^6 J Kg $^{-1}$, and R_v is the gas constant for water vapor, which is 461.5 J kg $^{-1}$ K $^{-1}$. As a result, α is about 0.06 K $^{-1}$, which is the same as Xie et al. (2010a).

3 Results

The performance of FGOALS-gl in reproducing the Indian Ocean warming is firstly assessed. Then we evaluate the relative contributions of different forcing agents (anthropogenic forcing, natural forcing and internal variability) to the warming by using both observations and model simulations. The warming mechanisms are further investigated by the diagnosis of the Indian Ocean mixed layer heat budget.

3.1 Characteristics of the warming in the Indian Ocean

Basin-averaged SST anomalies (SSTA) relative to the period of 1958–2004 mean in the Indian Ocean (40°S–15°N, 40°E–100°E) derived from the HadISST, Kaplan_V2 and FGOALS-gl all forcing run are shown in Fig. 1. A significant warming trend during 1958–2004 is seen in all the three datasets. The trends of the HadISST and Kaplan_V2 are both 0.54 K (47-year) $^{-1}$, while that of FGOALS-gl all forcing run is 0.46 K (47-year) $^{-1}$. To compare the amplitude of interannual variability in the three datasets, we calculate the standard deviation after removing the trend. The results show that the standard deviations of the detrended area-averaged SSTA in the Indian Ocean in the HadISST and Kaplan_V2 are both 0.14 K, but that in the FGOALS-gl all forcing run is only 0.1 K. Therefore, the model underestimates both the warming trend and the amplitude of interannual variability, but this difference is not statistically significant.

Fig. 1 Time series of Indian Ocean annual mean SSTA from (a) HadISST, (b) Kaplan_V2, (c) FGOALS-gl all forcing run. Units: K

The correlation coefficient of SSTA time series between HadISST and Kaplan_V2 is 0.99. The time series of FGOALS-gl all forcing run is well correlated with HadISST and Kaplan_V2, with coefficient reaching 0.71 and 0.72, respectively, indicating that the model can reasonably reproduce the basin-averaged SST evolution. Note the high correlation mainly comes from the warming trend. The natural variability is quite different between model and observation.

In this period, the SSTA transforms from negative to positive around 1976/1977 for HadISST and Kaplan_V2, while the transition time is around 1978/1979 for FGOALS-gl all forcing run. For homogeneity, the changes in all variables during 1958–2004 are defined as 1979–2004 mean minus 1958–1978 mean in the following analysis. The results do not significantly change compared to the results of 1977–2004 mean minus 1958–1976 mean given the long time scale considered.

To examine the spatial pattern of the warming, the changes of SST in the Indian Ocean of the three datasets are shown in Fig. 2. Since the pattern correlation between the SST warming trend and SST changes is very high (0.99, as shown in Fig. 2), we use the changes of variables

Fig. 2 The changes of SST in the Indian Ocean from (a) HadISST, (b) Kaplan_V2, (c) FGOALS-gl all forcing run. The dotted areas are statistically significant at the 5 % level. The numbers on the top right of each figure denote pattern correlation coefficients between the SST trends and changes. Units: K

(1979–2004 mean minus 1958–1978 mean) to represent trends patterns in the study for convenience. The changes in HadISST show a general SST warming in the whole Indian Ocean basin. This warming pattern has two maximum zones located in the equatorial band east of 60°E and in the southeast Indian Ocean off the Western Australia (Fig. 2a), which has been demonstrated by many previous studies (e.g., Alory et al. 2007; Alory and Meyers 2009). The Kaplan_V2 shows warming in most of the basin, with the maximum warming zone in the off-equatorial western basin (Fig. 2b). The differences in the two datasets verify the observed uncertainties in the Indian Ocean warming pattern. The pattern correlation coefficient and root-mean-square-difference (RMSE) of SST changes between HadISST and Kaplan_V2 are 0.90 and 0.15 K, respectively.

Though the all forcing run can reproduce the spatially inhomogeneous characteristics of the basin-wide warming pattern, its spatial distribution is different from the

observations. The maximum of the warming appears in the equatorial western Indian Ocean (Fig. 2c), and thus causes a strong gradient between the eastern and western Indian Ocean basins. This pattern is commonly termed as an IOD-like pattern, as demonstrated in many other climate models (Vecchi and Soden 2007; Du and Xie 2008; Stowasser et al. 2009; Zheng et al. 2010; Xie et al. 2010a). The pattern correlation coefficient and RMSE of SST changes between HadISST and FGOALS-g1 all forcing run are 0.90 and 0.15 K, respectively.

Above analysis demonstrates that the FGOALS-g1 all forcing run reasonably captures the basic characteristics of the Indian Ocean warming. This adds confidence to our further analysis on the mechanisms and processes dominating the warming trend pattern in the model.

3.2 The contributions of external forcing and internal variability to the Indian Ocean warming

The relative contributions of external forcing and internal variability to the Indian Ocean warming are estimated in this section. An empirical orthogonal functions (EOF)

analysis is applied to the SST in the Indian Ocean from 1958 to 2004 for all the three simulations introduced in Sect. 2.1. Since we mainly focus on the long-term variability, the SST is low-pass filtered with an 8-year cutoff by using Lanczos Filter (Duchon 1979). The first EOF mode of all forcing run accounts for 67.6 % of the total variance and has a spatially inhomogeneous warming (Fig. 3a). The corresponding Principal Component (PC) time series increases from early-1970s to the beginning of twenty-first century (Fig. 3b), indicating that the all forcing run can reasonably reproduce the Indian Ocean basin-wide warming trend. On the other hand, the dominant mode of FGOALS-g1 natural forcing run and control run do not show basin-wide warming pattern (Fig. 3c, e) or significant warming trend (Fig. 3d, f). By comparing the first EOF mode of the three simulations (Fig. 3), we argue that the anthropogenic forcing dominates the basin-wide warming trend in the Indian Ocean, while the natural forcing and internal variability nearly have no contributions.

To further distinguish the external forcing and internal variability quantitatively, three methods are applied to HadISST and Kaplan_V2. The first method supposes that

Fig. 3 The (a) first EOF of 8-year low-pass-filtered SST from FGOALS-g1 all forcing run, (b) PC time series for the first EOF from FGOALS-g1 all forcing run, (c, d) as (a, b), but for FGOALS-g1 natural forcing run, (e, f) as (a, b), but for FGOALS-g1 control run

the externally forced trend is linear and uniform over the period (Fig. 4a). We remove the linear trend from the original Indian Ocean SST. The linear trend of the observed Indian Ocean SST represents the external forcing, and the remaining part represents the internal variability (Ting et al. 2009, Fig. 5a, d). The second method is to use the global mean SST as a proxy for the external forcing signal. The time series of the global mean SST anomaly is shown in Fig. 4b. In this method, we regress the three-dimensional SST field against the time series of global-averaged SST (SSTg) and then take the internal variability as the local differences between the original SST field and the regression component (Ting et al. 2009, Fig. 5b, e). The third commonly used method is similar to the second one, but uses the global-averaged surface air temperature (SATg, Fig. 4c) as the proxy of the external forcing signal (Ting et al. 2009, Fig. 5c, f). Note that because the external

forcing should cause the consistent climate change in the global scale, we can use the SSTg and SATg to represent the external forcing. The two regression methods indicate that the external forcing dominates the warming trend (Fig. 5b, c, e, f, dashed lines), while the internal variability has no contributions (Fig. 5 b, c, e, f, solid lines). The results also confirm the rationality of the hypothesis in the linear trend method. In conclusion, the external forcing dominates the Indian Ocean basin-wide warming trend during 1958–2004.

We also discuss the contributions of external forcing and internal variability to the warming by comparing the warming trends during 1958–2004 (Fig. 6). From the results of HadISST, the linear warming trend method suggests that the external forcing signal trend is about $0.5 \text{ K (47-year)}^{-1}$ (Fig. 6a). The second method, regression on the SSTg, implies that the warming trend is largely attributed to the external forcing ($0.45 \text{ K (47-year)}^{-1}$), while the residual ($0.05 \text{ K (47-year)}^{-1}$) is attributed to the internal variability (Fig. 6a). Using the method of regression on SATg shows similar results to the first two methods (Fig. 6a). The Kaplan_V2 SST shows the similar results (Fig. 6b). Thus from the trends comparison, the contribution of the external forcing accounts for more than 90 % of the total trend in both HadISST and Kaplan_V2, while the internal variability has a little contribution.

The external forcing includes two parts: anthropogenic forcing (GHGs and sulfate aerosols) and natural forcing (solar constant and volcanic aerosols). We examine their respective contributions using the numerical simulations. In order to separate externally forced variability from internal variability in model, the signal of the control run eigenvector is filtered out from the other two forced simulations. Based on Clara Deser (2012, private communication), the specific procedures are as follows. We first apply EOF analysis to the Indian Ocean SST in the control run and get the first 20 dominant modes, except for the Indian Ocean Basin mode (IOB), to represent internal variability patterns. These modes account for about 83 % of the total variance in control run, thus they can represent the internal variability patterns. The IOB mode is excluded because this mode has a similar pattern to the dominant mode of all forcing run, both showing a basin-wide uniform change throughout the basin. Then we project SST from all forcing run and natural forcing run onto these internal variability patterns, and subtract the projection components from all forcing run and natural forcing run. The remaining residuals are for external forcing and natural forcing signals, respectively. According to Meehl et al. (2004), the effects of different external forcing are linear superposition. Thus the difference between external forcing and natural forcing is the anthropogenic forcing component. The results show that the external forcing dominates

Fig. 4 **a** SST linear trend averaged in Indian Ocean from HadISST. **b** The time series of globally averaged SSTA from HadISST. **c** The time series of globally averaged surface air temperature (SAT) anomaly from HadCRUT3. Units: K

Fig. 5 **a** The linear trend (dashed line) and detrended SST (solid line) averaged in Indian Ocean from HadISST. **b** Indian Ocean SST regressed onto the global mean SST (SSTg regression, dashed line) and the difference between the original SST and the SSTg regression component (solid line) from HadISST. **c** Indian Ocean SST regressed

onto the global mean surface air temperature (SATg regression, dashed line) and the difference between the original SST and the SATg regression component (solid line) from HadISST, **(d–f)** as **(a–c)**, but for the Kaplan_V2 SST. Units: K

the warming trend (Fig. 7a), and the anthropogenic forcing plays the key role (Fig. 7b) comparing with the natural forcing (Fig. 7c). During 1958–2004, the warming trend of the total external forcing is about $0.345 \text{ K (47-year)}^{-1}$ in FGOALS-gl. The trend is primarily contributed by the anthropogenic forcing ($0.341 \text{ K (47-year)}^{-1}$), while the contribution of the natural forcing is small (about $0.004 \text{ K (47-year)}^{-1}$) (Fig. 6c). Therefore, the anthropogenic forcing dominates the warming trend and it accounts for approximately 98.8 % of the total trend of the external forcing signal based on FGOALS-gl simulations.

3.3 Heat budget analysis of the Indian Ocean warming based on FGOALS-gl simulations

In this section, we further investigate the mechanisms responsible for the Indian Ocean warming through a mixed layer heat budget analysis. The diagnosis mainly focuses on the all forcing run. In addition, to evaluate the relative importance of anthropogenic forcing and natural forcing, the natural forcing run is also analyzed for comparison.

Derived from the Eq. (5), the changes of SST (T') are determined by the changes in atmospheric forcing via

Fig. 6 The linear trends during 1958–2004 of external forcing and internal variability calculated by the three methods (linear trend, regress on SSTg, regress on SATg) from (a) HadISST, (b) Kaplan_V2, (c) the linear trends of external forcing, anthropogenic forcing and natural forcing determined by FGOALS-gl simulations. Units: K (47-year)^{−1}

radiative and turbulent fluxes (Q'_a), ocean heat transport effect (D'_o), and the climatological latent heat flux ($\overline{Q_E}$) together, written as:

$$T' = \frac{(D'_o + Q'_a)}{\alpha \overline{Q_E}} \quad (6)$$

Q'_a heats almost the whole Indian Ocean basin, with a maximum located in the off-equatorial southeastern Indian Ocean (Fig. 8a). The ocean heat transport effect, estimated through $D'_o = -Q'_{net}$, shows a zonal dipole pattern over the equator, which is the most important in forming the IOD-like warming pattern (Fig. 8b). Therefore, the sum of atmospheric processes and oceanic processes has two maximum centers located in the equatorial western basin and off-equatorial southeastern basin, respectively (Fig. 8c). The distribution of the $\overline{Q_E}$ is generally symmetric about the equator, with maxima located in the off-equatorial zones of about 10°N–20°N and 10°S–20°S (Fig. 8d). As a result, T' present a similar horizontal distribution to the sum of the atmospheric

Fig. 7 a Time series of the contribution of external forcing to Indian Ocean annual mean SSTA from FGOALS-gl, (b) as (a), but for the contribution of anthropogenic forcing, (c) as (a), but for the contribution of natural forcing. Units: K

forcing and ocean processes, though the maximum in the off-equatorial southeastern basin is weakened due to the large climatological latent heat flux. Therefore, the equatorial IOD-like warming pattern stands out (Fig. 2c).

The atmospheric forcing via radiative and turbulent fluxes (Q_a) can be further decomposed into four parts: shortwave radiation (Q_S), longwave radiation (Q_L), sensible heat flux (Q_H) and latent heat flux due to atmosphere (Q'_E). The decreased surface shortwave radiation (Q'_S) cools most of the basin (Fig. 9a) due to the increase of cloud amount (not shown), while the other three components warm the Indian Ocean basin (Fig. 9b–d). Among them, Q'_E emerges as the main factor for the Indian Ocean warming (Fig. 9d). Q'_L due to the increasing GHG warms

Fig. 8 The changes of (a) atmospheric forcing via radiative and turbulent fluxes (Q'_a), (b) ocean heat transport effect ($D'_o = -Q'_{net}$), (c) the total atmosphere and ocean forcing ($Q'_a + D'_o$). **d** The

climatological surface latent heat flux ($\overline{Q_E}$) in the Indian Ocean from FGOALS-gl all forcing run. Set warming ocean is positive in (a, b, c). Units: W m^{-2}

the ocean (Fig. 9b), which is similar to the conclusion from CMIP3 models (Du and Xie 2008). Q'_H warms the whole basin, just with a much smaller magnitude comparing to the other three terms (Fig. 9c).

We further check the specific atmospheric and oceanic processes in the Indian Ocean warming. The changes in the wind effect on the atmospheric forcing part of latent heat flux is calculated by $Q'_E = \frac{\overline{Q_E} W'}{\overline{W}}$, where $\overline{Q_E}$ is the climatological latent heat flux, W' is the changes of the surface wind speed and $\overline{W}$ is the climatological surface wind speed. It has a maximum in warming ocean over the equatorial western Indian Ocean (Fig. 10a), which is in favor of the IOD-like warming pattern. It is indicated that the wind speed reduces in the western Indian Ocean and results in less evaporation and warmer SST. Thus the wind effect amplifies the east–west SST changes gradient and helps to explain the IOD-like warming pattern. Correspondingly, easterly wind anomalies are evident over the equatorial Indian Ocean (Fig. 10b, c), which are associated with the slowdown of the Walker circulation in global warming (Vecchi et al. 2006; Tokinaga et al. 2012a, b; Du et al. 2012). This is a robust result among observations from different datasets and many climate models (Held and

Soden 2006). Such anomalous easterlies may be amplified by Bjerknes feedback (1969), resulting in more precipitation (Fig. 10b) over the equatorial western Indian Ocean. Based on Bjerknes feedback (1969), the easterly wind anomalies also uplift the thermocline in the eastern basin (negative SSH anomaly, Fig. 10c), and deepen the thermocline in the western basin (positive SSH anomaly, Fig. 10c). The thermocline deepens in the southwestern TIO, where the shallow mean thermocline allows thermocline changes to affect SST readily (Xie et al. 2002; Schott et al. 2009). As a result, the deeper thermocline benefits the stronger warming in the equatorial western Indian Ocean. Meanwhile, the easterly anomalies drive westward anomalous equatorial currents, against the eastward climatology currents, which is in favor of the SST warming in the western basin via anomalous warm advection (Fig. 10d). In conclusion, both the atmospheric and oceanic processes are in favor of the IOD-like warming pattern formation over the equator.

To evaluate the relative importance of anthropogenic forcing and natural forcing in atmospheric and oceanic processes, the mixed layer heat budget of natural forcing run from FGOALS-gl is also analyzed. Q'_L and Q'_E do not

Fig. 9 The changes of (a) surface shortwave radiation (Q'_S), (b) surface longwave radiation (Q'_L), (c) sensible heat flux (Q'_H), (d) latent heat flux from atmospheric forcing (Q'_E) in the Indian Ocean from FGOALS-gl all forcing run. Set downward is positive, Units: W m^{-2}

show the basin-wide warming effect in this simulation (Fig. 11a, b). A comparison to all forcing run indicates that the contributions of Q'_L and Q'_E to the Indian Ocean basin-wide warming trend are mainly due to the anthropogenic forcing. As shown in Fig. 11c, d, the easterly wind anomalies over the equatorial Indian Ocean still exist, but with a smaller magnitude in contrast to those in the all forcing run. The corresponding changes in SSH (Fig. 11d) and Q'_E (Fig. 11c) over the equatorial western Indian Ocean are also smaller than that in the all forcing run (Fig. 10a, c). Therefore we infer that the equatorial easterly wind anomalies are induced by both anthropogenic forcing and natural forcing. We should acknowledge that whether this result is model-dependent deserves further study. The ongoing CMIP5 experiment has provided us an opportunity for future studies.

4 Summary and discussion

4.1 Summary

To understand the mechanism responsible for the Indian Ocean basin-wide warming trend during 1958–2004, three

sets of numerical experiments, viz. an all forcing run, a natural forcing run and a pre-industrial control run, are conducted by using a climate system model FGOALS-gl. The model results are compared to the observations. The relative contributions of external forcing (anthropogenic forcing and natural forcing) and internal variability to the warming are estimated quantitatively. The processes dominating the warming pattern are examined by a mixed layer heat budget analysis. The main conclusions are listed as follows:

1. The basin-wide warming trend is the dominant mode of the Indian Ocean SST variability during 1958–2004. The basin-averaged SSTA transforms from negative to positive in the late-1970s. Both the spatial pattern and time evolution of the Indian Ocean SST warming are reasonably reproduced by the all forcing run of FGOALS-gl model, having a pattern correlation coefficient (RMSE) of 0.89 (0.16 K) with the HadISST data.
2. The contributions of different forcing agents to the Indian Ocean warming are estimated quantitatively. In both the observations and simulations, the external forcing, mainly anthropogenic forcing, dominates the

Fig. 10 The changes of (a) wind effect on atmospheric forcing part of latent heat flux (Q_E' , Set warming ocean is positive, $W m^{-2}$), (b) precipitation (colors, $mm month^{-1}$) and surface wind (vector, $m s^{-1}$), (c) sea surface height (SSH, colors, cm) and surface wind

(vector, $m s^{-1}$), (d) surface current ($m s^{-1}$) at 12.5 m superimposed on the climatological SST (K) in the Indian Ocean from FGOALS-gl all forcing run

Indian Ocean warming trend. The observed SST warming trend during 1958–2004 ($0.5 K (47\text{-year})^{-1}$) is largely attributed to the external forcing (more than 90 % of the total trend), while the residual is attributed to the internal variability. Model results indicate that the anthropogenic forcing accounts for approximately 98.8 % contribution of the external forcing trend.

- Heat budget diagnosis is conducted for the model simulation. It demonstrates that the basin-wide warming trend in the Indian Ocean is primarily caused by atmospheric forcing via radiative and turbulent fluxes. The surface latent heat flux changes due to atmosphere and surface longwave radiation changes are in favor of the basin-wide warming trend. Both processes are mainly associated with the anthropogenic forcing.
- In the all forcing run of FGOALS-gl, the basin-wide warming is not spatially uniform, but shows a positive IOD-like pattern over the equator. The atmospheric processes, oceanic processes and climatological latent heat flux together form the equatorial IOD-like warming pattern, and the oceanic process is the most important in forming the zonal dipole pattern. Both

anthropogenic and natural forcings are in favor of the positive IOD-like warming pattern over the equator. In the atmosphere, the easterly wind anomalies reduce the wind speed in the equatorial western Indian Ocean, leading to less evaporation and warmer SST. In the ocean, the easterly wind anomalies uplift the thermocline, unfavorable to SST warming in the eastern basin, and contribute to SST warming via deeper thermocline in the western basin through Bjerknes feedback (1969). Meanwhile, the easterly anomalies drive westward anomalous equatorial currents, against the eastward climatology currents, which is in favor of the SST warming in the western basin via anomalous warm advection. Therefore, both the atmospheric and oceanic processes are in favor of the IOD-like warming pattern formation over the equator.

4.2 Discussion

The limitation of the current study should be noted. Different datasets always have different warming patterns

Fig. 11 The changes of (a) surface longwave radiation (Q'_L , W m^{-2}) (b) latent heat flux from atmospheric forcing (Q'_E , W m^{-2}), (c) wind effect on atmospheric forcing part of latent heat flux (Q''_E , W m^{-2}),

(d) sea surface height (SSH, colors, cm) and surface wind (vector, m s^{-1}) in the Indian Ocean from FGOALS-gl natural forcing run. Set warming ocean is positive in (a, b, c)

(Alory et al. 2007). Both the observational datasets and model results have large uncertainties. However, the positive IOD-like warming pattern due to the slowdown of the Walker circulation is a common phenomenon in models under global warming projections (Vecchi and Soden 2007; Du and Xie 2008; Stowasser et al. 2009; Zheng et al. 2010; Xie et al. 2010a), but the models' response has been argued to be in disagreement with the observations (Trenary and Han 2008). How to understand the model-observation inconsistency and what the mechanism responsible for the Indian Ocean warming pattern is remain to be challenges for climate change study community. We also acknowledge that the methods of separating external forcing from internal variability remain a controversial issue. A useful method to remove internal variability is multi-model ensemble or ensemble of different realizations from one specific model. Further efforts need to be devoted to this regard.

Acknowledgments We thank Clara Deser for the presentation in Institute of Atmospheric Physics (IAP). The title of the presentation is "Uncertainty in Climate Change Projections over North America: The role of Natural Variability". This work was jointly supported by Chinese National Program on Key Basic Research Project

(2010CB951904), Chinese Public science and technology research funds projects of ocean (201105019-3), and NSFC under grant No. 41125017.

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

- Alexander MA, Bladé I, Newman M, Lanzante JR, Lau NC, Scott JD (2002) The atmospheric bridge: the influence of ENSO teleconnections on air-sea interaction over the global oceans. *J Clim* 15:2205–2231
- Alory G, Meyers G (2009) Warming of the upper equatorial Indian Ocean and changes in the heat budget (1960–99). *J Clim* 22:93–113
- Alory G, Wijffels S, Meyers G (2007) Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms. *Geophys Res Lett* 34:L02606. doi:10.1029/2006GL028044
- Ashok K, Guan Z, Yamagata T (2003) Influence of the Indian Ocean dipole on the Australian winter rainfall. *Geophys Res Lett* 30:1821. doi:10.1029/2003GL017926
- Barnett TP, Pierce DW, Achutarao KM, Gleckler PJ, Santer BD, Gregory JM, Washington WM (2005) Penetration of human-induced warming into the world's oceans. *Science* 309:284–287

- Bjerknes J (1969) Atmospheric teleconnections from the equatorial Pacific. *Mon Wea Rev* 97:163–172
- Bonan GB, Oleson KW, Vertenstein M et al (2002) The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model. *J Clim* 15:3123–3149
- Briegleb BP, Bitz CM, Hunke EC et al (2004) Scientific description of the sea ice component in the Community Climate System model: version three. NCAR technical note NCARTN-463 + STR
- Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J Geophys Res* 111:D12106. doi:[10.1029/2005JD006548](https://doi.org/10.1029/2005JD006548)
- Cai W, Hendon HH, Meyers G (2005) Indian Ocean dipole-like variability in the CSIRO mark 3 coupled climate model. *J Clim* 18:1449–1468
- de Szoek SP, Xie SP, Miyama T, Richards KJ, Small RJO (2007) What maintains the SST front north of the eastern Pacific equatorial cold tongue? *J Clim* 20:2500–2514
- Du Y, Xie SP (2008) Role of atmospheric adjustments in the tropical Indian Ocean warming during the 20th century in climate models. *Geophys Res Lett* 35:L08712. doi:[10.1029/2008GL033631](https://doi.org/10.1029/2008GL033631)
- Du Y, Cai W, and Wu Y (2012) A new type of the Indian Ocean Dipole since the mid-1970s. *J Clim*. doi:[10.1175/JCLI-D-12-00047.1](https://doi.org/10.1175/JCLI-D-12-00047.1)
- Duchon CE (1979) Lanczos filtering in one and two dimensions. *J Appl Meteorol* 18:1016–1022
- Giannini A, Saravanan R, Chang P (2003) Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302:1027–1030
- Han W, Meehl GA, Hu A (2006) Interpretation of tropical thermocline cooling in the Indian and Pacific oceans during recent decades. *Geophys Res Lett* 33:L23615. doi:[10.1029/2006GL027982](https://doi.org/10.1029/2006GL027982)
- Harrison DE, Carson M (2007) Is the world ocean warming? Upper ocean trends, 1950–2000. *J Phys Oceanogr* 37:174–187
- Held IM, Soden BJ (2006) Robust response of the hydrological cycle to global warming. *J Clim* 19:5686–5699
- Hoerling M, Hurrell JW, Xu T, Bates GT, Phillips AS (2004) Twentieth century North Atlantic climate change. Part II: understanding the effect of Indian Ocean warming. *Clim Dyn* 23:391–405
- Huang G, Hu K, Xie SP (2010) Strengthening of tropical Indian Ocean teleconnection to the Northwest Pacific since the mid-1970s: an atmospheric GCM Study. *J Clim* 23:5294–5304
- Ihara C, Kushnir Y, Cane MA (2008) Warming trend of the Indian Ocean SST and Indian Ocean dipole from 1880 to 2004. *J Clim* 21:2035–2046
- Intergovernmental Panel on Climate Change (2001) Synthesis report. Cambridge University Press, New York 397
- Jin X, Zhang X, Zhou T (1999) Fundamental framework and experiments of the third generation of IAP/LASG world ocean general circulation model. *Adv Atmos Sci* 16:197–215
- Kaplan A, Cane MA, Kushnir Y, Clement AC, Blumenthal MB, Rajagopalan B (1998) Analyses of global sea surface temperature 1856–1991. *J Geophys Res* 103:18567–18589. doi:[10.1029/97JC01736](https://doi.org/10.1029/97JC01736)
- Kiehl JT, Gent PR (2004) The community climate system model, version two. *J Clim* 17:3666–3682
- Knutson TR, Delworth TL, Dixon KW, Held IM, Lu J, Ramaswamy V, Schwarzkopf MD (2006) Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *J Clim* 19:1624–1651
- Krishnan R, Ramesh KV, Samala BK, Meyers G, Slingo JM, Fennessy MJ (2006) Indian Ocean–monsoon coupled interactions and impending monsoon droughts. *Geophys Res Lett* 33:L08711. doi:[10.1029/2006GL025811](https://doi.org/10.1029/2006GL025811)
- Lau KM, Weng HY (1999) Interannual, decadal-interdecadal, and global warming signals in sea surface temperature during 1955–97. *J Clim* 12(5):1257–1267
- Lau NC, Nath MJ (2003) Atmosphere–ocean variations in the Indo-Pacific sector during ENSO episodes. *J Clim* 16:3–20
- Lau NC, Leetmaa A, Nath MJ (2006) Attribution of atmospheric variations in the 1997–2003 period to SST anomalies in the Pacific and Indian ocean basins. *J Clim* 19:3607–3627
- Levitus S, Antonov JI, Wang J, Delworth TL, Dixon KW, Broccoli AJ (2001) Anthropogenic warming of Earth's climate system. *Science* 292:267–270
- Levitus S, Antonov JI, Boyer T (2005) Warming of the world ocean, 1955–2003. *Geophys Res Lett* 32:L02604. doi:[10.1029/2004GL021592](https://doi.org/10.1029/2004GL021592)
- Li H, Dai A, Zhou TJ, Lu J (2010) Responses of East Asian summer monsoon to historical SST and atmospheric forcing during 1950–2000. *Clim Dyn* 34:501–514. doi:[10.1007/s00382-008-0482-7](https://doi.org/10.1007/s00382-008-0482-7)
- Liu H, Zhang X, Li W et al (2004) An eddy-permitting oceanic general circulation model and its preliminary evaluations. *Adv Atmos Sci* 21:675–690
- Liu Z, Vavrus S, He F, Wen N, Zhong Y (2005) Rethinking tropical ocean response to global warming: the enhanced equatorial warming. *J Clim* 18:4684–4700
- Liu JW, Zhou TJ, Wu CQ (2011) Water Vapor and cloud radiative feedback processes in the ocean-atmosphere coupled model FGOALS_g1 (in Chinese). *Chin J Atmos Sci* 35:531–546
- Lu J, Greatbatch RJ, Peterson KA (2004) Trend in Northern Hemisphere winter atmospheric circulation during the last half of the twentieth century. *J Clim* 17:3745–3760
- Man WM, Zhou TJ, Zhang LX (2010) The tropical Pacific interannual variability simulated with LASG/IAP climate system model FGOALS_g1 (in Chinese). *Chin J Atmos Sci* 34:1141–1154
- Man WM, Zhou TJ, Zhang J et al (2011) The 20th century climate simulated by LASG/IAP climate system model FGOALS_g1 (in Chinese). *Acta Meteorol Sin* 69:644–654
- Meehl GA, Washington WM, Ammann CM et al (2004) Combinations of natural and anthropogenic forcings in twentieth-century climate. *J Clim* 17:3721–3727
- Pierce DW, Barnett TP, AchutaRao KM, Glecker PJ, Gregory JM, Washington WM (2006) Anthropogenic warming of the oceans: Observations and model results. *J Clim* 19:1873–1900
- Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys Res* 108(D14):4407. doi:[10.1029/2002JD002670](https://doi.org/10.1029/2002JD002670)
- Revelle R, Broecker W, Craig H, Keeling C D, Smagorinsky J (1965) Appendix Y4, in restoring the quality of our environment—report of the environmental pollution panel. *Pres Sci Advis Comm.*, Washington, DC, pp 112–133
- Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. *Nature* 401:360–363. doi:[10.1038/43855](https://doi.org/10.1038/43855)
- Schneider EK, Fan MZ (2012) Observed decadal north Atlantic tripole SST variability. Part II: diagnosis of mechanisms. *J Atmos Sci* 69:51–64
- Schott FA, Xie SP, McCreary JP Jr (2009) Indian Ocean circulation and climate variability. *Rev Geophys* 47:RG1002. doi:[10.1029/2007RG000245](https://doi.org/10.1029/2007RG000245)
- Stowasser M, Annamalai H, Hafner J (2009) Response of the South Asian summer monsoon to global warming: mean and synoptic systems. *J Clim* 22(4):1014–1036

- Terray P, Dominiak S (2005) Indian Ocean sea surface temperature and El Niño–Southern Oscillation: a new perspective. *J Clim* 18:1351–1368
- Ting M, Kushnir Y, Seager R, Li C (2009) Forced and internal twentieth-century SST trends in the North Atlantic. *J Clim* 22:1469–1481
- Tokinaga H, Xie SP, Deser C, Kosaka Y, Okumura YM (2012a) Slowdown of the Walker circulation driven by tropical Indo-Pacific warming. *Nature* 491:439–443. doi:[10.1038/nature11576](https://doi.org/10.1038/nature11576)
- Tokinaga H, Xie SP, Timmermann A, McGregor S, Ogata T, Kubota H, Okumura YM (2012b) Regional patterns of tropical Indo-Pacific climate change: evidence of the walker circulation weakening. *J Clim* 25:1689–1710
- Trenary LL, Han W (2008) Causes of decadal subsurface cooling in the tropical Indian Ocean during 1961–2000. *Geophys Res Lett* 35:L17602. doi:[10.1029/2008GL034687](https://doi.org/10.1029/2008GL034687)
- Vecchi GA, Soden BJ (2007) Global warming and the weakening of the tropical circulation. *J Clim* 20:4316–4340
- Vecchi GA, Soden BJ, Wittenberg AT, Held IM, Leetmaa A, Harrison MJ (2006) Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* 441:73–76. doi:[10.1038/nature04744](https://doi.org/10.1038/nature04744)
- Wen XY, Zhou TJ, Wang SW et al (2007) Performance of a reconfigured atmospheric general circulation model at low resolution. *Adv Atmos Sci* 24:712–728
- Wu B, Zhou T (2012) Prediction of decadal variability of sea surface temperature by a coupled global climate model FGOALS_g developed in LASG/IAP. *Chin Sci Bull* 57:1–7. doi:[10.1007/s11434-012-5134-y](https://doi.org/10.1007/s11434-012-5134-y)
- Xie SP, Annamalai H, Schott FA, McCreary JP (2002) Structure and mechanisms of South Indian Ocean climate variability. *J Clim* 15:864–878
- Xie SP, Deser C, Vecchi GA et al (2010a) Global warming pattern formation: sea surface temperature and rainfall. *J Clim* 23:966–986
- Xie SP, Du Y, Huang G, Zheng XT, Tokinaga H, Hu K, Liu Q (2010b) Decadal shift in El Nino influences on Indo-western Pacific and East Asian climate in the 1970s. *J Clim* 23:3352–3368
- Yeager SG, Shields CA, Large WG, Hack JJ (2006) The low-resolution CCSM3. *J Clim* 19:2545–2566
- Yu YQ, Yu RC, Zhang XH, Liu HL (2002) A flexible global coupled climate model. *Adv Atmos Sci* 19:169–190
- Yu YQ, Zhang XH, Guo YF (2004) Global coupled ocean-atmosphere general circulation models in LASG/IAP. *Adv Atmos Sci* 21(3):444–455
- Yu L, Jin X, Weller RA (2007) Annual, seasonal, and interannual variability of air–sea heat fluxes in the Indian Ocean. *J Clim* 20:3190–3209
- Yu YQ, Zhi H, Wang B et al (2008) Coupled model simulations of climate changes in the 20th century and beyond. *Adv Atmos Sci* 25:641–654
- Zhang J, Zhou TJ, Man WM et al (2009) The transient simulation of little ice age by LASG/IAP climate system model (in Chinese). *Quat Sci* 29:1125–1134
- Zheng XT, Xie SP, Vecchi GA, Liu Q, Hafner J (2010) Indian Ocean dipole response to global warming: analysis of ocean–atmospheric feedbacks in a coupled model. *J Clim* 23:1240–1253
- Zhou TJ, Yu RC (2006) Twentieth century surface air temperature over China and the globe simulated by coupled climate models. *J Clim* 19:5843–5858
- Zhou TJ, Wang ZZ, Yu RC et al (2005a) The climate system model FGOALS_s using LASG/IAP spectral AGCM SAMIL as its atmospheric component (in Chinese). *Acta Meteorol Sin* 63:702–715
- Zhou TJ, Yu RC, Wang ZZ et al (2005b) The atmospheric general circulation model SAMIL and the corresponding coupled climate system model FGOALS_s (in Chinese). Meteorological Press, Beijing, p 288
- Zhou T, Yu Y, Liu H, Li W, You X, Zhou G (2007) Progress in the development and application of climate ocean models and ocean-atmosphere coupled models in China. *Adv Atmos Sci* 24(6):729–738
- Zhou TJ, Wu B, Wen XY et al (2008) A fast version of LASG/IAP climate system model and its 1000-year control integration. *Adv Atmos Sci* 25:655–672
- Zhou TJ, Yu R, Zhang J, Drange H, Cassou C, Deser C, Hodson DLR, Sanchez-Gomez E, Li J, Keenlyside N, Xin X, Okumura Y (2009) Why the western Pacific subtropical high has extended westward since the late 1970s. *J Clim* 22:2199–2215
- Zhou TJ, Li B, Man WM et al (2011) A comparison of the Medieval Warm Period, Little Ice Age and 20th century warming simulated by the FGOALS climate system model. *Chinese Sci Bull* 56:3028–3041. doi:[10.1007/s11434-011-4641-6](https://doi.org/10.1007/s11434-011-4641-6)
- Zhu YM, Yang XQ, Yu YQ et al (2008) Decadal variability in the North Pacific as simulated by FGOALS_g fast coupled climate model. *Chin J Geophys* 51:58–69