Tropical Indian Ocean Basin Warming and East Asian Summer Monsoon: A Multiple AGCM Study

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ABSTRACT

A basin-scale warming is the leading mode of tropical Indian Ocean sea surface temperature (SST) variability on interannual time scales, and it is also the prominent feature of the interdecadal SST trend in recent decades. The influence of the warming on the East Asian summer monsoon (EASM) is investigated through ensemble experiments of several atmospheric general circulation models (AGCMs). The results from five AGCMs consistently suggest that near the surface, the Indian Ocean warming forces an anticyclonic anomaly over the subtropical western Pacific, intensifying the southwesterly winds to East China; and in the upper troposphere, it forces a Gill-type response with the intensified South Asian high, both favoring the enhancement of the EASM. These processes are argued to contribute to the stronger EASM during the summer following the peak of El Niño than monsoons in other years. These model results also suggest that tropical Indian Ocean warming may not have a causal relationship to the synchronous weakening of EASM on interdecadal time scales.

1. Introduction

A basin-scale warming/cooling is the leading mode of tropical Indian Ocean SST variability on interannual time scales. It peaks in late winter and persists into the following spring and summer (Klein et al. 1999). It mostly emerges as a passive response to the heat flux anomalies induced by the El Niño–Southern Oscillation (ENSO; e.g., Klein et al. 1999; Reason et al. 2000), although ocean dynamic processes, especially the downwelling Rossby waves, may contribute to part of this SST variability in the southwestern tropical Indian Ocean (e.g., Wu and Lau 1992; Klein et al. 1999; Lau and Nath 2000; Alexander et al. 2002; Xie et al. 2002; Luo et al. 2005). It also feedbacks to ENSO through modulating convective heating and the Walker circulation or inducing an eastward-propagating Kelvin wave, thereby influencing the zonal winds associated with the developing or decaying phase of ENSO (e.g., Wu and Kirtman 2004; Annamalai et al. 2005; Kug et al. 2006). Recently, Yang et al. (2007) proposed that the Indian Ocean acts to accumulate and prolong the ENSO influence until the following summer. Moreover, this process induces an anticyclone anomaly in the lower troposphere over the subtropical northwestern Pacific, intensifying southwesterly winds to East China and hence the East Asian summer monsoon (EASM). This accounts for the observed fact that EASM is affected preferentially by the ENSO decaying phase rather than the growing phase, as well as the associated lower-level anomalous anticyclone (e.g., Huang and Wu 1989; Wang et al. 2000). However, Yang et al.'s (2007) results

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are based on a single coupled model with a coarse-resolution atmospheric model (R15). The modeled maximum rainfall response to the prescribed Indian Ocean SST warming is displaced to the south of the Bay of Bengal, in comparison with the observed composite maximum in the Arabian Sea (cf. their Figs. 5b, 4). Given the delicacy of the teleconnection between ENSO and EASM, the monsoon response is sensitive to the location of tropical convective heating and configuration of the model used for experiments. The consideration above substantiates the need to further verify and elaborate the results of Yang et al.(2007) using different models. This constitutes the first motivation of the present multiple atmospheric general circulation model (AGCM) study.

Meanwhile, a basin-scale warming trend in the tropical Indian Ocean since the middle of the twentieth century has been the most prominent among other tropical oceans (e.g., Hoerling et al. 2004). Concurrently, EASM has weakened substantially during the same period (e.g., Wang 2001). Previous studies imply that global or regional SST interdecadal variations may account for part of the EASM weakening (e.g., Li and Xian 2003; Yang and Lau 2004; Fu et al. 2009). It is therefore compelling to ask if the Indian Ocean warming has contributed to the weakening trend of EASM, a question that serves as the second motivation of this study.

In this paper, we conduct ensemble experiments using five AGCMs by prescribing idealized tropical Indian Ocean warming. The models used here are briefly introduced and experimental designs are described in section 2. The results are examined in section 3. A brief diagnosis is carried out with a linearized dry dynamical model to differentiate the remote response to tropical heating and the local feedback in section 4. At last, we summarize these model results and discuss their implication to the interannual and interdecadal variability of the EASM.

2. Model and experiments

A total of five AGCMs are used. The first AGCM is the Community Climate Model, version 3 (CCM3), of the National Center for Atmospheric Research (NCAR) (Kiehl et al. 1998). Using CCM3, an ensemble of 10 members, each starting from different initial fields and integrated for 12 yr, is performed with the same SST boundary condition. The 10 initial fields are taken from the restart files of previous experiments. An idealized time-ramping SST anomaly (SSTA) (warming) is superimposed on the model's climatological monthly SST. The spatial pattern of the SSTA is kept fixed (shading in Fig. 1a), with the maximum along the equator and gradually tapered toward 0 until 30°N and 30°S, while its amplitude ramps up linearly at a rate of $\sim$.2K year^{-1} from -0.2°C at the beginning to 2.2°C at the end of the integration. The first model year is discarded as spinup. The difference of the mean through model years 7–11 minus the mean through model years 2–6 is used to represent atmospheric trend response to a 1.0°C Indian Ocean warming. The amplitude of 1.0°C corresponds largely to the strength of observed Indian Ocean warming during the second half of the twentieth century (Hoerling et al. 2004).

The second AGCM is the atmospheric component model of the Community Climate System Model, version 3 (CCSM3), of NCAR (Collins et al. 2006), the Community Atmosphere Model, version 3 (CAM3). An ensemble of a smaller size of five members is performed using CAM3.

The third AGCM used here is the Global Forecasting System (GFS) of the National Centers for Environment Prediction (NCEP; Kanamitsu et al. 1991). The initial fields are taken from the NCEP–NCAR reanalysis (Kalnay et al. 1996). A similar ensemble, but with 11 members, is performed.

The fourth AGCM is the Atmospheric Model, version 2.0 (AM2.0), of the Geophysical Fluid Dynamics Laboratory (GFDL) (GAMT 2004). A similar ensemble with 10 members is performed. Initial fields were obtained from the output of the previous simulations by AM2.0.

The last model is the AGCM, version 5.0, of the Max Planck Institute for Meteorology, ECHAM5 (Roeckner et al. 2003). A similar ensemble, but with nine members, is performed. Initial conditions are obtained from the output of the previous simulations.

The resolutions of all the five models and the experiments are summarized in Table 1.

3. Modeled responses

a. Upper-tropospheric circulation

Figure 1 displays the July–August mean 200-hPa height responses. Over the tropics, the responses among these AGCMs bear a substantial resemblance to each other, with one strong positive response over the equatorial Indian Ocean extending to the east and becoming equatorially confined over the tropical western Pacific. These responses are largely symmetric with respect to the equator, with an equatorial maximum of $\sim$40 gpm. The general interhemispheric symmetry about the equator and the first baroclinic vertical structure (discerned from comparison between 200- and 850-hPa circulation patterns) in the response are consistent with the interpretation of equatorial wave response to an equatorial heating as first theorized by Gill (1980).

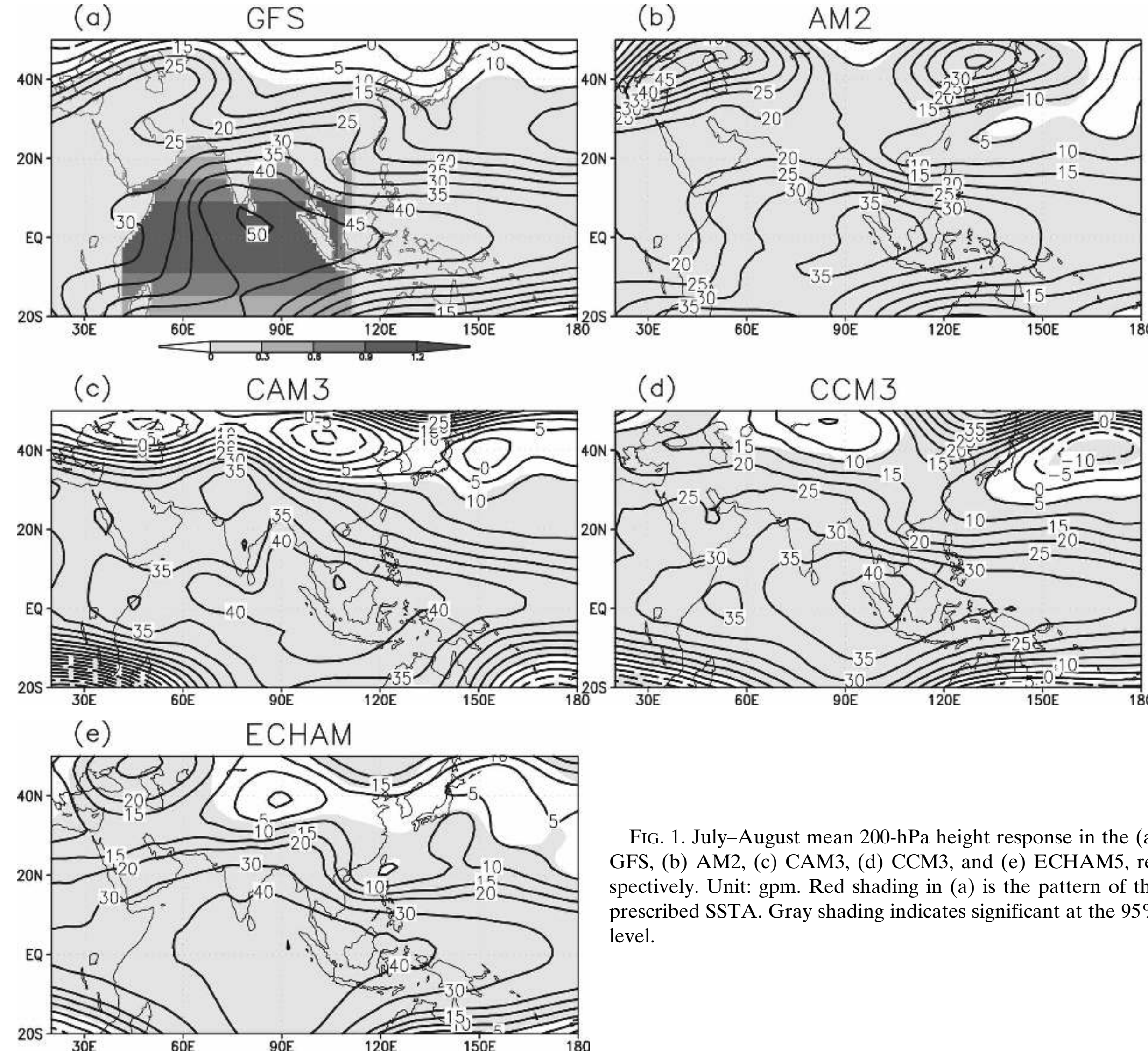

FIG. 1. July–August mean 200-hPa height response in the (a) GFS, (b) AM2, (c) CAM3, (d) CCM3, and (e) ECHAM5, respectively. Unit: gpm. Red shading in (a) is the pattern of the prescribed SSTA. Gray shading indicates significant at the 95% level.

Away from the tropical Indian Ocean, a high near the Caspian Sea and central Asia and a low off the East Asian coast appear to be common features shared by all the five models. The former projects positively on the index of the South Asian high (SAH), which is an important ingredient of the EASM circulation system, conforming the observed positive correlation between the basin-wide Indian Ocean warming and the high SAH index (Yang et al. 2007); The latter, together with the corresponding anticyclone at the lower levels, gives rise to a baroclinic structure even in regions away from the direct forcing of the Indian Ocean warming.

TABLE 1. Summary of model configurations and experiments.

	NCAR CCM3	NCAR CAM3	NCEP GFS	GFDL AM2	ECHAM5
Horizontal resolution/grid	T42 128 × 64	T42 128 × 64	T42 128 × 64	Arakawa B 144 × 90	T63 192 × 96
Vertical resolution/top of model	18 levels 3 hPa	26 levels 3 hPa	28 levels 1 hPa	24 levels 3 hPa	19 levels 3 hPa
Reference	Kiehl et al. 1998	Collins et al. 2006	Kanamitsu et al. 1991	GAMT 2004	Roeckner et al. 2003
Ensemble members	10	5	11	10	9

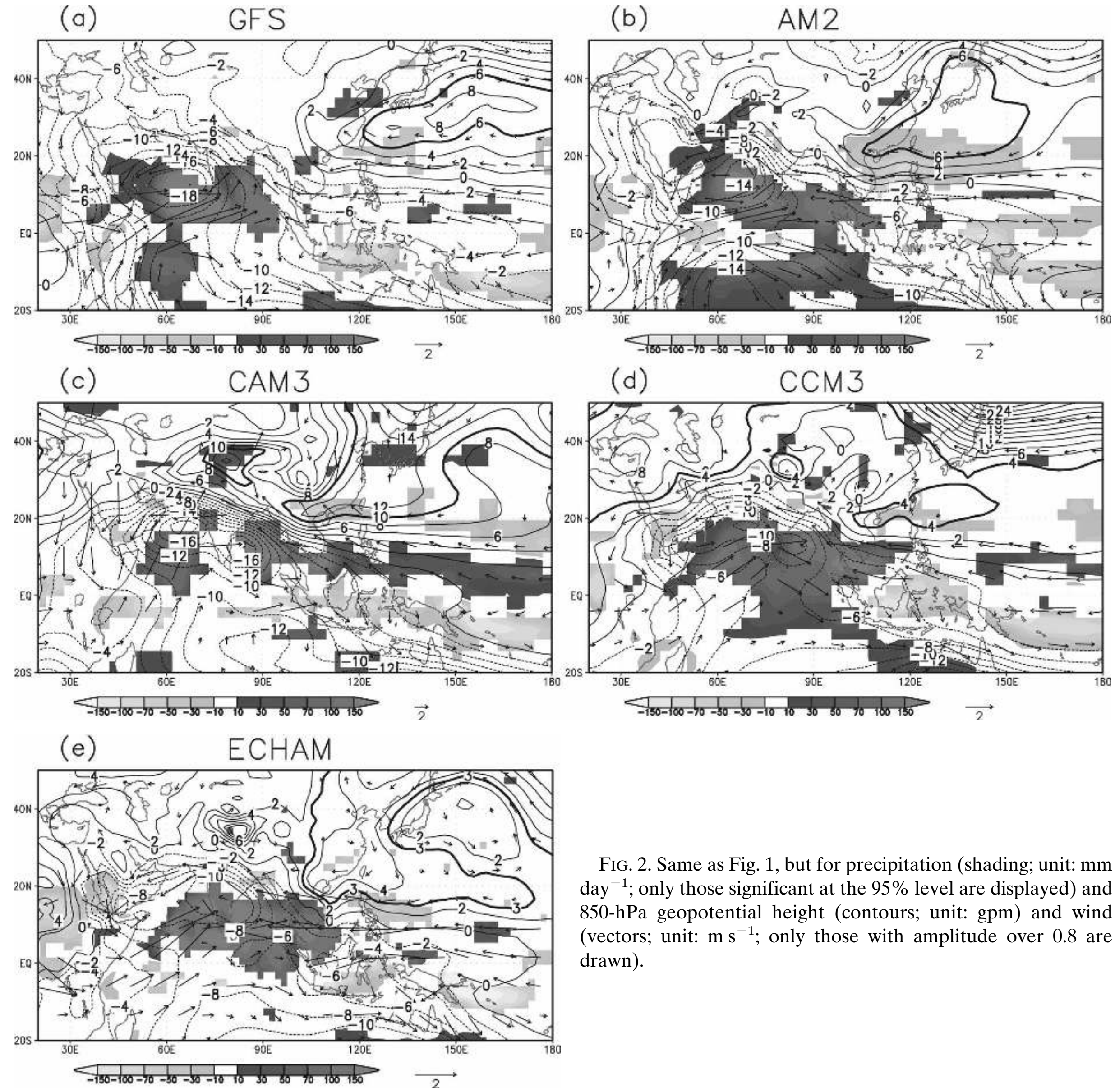

FIG. 2. Same as Fig. 1, but for precipitation (shading; unit: mm day^{-1}; only those significant at the 95% level are displayed) and 850-hPa geopotential height (contours; unit: gpm) and wind (vectors; unit: m s^{-1}; only those with amplitude over 0.8 are drawn).

b. Precipitation and lower-level circulation

Figure 2 shows the surface rainfall and 850-hPa height and horizontal wind responses. First, large-scale rainfall responses in all these five AGCMs are visually similar to each other. There is enhanced rainfall over the tropical Indian Ocean extending eastward to the southern South China Sea. The situation in which the most significant enhancement is not on the equator but to the north of it may be related to the seasonal variation of climatological SST, as the convection anomaly depends on the total SST value rather than on the anomaly. The enhanced rainfall area is largely surrounded by suppressed areas including subtropical Africa, northern India, the northern South China Sea and coastal South China, the western subtropical Pacific, and the Maritime Continents. The strongest rainfall is situated near the areas southwest to the Indian Peninsula and south to the Bay of Bengal, in better agreement with the observational composite than with the coupled model simulation of Yang et al. (2007) (cf. Fig. 2 with their Figs. 4, 5b). Corresponding to the enhanced rainfall, there are low-level cyclonic circulation responses over the tropical Indian Ocean. These responses, together with the upper-level positive height anomalies, suggest a baroclinic mode, as predicted by Gill's (1980) linear theory.

As far as the East Asian region is concerned, four out of the five models, except ECHAM5, show decreased rainfall near coastal southeastern China and increased rainfall in the middle and lower valley of the Yangtze River in the north, in general agreement with the observed EASM enhancement. The overall consistency among the AGCMs suggests that the connection from the Indian Ocean warming to EASM shown by Yang et al. (2007) is relatively robust and not strongly dependent on the detail structure of the warming and the different model configurations.

The southwesterly wind flanking the west side of the low-level western Pacific anticyclone plays a vital role in the enhancement of the monsoonal wind and rainfall in mainland China and other East Asian countries alike. This anticyclonic wind can, at least superficially, be interpreted as a direct planetary wave response to cooling associated with the reduced condensation over the western subtropical Pacific, as hinted by the baroclinic vertical structure of the circulation. However, the cooling itself is just a response to the prescribed Indian Ocean warming by the nature of the present experimental design. In fact, further diagnosis with a dry model indicates that the intensified convective heating over the Indian Ocean can directly influence the East Asia summer monsoon wind, which is to be further reinforced by the feedbacks from the western Pacific cooling. Next, a linearized dry dynamical model (Peng and Whitaker 1999) is implemented to elaborate on this point.

4. Diagnosis with a linearized dry model

A nine-level primitive equation atmospheric dynamical model is first linearized about the summertime climatological background based on the NCEP–NCAR reanalysis. The model is driven with an anomalous heating pattern, which is constructed from the precipitation response in the GFS model (Fig. 2a) and prescribed with a vertical maximum at a 400-hPa level. We choose the GFS model rainfall because its response is of greatest resemblance to the observed composite (cf. Figs. 2d, 4 of Yang et al. 2007). Many of the large-scale features in the GFS response, including the low-level anticyclone over East Asia and offshore, are replicated by the linear dry response to the anomalous heating/cooling applied (Figs. 3a,b). Notwithstanding, with the cooling over the subtropical western Pacific removed (set to be 0) in the forcing pattern, the low-level anticyclone response is much impaired (Figs. 3c,d), while the northwestward monsoonal winds over much of continental China still largely endure. Comparing the cases with and without the cooling (Figs. 3a,b versus Figs. 3c,d), one may argue that the basic feature of the increased monsoonal circulation over continental China is set by the enhanced convection over the equatorial Indian Ocean, while the precipitation (convection) feedback over the subtropical western Pacific tends to reinforce the southerly winds (Fig. 3f). In view of the design of these SST-slice experiments (Figs. 1, 2), the cooling offshore the East Asia continent and the associated anticyclone can only be interpreted as the effects of the Indian Ocean heating. Meanwhile, this feedback does contribute significantly to the moisture influx into the continent through its feedback to the monsoonal flow at the rear of the anticyclone. On the other hand, another factor of dynamical importance to EASM, the elevated upper-level South Asian high, results directly from the dynamical response to the intensified convective heating over the tropical Indian Ocean and also aids to reinforce EASM.

5. Conclusions and discussion

The results from the five AGCMs corroborate with Yang et al. (2007) that the Indian Ocean basin-scale warming enhances EASM through inducing a lower-tropospheric subtropical anticyclone over the subtropical northwest Pacific and intensifying the upper South Asia high.

While the western North Pacific lower-level anticyclone is found playing a vital role in teleconnecting the decaying El Niño to a stronger EASM in the following summer (e.g., Huang and Wu 1989; Wang et al. 2000), clarification needs to be made about its origination. Wang et al. (2000) attributed it to a Rossby wave response to local suppressed convective heating. The heating suppression is induced by both the in situ ocean surface cooling and the subsidence forced remotely by the central and eastern equatorial Pacific warming (El Niño). The present result, in alignment with Yang et al. (2007), purports an alternative source for the suppressed convective heating over the subtropical western Pacific and the associated anticyclone—Indian Ocean basin-scale warming. As a capacitor in an electric circuit being charged, the Indian Ocean warms by accumulating influence from the central and eastern equatorial Pacific during the growing phase of El Niño. It is via the discharge of the accumulated warming that the Indian Ocean prolongs the El Nino influence on the EASM in the following summer. The results of this study complementarily enrich the ENSO teleconnection pathways for ENSO to influence the EASM.

Recently, ENSO forcing has been found not to be the whole story of the tropical Indian Ocean warming. The equatorial and tropical South Indian Ocean warming cannot be explained alone by the atmospheric bridge

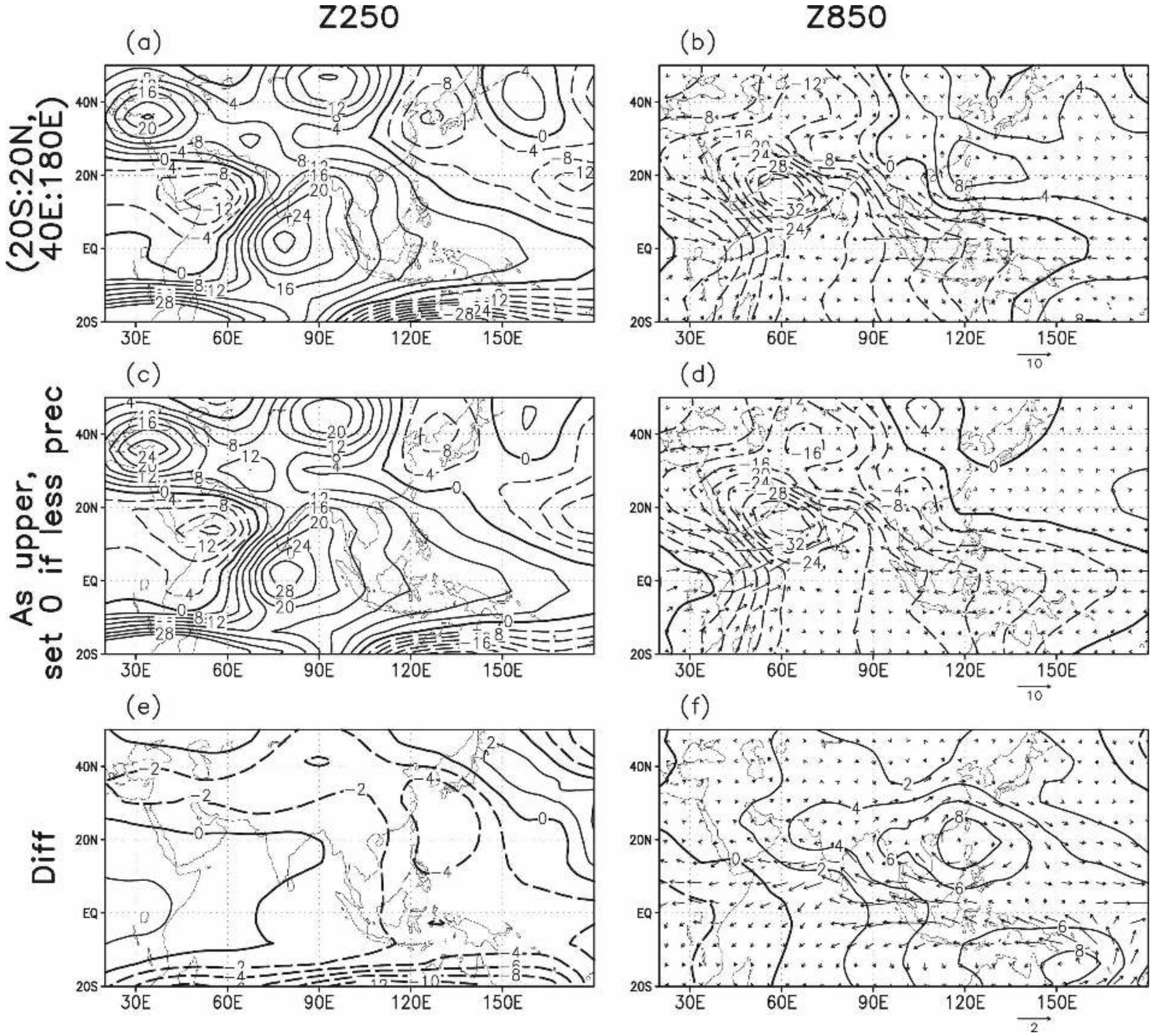

FIG. 3. Linear model-simulated atmospheric responses to prescribed tropical heating anomalies. (a), (b) For the prescribed heating anomalies over the domain (20°S–20°N, 40°–180°E). (c), (d) Same as (a), (b), but with the cooling (less rainfall) within the prescribed heating domain removed. (e), (f) Difference between (a), (b) and (c), (d). (left) 250-hPa geopotential heights (unit: gpm); (right) 850-hPa geopotential heights (unit: gpm) and horizontal wind vector (unit: m s^{-1}).

forced by ENSO (e.g., Klein et al. 1999; Lau and Nath 2000; Shinoda et al. 2004). Both ocean model results (Murtugudde and Busalacchi 1999; Murtugudde et al. 2000; Behera et al. 2000; Huang and Kinter 2002; Luo et al. 2005) and empirical analyses (e.g., Xie et al. 2002) suggest that ocean dynamic processes may contribute to the Indian Ocean SST variability. Thus, the inclusion of Indian Ocean dynamics might be beneficial to improving EASM prediction, in addition to the known ENSO signals.

It has been noticed that the significant interdecadal weakening of EASM concurred with the prominent Indian Ocean SST warming (e.g., Yang and Lau 2004). However, an inspection of the circulation and precipitation trend reveals a very different pattern over East Asia and the western Pacific area. The observed 40-yr trend in the geopotential height from the European Centre for Medium-Range Weather Forecasts Re-Analysis (ECMWF) (Uppala et al. 2004), in comparison with the signal forced by Indian Ocean basin warming, is an eastward shift with the maximum over the Maritime Continent rather than over the eastern equatorial Indian Ocean. Correspondingly, there is an eastward movement of strong rainfall anomalies accompanied by a lower-tropospheric cyclonic trend over the Philippines (Fig. 4b). No lower-level anticyclone is ob-

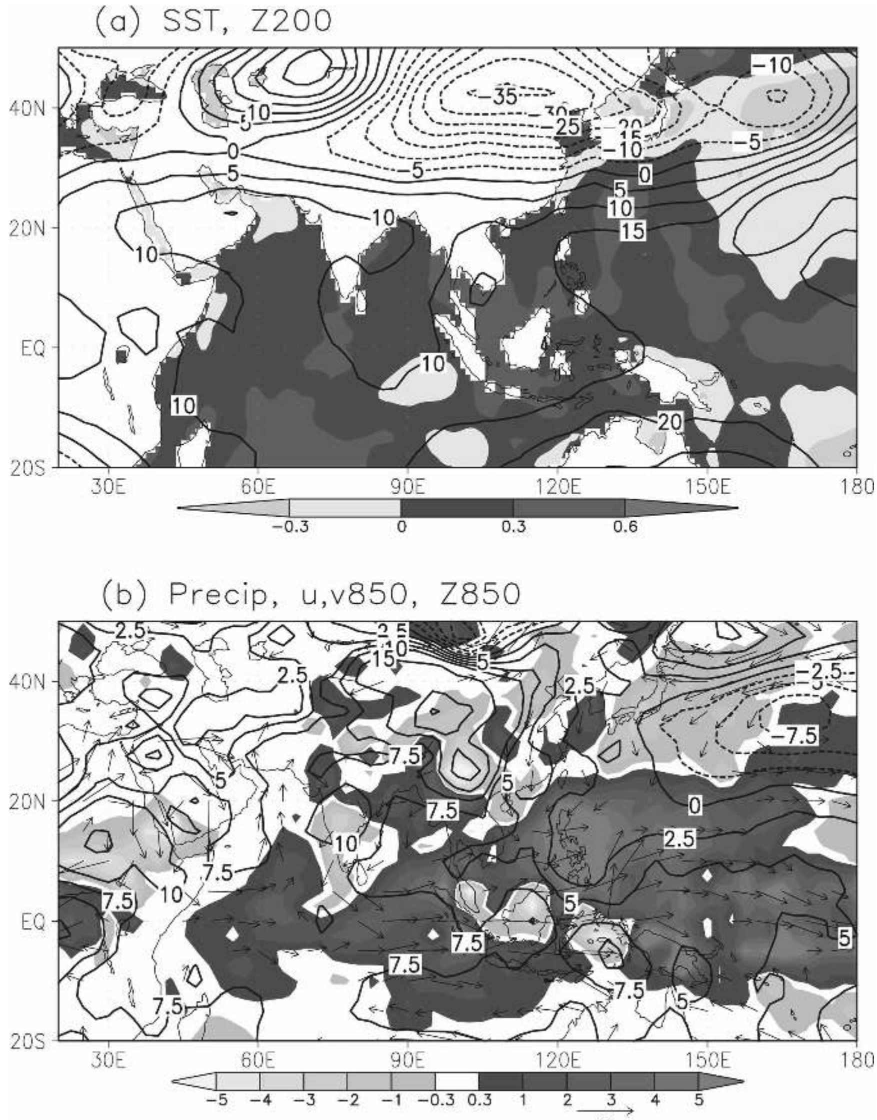

FIG. 4. Observed interdacadal trend expressed as the difference of the mean through the period of 1978–97 minus that of 1958–77. (a) July–August mean 200-hPa height (contours; unit: gpm) and SST (shadings; unit: °C). (b) Same as (a), but for rainfall (shadings; unit: mm day^{-1}) and 850-hPa height (contours; unit: gpm) and wind (vector; unit: m s^{-1}; only winds with amplitude greater than 0.5 are displayed). The 40-yr ECMWF Re-Analysis (ERA-40) (Uppala et al. 2004) and the Global Sea Ice and Sea Surface Temperature dataset (GISST; Rayner et al. 1996) are used.

served in the subtropical northwestern Pacific. East China is governed by lower-tropospheric northerly anomaly, in contrast with the modeled southwesterly anomaly. This suggests that the tropical Indian Ocean interdecadal warming alone, albeit being most pronounced in the global open ocean, cannot explain the observed interdecadal weakening of EASM during the recent decades.

On an interdecadal time scale, the Indian Ocean warming may be a passive response to remote SST warming and the increasing greenhouse gas forcing (Copsey et al. 2006; Knutson et al. 2006); the air–sea heat flux associated with the warming trend is downward, in the opposite direction to that induced by the prescribed SST warming. In other words, the Indian Ocean always stays in the *recharging* phase on the interdecadal scale. As a result, the Indian Ocean SST warming would be much less efficient in driving the convection and the associated circulation. Under such circumstance, the trend in the EASM circulation could well be dominated by forcing elsewhere, such as in the tropical western Pacific.

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