GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19705, doi:10.1029/2009GL039559, 2009

Basin mode of Indian Ocean sea surface temperature and Northern Hemisphere circumglobal teleconnection

Jianling Yang,[1,2] Qinyu Liu,[1] Zhengyu Liu,[1,3] Lixin Wu,[1] and Fei Huang[1]

Received 10 June 2009; revised 14 August 2009; accepted 28 August 2009; published 6 October 2009.

[1] Observational analysis and model experiments show that the sea surface temperature anomaly associated with the Indian Ocean Basin mode (IOBM), which persists from spring to summer, can generate significant circumglobal teleconnection (CGT) in the Northern Hemisphere summer midlatitude atmosphere. A warm IOBM can induce a new atmospheric heating source in the south Asia through a positive feedback. An enhanced Indian summer monsoon through the increased precipitation in the south Asia induces an atmospheric heating source there. This new atmospheric heating source generates an anomalous high to its northwest over the western-central Asia, which in turn generates an eastward downstream atmospheric wave train, forming the CGT. **Citation:** Yang, J., Q. Liu, Z. Liu, L. Wu, and F. Huang (2009), Basin mode of Indian Ocean sea surface temperature and Northern Hemisphere circumglobal teleconnection, *Geophys. Res. Lett.*, *36*, L19705, doi:10.1029/2009GL039559.

1. Introduction

[2] Teleconnections associated with the Asian summer monsoon have received increasing attention in recent decades. *Ding and Wang* [2005] (hereinafter referred to as DW05) first revealed a recurrent circumglobal teleconnection (CGT) pattern in the summertime midlatitude circulation in the Northern Hemisphere (NH). The CGT corresponds to six prominent "centers of action" over western Europe, European Russia, west-central Asia, east Asia, the north Pacific and north America. This anomaly pattern of 200-hPa geopotential height represents the second leading empirical orthogonal function of interannual variability of the upper tropospheric circulation and has a zonal wavenumber-5 structure, which is primarily positioned within a waveguide that is associated with the westerly jet stream.

[3] DW05 pointed out that the CGT has significant correlations with the Indian summer monsoon (ISM) and El Niño-Southern Oscillation (ENSO). However, in normal ISM years the CGT-ENSO correlation disappears; on the other hand, in the absence of El Niño or La Niña, the CGT-ISM correlation remains significant. They proposed that the ISM acts as a "conductor" connecting the CGT and ENSO.

[4] Recently, our studies [*Yang et al.*, 2007; J. Yang et al., Linking Asian monsoon to Indian Ocean SST in the observation: Possible roles of Indian Ocean Basin Mode and Dipole mode, submitted to *Journal of Climate*, 2009, hereinafter referred to as Yang et al., submitted manuscript, 2009] show that the tropical Indian Ocean (TIO) Basin Mode (IOBM) (Figure 1), as a "capacitor" lingering the ENSO's influences, can persist from spring to summer after the mature phase of ENSO, and exert a major impact on the precipitation over the south Asia, affecting the South Asian High (SAH) and the ISM. So above results raise the question if IOBM Sea Surface Temperature (SST) can affect the CGT through ISM, and even connect the ENSO and the CGT.

[5] Here, through observational analysis and coupled model experiments, we show that the IOBM is important in exciting the CGT and, in turn, influencing climate variability in the east Asia and even North Hemisphere. The IOBM also provides a delay mechanism that correlates ENSO with the CGT several months later.

2. Data and Model

[6] We use the monthly data of geopotential height at 200hPa (hereafter H200), horizontal wind at 850hPa, and precipitation as derived from the NCEP-NCAR reanalysis [*Kalnay et al.*, 1996] and the SST from the Hadley Center SST data set, all in the period of 1950–2004. Interannual anomalies are defined as the deviations from the seasonal climatology. A third-order polynomial is subtracted from the 55-year time series by a least square fit at each grid point to remove the trend and multi-decadal variability.

[7] We also performed experiments using the Fast Ocean-Atmosphere Model (FOAM) version 1.5. The atmospheric component is a parallel version of the NCAR CCM2.0 with CCM3 physics, rhomboidal truncation at zonal wavenumber 15 in the horizontal and 19 sigma levels in the vertical. The ocean model is similar to the Geophysical Fluid Dynamics Laboratory Modular Ocean Model, with a resolution of 1.4°lat × 2.8°lon and 24 vertical levels. Without flux adjustment, the model has been run for more than a thousand years without major climate drifts, with a climatology comparable with other state-of-art climate models, such as the NCAR CCSM1 [*Liu et al.*, 2003]. FOAM generates climate variability, such as ENSO, PDO and NAO, reasonably well and has been used to study climate variability extensively [e.g., *Liu et al.*, 2000; *Wu and Liu*, 2003]. FOAM has also been successful in reproducing the anomaly patterns associated with the IOBM in the region of Asia and western Pacific Ocean [*Yang et al.*, 2007].

3. TIO Basin Mode and the CGT

3.1. Observation

[8] In our recent study of the impact of the TIO SST anomaly (SSTA) on the Asian monsoon circulation [*Yang et*

[1]Physical Oceanography Laboratory and Ocean-Atmosphere Interaction and Climate Laboratory, Ocean University of China, Qingdao, China.
[2]Key Laboratory of Meteorological Disaster Preventing and Reducing in Ningxia, Ningxia Climate Center, Yinchuan, China.
[3]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA.

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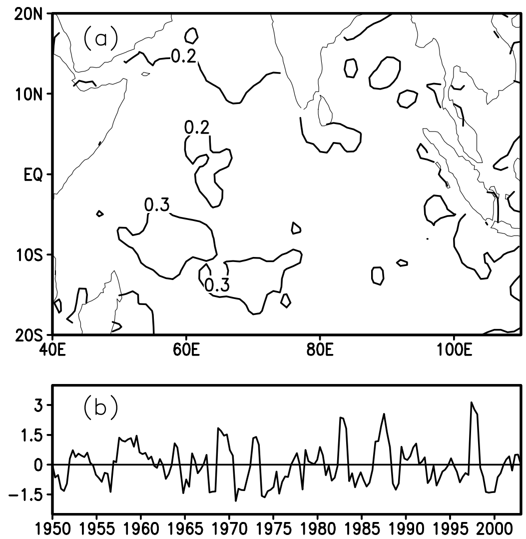

Figure 1. EOF1 (a) spatial pattern and (b) time series of the spring (MAM) TIO SSTA, respectively.

al., 2007; Yang et al., submitted manuscript, 2009], it is shown that the Asian monsoon circulation is closely related to the two dominant SSTA modes: the IOBM and the Indian Ocean Dipole Mode (IOD), with the impact of the IOBM on Asian summer monsoon much stronger than that of IOD. The IOBM, which peaks in late winter to early spring, usually after the mature phase of an El Niño event, can persist into the boreal summer. Beyond being simply a passive response to the ENSO, which peaks in boreal winter, the IOBM can induce a robust summer atmospheric response over the Indo-west Pacific region through a "capacitor" effect, prolonging the El Niño's influence after the demise of the tropical eastern Pacific SSTA. This delayed effect of IOBM on the summer atmosphere has been confirmed in further studies recently [*Li et al.*, 2008; *Xie et al.*, 2009].

[9] Here, the linkage of the IOBM with the NH atmospheric circulation can be seen in regression maps of the spring (MAM) IOBM index (IOBMI) with H200 anomalies in the following summer (JAS) (lag = 4 months) (Figure 2a). The IOBMI is defined as the EOF1 time series of the SSTA in the TIO as shown in Figure 1b. For convenience, the spatial pattern of the EOF1 SSTA is also shown in Figure 1a, which exhibits a basin-wide monopole anomaly with the center in the western TIO. The direct effect of ENSO is filtered out from H200 with a linear regression of the Niño3 SST of 2 months earlier at each grid point. It is worth to point out that this method can only remove the linear direct signal of ENSO but not all the effects of the ENSO completely. The most striking feature of the NH atmospheric response is a teleconnection pattern that resembles the CGT pattern reasonably well [*Ding and Wang*, 2005, Figure 2b]. As DW05 pointed out the quasi-zonal alignment of the anomalous high pressure (or ridge) center is primarily confined to 35°–45°N and has approximately a zonal wavenumber-5 structure with six prominent "centers of action" over the western Europe, European Russia, west-central Asia, east Asia, the north Pacific, and north America, as represented by "+" and "−" in the schematic diagram [*Ding and Wang*, 2005, Figure 2c].

[10] To check the robustness, we also plotted the regression maps as in Figure 2a but using the domain averaged SST in TIO (20°S–20°N,40°–110°E) instead of EOF1 time series. The result (not shown) is found to be almost identical to Figure 2a. This is not surprising because the evolutions of the EOF1 time series of the IOBM and the domain averaged SST are highly correlated with a correlation of 0.99, after the removal of the seasonal cycle and the long term trend.

[11] In order to check whether all CGTs correspond to the IOBM, the typical positive CGT and negative CGT years are selected based on a CGT index (index exceeding one standard deviation). The CGT index is defined using the interannual variability of H200 averaged over the reference area to the northwest of India (west-central Asia) (35°–40°N, 60°–70°E) (DW05). The nine typical positive CGT years are 1953, 1956, 1959, 1961, 1973, 1978, 1983, 1990, 2003, and the eight negative years are 1951, 1957, 1963, 1965, 1972, 1974, 1982, 1989. Comparing these positive and negative typical CGT years with 11 warm IOBM event years (1958, 1959, 1969, 1970, 1973, 1983, 1987, 1988, 1991, 1998, 2003) and 11 cold IOBM event years (1955, 1956, 1965, 1968, 1971, 1974, 1984, 1985, 1989, 1994, 2000), we find that 4 (1959, 1973, 1983, 2003) out of 9 positive CGT years correspond to warm IOBM years, accounting for about 44% of CGT years; and 3 (1965, 1974, 1989) out of 8 negative CGT years correspond to cold IOBM years, being about 37.5%. Therefore, about 40% CGT years concur with the IOBM years, consistent with the possible role of the IOBM in inducing the CGT.

3.2. Coupled Model Experiment

[12] To further substantiate our hypothesis that the IOBM can excite CGT, we performed a sensitivity experiment using the coupled GCM of FOAM1.5. In the experiment, the ocean temperature in the upper 40-m of the TIO is increased by a maximum of 2°C on July 16, and the model is then integrated for one year. The initial warming, which has a half-cosine shape that peaks at 75°E on the equator, diminishes gradually to about 20°N and 20°S poleward, and to about 40°E and 110°E zonally. A 50-member ensemble is performed, with the initial condition selected from different years of a long control run. The ensemble mean response is presented here to represent the coupled response to the initial surface warming over the TIO.

[13] The model captures the observed features of the atmospheric anomalies associated with the IOBM discussed before reasonably well. Figure 2d shows the H200 response in August. A teleconnection wave pattern similar to CGT is simulated in the NH mid-latitude. Furthermore, the anomalous centers are also located over western Europe, European Russia, west-central Asia, east Asia, the north Pacific, and north America, consist with those of *Ding and Wang* [2005, Figures 2b and 2c] and our regression analyses (Figure 2a). In the mean time, we note some discrepancies between the model simulation and the observation. In particular, the center over western Europe is poorly captured. This poor simulation may be due partly to our model deficiency. However, it is very likely that this center itself is variable in its location and intensity, as pointed out by DW05, and therefore sensitive to the background conditions and forcing. Also the idealized pattern of the initial SSTA in our experiment is not identical to that in the observation. Furthermore,

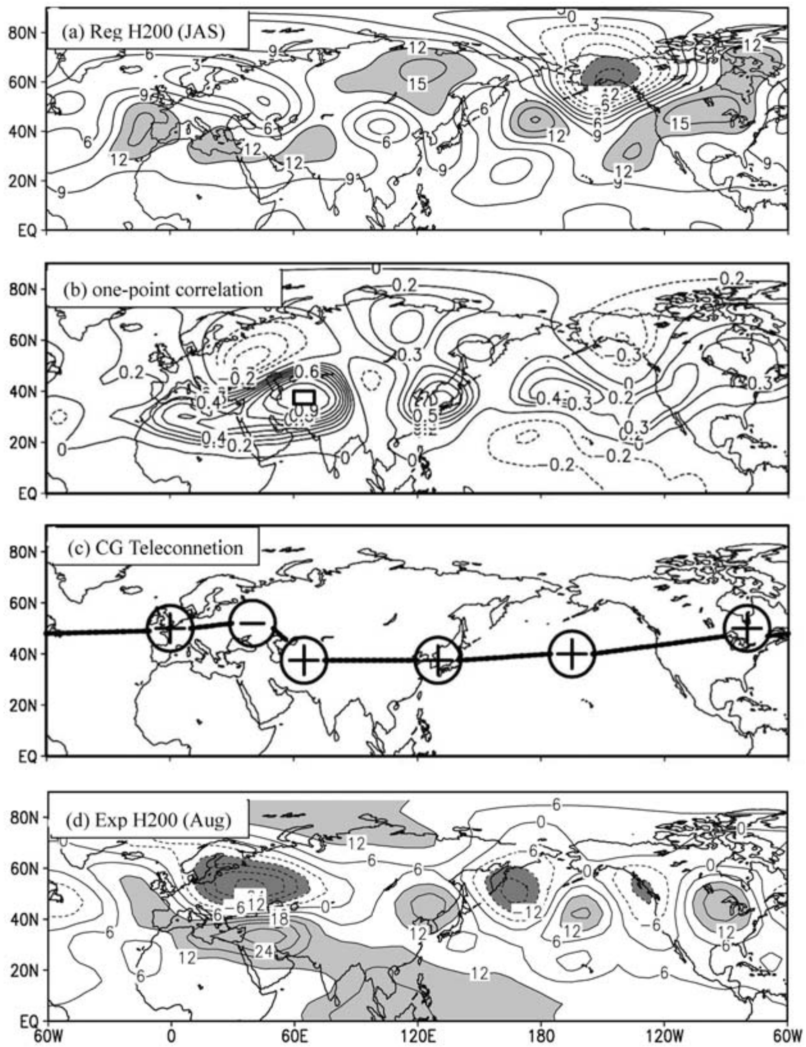

Figure 2. (a) Regression maps of the IOBMI in spring (MAM) with H200 without Niño3 index in the following summer (JAS) as lag 4 months. (b) One-point correlation map between the base-point(box) and summertime(JJAS) H200 for 1948–2003. (c) Schematic illustrating six main action centers of the CGT. (d) August H200 ensemble-mean response of FOAM to an initial warming over the top 40 m of the TIO. Light (heavy) shading in Figure 2a, 2d denotes anomalous change more(less) than 12(−12) m. Figures 2b and 2c are Figures 1c and 1d of *Ding and Wang* [2005].

we have also performed a similar experiment but with the SSTA imposed in the eastern equatorial Pacific Ocean (not shown). In sharp contrast to the experiment forced by TIO SSTA (Figure 2d), the atmospheric response in the NH mid-latitude shows little sign of CGT. Therefore, our model, in spite of its deficiencies, supports the unique role of the IOBM in generating the CGT. Overall, in spite of some minor discrepancies, the FOAM experiment is almost successful and provides a strong support to our conclusion that the IOBM can induce a significant CGT. Now, we further discuss the physical mechanism by which the IOBM induce the CGT.

4. Possible Feedback Mechanism Between the Atmosphere Heat Source and ISM

[14] How does the IOBM generate CGT? On the one hand, DW05 suggested that the ISM can play an active role in the formation of CGT. An enhanced ISM initially generates an upper-level high to its northwest over west-central Asia as a Gill-type Rossby wave response, which in turn excites successive downstream cells along the westerly waveguide through the Rossby wave dispersion in the so called "Silk Road" teleconnection [*Enomoto et al.*, 2003], forming the CGT, with the Asian westerly jet stream acting as the waveguide of the NH stationary Rossby wave in summer [e.g., *Ambrizzi et al.*, 1995]. On the other hand, our previous studies [*Yang et al.*, 2007; Yang et al., submitted manuscript, 2009] suggest that the IOBM can induce precipitation response in the western-central Asia reminiscent of the upper-level high generated by the ISM. Combining these previous studies of the IOBM impact on ISM and the ISM impact on CGT, we speculate that the IOBM can affect the ISM and, in turn, the CGT.

[15] We first show that a warm TIO SSTA strengthens the ISM and SAH through a positive feedback process. This process can be inferred from the regression maps of 850hPa wind and precipitation rate (Figure 3) from spring (MAM) to summer (JAS) against the IOBMI in the preceding spring (MAM). (The direct ENSO impact has been removed using

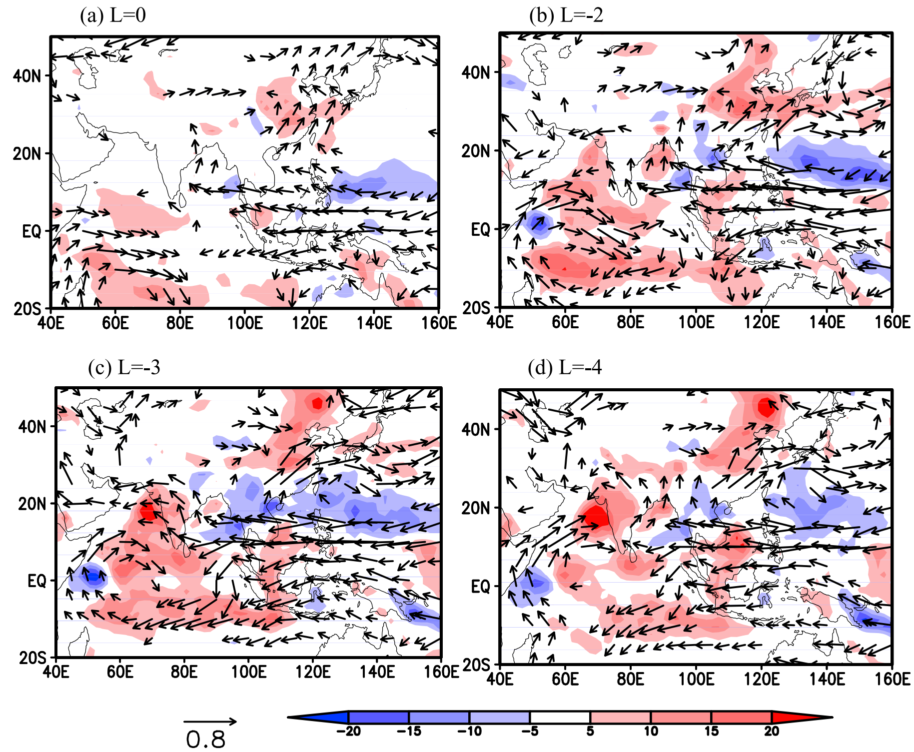

Figure 3. Regression maps of horizontal wind at 850hPa (vector in m s^{-1}) and precipitation rate (shaded in mm $month^{-1}$; ENSO effects are removed statistically) from spring (MAM) to summer (JAS) with the IOBMI in spring (MAM). These results are shown from lag 0 to 4 months (IOBMI is fixed in MAM) (a) MAM, (b) MJJ, (c) JJA, (d) JAS.

a linear regression against the Niño3 index). In spring (MAM in Figure 3a), the warm IOBM induces a westerly anomaly over the southwestern TIO as well as an easterly anomaly over a broad region from the western Pacific extending into the eastern TIO, or even the western Bengal. These low level wind anomalies induce a low level convergence over the TIO and an anti-cyclone over the northwest Pacific Ocean, and in turn, increased precipitation over the TIO and east Asia, but reduced precipitation over the northwest Pacific Ocean. In early summer (MJJ in Figure 3b), anomalous precipitation appears over the south Asia, notably the eastern Arabian Sea-India. It is the onset of the climatological southwesterly summer monsoon that induces this anomalous precipitation. The onset of the climatological southwesterly of the summer monsoon transports more moisture ($\overline{v}q' > 0$) associated with the warm TIO into the south Asia with an increased precipitation [*Liu et al.*, 2006], forming a new heating source. In the mean time, the easterly from west Pacific to west Bengal also contributes to the new heating source by transporting additional moisture into the monsoon region. Lately in the summer (JJA in Figure 3c), this new heating source further enhances the atmospheric monsoon circulation with an enhanced Somali jet ($v' > 0$), which further increases the water vapor transport into the south Asian monsoon region ($v'\overline{q} > 0$). In later summer (JAS in Figure 3d), the anomalous precipitation over the south Asia reaches its maximum, and the associated heating source in turn induce a stronger southwesterly over the Arabian Sea and easterly from western Pacific to the western Bengal. The increased southwesterly over the Arabian sea and Somali jet and easterly from west Pacific to west Bengal transport additional moisture ($v'q$) into the heating source, forming a further positive feedback with the monsoon rainfall.

[16] The IOBM impact on CGT is most clear in the summer for two reasons. First, the summer background circulation in the NH favors a southward migration of the westerly jet and the establishment of the CGT atmospheric teleconnection [*Enomoto et al.*, 2003]. Second, the summer climate background circulation also favors the IOBM impact on the ISM and SAH. This point can be clearly seen by comparing the atmospheric responses in spring and summer. We performed another initial value experiment starting in spring. This experiment is the same as the summer initial experiment discussed in Figure 2d except that the SSTA is added on March 16. The ensemble mean responses of the spring and summer initial value runs are shown for April and August, as shown in Figures 4a and 4b, respectively. It is seen that, in both spring and summer, the IOBM can induce the Matsuno-Gill type pattern at upper level. However, the geopotential high anomaly west of the Tibetan Plateau is shifted northwestward in summer, more co-located with the SAH. Therefore, the background circulation of the summer monsoon is important to the establishment of the new heat source in the eastern Arabian Sea-India. During summer a positive SSTA more effectively induces an anomaly in the SAH, and, in turn, the summer monsoon.

[17] Overall, our study suggests that the IOBM can induce the CGT through changing the ISM and in turn precipitation

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039559.

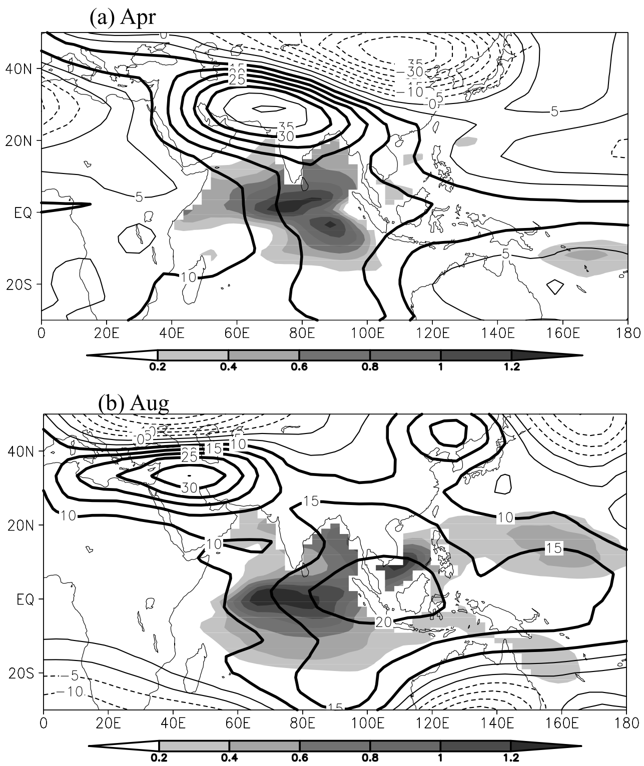

Figure 4. Ensemble-mean responses of H200 (contour in m) and SSTA (shaded in °C) in (a) April and (b) August to an initial warming in the upper 40m of the TIO.

over the eastern Arabian Sea-India with a positive feedback between atmospheric heat source and ISM.

[18] To further confirm the relationship between the IOBM and precipitation over the eastern Arabian Sea-India, we compute the lead-lag correlation coefficients between the IOBMI and the precipitation index (AIPI, averaged precipitation rate between 62–67°E, 12–21°N) (as shown in the auxiliary material).[1] The correlations are significant as the summer AIPI (July and August) lagging the IOBMI 0–6 months, with the maximum being up to 0.5 when IOBMI leads AIPI about one month. This further proves that the SSTA associated with the IOBM from the spring to summer is significantly correlated with the precipitation over the south Asia in the succeeding summer.

[19] It is also interesting to note that the AIPI in November also shows a significant correlation for the subsequent IOBMI of 1–6 months. This implies that the AIPI in the late autumn may impact the IOBM in the succeeding winter and spring. The associated process and physical mechanism are beyond the scope of this study and will be studied in the future.

5. Conclusions and Discussions

[20] Based on our observational and modeling studies, it is shown that the IOBM provides an important mechanism for the generation of the CGT. Physically, the IOBM excites the CGT as follows: A warm SST associated with the IOBM persists from spring to summer, enhancing evaporative moisture supply. This moisture supply over the TIO is transported into the eastern Arabian Sea-India at the onset of the summer monsoon. The latter forms an additional atmosphere heating source, which induces further convergence at lower level, strengthening the ISM, the moisture transport, and the heating source. The atmospheric heating source in the south Asia enhances the ISM with each other, forming a positive feedback. Within this positive feedback process, the IOBM helps to enhance the transport of moisture. The enhanced ISM then induces an upper-level anomalous high to its northwest over west-central Asia, exciting downstream waves in the westerly waveguide, generating the CGT through the Rossby wave dispersion.

[21] Our analysis shows that the IOBM influences the atmospheric circulation in the NH and even in the globe. Many previous studies have shown that the TIO SSTA is significantly associated with the atmospheric circulation and precipitation in East Asia. This study suggests a possible mechanism of the TIO SSTA influencing the atmosphere in the East Asia.

[22] **Acknowledgments.** We would like to acknowledge Shang-Ping Xie and Bin Wang for useful discussions, and Chun Li, Xiaotong Zheng, and Shu Wu for assistance in the model experiments. This research is supported by the Chinese NSF 40676010, 40830106, NXSF NZ08159 and the Ocean University of China "Green Card" Project and "Zhu Feng" Project. All simulations are carried in the High Performance Computer Center of Ocean University of China.

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F. Huang, Q. Liu, L. Wu, and J. Yang, Physical Oceanography Laboratory, Ocean University of China, No. 238 Songling Road, Qingdao 266003, China. (liuqy_ouc@sina.com)

Z. Liu, Center for Climatic Research, University of Wisconsin, 1225 West Dayton Street, Madison, WI 53706-1695, USA.