The interannual relationship between anomalous precipitation over southern China and the south eastern tropical Indian Ocean sea surface temperature anomalies during boreal summer

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1. Introduction

China covers a large area of the territory, and its precipitation distribution is both spatially and temporally uneven (e.g. Zou et al., 2005; Zhai et al., 2010; Jin et al., 2015). In the summer, China has sufficient precipitation in the southeast region, and precipitation gradually decreases toward the northwest region, with the maximum precipitation located in the Guangxi Autonomous Region and Guangdong Province (hereafter, GG). The climatological summer precipitation is greater than 800 mm in most parts of GG, and its standard deviation is greater than 200 mm (e.g. Jin et al., 2015). GG is also a more developed region of China. Excessive rainfall in this region could cause huge economic losses and affect the life of the local people, with the extreme flood event that occurred in 2010 serving as an important example. (Yuan et al., 2012).

Southern China summer rainfall has a close relationship with sea surface temperature (SST) in the tropical Indian-Pacific Ocean (e.g. Guan and Yamagata, 2003; Wu et al., 2010, 2012; Yuan et al., 2012; He and Wu, 2014; He et al., 2016; Hu and Wu, 2016; Jin et al., 2016; Wang and Gu, 2016). The tropical eastern Indian Ocean and western Pacific, or Maritime Continent, are important regions that concatenate the Indian Ocean and the Pacific Ocean (Ramage, 1968). Wu et al. (2010) noted that the summer rainfall negatively correlated with the SST anomaly (SSTA) in the southeastern tropical Indian Ocean (hereafter, SETIO). The SETIO SSTAs could influence the summer rainfall anomaly over southern China by altering the meridional vertical circulation in East Asia. SETIO is the eastern polarity of the Indian Ocean dipole (IOD; Saji et al., 1999; Webster et al., 1999). In the positive phase of IOD, cooling over the SETIO favours water vapour divergence in this region and convergence in southern China (Guan and Yamagata, 2003). Recently, Chen et al. (2016) found that the rainfall anomalies over southern China are closely connected to the SSTA in the tropical eastern Indian Ocean since the early 1990s. The interdecadal change between the southern China rainfall anomaly and the SSTA over the tropical eastern Indian Ocean is mainly due to a change in the local Hadley circulation in East Asia. Before (after) the early 1990s, the response of anomalous local Hadley circulation to heating over the tropical eastern Indian Ocean was weaker (stronger), which contributed to the weaker...
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(1) descent over southern China, and weakened (strengthen) their connection. The aforementioned results imply that the anomalous rainfall over southern China is related to the SSTA over the (south) eastern tropical Indian Ocean.

However, the extent of the SSTA over the (south) eastern tropical Indian Ocean related with the precipitation of southern China has some variances (Wu et al., 2012; Chen et al., 2016). Water vapour is another important condition that favours precipitation. Both Wu et al. (2012) and Chen et al. (2016) did not evaluate how the transportation of water vapour is related to the anomalous $P_{GG}$. Consequently, it is necessary to revisit the relationship between anomalous rainfall over GG and the SSTA in the (south) eastern tropical Indian Ocean. This should include the accurate extent of the SSTA over the (south) eastern tropical Indian Ocean, transportation of water vapour and the meridional vertical circulation, which are all related to the anomalous rainfall over GG. Understanding these questions could provide the clues for interpretation and monitoring of the anomalous $P_{GG}$. The present study is organized as follows: The data and model used in this study are described in Section 2. Section 3 presents the relationship between the SETIO SSTA and the anomalous precipitation in GG ($P_{GG}$) as well as the possible mechanism. Discussion and conclusions are presented in Section 4.

2. Data and model

Daily precipitation data of GG in the boreal summer (June–July–August) are obtained for the years 1979–2009 for 36 in situ stations (Figure 1(a)) from the National Climate Center of China Meteorological Administration. Daily precipitation data from 2010 to 2015 are extracted from the Meteorological Information Combined Analysis and Process System (MICAPS) version 3.0, which has the same observational gauges of rainfall data from the China Meteorological Administration. Precipitation data from the 36 observational stations, which are selected based on Jin et al. (2015), is independent from others in Mainland China (Figure 1(a)). Monthly SST data for 1979–2015 are obtained from the Met Office Hadley Centre with horizontal resolution of 1° (HadISST1) (Rayner et al., 2003). Data for monthly environmental variables are obtained from the NCEP/NCAR reanalysis I (Kalnay et al., 1996) with horizontal resolution in 2.5° for 1979–2015. In this study, the analysis is focused on an interannual time scale of shorter than 8 years. Variations of 8 years and longer decadal signals have been filtered and removed using a trend and a 9-year sliding mean, which is widely used in climate analyses (e.g. Wu et al., 2012; Huo et al., 2015).

The atmospheric linear baroclinic model (LBM) used in this study is a primitive equation sigma coordinate model with T42 horizontal resolution and 20 vertical levels; more detailed information about the LBM can be found in Watanabe and Kimoto (2000). The damping time scale is set to 1 day for the lowest three levels and the topmost two levels, 5 and 15 days for the fourth and fifth levels and 30 days elsewhere. The model is integrated for 30 days, and the results of the 10-day average from day 20 to 30 are analysed as the steady response to a prescribed forcing source. The seasonally varying basic state of summer climatology prescribed in the numerical model is on the basis of NCEP/NCAR reanalysis I data for the period from 1979 to 2014.

3. Result

3.1. Relationship between $P_{GG}$ and SETIO

The $P_{GG}$ is negatively correlated with the SSTAs over SETIO (Figure 1(b)). This is consistent with Wu et al. (2012), and it implies that the $P_{GG}$ has a closer relationship with SETIO (Wu et al., 2012) than the eastern tropical Indian Ocean (Chen et al., 2016). To conveniently study the connection between $P_{GG}$ and the SSTAs over SETIO, the SST index of SETIO ($I_{SETIO}$) is defined as the regional mean SST over the area 95–110°E and 15–5°S, which is the location of the maximum absolute values of the correlation coefficients (Figure 1(b)). The simultaneous correlations between $I_{SETIO}$ and the southern China summer rainfall show the $I_{SETIO}$ is negatively correlated with the GG region except in the northern part of the Guangxi Autonomous Region (Figure 1(c) and (d)). The correlation coefficient between $P_{GG}$ and $I_{SETIO}$ is $-0.52$. It may have an interdecadal change when the influence of ISETIO on PGG is taken into account (Chen et al., 2016). Then we calculate the correlations of $P_{GG}$ and $I_{SETIO}$ in the periods 1979–1992 and 1993–2015, and find the correlation coefficients to be $-0.58$ and $-0.45$, respectively. This indicates that despite the weakening influence of $I_{SETIO}$ on $P_{GG}$ since the early 1990s, the connection still exists during the last two decades analysed.

3.2. Water vapour transportations related with $I_{SETIO}$

In SETIO warming years, the water vapour convergences in SETIO and divergences over GG region (Figure 2), which is favourable for excessive and deficient rainfall in SETIO and GG regions, respectively. An anti-cyclonic transportation of water vapour exists in southern China and the South China Sea region, and the easterly transportation could be extended to North Africa through the Bay of Bengal and Arabian Sea between 10 and 20°N. There are two anomalous water vapour transportations isolated from the easterly transportation: one turns south at the Bay of Bengal, near 85°E, and one turns south at the Arabian Sea, near 65°E. The two transportations then converge in SETIO. It is also noted that an anomalous water vapour transports from the central tropical Pacific to SETIO and vice versa.
3.3. Anomalous horizontal circulation

There are two cyclonic circulations along the equator, located at the west side of SETIO during warm SETIO SSTA years (Figure 3(a)). The cyclone in the southern hemisphere is stronger than in the northern hemisphere. These are Rossby wave responses to the heating over the SETIO. We can also observe easterlies as Kelvin wave responses to SETIO warming (Matsuno, 1966; Gill, 1980) from the tropical central Pacific (Figure 3(a)). The easterlies in the western north Pacific enhance the western Pacific high, which can be further manifested by the weakening of vorticity in low levels over the South China Sea and east of the Philippine Sea (Figure 3(a)). The anomalous vorticity in GG region is unfavourable for precipitation. The transportation of water vapour agrees with the low level wind responses (Figure 2) and vice versa. This demonstrates that the SETIO SSTA could influence the anomalous vorticity and water vapour transportation through the responses to the heating of the atmosphere.

3.4. Anomalous vertical circulation

Anomalous meridional vertical circulation could affect the rainfall anomalies in the GG region through modification of the local vertical velocity (Wu et al., 2012; Chen et al., 2016). In this section, we will discuss the vertical circulation from the perspective of anomalous SST over SETIO.

The regression of the velocity potential for the low and high levels onto the $I_{SETIO}$ is shown in Figure 3(b) and (c). Responding to the warm SST in SETIO, positive (negative) velocity potential anomalies coincided with convergent (divergent) airflow that can be found over SETIO and in the vicinity of Australia in low (high) levels (Figure 3(b) and (c)). It is also observed that the convergence and divergence in SETIO is stronger than in the vicinity of Australia. Additionally, pronounced quasi-meridional divergent (convergent) airflow from GG region to SETIO at low (high) level has been observed (Figure 3(b) and (c)). The above convergence and divergence configurations may alter the anomalous local Hadley circulation. Regression of the vertical circulation anomalies averaged over 105–117.5°E, which is the zonal extent of the GG region, onto the $I_{SETIO}$ is shown in Figure 3(d). The ascent motion is significant in the SETIO due to the warm SST in SETIO (Figure 3(d)). The cyclonic circulation located in SETIO and the Australian region weakened the Australian high (Figure 3(a)), which also strengthened the convergence over SETIO in the low level (Figure 3(b)). All of the above configurations...
3.5. Model results

To verify if the SSTA over SETIO results in the anomalous rainfall in GG, a numerical experiment is run. The elliptic thermal forcing is prescribed with its centre at 103°E, 12°S and spans 90–116°E and could favour the ascent over SETIO and strengthen the anomalous local Hadley circulation in the northern hemisphere. This will allow the descent motion over the GG region to be enhanced (Figure 3(d)) which favours below normal rainfall (Figure 1(c)) and vice versa.

Figure 2. The regressed water vapour fluxes integrated from the surface up to 300 hPa (in Kg/ms; vectors) and their divergence (in 10^-6 kgms^-2; shades). Shaded areas with dots denote the correlation coefficients at or above 95% confidence levels by using F-test.

Figure 3. Shown in (a) is same as in Figure 2, but for 850 hPa vorticity (in 10^-6 s^-1) at 850 hPa with the horizontal rotational winds (in ms^-1). (b) and (c) are same as in (a), but for the velocity potential (in 10^6 m^2 s^-1) with the divergent winds (in ms^-1) at 850 (b) and 200 hPa (c). (d) shows the same as in (a), but for the meridional vertical circulation averaged over 105–117.5°E.
20°–4°S. Its maximum at the 0.55 sigma level is 1 K/day (Figure 4(a)).

The response of low level vorticity to the diabatic heating over SETIO shows that there are two cyclones along the equator in the tropical Indian Ocean (Figure 4(a)). In addition, the easterlies from the tropical central Pacific could also be reproduced. The negative vorticity and anomalous anticyclone also appear in the model results, although the magnitude is weaker (Figure 4(a)). The convergence/divergence and divergence/convergence in SETIO and GG at the low/high level is also well simulated in the LBM (Figure 4(b) and (c)). This demonstrates that the thermal forcing in SETIO could induce the anomalous rainfall in GG.

4. Discussion and conclusions

This study discusses the connection between the anomalous precipitation in GG and the SSTA over SETIO during the boreal summer. \( P_{GG} \) is negative correlated with the SSTA in SETIO. During the warm SETIO SSTA years, there exist two cyclonic circulations along the tropical Indian Ocean and easterlies from the tropical central Pacific attributed to the Matsuno-Gill responses of atmospheric fields to the warming over SETIO. GG is controlled by an anomalous negative vorticity. The transports of water vapour integrated from the surface to 300 hPa have a similar pattern to the low level wind fields. The water vapour in GG and SETIO is divergent and convergent, respectively. The anomalous ascent motion in SETIO is enhanced, which favours the strengthening of the meridional vertical circulation over East Asia. This anomalous meridional vertical circulation indirectly enhances the anomalous descent motion in GG. These anomalous circulations could favour below normal rainfall in GG and vice versa. The response of anomalous circulation to the thermal forcing in SETIO can be reproduced by the atmospheric linear baroclinic model.

The novel aspects of this work compared to the previously published studies by Wu et al. (2012) and Chen et al. (2016) are mainly included as following aspects. Firstly, the water vapour, which is an essential variable for the precipitation, related between the SETIO SSTAs and the anomalous \( P_{GG} \) is diagnosed in the present study. Secondly, the research period is extended to the recent decade. Thirdly, the current work is focused on a specific area of southern China (the Guangxi Autonomous Region and Guangdong Province; GG) rather than the whole southern China region. Finally, a series of numerical experiments are designed to validate the observational results.

It should be noted that, summer rainfall anomalies in southern China could be connected with the North Atlantic Oscillation (NAO; Hurrell, 1995) through Eurasian teleconnection (Su and Lu, 2014; Chen et al., 2016). Do the SETIO SST anomalies and NAO have a conjunctive influence on anomalous summer precipitation in southern China? In addition, southern China rainfall anomalies have a close relationship with tropical cyclone activity in the western north Pacific (e.g. Li and Zhou, 2015). This study reveals that the SSTA over SETIO can influence the anomalous low level vorticity in the South China Sea and to the east of the Philippine Sea (Figures 3(a) and 4(a)). It is well-known that the low level vorticity is a large scale kinematic condition crucial to tropical cyclone formation over the western north Pacific (e.g. Gray, 1968; Huo et al., 2015). Is there any relationship between the SSTA in SETIO and tropical cyclone activity in the western north Pacific or the South China Sea? If this relationship does exist, could the SETIO SST anomalies, by influencing tropical cyclones activity, indirectly affect the \( P_{GG} \)? These questions are the objectives of additional studies.

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