Responses of atmospheric circulation to sea surface temperature anomalies in the South China Sea

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ABSTRACT

The sea surface temperature (SST) anomalies in the South China Sea (SCS) and their influences on global atmospheric circulation were studied. The results of the simple atmospheric model suggested that the SCS SST anomalies can induce several barotropic wave trains from the SCS to other regions such as North America, high latitudes of the Southern Hemisphere and the Mediterranean. The baroclinic stream function anomalies from the simple model showed an anticyclonic vortex pair in East Asia and southern tropical Indian Ocean and a cyclonic vortex in the North Pacific and the Southwest Pacific. It is suggested that the spatial pattern of SST anomalies in the SCS can affect the magnitude of stream function anomalies, although it cannot affect the spatial pattern of atmospheric circulation.

1. Introduction

The South China Sea (SCS, 0-25°N, 100-125°E) is the largest marginal sea in the Northwest Pacific. The sea surface temperature (SST) in the SCS has a significant seasonal cycle. The climatological SSTs in summer (June to August) and winter (December to February) over the SCS are shown in Fig. 1. The SST in summer is mostly above 28°C, with a pronounced cold tongue veering off central Vietnam (Fig. 1a). During winter, the SST is cold in the northwest and warm in the southeast of the SCS (Fig. 1b).

The SST in the SCS had a robust warming trend during past several decades (Luo et al., 1986; Fang et al., 2006; Xie et al., 2010; Zhang et al., 2010; Liu and Zhang, 2013). Based on the Optimum Interpolation Sea Surface Temperature (OISST) dataset, Fang et al. (2006) concluded that the SST in the SCS had the positive linear trend of 5 °C100a^{-1} during 1993-2003. The summer and winter SST trends in the SCS from 1982 to 2011 are also shown in Fig. 1. Whether in summer or in winter, the SCS warming trend is significant; with1.64°C100a^{-1} in summer and 2.04°C100a^{-1} in winter. The maximum SST trend can exceed 9.50°C100a^{-1}. The averaged SST trend of the SCS is smaller than that reported by Fang et al. (2006), which used the data from 1993-2003. During summer, the larger warming is in the western SCS and the smaller in the eastern SCS. While During winter, the larger warming is in the eastern SCS and the smaller in the western SCS. It should be noted that the SCS warming is faster than global average, and the warming is largest between 0-20°N globally.

Many studies focused on the effects of the positive SST anomalies in the SCS on precipitation and climate in China (Zhang et al., 2003; Fong et al., 2004; Roxy and Tanimoto, 2012). According to Zhang et al. (2003), the positive SST anomaly in summer from the seasonal climatology in the SCS~~the positive SST anomaly in the SCS in summer~~ was followed by anomalous southward wind, and then more moisture was transferred to South China, which resulted in floods in the Yangtze River Valley. Fong et al. (2004) suggested that the SCS surface warming can enhance latent and sensible heat fluxes from the sea surface and result in a cyclonic circulation anomaly in the lower troposphere and an anti-cyclonic circulation anomaly in the upper troposphere, which then affect the climate of South China. Roxy and Tanimoto (2012) pointed out that the positive SST anomalies over the SCS tended to form a favorable condition

for convective activity and enhanced the northward propagating precipitation anomalies during the SCS summer monsoon. Other studies showed that the SST anomalies in the SCS can influence SCS monsoon onset (Johnson and Ciesielski, 2002; Ding et al., 2004; Lestari and Iwasaki, 2006) and its variability (Liu and Xie, 1999; Lestari et al., 2011; Roxy and Tanimoto, 2012).

Teleconnections are well known and well frequently reported (Wallace and Gutzler 1981; Huang, 1984; Nitta, 1986; Nitta, 1987). A local change in the surface boundary condition can have far reaching influences elsewhere. For examples, the diabatic heating anomaly over the central equatorial Pacific during ENSO can excite a stationary barotropic Rossby wave train propagating into extratropical regions. This teleconnection is known as the Pacific-North American (PNA) pattern (Wallace and Gutzler, 1981) in the Northern Hemisphere. Nitta (1987) found an association between abnormal convective activity over the tropical western North Pacific and atmospheric circulation anomalies over the midlatitude of East Asia in summer which named as the Pacific-Japan (PJ) pattern.

Previous studies mostly discussed how the SST in the SCS affected the local climate and the teleconnections between the SCS and global atmosphere circulation are not clear.~~Previous studies mostly discussed how the SST in the SCS affected the local climate. But the extent of impact of the SST anomalies in the SCS is still not known.~~ In this paper, we use a simple atmospheric model to discuss it. The rest of this paper is organized as follows. Section 2 describes the data and model used in this study. The results obtained with the simple atmospheric model are presented in Sect. 3. Summary and discussion are provided in Sect. 4.

2. Data and model

2.1 Data and method

Two datasets are used in this study. The climatological stream functions are from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NECP/NCAR) reanalysis, which is available on a 2.5° latitude by 2.5° longitude grid (Kalnay et al., 1996). OISST analysis product is from the National Oceanic and Atmospheric Administration (NOAA), which has the spatial resolution of 0.25° latitude by 0.25° longitude (Reynolds et al., 2002). The period of the two datasets used is from 1982 to 2011.

The basic mean flows are represented by the stream functions at 250 and 750 hPa from the monthly NCEP/NCAR reanalysis. The stream functions at 750 hPa are constructed by linear interpolation with all standard pressure levels, as 750 hPa is not a standard pressure level. Since the model atmosphere is simplified to two levels (centered at 250 and 750 hPa), the stream functions can be separated into the barotropic and baroclinic components as follows:

$$\psi_{barotropic} = 0.5 \cdot (\psi_{250hPa} + \psi_{750hPa}), \quad (1)$$

$$\psi_{baroclinic} = 0.5 \cdot (\psi_{250hPa} - \psi_{750hPa}), \quad (2)$$

where ψ stands for stream function.

Figure 2 shows the spatial pattern of mean barotropic stream function (a) and baroclinic stream function (b) from 1982 to 2011. Whether barotropic or baroclinic stream function, it was always the westerly in high latitudes. Generally, there were two westerly jet cores in the Northern Hemisphere and consistent westerly in the Southern Hemisphere. In the equatorial and tropical regions, the flows fluctuated due to strong convections.

2.2 Atmospheric model

We use a simple atmospheric model developed recently by Lee et al. (2009) to simulate global atmospheric circulation. This is a steady-state two-level (centered at 250 and 750 hPa) spherical-coordinate primitive equation model, linearized about prescribed background mean flows. The model uses triangular 18 truncations for horizontal grids. The formulation is similar to that of the multi-level linear baroclinic model used by Hoskins and Simmons (1975) and others, but its governing equations are greatly simplified by employing Gill's (1980) simple thermodynamic equation. Detailed description of the simple model can be found in the paper of Lee et al. (2009). This model successfully simulated the local and remote responses of the atmosphere to tropical heating anomalies (Lee et al., 2009; Wang et al., 2010; Zheng et al., 2013). In this study, we use the basic mean flows as the initial conditions and heating in the SCS as the forcing conditions to run this model.

3. Results

3.1 Influence of SST anomalies in the meridional direction

Two experiments are set up to see how basin-scale SST anomalies affect the atmospheric circulation: 1) uniform heating in the SCS (Case 1) and 2) heating decreased northward in the SCS to consider the differences in solar radiation in the northern and southern SCS (Case 2). To test the effects of seasonal SST anomalies in the SCS, we set up two more experiments: 3) heating pattern similar to the SST winter pattern (Case 3) and 4) heating pattern similar to the SST summer pattern (Case 4) in the SCS. As shown in Fig. 1, the SST in the winter is low in the northwest and high in the southeast SCS, which is used in Case 3, while the summer pronounced cold tongue veering off central Vietnam is included in Case 4. Heating patterns derived from SST anomalies for these four experiments are summarized in Fig. 3. The calculations are listed in Table 1. Note the total heat input is the same for the four experiments to ensure comparability.

Figure 4a shows the barotropic stream function anomalies from Case 1. There are three robust waves in the barotropic stream function. The first one is from the SCS to North America through the northwestern Pacific, which is somewhat similar to the classical PNA pattern (Wallace and Gutzler, 1981; Nitta, 1986; Huang, 1984). The second one is from the SCS to high latitudes of the Southern Hemisphere across the equator. As shown by Wang et al. (2010), the background vertical wind shear is important in converting energy from the heating-induced baroclinic flow anomalies into barotropic motions near the heating source. The barotropic anomalies in turn interact with the mean westerly wind to transmit the barotropic signals to the high latitudes of the Southern Hemisphere. Note another small wave train is from the SCS to the Mediterranean. According to the classical theory of energy dispersion (Yeh, 1949) and the great circle theory (Hoskins and Karoly, 1981), disturbances produced by local heating can spread westward.

The baroclinic stream function anomalies from the simple model show an anticyclonic vortex pair in East Asia and southern tropic Indian Ocean (Fig. 4b). Accordingly, a cyclonic vortex pair appears in the north and southwest Pacific, quite similar to the Matsuno–Gill model (Gill, 1980) and consistent with the results of Heckley and Gill (1984) and Smagorinsky (1953). The response of atmospheric circulation to the heating anomaly in the SCS suggests that the Gill dynamics is at work.

We calculate the seasonal cycle of the air-sea temperature difference (Figures not shown here); it suggests that atmosphere reduces heat loss to the ocean during the boreal winter in the

northern SCS and increases heat flux from the ocean during the summer in the northern SCS. It was supported by He and Wu (2013) that the boreal winter SST in the northern SCS are independent from the atmospheric conditions, it gives the opportunity to look in the used observational data sets find support for the described teleconnections. The correlation between the winter SSTA in northern SCS and the barotropic/baroclinic streamfunction are calculated. As shown in Fig. 5, the correlation in Fig. 5a demonstrated two waves: one is from SCS to North America and the other is from SCS to the Southern Hemisphere; the correlation in Fig. 5b showed positive anomalies in East Asia and the Southwest Pacific and negative anomalies in the North Pacific and southern tropical Indian Ocean. These support the described teleconnection between SCS SST and the global atmospheric circulation.

The barotropic and baroclinic stream function anomalies for Cases 2-4 are basically the same as for Case 1, which indicates that the positive heating anomalies in the SCS can all induce three waves in the barotropic stream function and two vortex pairs in the baroclinic stream function regardless of the spatial pattern of the heating. The amplitudes are slightly different in the four experiments. For the PNA-like pattern wave train and the Southern Hemisphere wave train, the barotropic stream functions in Cases 1 and 4 are weaker than those in Cases 2 and 3 in the anticyclonic anomalies, but they are stronger than those in Cases 2 and 3 in the cyclonic anomalies (Fig. ~~5a~~6a). Conversely, the baroclinic stream functions of Cases 1 and 4 are weaker than those in Cases 2 and 3 in the cyclonic anomalies, but are stronger than those in Cases 2 and 3 in the anticyclonic anomalies (Fig. ~~5b~~6b). The differences among the four cases suggest that the spatial pattern of SST anomalies can affect the magnitude of stream functions, although it cannot affect the spatial pattern of atmospheric circulation. The role of asymmetric heating in influencing atmosphere circulation also can be seen in many literatures such as Fu et al. (1980) and Dunkerton (1989).~~The results support that the waves n=1, 2 are distinctly controlled by the asymmetric heating sources revealed by Fu et al. (1980).~~

3.2 Influence of SST anomalies in the zonal direction

To test the effects of the SST warming differences in the zonal direction on atmospheric circulation,~~To test the effects of the SST warming patterns in the SCS on atmospheric circulation in the zonal direction,~~ we carry out two more experiments, using summer and winter SST

warming trend heating patterns, respectively. Figure ~~6~~ 7 shows the stream function anomalies of the barotropic and baroclinic components for Cases 5 and 6, which are also summarized in Table 1. Note the heating pattern in the two experiments is similar to the warming trend pattern, while the total heat input in these two cases is the same as in Cases 1-4 to ensure comparability.

The spatial patterns of the stream function anomalies for Cases 5 and 6 are also quite similar to those in Case 1 for both barotropic or baroclinic components. For the PNA-like pattern wave train or the Southern Hemisphere wave train, the barotropic stream function in Case 5 is weaker than that in Case 6 in the cyclonic anomalies, but is stronger than that in Case 6 in the anticyclonic anomalies (Fig. ~~6a~~7a). Conversely, the baroclinic stream function in Case 5 is weaker than that in Case 6 in the anticyclonic anomalies, but is stronger than that in Case 6 in the cyclonic anomalies (Fig. ~~6b~~7b). As shown in Fig. 1, the larger warming trend is in the western SCS for the summer but in the eastern SCS for the winter. The difference between Cases 5 and 6 suggests that the larger warming trend in the western (eastern) SCS heating pattern can weaken (strengthen) the cyclonic anomalies and strengthen (weaken) the anticyclonic anomalies in the barotropic component. On the contrary, the larger warming trend in the western (eastern) SCS heating pattern can strengthen (weaken) cyclonic anomalies and weaken (strengthen) the anticyclonic anomalies in the baroclinic component. It also suggests that the spatial pattern of SST trend can affect the magnitude of stream functions, although it cannot affect the spatial pattern of atmospheric circulation.

4. Summary and discussion

In this study, the influences of SST anomalies in the SCS on global atmospheric circulation were studied. The results of the simple atmospheric model suggested that the SCS heating can induce a barotropic wave train from the SCS to the Northwest Pacific and North America, which is somewhat similar to the classical PNA pattern. Simultaneously, the SCS heating can induce a barotropic wave train from the SCS to high latitudes of the Southern Hemisphere. In particular, we noticed a weak barotropic wave train from the western SCS to the Mediterranean. The baroclinic stream function anomalies from the simple model showed an anticyclonic vortex pair in East Asia and the southern tropic Indian Ocean and a cyclonic vortex in the North Pacific and the Southwest Pacific. The stream function anomalies of the barotropic and baroclinic

components for all six cases are basically the same, with slight differences in amplitude. It suggests that the spatial pattern of heating can cause some differences in magnitude, but not in circulation patterns. Our findings in this study may be important for the regional and global climate research. For example, we calculate the correlation between the northern SCS SSTA and the rainfall. The correlation pattern is quiet similar to Fig. 4a, which also showed two waves: one is from SCS to North America and the other is from SCS to the Southern Hemisphere (Figures not shown here), thus this study may help to forecast climate-related events like rainfall in the North America based on the SCS SST anomalies.~~For example, we may forecast climate-related events based on the SCS SST anomalies.~~

Note heating in the atmosphere is not necessarily collocated to SST warming in observations. In some cases, the SST warming results from descending in the atmosphere and thus it may not be a cause of heating. For example, He and Wu (2013) indicated that the SST anomalies in the South China Sea are mostly response to the atmospheric changes except for boreal winter in the northern South China Sea. We completely ignore the situation and simply consider that the SST anomalies can induce heat to the atmosphere. Thus a more complete atmospheric general circulation model is necessary to confirm these findings.

Acknowledgments. We thank Dr. Sang-Ki Lee and Dr. Chunzai Wang for sharing the model code and helping to run the model. This study was supported by the National Basic Research Program of China and the National Natural Science Foundation of China.

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Table 1. The heat forcing Q at each grid for Cases 1-6.

Exp.	Heat forcing in the SCS	Description
Case 1	$Q(i, j)=Q_0^*$	Uniform heating
Case 2	$Q(i, j)=Q_0 \cdot (25-lat(i, j))/12.5$	Heating less in the north
Case 3	$Q(i, j)=Q_0 \cdot ((25-lat(i, j))+(125-lon(i, j)))/25$	Similar to SST winter pattern
Case 4	$Q(i, j)=Q_0 \cdot ((12.5-lat(i, j))^2/10+lon(i, j)-100)/18.125$	Similar to SST summer pattern
Case 5	$Q(i, j)=Q_0 \cdot$ summer SST trends pattern/1.64	summer SST trends pattern
Case 6	$Q(i, j)=Q_0 \cdot$ winter SST trends pattern/2.04	winter SST trends pattern
		$^*Q_0=1.16\times10^{-2}$ W kg^{-1} (1 °C day^{-1})

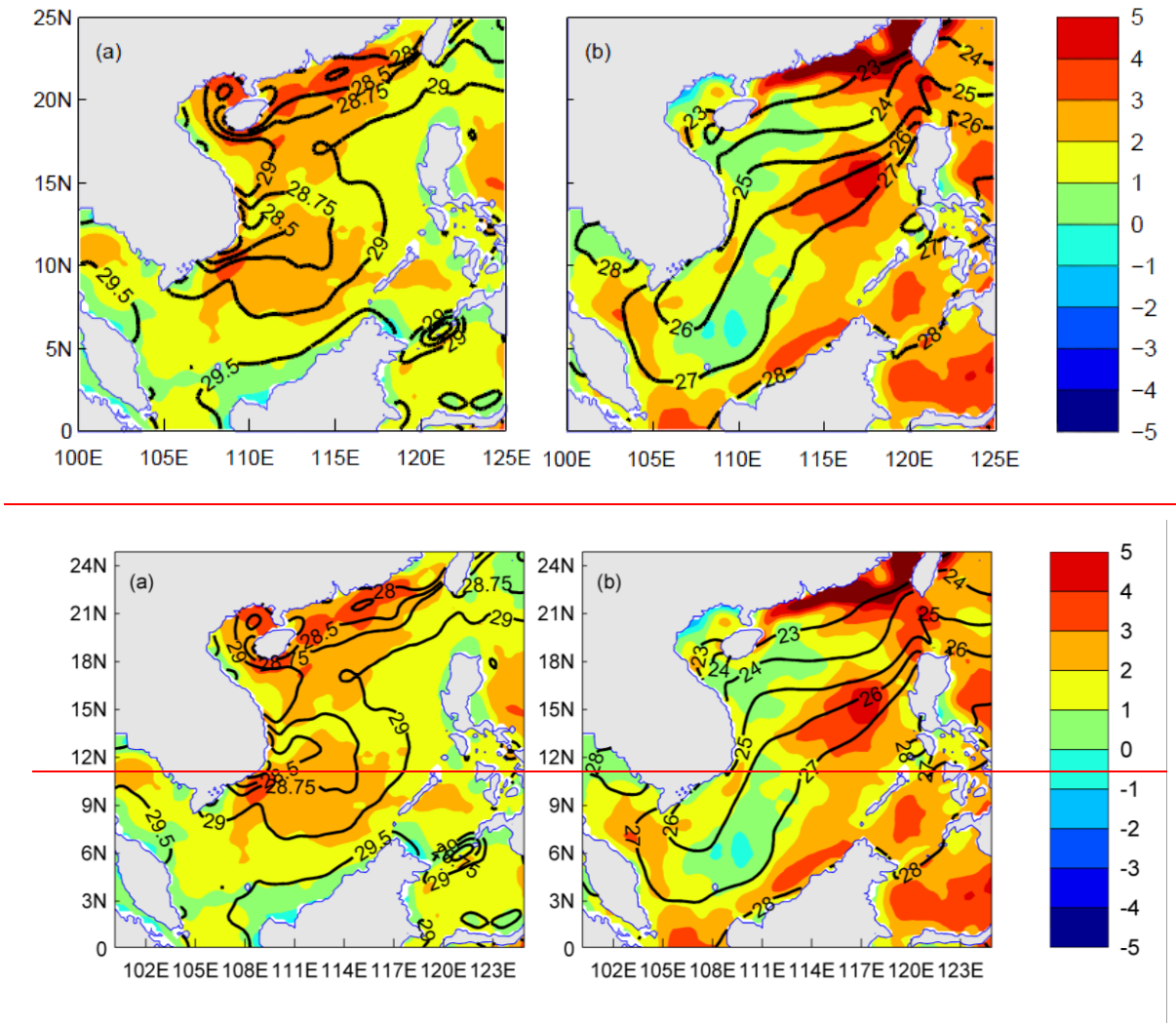

Figure 1. (**a**) Summer- and (**b**) winter-mean SST (contours; units: °C) and SST trends (color shading; units: °C100a^{-1}) in the SCS from 1982 to 2011.

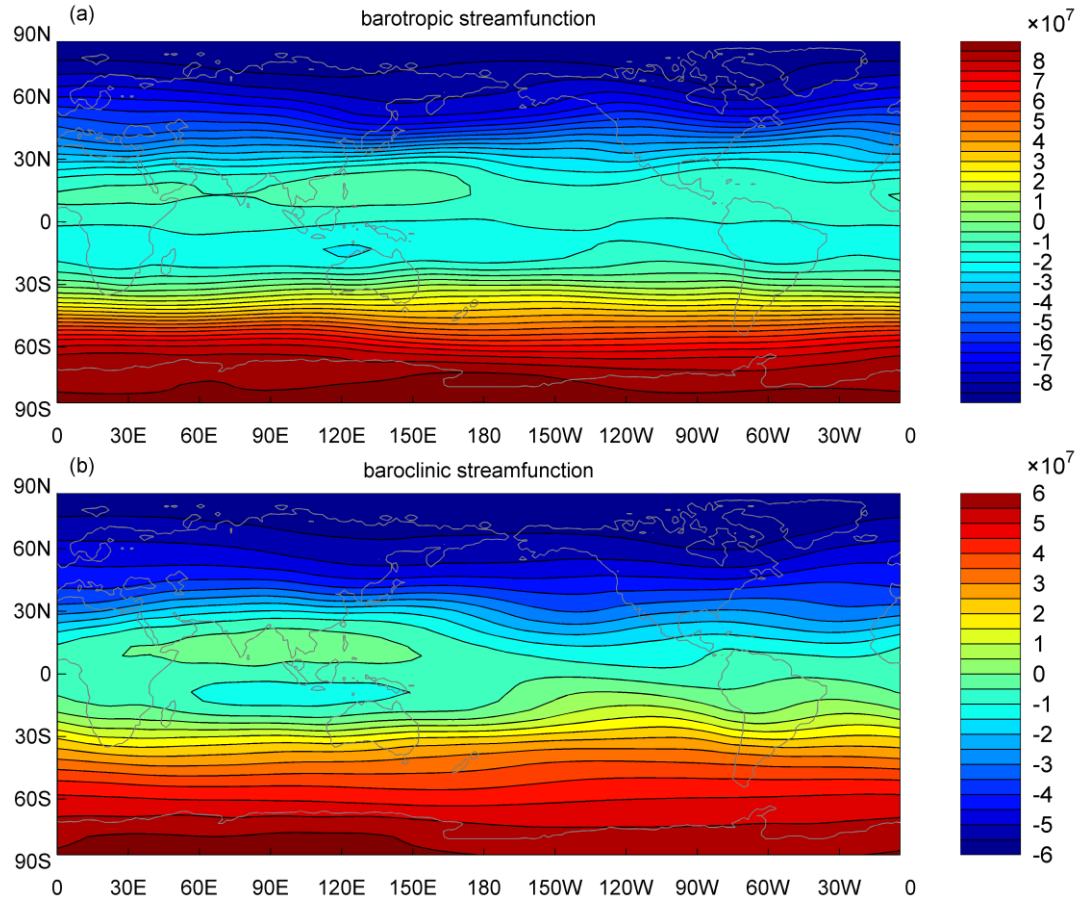

Figure 2. (**a**) Barotropic and (**b**) baroclinic stream functions in climatology. The contour interval is $5.0\times10^{6}\,m^{2}\,s^{-1}$.

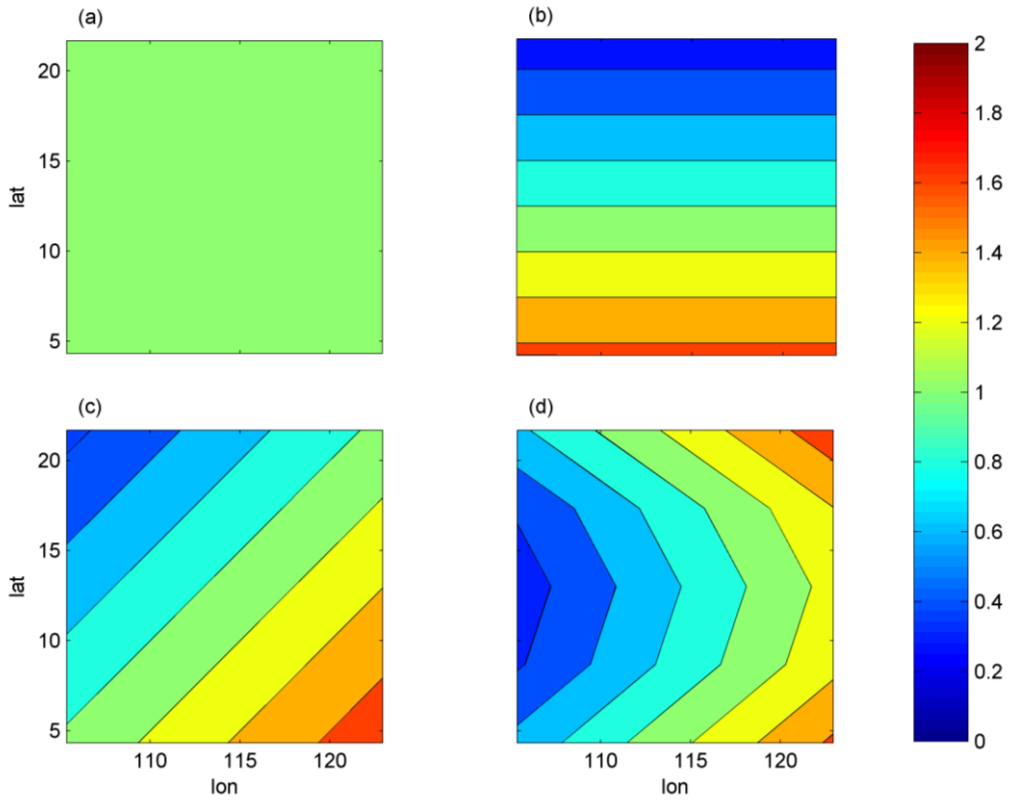

Figure 3. Spatial patterns of heat forcing Q for case 1-4 (**a-d**, units: Q_0).

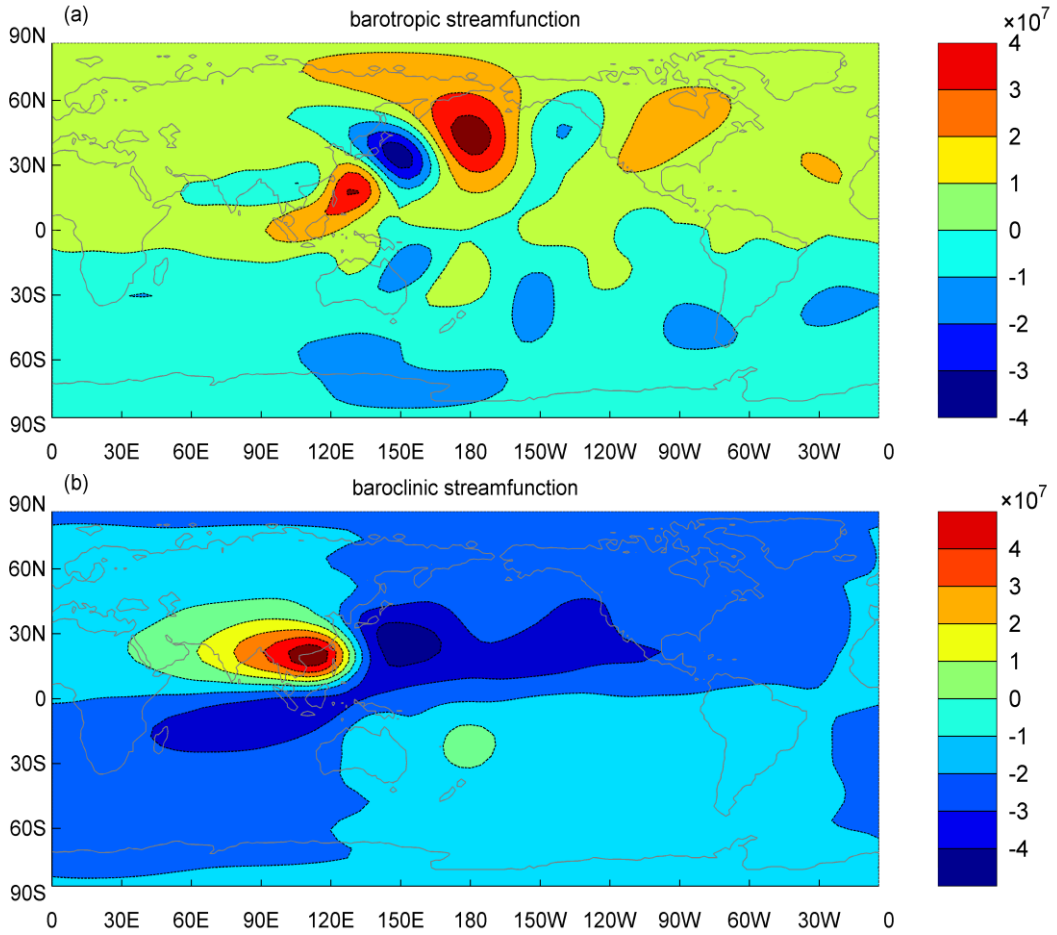

Figure 4. Barotropic (**a**) and baroclinic (**b**) stream function anomalies for Case 1. The contour interval is 1×10^6 m^2 s^{-1}.

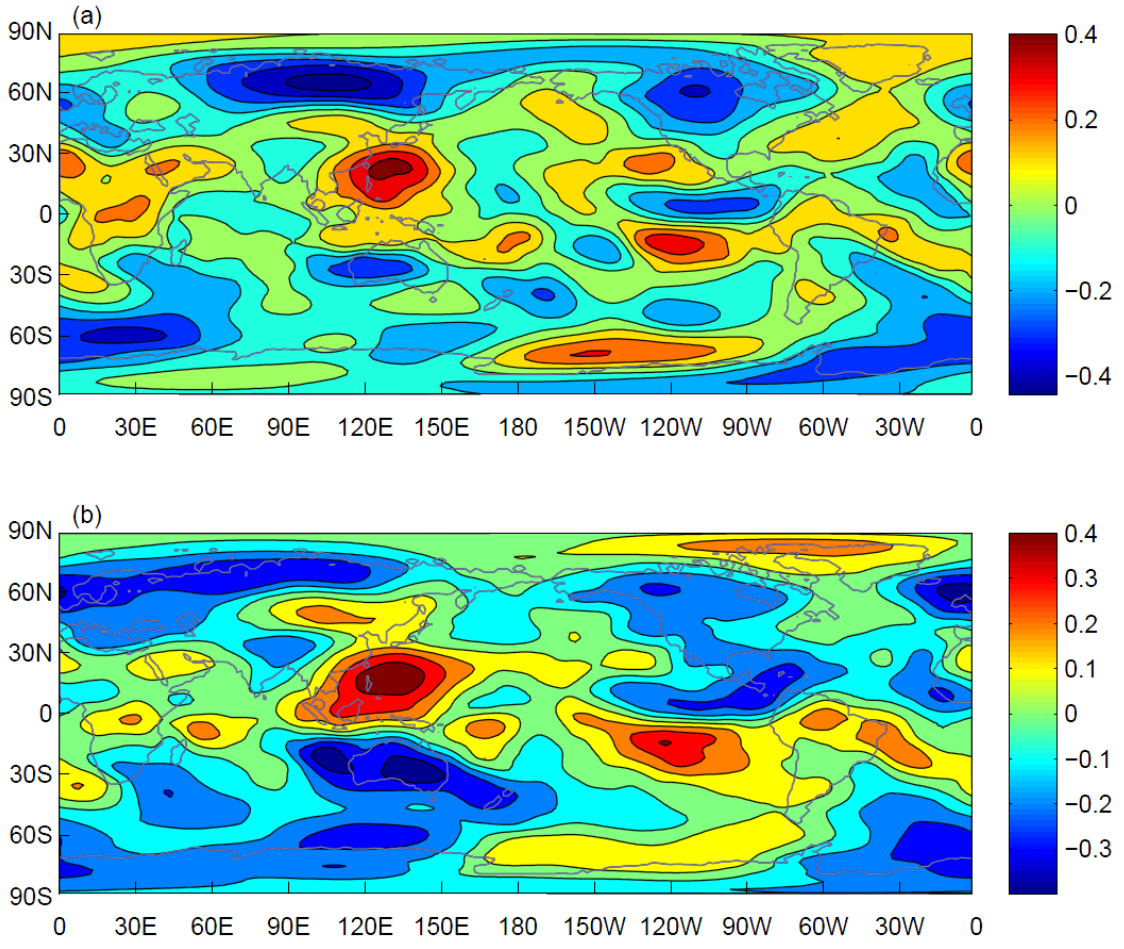

Figure 5. Lag correlation maps (lag day=15 day) of the northern SCS (12–23°N, 110–121°E) SSTA in the winter (October 2003 to March 2004) with global barotropic stream function (**a**) and baroclinic stream function (**b**).

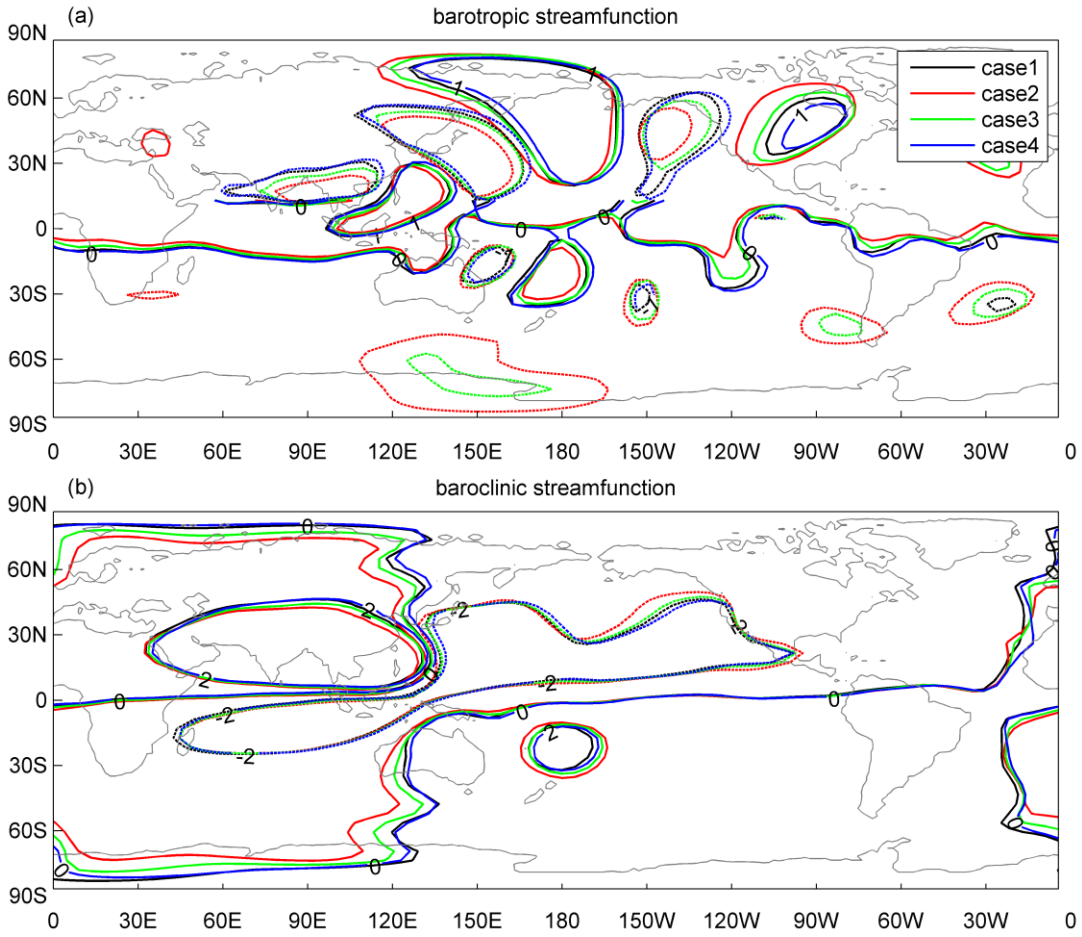

Figure ~~5~~6. (**a**) Barotropic and (**b**) baroclinic stream function anomalies (units: $10^6 m^2 s^{-1}$) for Cases 1-4 (the black, red, green, and blue contours are stream function anomalies for Cases 1, 2, 3, and 4, respectively). The contour interval is 2×10^6 m^2 s^{-1}.

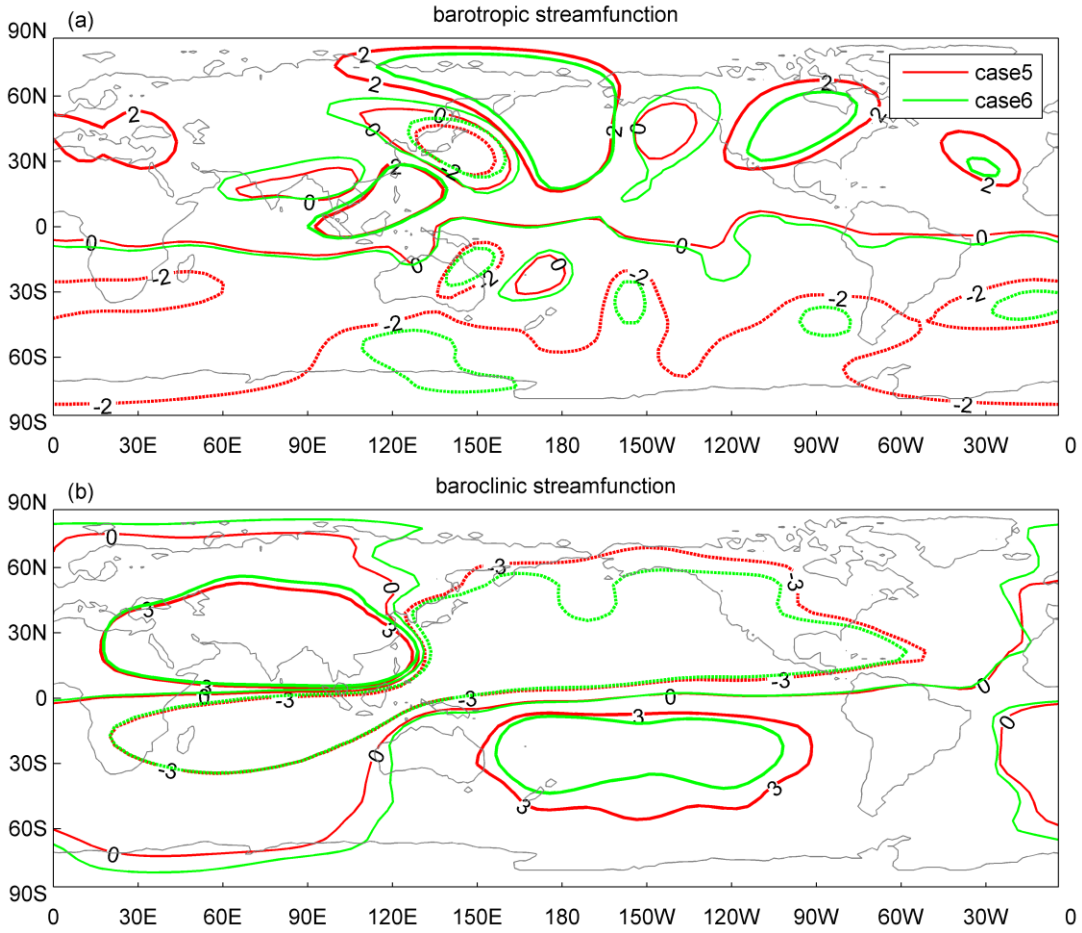

Figure ~~6~~7. (**a**) Barotropic and (**b**) baroclinic stream function anomalies (10^6 m^2 s^{-1}) for Cases 5 (red contours) and 6 (green contours). The contour interval is 2×10^6 m^2 s^{-1} in the top panel and 3×10^6 m^2 s^{-1} in the bottom panel.