Science in China Series D: Earth Sciences

© 2007 SCIENCE IN CHINA PRESS

Dynamical mechanism of the stratospheric quasi-biennial oscillation impact on the South China Sea Summer Monsoon

ZHENG Bin†, GU DeJun, LIN AiLan & LI ChunHui

Guangzhou Institute of Tropical and Marine Meteorology/Key Open Laboratory for Tropical Monsoon, China Meteorological Administration, Guangzhou 510080, China

The National Center for the Atmospheric Research (NCAR) middle atmospheric model is used to study the effects of the quasi-biennial oscillation in the stratosphere (QBO) on the tropopause and upper troposphere, and the relationship between the QBO and South China Sea Summer Monsoon (SCSSM) is explored through NCEP (the National Centers for Environmental Prediction)/NCAR, ECMWF (European Centre for Medium-Range Weather Forecasts) monthly mean wind data and *in situ* sounding data. The simulations show that the QBO-induced residual circulations propagate downwards, and affect the tropopause and upper troposphere during the periods of mid-late QBO phase and phase transition. Meanwhile, diagnostic analyses indicate that anomalous circulation similar to SCSSM circulation is generated to strengthen the SCSSM during the easterly phase and anomalous Hadley-like circulation weakens the SCSSM during the westerly. Though the QBO has effects on the SCSSM by meridional circulation, it is not a sole mechanism on the SCSSM TBO mode.

stratospheric quasi-biennial oscillation, South China Sea Summer Monsoon, tropospheric biennial oscillation

Monsoon, as a part of global climatic system, plays a greatly important role in climate change that has effects on our lives. Asian monsoon, the main member of monsoon system, influences the seasonal and interannual variability of the tropical atmospheric circulation, which are largely different during the strong and weak Asian monsoon years. The South China Sea Summer Monsoon (SCSSM) has direct effects on the climate of China and it is responsible for the distribution of precipitation, movement of rainfall band and disasters by drought and flood in China.

Biennial mode is a fundamental feature for the atmospheric circulation and interannual climatic variability. In the early 1980s, Mooley and Parthasarathy[1,2] revealed the biennial variability in the Indian summer monsoon rainfall by means of power spectrum analysis. To avoid confusion with the stratospheric quasi-biennial oscillation (QBO), it is named tropospheric biennial oscillation (TBO). Subsequently, Mukherjee et al.[3] found the biennial mode of the Indian monsoon rainfall and argued its relationship to the QBO. Moreover, Yasunari[4] pointed out that the monsoon-atmosphere-ocean system (MAOS) exists the biennial variability. Meanwhile, various studies have shown that the TBO is manifested over East Asia as well[5,6] and is a significant signal of rainy season over China[7−9]. Furthermore, both the precipitation and rainfall band over China have coherent links to the QBO[10,11]. The QBO in question is the steadiest oscillation in the atmosphere on the interannual time-scale by alternating easterly and westerly with a period around 2 years in the lower stratosphere. In the early 1960s, Reed et al.[12] found that the zonal wind in

Received January 17, 2007; accepted March 8, 2007
doi: 10.1007/s11430-007-0075-z
†Corresponding author (email: zbin@grmc.gov.cn)
Supported by the National Natural Science Foundation of China (Grant No. 40505019)

the tropical lower stratosphere is characterized by oscillating with a quasi-biennial period. Seven years after, the term of quasi-biennial oscillation (QBO) was used by Belmont and Dartt[13] in their work on the stratospheric biennial variablity. Driving force for the QBO was developed by Lindzen and Holton[14], Holton and Lindzen[15] as the upward-propagating planetary wave theory.

As well, several theories and hypothesizes have been proposed to explain the TBO. Yasunari[16] emphasized summer monsoon from the MAOS. Weak (strong) summer monsoon favors in the development of El Niño (La Niña) in the tropical Pacific and high (low) index in the middle latitudes by wave forcing, and corresponding suppressed (enhanced) winter monsoon and decreased (increased) Eurasian snow-cover would result in strong (weak) summer monsoon in following summer. Reversely, Li et al.[17] focused on winter monsoon and its interaction with El Niño-Southern Oscillation (ENSO) to study the TBO in the East Asian monsoon. Persistent strong (weak) East Asian winter monsoon excites El Niño (La Niña) by air-sea interaction, then through teleconnection, El Niño (La Niña) would lead to a weak (strong) East Asian winter monsoon. Chang and Li's theory indicates that the TBO is an inherent result of the interactions between northern summer and winter monsoon and the tropical Indian and Pacific Oceans[18]. Thus, it is an important component of the tropical ocean-atmosphere interaction system, separate from the ENSO. Recently, Yu et al.[19] have done three experiments by a coupled atmosphere-ocean general circulation model (CGCM). The results showed that the in-phase TBO transition from a strong (weak) Indian summer monsoon to a strong (weak) Australian summer monsoon occurs more often in the CGCM experiments that include an interactive Pacific Ocean. The out-of-phase TBO transition from a strong (weak) Australian summer monsoon to a weak (strong) Indian summer monsoon occurs more often in the CGCM experiments that include an interactive Indian Ocean. Loschnigg et al.[20] simulated the TBO by using the NCAR (the National Center for the Atmospheric Research) climate system model, and the results showed that the coupled ocean-atmosphere dynamics and cross-equatorial heat transport contribute to the interannual variability and biennial nature of the ENSO-monsoon system, by affecting the heat content of the Indian Ocean and resulting SST anomalies over multiple seasons, which is a key factor in the TBO.

These so many studies confirmed that the air-sea-land interaction plays an important role in the TBO. In an entirely different mechanism, TBO is, at least partly, considered as the result of the forcing from the QBO in the lower stratosphere, though it is unclear that in which way the stratospheric QBO drives the TBO in the South China Sea summer monsoon (SCSSM). Both the results of numerical simulations by a middle atmosphere model (introduced in section 1) and reanalysis products are used in this paper to explore the effects of the stratospheric QBO on the SCSSM TBO. The primary data used for this study are from the National Centers for Environmental Prediction (NCEP)/NCAR reanalysis, European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 and in situ sounding. The monthly mean data (both NCEP and ECMWF reanalysis) have a horizontal resolution of 2.5º latitude by 2.5º longitude and 12 pressure levels vertically.

1 Effects of stratospheric QBO on tropical circulation

In general, the tropospheric meridional circulation can be divided into three cells, namely Hadley cell in the low latitudes, Ferrel cell in the middle latitudes and polar cell. The cells are broken in the SCSSM region due to the summer monsoon meridional circulation. Liang et al.[21] considered that meridional wind is important to the SCSSM as well as zonal wind and the SCSSM index should include both zonal and meridional winds. The SCSSM meridional circulation develops over the Arabian Sea and moves into the South China Sea (SCS) in May[22]. Since the summer monsoon circulation replaces the Hadley cell over the SCS and South China during the SCSSM, Wang and Ding[23] signed the establishment of meridional monsoon circulation over East Asia as onset of the SCSSM. Figure 1 shows seasonal evolution of northern meridional circulation along 115ºE. It is showed in the Figure 1 that Hadley cell is greatly weakened in March and April and the summer monsoon circulation establishes in the tropics and low latitudes while winter monsoon circulation is still active in the middle latitudes in May. As summer (June—August) comes, the summer monsoon circulation becomes dominant and the winter monsoon circulation fades away. Again active the winter monsoon becomes in September when the summer monsoon begins to withdraw and its dominant region reduces as well. In the

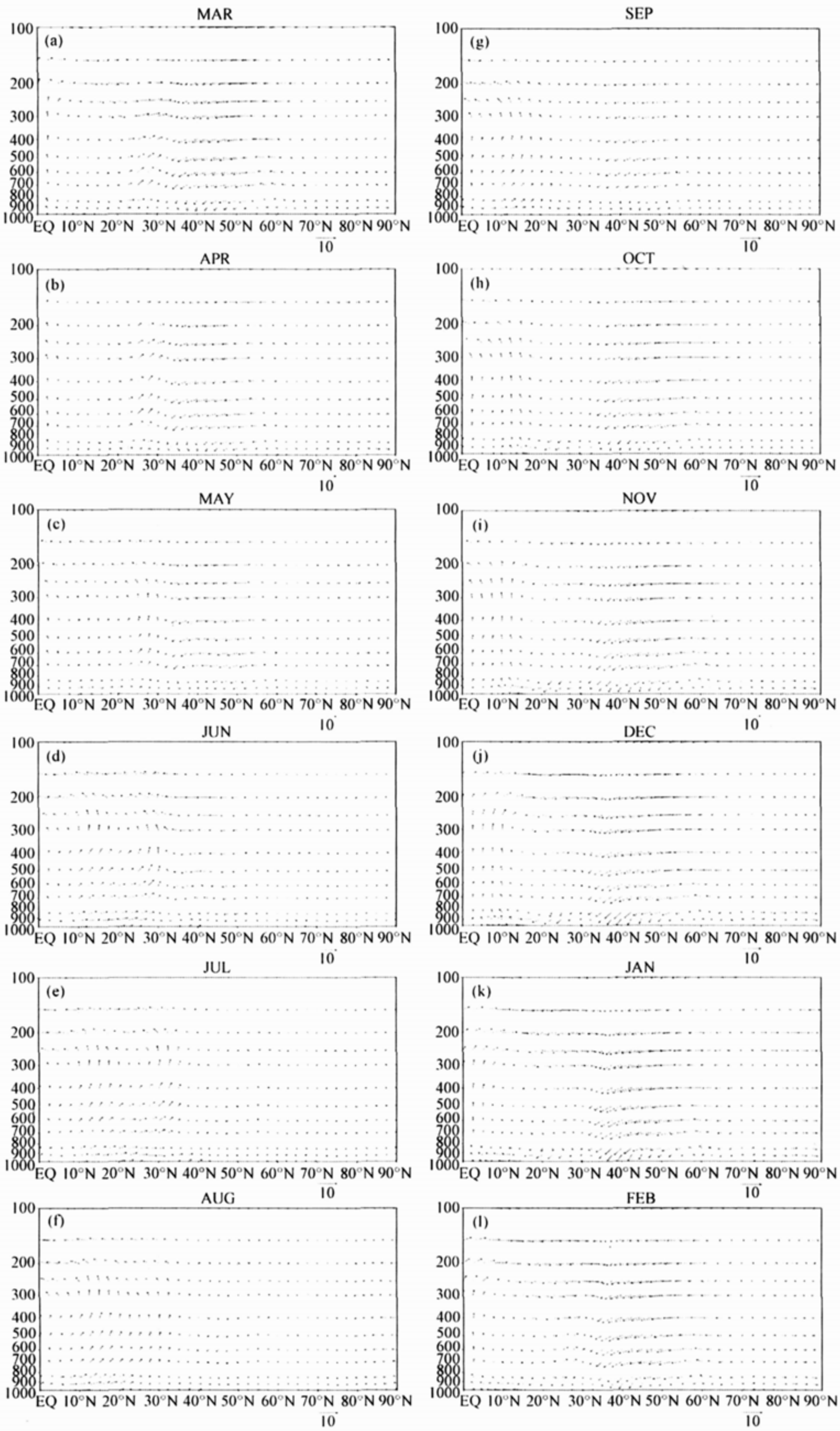

Figure 1 Climatological meridional circulation in the Northern Hemisphere along 115ºE (vertical axis is pressure height with unit of hPa. Vertical pressure velocity is amplified by 50 times).

mid-late fall, while weakening of the summer monsoon, the Hadley cell is established again. The cells in the tropics and low latitudes are maintained to the succeeding winter (December—February) when the winter monsoon comes to power in the middle latitudes.

Figure 1 shows that the SCSSM circulation is a system full of the tropospheric height. Since that, the SCSSM is not only affected by underlying surface conditions (land surface or ocean) but also modified by the stratospheric situation. The strongest and steadiest signal is the QBO in the stratosphere. Gray et al.[24] pointed out that the stratospheric QBO can influence the tropopause and even the troposphere by the zonal wind shear. During the period of easterly shear in the lower stratosphere, there is anomalous ascending flows and raised pressure surface in the equatorial upper troposphere. Reversely, the anomalous descending flow and lower height of pressure surface during the westerly shear. Li and Long[25] had studied the effects of the stratospheric QBO on the western Pacific high by using IAP-GCM. Following the result of Gray et al.[24], the height anomalies at 200 hPa in the selected region were put into the model to represent the stratospheric QBO since the model excludes the stratosphere. The simulation results showed that the stratospheric QBO can affect the western Pacific high by induced pressure anomalies in the upper troposphere. Although that, the anomalous pressure and vertical flows in the upper troposphere induced by the stratospheric QBO were given rather than simulated in the model.

A NCAR interactive chemical dynamical radiative two-dimensional model (SOCRATES) was used in this paper. The QBO forcing (Figure 2) was put into the model to simulate the associated residual circulation. Chen et al.[26] had explained the subtropical ozone QBO by the residual circulation and had noticed that the cells propagate downwards as shown in Figure 3. The detailed model description and experiment design were referred in [26]. The effects of residual circulation on the transport of ozone were emphasized in [26], while the effects on the troposphere were not considered for it is beyond its scope.

In general, the zonal wind at 30 hPa (about 25 km) can represent the QBO wind shear very well. It can be seen from Figures 2 and 3 that there are anomalous equatorial descending flows and subtropical ascending flows in the stratosphere during the mid-early period of

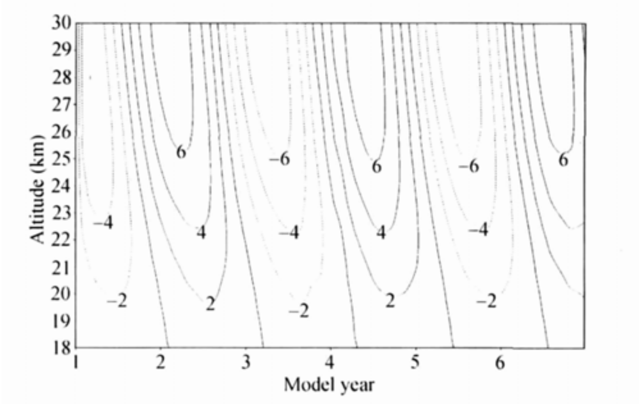

Figure 2 The equatorial zonal wind QBO forcing put into the model (m/s).

westerly (the greatest and smallest zonal wind at 25 km altitude represents the mid-period of westerly and easterly, respectively. Zero zonal wind the phase transition). The residual circulation does not affect the troposphere until October (mid-late period of westerly) when the tropical tropopause is obviously influenced by anomalous descending flows. As well in January of the fifth model year (late westerly phase), the residual circulation moves downwards to affect the tropopause and the upper troposphere except for the weak subtropical vertical flows. Moreover, the opposite circulation follows the underlying cell and can be well seen at that time. During the period of phase transition (westerly to easterly in April of the fifth model year), the opposite circulation still is located in the stratosphere although it has propagated downwards somewhat, the descending flows in the upper troposphere have weakened. In July of the fifth model year (early easterly phase), the opposite circulation moves downwards to the lower stratosphere and the underlying circulation almost disappears since it has transform into another type of anomaly in the upper troposphere. The half cycle for westerly phase so finishes and follows by another half cycle for easterly phase with opposite cells. As shown in Figure 3, the residual circulation evolves as a QBO period. The locations of residual circulation during various periods of westerly phase have been listed in Table 1.

The simulated results indicate that the stratospheric QBO affects the troposphere mainly in the periods of mid-late phase and phase transition. From the mid-period of westerly to the transition of westerly to easterly, there are anomalous descending flows in the tropical tropopause and upper troposphere and anomalous

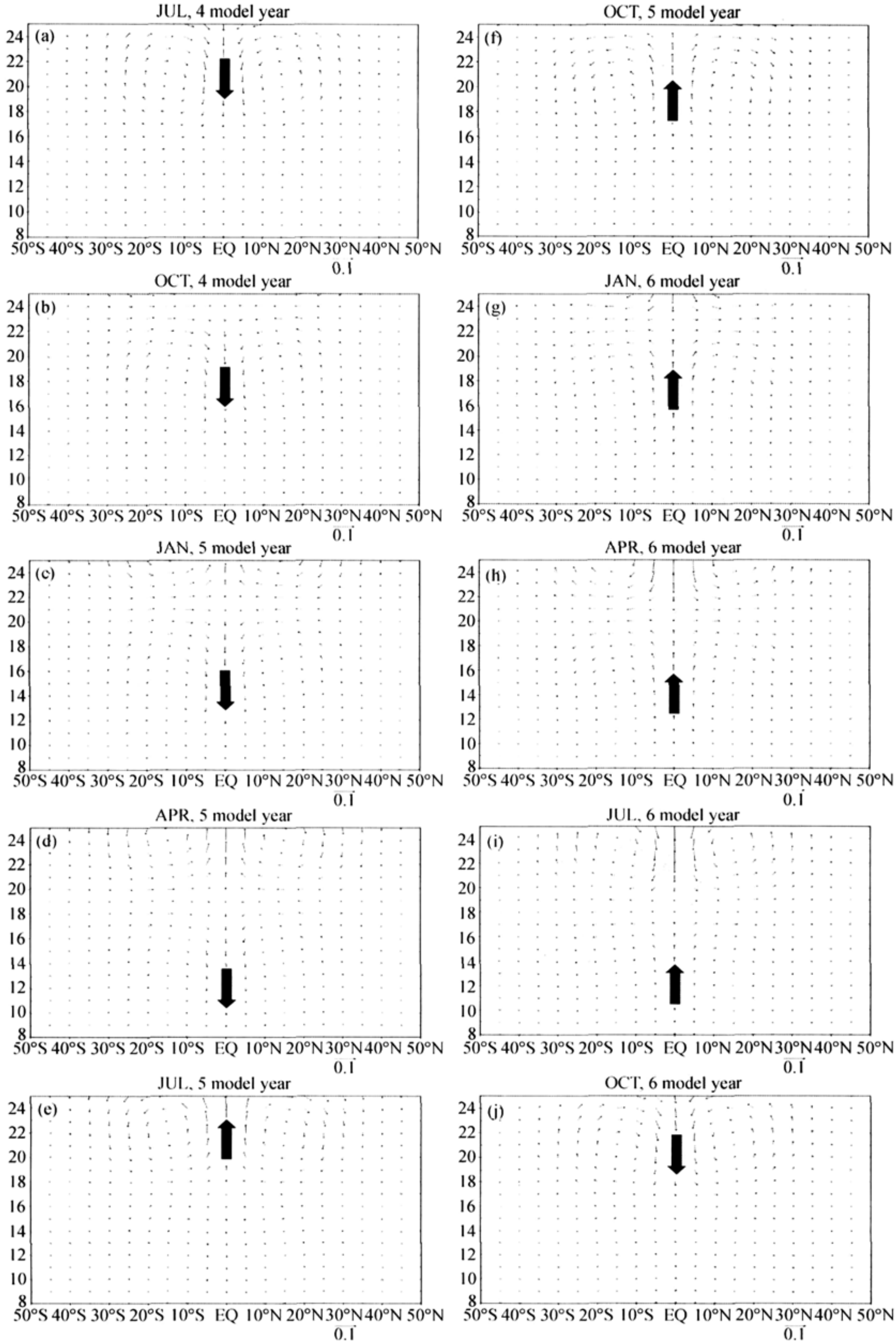

Figure 3 The simulated anomalous circulation induced by the QBO. The residual circulations are shown from July of the fourth model year to October of the sixth model year by every three months. Vertical axis is altitude height with unit of km. Vectors denote the anomalous winds with unit of m/s and vertical velocity is amplified by 500 times.

Table 1 One phase of residual circulation (another phase with opposite residual circulation)

QBO phase	Location of residual circulation
Mid-early period of westerly	Anomalous equatorial descending flows and subtropical ascending flows in the lower stratosphere.
Mid-late period of westerly	The residual circulation propagates downwards and affects the tropopause.
Later period of westerly	The residual circulation continues moving downwards to affect the tropopause and upper troposphere; opposite circulation appears in the middle stratosphere and propagates downwards.
Transition from westerly to easterly	The opposite circulation continues moving downwards but still in the stratosphere; the former circulation keeps on affecting the tropopause and upper troposphere.
Early period of easterly	The opposite circulation still propagates downwards in the stratosphere; the former circulation die out.
Mid-early period of easterly	The opposite circulation appears in the lower stratosphere.

ascending flows from the mid-period of easterly to the transition of easterly to westerly that imply the stratospheric QBO does not affect troposphere in all time.

2 Effects of stratospheric QBO on SCSSM

The SOCRATES model, as a middle atmospheric model, emphasizes the dynamical processes above the troposphere, so the tropospheric processes need other diagnoses for the reanalysis data.

Figure 4 shows the zonal winds in the low stratosphere evolved from 1987 to 2001 with the NCAR/NCAR reanalysis and Singapore sounding data. In order to compare to the Singapore sounding data (located in ~1ºN, 104ºE), the grid of 0º, 105ºE is selected for NCAR/NCEP reanalysis data. Figure 4 shows that the reanalysis data are very close to the observations and the phases are consistent completely. The years when the periods SCSSM prevailing (June—August) meet the mid-late period of westerly and phase transition from westerly to easterly have 1989, 1991, 1994, 1996, 1998 and 2000. While the years with the mid-late period of easterly and phase transition from easterly to westerly have 1987, 1990, 1992 and 2001.

The stratospheric dynamical processes first influence the upper troposphere before affecting the lower troposphere. The anomalous tropical vertical flows shown in Figure 3 cause anomalous divergence leading to pressure or height anomalies. Figure 5 shows meridional gradient anomalies of potential height at 100 hPa during various QBO phase (∂h′/∂y, negative values in the Southern Hemisphere and positive anomalies denote equator-ward gradient forces.), composites by the years given above. It can be seen from Figure 5 that there are equator-ward gradient forces in the upper troposphere during westerly phase (solid line) and polar-ward gradient forces during easterly phase (dash line). It is noticeable that the height gradients between 0º and 8ºN, despite small magnitudes, have opposite sign to those in the north of 10ºN. While westerly (easterly), equator (polar)-ward gradient forces drive an anomalous convergence (divergence) in the upper troposphere, which leads to anomalous descending (ascending) flows in the middle troposphere, finally it causes an anomalous divergence (convergence) in the lower troposphere.

Figure 6, composited by the years given above, shows the anomalies of equatorial stratospheric vertical flows and June—August mean tropospheric circulation associated with the stratospheric QBO. Just consider the anomalous vertical flows because of not only the much weaker horizontal residual flows shown in Figure 3 but

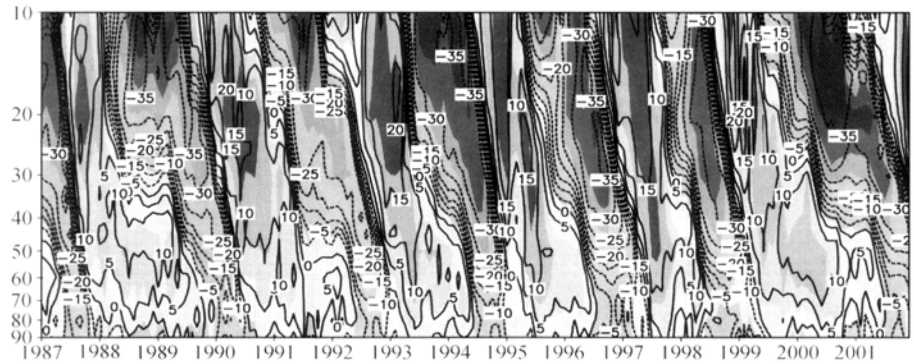

Figure 4 The time-pressure cross section for the equatorial zonal winds. m/s: shaded area for NCEP/NCAR reanalysis data at point of 0º, 105ºE; the contours for Singapore sounding data at ~1ºN, 104ºE.

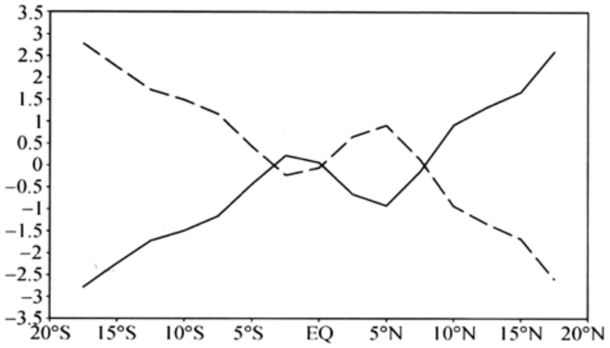

Figure 5 June—August mean height gradient anomalies along 105ºE during westerly phase (solid line) and easterly phase (dash line) (10^{-3} gpm/km).

also the rough vertical resolution to the ERA-40 data (only 70, 50, 30 and 20 hPa in the low stratosphere). It can be seen from Figure 6(a) that there are anomalous descending flows in the lower stratosphere in January (westerly phase, see the solid line left in Figure 6(a). Positive values denote anomalous ascending flows.), and there are anomalous ascending flows above it with the maximum at around 30 hPa, which agree with Figure 3(c). There are much weaker anomalous vertical flows in the lower stratosphere and enhanced ascending flows above it in July, as shown right in Figure 6(a) that is in general similar to Figure 3(e) except for the location of the maximum value likely due to the rough data resolution. There are opposite signs on the easterly phase to those of westerly (see the dash line in Figure 6(a)). The anomalous vertical flows associated with QBO propagate downwards and are weakened and are transformed into another type of anomalies. As indicated by Figure 5, the stratospheric velocity anomalies cause pressure (height) anomalies in the upper troposphere through adiabatic process, then leading to velocity anomalies in the troposphere. Equator-ward anomalous flows in the upper troposphere on the westerly phase are shown clearly in Figure 6(b) that corresponds to the anomalous pressure gradient force in Figure 5. The anomalous convergence accumulates air mass that goes down and induces anomalous divergence in the lower troposphere. So an anomalous anti-Hadley circulation is formed over the north of 10ºN and opposite to the south one, which is strictly consistent with the height gradient in Figure 5. Contrary to that on westerly phase, there are obvious polar-ward anomalous flows in the upper troposphere and equator-ward anomalous velocities in the lower troposphere on easterly phase. Then Hadley-like circulation is formed over the north of 10ºN and is opposite to the south one as well.

Vertical flows change their signs in 15ºN around in Figure 6(b) so that the south anomalous circulation is almost contrary to the SCSSM circulation on the westerly phase, which suppresses the SCSSM since its meridional component play an almost same role as zonal one, and anomalous circulation on easterly phase is nearly the same as the SCSSM and so enhances it. It is undoubted that the stratospheric QBO would affect the SCSSM. Whereas, due to uncertainty of the QBO period (quasi-period) as shown in Figure 4, not all the mid-late period of QBO phase would meet summer (June—August). Moreover, the zonal component of the SCSSM is important as well. Both of them determine that the stratospheric QBO is not a sole factor for the SCSSM TBO.

The effects of the stratospheric QBO on the troposphere are shown in Figure 7. Firstly, the residual cir-

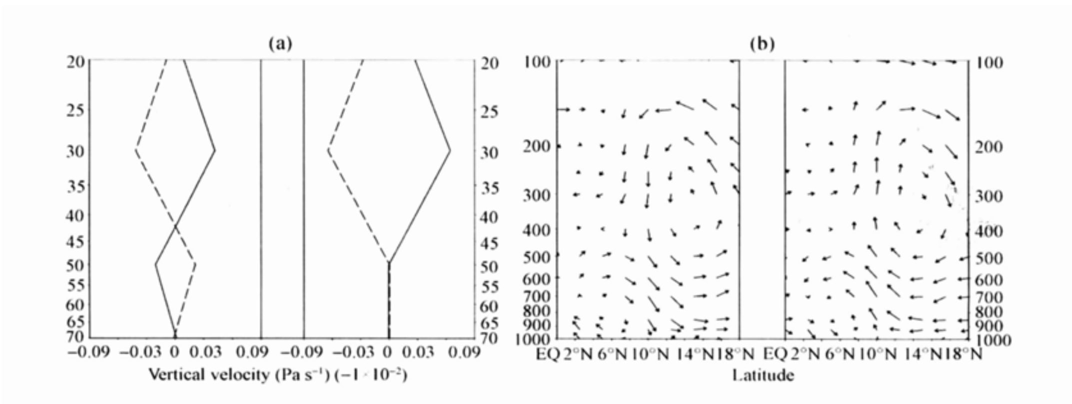

Figure 6 (a) Stratospheric vertical velocity anomalies above equatorial 105ºE in January (left) and in July (right), (solid line denotes the anomalies on westerly and dash line on easterly); (b) June—August mean anomalous tropical circulation along 105ºE on the westerly phase (left) and easterly phase (right). Vertical axis is pressure surface with unit of hPa.

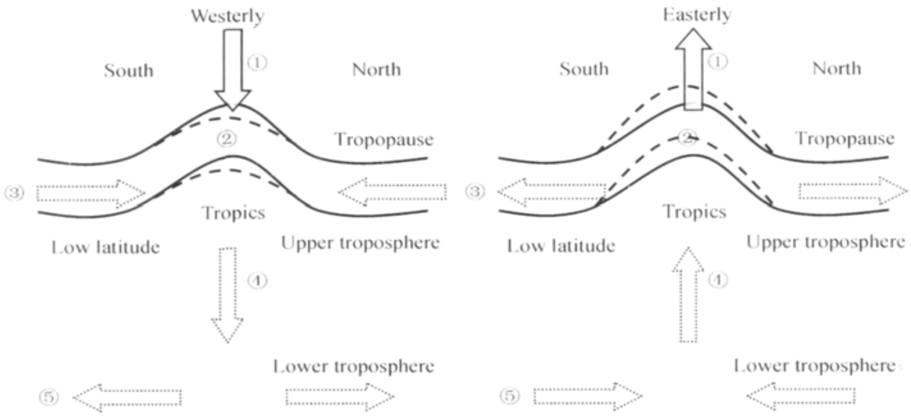

Figure 7 Sketch for the processes of the stratospheric QBO influencing the troposphere. ① QBO-induced anomalous vertical flows in the lower stratosphere; ② height or pressure anomalies in the upper troposphere; ③ anomalous convergence and divergence; ④ anomalous vertical flows in the middle troposphere; ⑤ anomalous divergence and convergence in the lower troposphere.

culation associated with the stratospheric QBO propagates downwards. The anomalous descending (ascending) flows come to the lower stratosphere on the westerly (easterly) phase and induce lower (higher) pressure in the tropopause and upper troposphere, which causes the anomalous convergence (divergence). And then the anomalous convergence (divergence) leads to anomalous descending (ascending) flows in the middle troposphere that force an anomalous divergence (convergence) in the lower troposphere. Finally, the anomalous circulation in the tropical troposphere is generated. Figure 7 is a sketch for common situation, namely is appropriate to the condition no matter what time the mid-late periods of the QBO phase meet. For summer, the anomalous circulation is made a departure from the equator to the Northern Hemisphere.

3 Summaries and discussion

The processes of the stratospheric QBO on the tropopause and upper troposphere are simulated by the NCAR SOCRATES model. And then with the NCEP and ERA-40 reanalysis data and observational sounding data, the effects of the stratospheric QBO on the SCSSM are studied and the results are summarized as follows:

(1) The QBO-induced residual circulation propagates downwards and affects the tropopause and upper troposphere during the mid-late periods and transition of QBO phase. While on the mid-late westerly phase and transition from westerly to easterly, there are anomalous descending flows influencing the tropopause and upper troposphere; while on the mid-late easterly phase and transition from easterly to westerly, anomalous ascending flows play its role; the early phase of QBO is transition for the anomalous vertical flows when the QBO has rare effects on the troposphere.

(2) While the SCSSM prevails, the anomalous circulation contrary to the SCSSM is excited and causes vigorous descending flows over the SCS to suppress it on the westerly phase, so there is a relatively weak SCSSM in the current year. While on the easterly phase, the anomalous circulation similar to the SCSSM is driven in the tropical troposphere and leads significant ascending flows over the SCS to enhance it, so there is a strong SCSSM year. That is the mechanism for the SCSSM TBO by the stratospheric QBO.

Though the results confirm the effects of the stratospheric QBO on the SCSSM, the quasi-period of the QBO and importance of zonal circulation of the SCSSM determine that it is not a sole factor for the SCSSM TBO. TBO mechanism is developing[27], and this paper just gives a possible cause of the SCSSM TBO by emphasizing the stratospheric QBO. Furthermore, Figures 5 and 6(b) show an equatorial asymmetry against the symmetry of the QBO that may relate to thermal and dynamical conditions in summer, but detailed interactive processes are unclear.

We would like to express our thanks to NOAA-CIRES CDC (http://www.cdc.noaa.gov/) for NCEP/NCAR reanalysis and ECMWF (http://data.ecmwf.int/) for ERA-40 reanalysis and to NCAR for the SOCRATES model.

1 Mooley D.A, Parthasarathy B. Variability of the Indian summer monsoon and tropical circulation features. Mon Wea Rev, 1983, 111(7): 967－978
2 Mooley D A, Parthasarathy B. Indian summer monsoon and the east equatorial Pacific sea surface temperature. Atmosphere-Ocean, 1984, 22: 23－35
3 Mukherjee B K, Indira K, Reddy R S, et al. Quasi-biennial oscillation in stratospheric zonal wind and Indian summer monsoon. Mon Wea Rev, 1985, 113(9): 1421－1424
4 Yasunari T. The monsoon year—A new concept of the climate year in the tropics. Bull Amer Meteor Soc, 1991, 72(9): 1331－1338
5 Xu J J, Zhu Q G, Shi N. The singular spectral analysis of periodic oscillation in long-term variation of East-Asian monsoon in recent century. Acta Meteorol Sin (in Chinese), 1997, 55(5): 620－627
6 Xu J J, Zhu Q G, Zhou T H. Sudden and periodic changes of East Asian winter monsoon in the past century. Quart J Appl Meteorol (in Chinese), 1999, 10(1): 1－8
7 Zhao H G. A preliminary study of the characteristics of the precipitation oscillation in China. Chin J Atmos Sci (in Chinese), 1986, 10(4): 426－430
8 Huang J Y. The spatial and temporal analysis of the representations of the quasi-biennial oscillation in precipitation over China. Chin J Atmos Sci (in Chinese), 1988, 12(3): 267－273
9 Zhu Q G, Zhi X F. Quasi-biennial oscillation in rainfall over China. J Nanjing Institute of Meteorology (in Chinese), 1991, 14(3): 261－267
10 Liao Q S, Wang Y G. The relationship between quasi-biennial oscillation (QBO) of equatorial stratosphere and the rainfall belt of July in China. Quart J Appl Meteor (in Chinese), 1998, 9(1): 104－108
11 Liang P D. The relationship between the stratospheric QBO and rainfall over North China. In: Zhang J eds. Long Range Weather Forecast. Beijing: China Ocean Press, 1992. 151－155
12 Reed R J, Campbell W J, Rasmussen L A, et al. Evidence of the downward-propagating annual wind reversal in the equatorial stratosphere. J Geophys Res, 1961, 66(6): 813－818
13 Belmont A D, Dartt D G. Variation with longitude of the quasi-biennial oscillation. Mon Wea Rev, 1968, 96(5): 767－777
14 Lindzen R S, Holton J R. A theory of the quasi-biennial oscillation. J Atmos Sci, 1968, 25(9): 1095－1107
15 Holton J R, Lindzen R S. An updated theory for the quasi-biennial cycle of the tropical stratosphere. J Atmos Sci, 1972, 29(8): 1076－1080
16 Yasunari T. Global teleconnections associated with Indian monsoon and ENSO. Meteor Res Report, University of Tokyo, 1988, 1: 30－38
17 Li C, Sun S, Mu M. Origin of the TBO——Interaction between anomalous East-Asian winter monsoon and ENSO cycle. Adv Atmos Sci, 2001, 18(4): 554－566
18 Chang C P, Li T. A theory for the tropical tropospheric biennial oscillation. J Atmos Sci, 2000, 57(14): 2209–2224
19 Yu J Y, Weng S P, Farrara J D. Ocean roles in the TBO transitions of the Indian–Australian monsoon system. J Climate, 2003, 16(18): 3072–3080
20 Loschnigg J, Meehl G A, Webster P J, et al. The Asian monsoon, the tropospheric biennial oscillation, and the Indian Ocean zonal mode in the NCAR CSM. J Climate, 2003, 16(11): 1617－1642
21 Liang J Y, Wu S S, You J P. The research on variations of onset time of the SCS summer monsoon and its intensity. J Tropical Meteorol (in Chinese), 1999, 15(2): 97－105
22 Jiang J, Qian Y P. Tropical circulation evolution and the onset of the South China Sea monsoon. J Nanjing Institute of Meteorology (in Chinese), 2001, 24(1): 83－91
23 Wang Q, Ding Y H. Climatological aspects of evolution of summer monsoon over the northern South China Sea. Acta Meteorol Sin (in Chinese), 1997, 55(4): 466－483
24 Gray W M, Sheafer J D, Knaff J A. Influence of the stratospheric QBO on ENSO variability. J Meteor Soc Japan, 1992, 70(5): 975－994
25 Li C Y, Long Z X. Study on Subtropical High Activity over the Western Pacific and QBO in the Stratosphere. Chin J Atmos Sci (in Chinese), 1997, 21(6): 670－678
26 Chen Y, Zheng B, Zhang H. The features of ozone quasi-biennial oscillation in tropical stratosphere and its numerical simulation. Adv Atmos Sci, 2002, 19(5): 777－793
27 Zheng B, Liang J Y. Advance in studies of tropospheric biennial oscillation. J Tropical Meteorol, 2005, 11(1): 1－9