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STRUCTURE OF SOUTH ASIA HIGH IN THE STRATOSPHERE AND INFLUENCE OF ENSO

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Abstract: The structure of the South Asia High (SAH) in the stratosphere and the influence of ENSO on the SAH are systematically investigated with the long-term ECMWF reanalysis data. The results show that the SAH only exists in low levels of the stratosphere. The maximum intensity of the High is located at around 150 hPa and there is no obvious anti-cyclonic structure above 50 hPa. The axis of the SAH center tends to be northwest slanting from lower levels to higher levels. Further analyses show that the geopotential height and temperature fields of the SAH have dramatic anomalies during El Niño years and La Niña years. Corresponding to the ENSO, the SAH is weaker (stronger) at the warm (cold) phase.

Key words: SAH; structure feature; ENSO influence

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1 INTRODUCTION

South Asia high (SAH) is a large anti-cyclonic system in the upper troposphere and lower stratosphere above Tibetan Plateau (to be referred to as “the plateau” hereafter) during summertime. It is the strongest and steadiest weather/climate system in the tropical and subtropical parts of of the Northern Hemisphere.

According to "International Geophysical Year" data for 1957–1958, Mason et al.[1] first studied a southern Asia anticyclone at 100 hPa in summer and found that the anticyclone is a relatively stable system. Later, Tao et al.[2, 3] indicated that the anticyclone in South Asia tends to oscillate around its average position in summer, which is closely related to the westward advancement and eastward retreatment of the West Pacific subtropical high. Meanwhile, they pointed out that when the South Asian anticyclone’s centre oscillates, the weather in low altitudes will change correspondingly, which demonstrated the close relationship between the South Asia anticyclone and weather/climate change in Southeast Asia.

Furthermore, Zhu et al.[4] formally named the South Asian anticyclone as the SAH and depicted the basic features and variation of the SAH as well as the connection between the SAH and middle- and lower-tropospheric circulation. The relationship between the SAH and the weather/climate change, including precipitation in Northwest China[5], summer precipitation in North China[6], and climate change in other regions in summer, were revealed by subsequent studies[7, 8].

An important viewpoint on SAH and its activities needs to be noted here. Tao et al.[2] found that when the South Asian anticyclone shifts eastward and weakens, there will be "an establishment of a new anticyclone above the Caspian sea" in general. He believed that it may be related to the mid-latitude westerly disturbance activities. Zhang et al.[7] further suggested that SAH has two basic interchangeable modes, which has an impact on climate.

The thermal forcing of the plateau is considered as the natural mechanism of the formation of SAH in summer. Recent analysis shows that not only the sensible heating is a plateau thermal source, but also the latent heating is important. Especially in the summer, the latent heating plays a more important role[9, 10]. Furthermore, the dynamics researches reveal the mechanism of sensible heating and latent heating of the plateau [11, 12].

Nevertheless, many issues about the SAH remain unclear, such as the SAH structure, especially the vertical structure, in the stratosphere, and the El Niño

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and Southern Oscillations (ENSO) impact on its variation. To statistically analyze the above issues, we used the European Centre for Medium-Range Forecast (ECMWF) reanalysis dataset to conduct an intensive analysis of the SAH features in the stratosphere.

2 DATA AND METHODS

The data used in this study are the ECMWF reanalysis data (ERA-40) from September 1957 to August 2002. This dataset has a 2.5° × 2.5° horizontal resolution and extends from 1000 hPa to 1 hPa with 23 pressure layers in the vertical direction. Because the strongest phase of the SAH is in summer, our research focuses on summer (from June to August). For studying the impact of ENSO on SAH, we employed the United Kingdom Hadley Centre's monthly mean sea surface temperature (SST) data.

We used an ENSO index[13] to define El Niño and La Niña. Based on the SST data, we selected 11 warm events (El Niño), respectively in 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991, 1997 and 9 cold events (La Niña), respectively in 1964, 1967, 1970, 1973, 1975, 1984, 1988, 1998, and 1999.

3 VERTICAL STRUCTURE OF SAH

Relative to earlier work, we have a certain understanding about the horizontal structure of SAH. Here, the vertical structure, especially the stratospheric structure, of SAH is mainly analyzed and discussed. Having studied the average vertical structure of temperature for summer, we believe that because of the thermal effect of the plateau, its overlying tropopause is higher at heights, around 100 hPa to 70 hPa, than at other latitudes. As a result, the geopotential height of 100 hPa is taken as the start of the stratosphere over the plateau. Composite analysis of temperature, geopotential height and wind in the boreal summer (JJA) in the 45 years is conducted to reveal the vertical structure of SAH.

3.1 *Temperature characteristics*

Generally, temperature increases with height and latitude in the stratosphere in boreal summer. However, because of the existence of the plateau, temperature fields over the plateau have different characteristics. Figs. 1a & 1b give the 45-year climatological temperature distribution at 200 hPa and 100 hPa. A warm center is located over the western plateau at 200 hPa near 35° N, 75° E, which disappears at 100 hPa where the temperature distribution is zonally uniform and increases with latitude. Indeed, the warm center of the 200-hPa temperature field is not above the heartland of the plateau, but on its west side and tilts to the Iranian Plateau. As the vertical section of zonal temperature deviation along 30° N (Fig. 1c) shows, a pronounced cold center is near 100 hPa at about 70° E to 80° E. In the vertical section of temperature along 30° N (figure omitted), the cold center can also be found near 100 hPa, and temperature decreases with height from the cold center to higher stratosphere. And due to the existence of the plateau, the vertical temperature gradient of SAH below 30 hPa is significantly larger than at other latitudes.

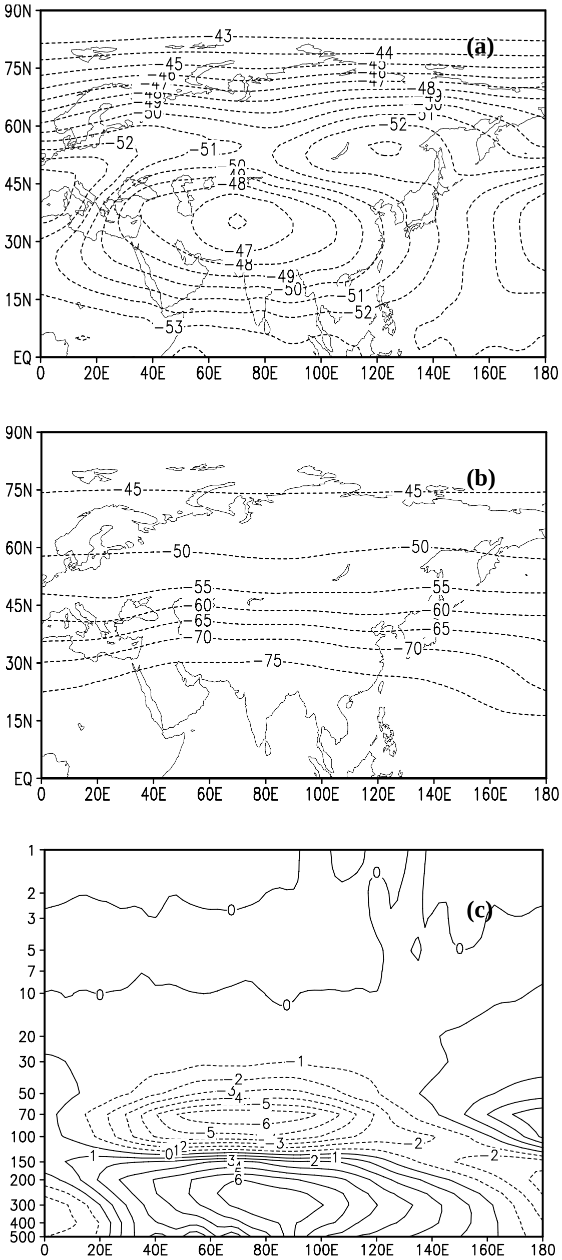


Fig. 1. 45-year averaged temperature (° C). a: 200-hPa temperature; b: 100-hPa temperature; c: vertical sections of zonal temperature deviation at 30° N.

Therefore, because of the powerful plateau thermal forcing in summer, the air heated above the plateau rises to form a warm center in the upper troposphere (Yang et al.[9]; Wu et al.[11]). However, the thermal effect of the plateau (from either sensible heat or latent heat) cannot heat the air over the plateau without limit. Temperature decreases as air rises above 200 hPa, weakening the warm center rapidly and causing a cold centre to form near 100 hPa. Meanwhile, the cooling effect of rising air can lead to a weakened divergence in high levels, which results in a less intense SAH. The stratospheric SAH cannot develop to higher levels just as temperature structure changes dramatically with height in the stratosphere. Next, further analysis will be done on the geopotential height and wind characteristics.

3.2 *Geopotential height characteristics*

The 100-hPa geopotential height was used to define the SAH in previous studies. In order to analyze the vertical structure of the SAH, Fig. 2 displays geopotential heights and wind fields at 200 hPa, 150 hPa, 100 hPa and 70 hPa. It is noticeable that there are four powerful high-pressure centers near 30° N at each of the levels centered at (85° E, 28° N), (78° E, 29° N), (75° E, 30 ° N), and (65° E, 32° N) respectively. Obviously, the center of SAH at each level leans to the northwest slightly with height.

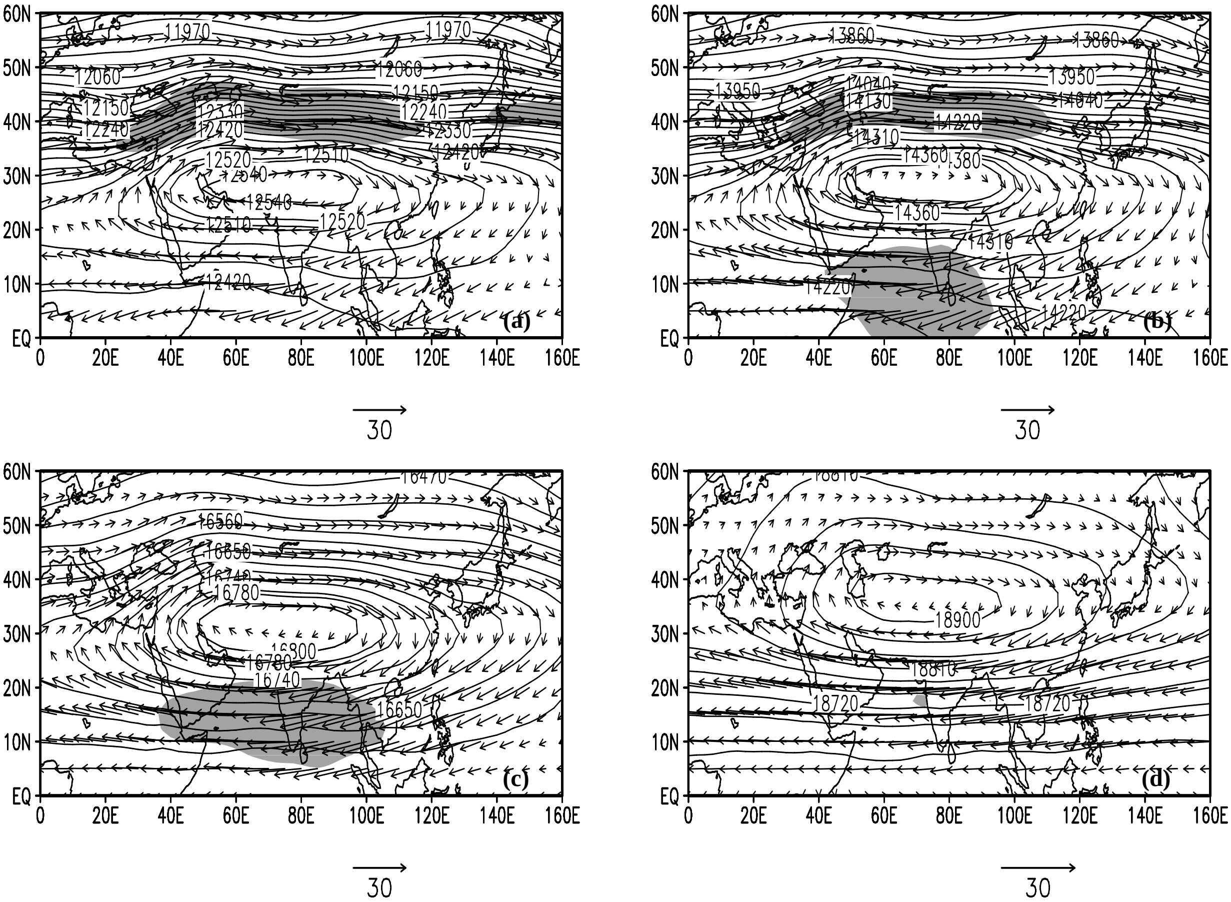


Fig. 2. 45-year averaged geopotential height field (gpm) and wind field (m s^{-1}) at 200 hPa (a), 150 hPa (b), 100 hPa (c) and 70 hPa (d). Winds>25 m s^{-1} are shaded.

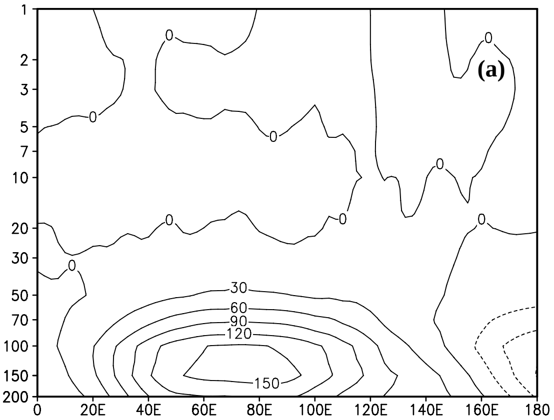
Vertical sections of geopotential height along 30° N are given in Fig. 3a to further reveal the SAH structure in the stratosphere. There is a pronounced high-pressure center at (55° E to 95° E, 170 hPa to 90 hPa), with its maximum near 150 hPa. No pressure center can be noticed above 50 hPa. Therefore, the SAH only exists in the upper troposphere and lower stratosphere.

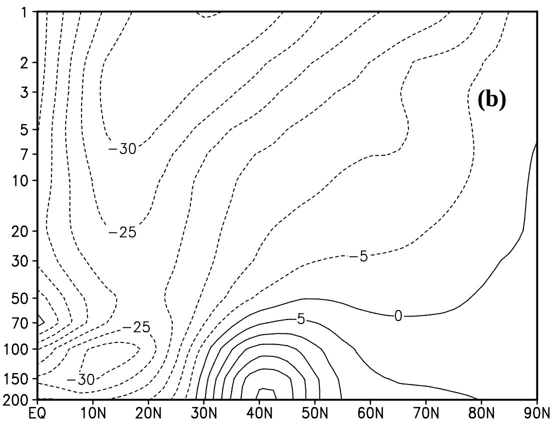
3.3 *Wind field characteristics*

As the enclosed pressure center of the SAH is always accompanied by an anti-cyclone wind field, knowledge about the wind structure will be helpful in understanding more of the vertical structure of the SAH.

At 200 hPa, westerlies control the central and northern side of the plateau while easterlies occupy the southern side of the plateau. Two westerly jet streams are right over the plateau and its western side and a strong easterly jet stream is over the Indian Ocean off the southeastern side of the plateau (figure omitted). Westerlies over the central plateau and its northern side weaken with height while easterlies strengthen on the southern side. The westerly jet stream over the western side of the plateau disappears at 150 hPa, being consistent with easterlies that keep expanding northward. Although easterlies continue to spread northward, the centers of westerlies and easterlies still exist on the northern and southern side of the plateau at 100 hPa, where westerlies decrease and easterlies strengthen noticeabley as compared to that at 200 hPa. Easterlies develop dramatically at 70 hPa where westerlies almost dissipate correspondingly. Easterlies dominate the entire boreal stratosphere above 50 hPa. In addition, the easterly jet stream on the southern side of the plateau can extend up to layers above 200 hPa, with its center slanting northward and its maximum at about 150 hPa to 100 hPa. In general, the enclosed high pressure corresponds to an anti-cyclone circulation, which is consistent with the westerly on the northern side and the easterly on the southern side. Meanwhile, the zero line of zonal wind denotes the high-pressure ridge. The pressure center reduces with height and the flow decreases in consequence.

Figure 3b shows the vertical section of zonal wind along 80° E. The figure shows that westerlies and easterlies are on the southern and northern edge of the plateau respectively from 200 hPa to 70 hPa, with the easterly maxima (easterly jet) centered on 13° N near 100 hPa, westerly maxima (westerly jet) located at 41° N near 200 hPa. Easterlies dominate the boreal stratosphere above 70 hPa while westerlies weaken rapidly with height.





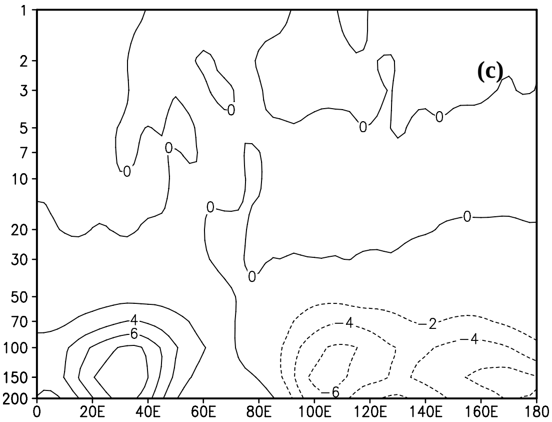


Fig. 3. Vertical sections of geopotential height at 30° N (a); vertical sections of meridional wind at 30° N (b); vertical sections of zonal wind at 80° E (c).

Averaged meridional wind at 200 hPa, 150 hPa, 100 hPa, 70 hPa, 50 hP and 30 hP in the 45-year period demonstrates that a stronger southerly is on the western side of the plateau (west of SAH), with its center (jet) near 37° E. The northerly is on the eastern side of the plateau (east of SAH), with its center (jet) near 108° E, which is weaker as compared to the southerly on the western side of the plateau. This situation of meridional wind could maintain up to 50 hPa. However, the northerly tends to develop with height. Above 50 hPa, the situation is somewhat complicated as it is discrepant at different levels as the meridional wind distributes asymmetrically (figure omitted).

The vertical section of the meridional wind along 30° N (Fig. 3c) shows that the northerly and southerly maxima are located on the eastern and western side of the plateau from 200 hPa to 70 hPa and the eastern northerly spreads westward with height.

All together, the distribution of the meridional wind and zonal wind mentioned above represents the anti-cyclonic circulation of SAH (Fig. 2). As the flow always suits the geopotential height well, the anti-cyclonic circulation corresponds to the high-pressure center of SAH. The strongest element is at 150 hPa, and its center tends to tilt slightly northwest with height, which is consistent with the pressure center. The anti-cyclonic circulation disappears and the easterly dominates completely above 50 hPa.

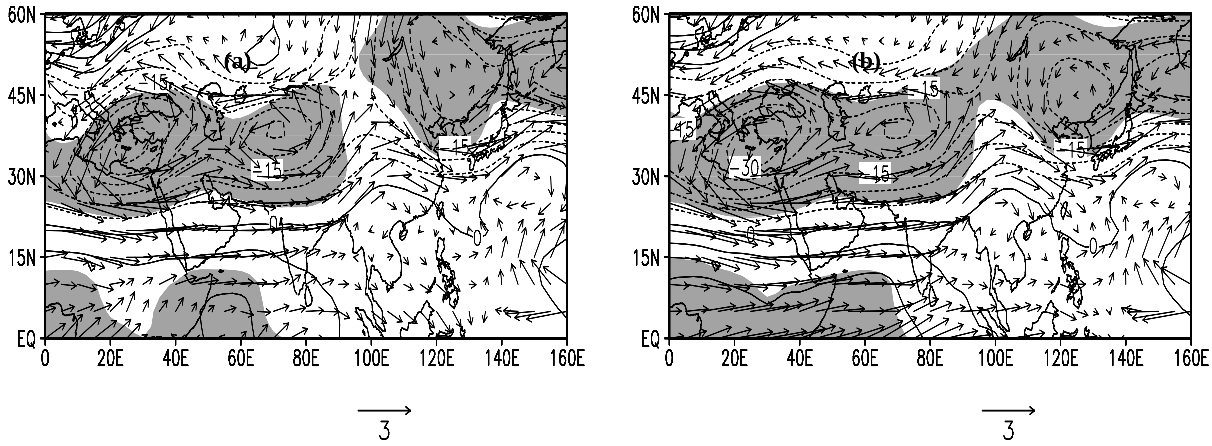
4 STRUCTURE OF THE SAH DURING ENSO

ENSO is known as the strongest interannual climate signal, which causes weather and climate anomalies in the world. Meanwhile, previous studies have shown that ENSO can also have some influence on the stratospheric circulation. Usually when the El Niño events occur, geopotential height and temperature in the stratosphere will be increased, a stratospheric polar-night jet will be weakened and a subtropical westerly will be enhanced[14]. El Niño can also affect the evolution process of the stratospheric Quasi-Biennial Oscillation (QBO). After the El Niño, usually, the westerly phase of QBO will be shortened and the westerly at 30 hPa will be reduced by about 40%–50%[15, 16]. However, only a few researches have been conducted about the impact of ENSO on the stratospheric SAH while many issues remain unclear yet, though the question about the impact of an abnormal mode of tropical Pacific-Indian Ocean temperature on SAH has been discussed recently[17].

Related studies imply that SAH has a significant annual variation, but the reason is not well settled. With the SAH considered as an important subtropical system, its variation may be related to tropical climate systems like ENSO. Hence we focus on determining if ENSO would have some influence on SAH. To highlight the results, 11 El Niño years and 9 La Niña years are selected by calculating the ENSO index during 1957 to 2002. Composite analysis is applied of summer circulations in El Niño and La Niña years. By comparing the difference of circulation, especially the anomaly of circulation, the impact of ENSO on SAH is revealed.

Composite analysis of geopotential height in the El Niño summer illustrates that SAH is less intense than the climatological value at 200 hPa, with its center shifted slightly eastward (figure omitted). The situation at 150 hPa is consistent with that at 200 hPa, in which the enclosed center moves northwest to about 30° N, 80° E at 100 hPa and the intensification is weaker than the climatological value at 70 hPa, with the center lying close to its normal position. Different from the El Niño year, the intensification of SAH in the La Niña year is close to the climatological value at 200 hPa in the summer with the center located west of its normal position. The condition is similar at 150 hPa. The SAH is weak at 100 hPa with its center close to the normal position. A decrease in the intensity of SAH is present up to 70 hPa with the center located westward. In addition, an enclosed weak center of geopotential height is noted at 50 hPa at high latitudes.

From comparisons of the difference in geopotential anomaly, the characteristics and differences of the stratospheric SAH are found to be dominant in El Niño and La Niña years. Fig. 4 is the composite geopotential and zonal wind anomaly at 200 hPa, 150 hPa, 100 hPa and 30 hPa in the El Niño summer. It is noticeable that negative geopotential anomaly occupies a zone at mid-latitudes from 200 hPa to 100 hPa (actually to 70 hPa), moves northward with height, while positive geopotential anomaly controls the high latitudes in the Northern Hemisphere. However, positive geopotential anomaly prevails in the Northern Hemisphere above 50 hPa with a maxima center between 40° N and 45° N. Different from El Niño years (Fig. 5), La Niña years witness a positive anomaly zone in mid-latitudes from 200 hPa to 150 hPa, although positive anomaly is weak over the plateau. Negative anomaly occupies the plateau at 100 hPa, whereas positive anomaly centers are still at the eastern and western side of the plateau. With increasing height, negative anomaly enlarges to cover the entire Northern Hemisphere except high-latitudes, and an enclosed center is located at 20° N to 25° N (30 hPa). Comparisons of Fig. 4 with Fig. 5 show that differences in geopotential height anomaly between the El Niño and La Niña years are clear: it is negative above the plateau from 200 hPa to 100 hPa and replaced by positive anomaly above 100 hPa in El Niño years, while the opposite occurs in La Niña years. In a sense, the result shows that ENSO could have some influence on SAH in the stratosphere, El Niño may weaken SAH, and La Niña may slightly strengthen SAH.



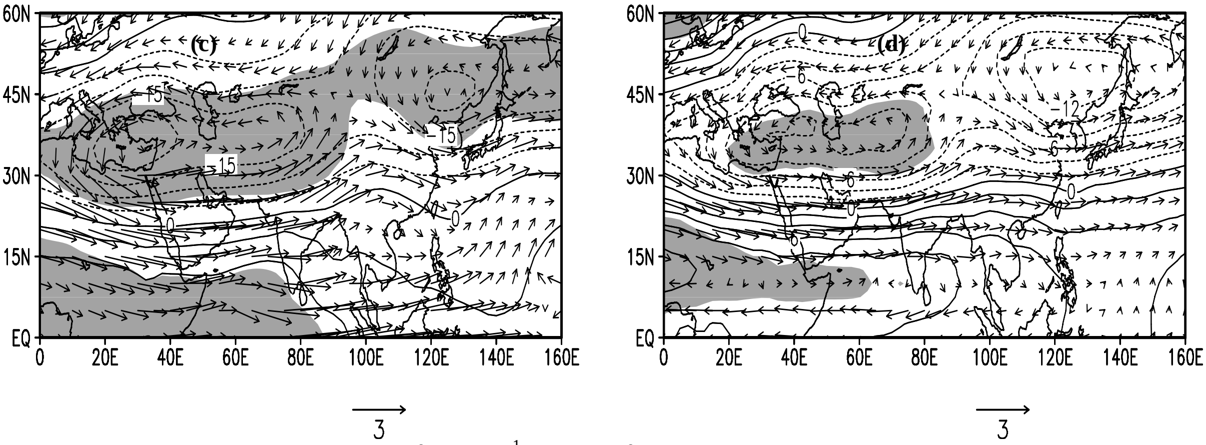


Fig. 4. Geopotential height (gpm) and wind field (m s^{-1}) anomaly for 200 hPa (a), 150 hPa (b), 100 hPa (c) and 50 hPa (d) in the summer of El Niño years (Shading denotes the region above the 90% significance level.)

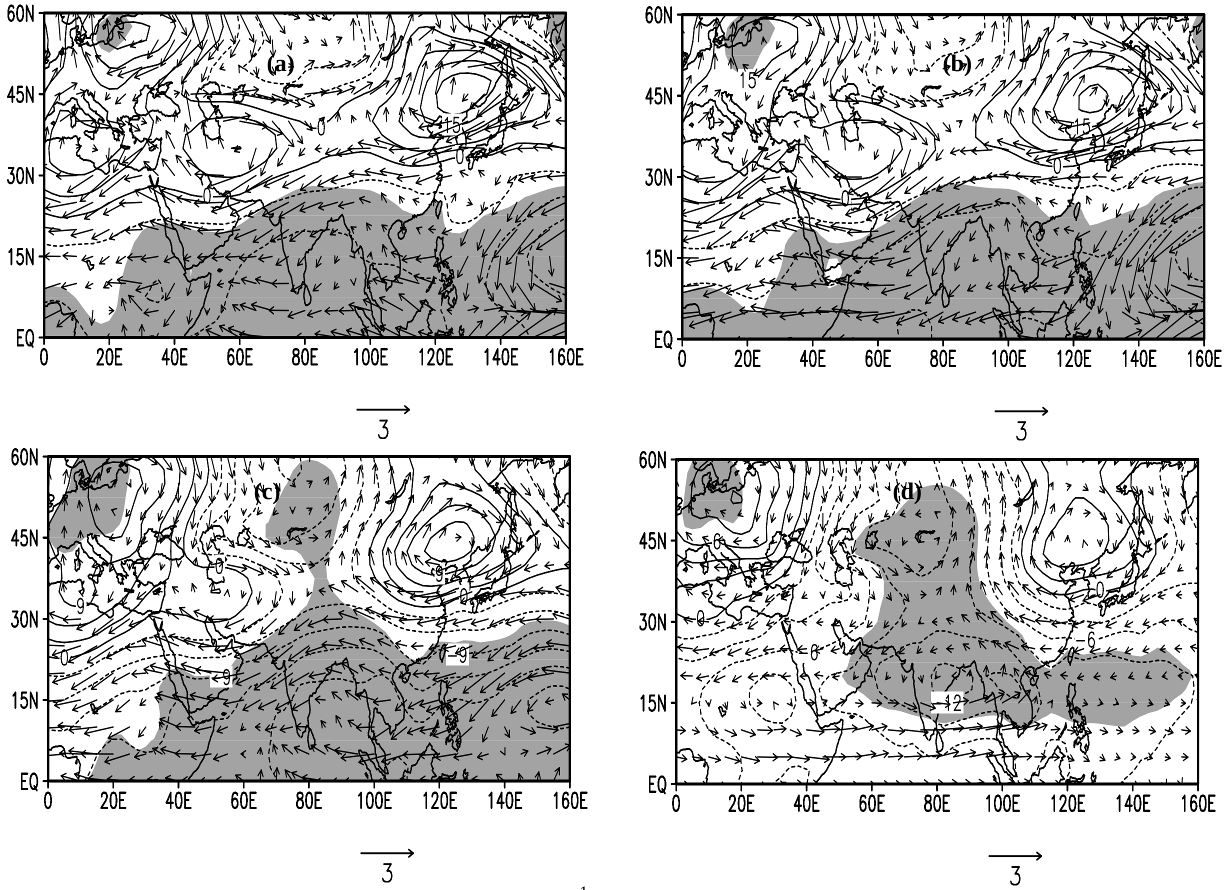


Fig. 5. Geopotential height (gpm) and zonal wind field (m s^{-1}) anomaly for 200 hPa (a), 150 hPa (b), 100 hPa (c) and 50 hPa (d) in the summer of La Niña year (Shading denotes the region above the 90% significance level.)

Composite temperature fields in the El Niño summer at 250 hPa and 200 hPa show that the warm center is weaker than the climatological value but close to its normal position. Meanwhile, the location and intensity of the temperature center is normal in the La Niña years except that it is less intense at 200 hPa. Because the formation of SAH is mainly due to the thermal forcing of the plateau, the temperature is consistent with the geopotential height field. It can be observed from the temperature anomaly that the negative anomaly occupies a zone in mid-latitudes at 250 hPa and 200 hPa in the El Niño summer with its center on the northwestern side of the plateau. On the contrary, positive anomaly occupies a zone in mid-latitudes at 250 hPa and 200 hPa in the La Niña summer. In the upper troposphere and lower stratosphere, positive temperature anomaly dominates the South Asia in the El Niño years, while the situation is different in various levels in the La Niña years, which are not all controlled by negative temperature anomaly (figure omitted).

Zonal wind distribution in the El Niño and La Niña summer is close to the climatological zonal wind (figure omitted). Easterlies and westerlies, from 200 hPa to 100 hPa, are on the northern and southern side of the plateau respectively, and easterlies occupy the Northern Hemisphere above 70 hPa. Specifically, the intensity and center location of the zonal wind in the La Niña summer are normal, while the zonal wind in the El Niño summer is weaker than that in the La Niña summer. Composite zonal wind anomaly in the El Niño summer (Fig. 6) suggests that the plateau is controlled by positive zonal wind anomalies over 200 hPa, and zonal wind anomalies are positive and negative on southern and northern sides of the plateau respectively at 200 hPa, 150 hPa, 100 hPa, with a negative zonal wind anomaly centered on the northwestern side. However, there are negative and positive anomalies on the southern and northern sides of the plateau respectively from 200 hPa to 70 hPa in the La Niña summer (Fig. 7), and the plateau is covered by positive zonal wind anomalies above 70 hPa. Following an analysis of zonal wind anomalies, El Niño will undermine easterlies on the southern side of the plateau and enhance westerlies on the northern side, while it is the opposite in the La Niña summer. ENSO imposes the same impacts on zonal wind from the tropopause to the lower stratosphere: easterlies and westerlies on the northern and southern side of the plateau are reduced in the El Niño summer and strengthened in the La Niña summer.

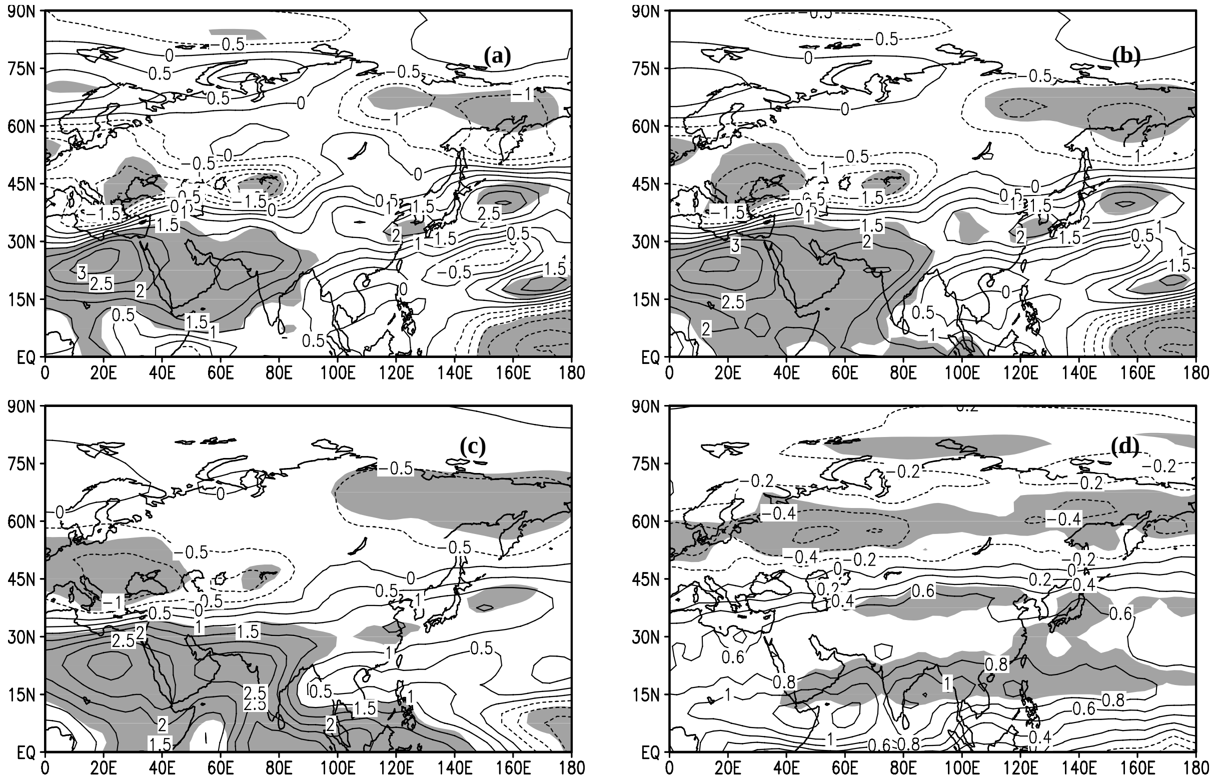
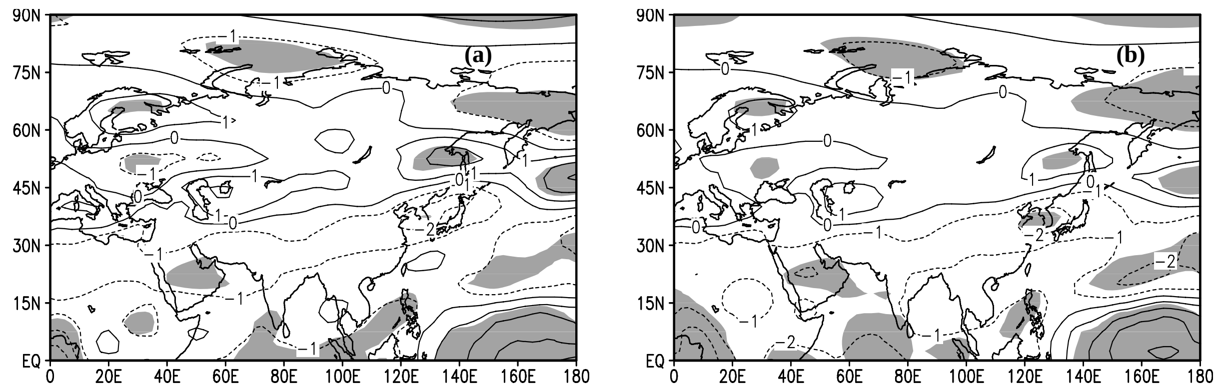


Fig. 6. Zonal wind (m s^{-1}) anomaly for 200 hPa (a), 150 hPa (b), 100 hPa (c) and 50 hPa (d) in the summer of the El Niño year (Shading denotes the region above the 90% significance level.)



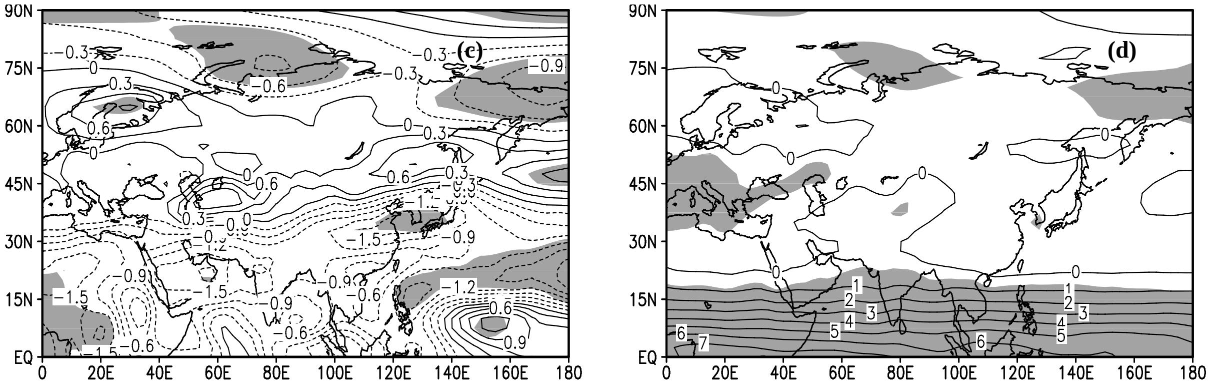


Fig. 7. Zonal wind (m s^{-1}) anomaly for 200 hPa (a), 150 hPa (b), 100 hPa (c) and 50 hPa (d) in the summer of the La Niña year (Shading denotes the region above the 90% significance level.)

Meridional wind distribution is normal in the El Niño and La Niña summer. Northerlies are on the eastern part and east side of the plateau, while southerlies are on the western part and west side of the plateau (figure omitted). Like the zonal wind, the composite meridional wind is weaker in the El Niño than in the La Niña summer. As shown in the composite map of meridional wind anomalies (figure omitted), a center of positive meridional wind anomalies is over the plateau at 200 hPa in the El Niño summer which extends to higher levels, and a center of negative meridional wind anomalies is over the plateau at 200 hPa in the La Niña summer, which is replaced, gradually with height, by the positive anomalies. This distribution of meridional wind anomalies could make the center of the SAH eastward in the El Niño years and westward in the La Niña years.

It can be observed from composite circulation that the anti-cyclone circulation over the plateau at 200 hPa in the El Niño summer is the same as its normality (figure omitted) but less intense, with its center located eastward as indicated in the analysis of the geopotential height field. The anti-cyclone moves to the northwest with height and disappears at about 50 hPa in the El Niño summer. Viewed from the circulation anomalies (Fig. 4), a cyclonic anomaly is on the western plateau from 200 hPa to 70 hPa in the El Niño summer, indicating that the intensity is weaker than normal and the central location is slightly eastward.

In the La Niña summer, the intensity and the central location of the anti-cyclone are consistent with its multi-year mean. Fig. 5 shows the circulation anomalies, in which anti-cyclonic anomalies are on the west and east side of the plateau from 200 hPa to 100 hPa, which is different from that in the El Niño summer. It can be noticed from composite circulation anomalies that the SAH is weaker in the El Niño summer than in the La Niña summer and its center is located more eastward.

From the analysis of wind fields (including the zonal wind and meridional wind), the circulation field, geopotential height and temperature, it is clear that ENSO can exert some impacts on the stratospheric SAH. The SAH is weak in the El Niño summer but slightly stronger in the La Niña summer. Circulation anomalies also imply that the central location of SAH shifts eastward in the El Niño summer. The changes of the intensity and central location of SAH are mainly due to different atmospheric circulation, which includes zonal and meridional circulation differences forced by SST anomalies and different surface condition during different phases of ENSO. Nevertheless, specific processes involved are complex, which need some intensive research in the future.

5 CONCLUDING REMARKS

Based on the long-term ECMWF reanalysis dataset, composite analysis is conducted to reveal the structure of stratospheric SAH and the influence of ENSO on it. The main results can be summarized as follows.

(1) The SAH is a significant subtropical system in the boreal summer. However, both the geopotential field and flow structure can only exist in the lower stratosphere, and the high-pressure (anti-cyclone) structure is not observable higher than 50 hPa. The strongest part of the SAH is at about 150 hPa.

(2) From 200 hPa to 70 hPa, the pressure centers of SAH appear at (85° E, 28° N), (78° E, 29° N), (75° E, 30° N) and (65° E, 32° N), respectively, leaning to the northwest with height.

(3) A warm center is over the plateau above the 30° N at 200 hPa, but a cold center appears at 100 hPa up to 50 hPa. This temperature distribution indicates that the air over the plateau is heated by the thermal forcing of the plateau to form a warm center at the upper troposphere. On the other hand, this is exactly the reason why the SAH cannot develop higher in the stratosphere.

(4) Both the geopotential height and flow distribution of the SAH are quite different in the El Niño and La Niña years, which means ENSO could have some impacts on the stratospheric SAH.

Generally, the SAH is weak in the El Niño years but strong in the La Niña years.

(5) Negative temperature anomaly occupies a zone in mid-latitudes of the Northern Hemisphere from 250 hPa to 200 hPa, with its center located on the northwestern plateau in the El Niño summer. The situation is just the opposite in the La Niña summer. In the upper troposphere above 200 hPa and the lower stratosphere, South Asia is basically controlled by positive temperature anomalies in the El Niño summer. However, different levels have various distribution in the La Niña summer and they are not all controlled by negative temperature anomalies.

(6) As the composite circulation anomalies indicate, the central location of the SAH shifts more eastward in the El Niño summer than in the La Niña summer. Differences in the intensity and central location of SAH are mainly attributable to the circulation difference, which includes the zonal and meridional wind forced by SST anomalies and the various surface condition (especially snow cover) during various phases of ENSO. Meanwhile, the SAH will react differently under various planetary wind systems and different boundary conditions. The specific process is complex, and intensive research needs to be carried out in the future.

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