Northward shift in circulation system over the Asian mid-latitudes linked to an increasing heating anomaly over the northern Tibetan Plateau during the past two decades

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ABSTRACT: The northward shift in circulation exhibited by a geopotential height of 5700-gpm at 500 hPa and the westerly jet at 200 hPa covers more than 40° of longitude (80°–120°E) in Asia. The northward shift in circulation is also exhibited by a northward shift in eddy, showing the ascending (descending) motion anomalies on the north of the previous convergence (divergence) regions. The latitude position of circulation correlates well with the northern ridge and the central latitude of the South Asian High (SAH), which shows weak negative correlation with the eastern Pacific sea surface temperatures (SSTs), the potential connection with the La Nina SST pattern and the negative Pacific Decadal Oscillation pattern, and positively correlated with the land surface temperatures over North America, Eastern Europe and the region between the Tibetan Plateau (TP) and the Lake Baikal in Asia. The local thermal forcing of the TP (north of 33°N) leads to increasing convergence in the lower troposphere, contributing to a positive latent heat of condensation, higher temperatures in the middle-upper troposphere, a stronger SAH, as well as northward secondary circulation in the middle troposphere. The northward extension of the SAH and a south wind anomaly encourage warming convection towards the north in the middle-upper troposphere, which leads to northward shift in atmospheric baroclinicity, and further be helpful to northward shift in eddy. These coupled thermodynamic and dynamic processes contribute to a northward shift in circulation in the mid-latitudes.

KEY WORDS northward shift; TP heating; latent heat of condensation; thermodynamic and dynamical effects; eddy shift

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1. Introduction

Northward shifts in planetary systems and atmospheric circulation have been documented (Frierson and Hwang, 2012; Zhang et al., 2015a). Observations show a poleward shift in the eddy, an expansion of the Ferrel cell centre (FC) and Hadley cell edge (HC) in recent decades, no matter in the Southern Hemisphere (SH) or in the Northern Hemisphere (NH) (Johnson and Fu, 2009; Staten and Rechler, 2013). Rimbu et al. (2003) have observed shifts in the El Nino–Southern Oscillation tele-connections over Europe and the Middle East, Chou and Neelin (2003) demonstrate northward extensions of the summer monsoon convergence zones in the North America, Asia and Africa. As the primary component of planetary systems, the subtropical westerly jet (STWJ) in the western Asia exhibits an obvious northward shift (Zhang et al., 2015b). As demonstrated by these shifts, poleward shift is obvious in the tropical and subtropical. Similarly, poleward shifts in circulation and planetary systems also occur frequently in the mid-high latitudes in the NH. The strengthening of the anticyclonic anomaly near Lake Baikal is related to meridional shifts or northward elongation in the planetary wave ridges (Zhang et al., 2015a). A simulation by Rivière (2011) indicates that poleward shifts in storm tracks over the Atlantic Ocean and eddy-driven jets in the northern Europe. Such systematic shifts can cause anomalous distributions of droughts and floods due to the large scale and relative stability of planetary waves (Frierson and Hwang, 2012; Cai and Tim, 2013; Cai et al., 2015). Therefore, it is critically important to explore the mechanism of shifts in planetary systems, so as to well predict drought disaster.

Thermodynamic factors are fundamental conditions for the northward shift in planetary systems and circulation. The factors include global warming due to increasing greenhouse effect and stratospheric ozone (McLandress et al., 2011; Polvani et al., 2011), sea surface temperature (SST) anomalies, land surface temperature (LST) anomalies and other forces (He et al., 2014), which can lead to decadal, inter-annual and seasonal anomalies. With global warming, increasing temperature exhibits inhomogeneity. Arctic warming is favourable for cyclonic anomalies in the lower troposphere over the Arctic, which results in the positive meridional wind anomaly, the weaker polar cell
and the broad downward motion in the mid-latitudes, as well as northward extension of FCs (Zhang et al., 2015a). Increasing SSTs over the tropical Indian Ocean (TIO) coincide with an increasing in north-to-south SST gradient and intertropical convergence zone (ITCZ) shifts (Cai et al., 2015). The paleo-warm pool enhances northern tropical convection (Lee et al., 2011), the positive convective heating results in the establishment of a convergence zone for northward extension of the northern summer monsoon. Lorenz (2014) demonstrates that increasing meridional temperature gradient could lead to an increase in the magnitude of the wave activity that acts to strengthen the jet. The jet structure can exhibit a double-jet state with weak tropical heating and strong high-latitude cooling or with strong tropical heating (Son and Lee, 2005), which demonstrates the effects of systematic forcing. Rainfall anomalies over the United States in summer and fall are associated with several thermodynamic factors, such as sea ice loss in the Arctic, land warming and the northward shift in the ITCZ (Rym et al., 2014). These studies illustrate the common effects of different thermal forcing.

Poleward shifts in planetary systems are also caused by dynamic factors. Charlotte et al. (2013) determines that the increasing SST is not the key mechanism for the northward propagation of the 30- to 50-day intraseasonal oscillation but a non-negligible factor because increasing SST results in dynamic processes, including strong boundary layer moisture advection and barotropic vorticity. The northward shift in the mid-latitude jet stream directly responds to dynamic factors, such as changes of storm tracks, eddy maintenance on the poleward side (Held and Suarez, 1994; Lorenz, 2014) and other factors. Increasing eddy phase speeds in pushing the jet poleward has been already discussed (Chen et al., 2007). Increase in static stability reduces the eddy generation on the equatorward side of the storm track, shifting the eddy source and thus the eddy-driven jet poleward (Lu et al., 2008). Tang et al. (2014) reveal that polar amplification increases the upper-level height and weakens the upper-level zonal wind at high latitudes, which leads to an amplified upper-level pattern and a northward shift in the jet stream. The baroclinic Rossby waves’ dynamic factors determine how far northward of the wave extension. However, the contributions on the dynamic effects of the baroclinic Rossby waves differ over Asia, South America and North America. These results show inhomogeneous of dynamic process. These dynamic factors are generally caused by thermodynamic factors.

However, dynamic factors mainly contribute to short-term circulation patterns, such as changes in storm tracks and eddy maintenance (Ren et al., 2010), its persistent effects relay on thermodynamic forcing, illustrating the common effects of both thermodynamic and dynamic factors. With global warming, heterogeneous increases in SST/LST increase the external forcing and baroclinicity (Geng and Sugi, 2003), which can change the wave activity or generate new waves, thereby causing anomalous circulation patterns.

The northward shifts in the circulation and planetary wave cover more than 40° of longitude (80°–120°E) over the Asian mid-latitudes (Zhang et al., 2015b). Such large-scale shifts could cause a wide-range climate anomalies (Zhang et al., 2013), relating to prolonged dry spells and droughts in the northern China, etc. (Wang et al., 2008, 2014; Zhao et al., 2010; Wu et al., 2012; Cheng and Zhou, 2013). Therefore, it is critically important to explore the effect and mechanism of the northward shift at regional scale. Because the shift width in the planetary wave motion and circulation is obvious in the north of the Tibetan Plateau (TP), the joint belt of the East Asia subtropical monsoon and the westerlies. Meanwhile, the thermal factors increasing temperature and thermal anomaly over the TP influence atmospheric circulation around the TP (Duan et al., 2013). In this study, we investigate the shifts in circulation in the Asian mid-latitudes and the possible relationship with thermodynamic forcing over the TP. The data and methods are described in Section 2. The temporal and spatial variability in South Asian High (SAH) and other circulation system is analysed, the relationship with the thermodynamic factors reflected by LST/SST anomalies are discussed in Section 3, and the possible mechanisms underlying planetary wave and local thermal anomalies are explored. The sensitivity simulation by the model for the thermal anomaly over the TP is also discussed in Section 3. The conclusions are presented in Section 4.
LST data are used to analyse the temperature gradients over the northern China and the adjacent regions, as well as the land forcing on the planetary wave and circulation systems. The Met Office Hadley Centre’s SST dataset is unique combination of monthly globally complete fields of SST with a 1° latitude–longitude grid from 1870 to the present. This dataset is used to analyse the SST’s forcing on circulation.

The statistical metrics and methods applied in this study include correlation coefficients, trend analysis and diagnostic analysis. Reliability tests are also performed using Monte Carlo tests (Livezey and Chen, 1983).

The STWJ at 200 hPa is defined as the region with more than 30 m s$^{-1}$ $U$ vector at 200 hPa. This pattern occurs over subtropical zones and represents the Asian STWJ in this study. The position of the STWJ in this study is defined as the latitude with the largest $U$ vector greater than 30 m s$^{-1}$. The Sahel is the thermal high-pressure system in the upper troposphere. The Sahel is defined by the 12 200-gpm contour region when its north ridge is analysed (because it is located just the north of the TP), and it is defined by the 12 300-gpm isoline when its eastern ridge is analysed (because it is continuous and can be used to visualize the eastern ridge over the Asian continent). In addition, because the 12 300-gpm isoline is located over the TP, its movement clearly indicates the shift in the Sahel and the relationship with the thermal anomaly over the TP. The centre of the Sahel is the location with the highest pressure within the 12 300-gpm contour isoline at the 200-hPa level.

2.2. CAM5 model and experiments

The atmospheric module of the community earth system model [i.e. the Community Atmospheric Model version 5.1 (CAM 5.1); Neale et al., 2011] is developed at the National Center for Atmospheric Research. The dynamic scheme includes four frameworks, including a finite volume method, a spectral element method, an Euler method and a half-Lagrange method. This study applies the finite volume dynamic framework with a horizontal resolution of $1.9^\circ \times 2.5^\circ$ and 30 vertical layers in the $\sigma$–$p$ vertical coordinate. CAM 5.1 is coupled with the CLM4 land process model. The moist perturbation scheme is used to simulate interaction of cloud, radiation and turbulence; the macro-physical scheme is used to simulate cloud process; the fast flux transmission method is used for radiation flux. The CLM model includes the processes of carbon and nitrogen cycle, dynamic vegetation, hydrological modules, etc. Only the land surface data are changed in the sensitivity experiments. A detailed description of the model is available at http://www.ccsm.ucar.edu/models/atm-cam/. We change the surface characteristics over the TP to simulate increases in the air temperature over the TP and heating effects. The changes in the surface characteristics could be set considering receding glaciers, permafrost degradation, desertification, decreased soil moisture and vegetation degradation. However, we just select one way to perform sensitivity experiments with a 30% decrease in vegetation leaf area index (LAI) (30°–40°N, 70°–100°E), which is consistent with the vegetation trend over the southern TP throughout the first part of the 21st century. The initial background data are the mean values from the past three decades (i.e. 1980–2010), which included atmospheric and surface data. The control simulation and sensitivity simulation are performed for 60 a; the results in July and August (JA) for the final 30 a are analysed in the study.

3. Results and discussion

3.1. Characteristics of planetary waves and planetary systems over Asian mid-latitudes

The circulation anomaly could be exhibited by planetary waves, therefore, the planetary wave position is used for analysing the circulation anomaly. The characteristics of the planetary wave are clear in the mid-upper troposphere; thus, the 500-hPa field is selected to analyse the circulation anomaly. Information from numerous radiosondes and satellite retrievals constrain the field; the atmosphere is free from surface effects, and upper-level wave patterns appear in the field. These characteristics ensure the availability of high-precision information on planetary wave motion. The 5700-gpm isoline at 500 hPa passes through the Asian mid-latitudes and is therefore selected to reflect the planetary wave anomaly in the Asian mid-latitudes.

Figure 1(a)–(c) shows the 5700-gpm isoline in summer for the past three decades from the ERA-Interim data and the pre-1980 isoline from the ERA40 data. The isolines for the three decades are similar with each other and exhibit a slight southward shift in June between 80° and 110°E over the past two decades (Figure 1(a)). However, this pattern differs from that of the isolines in JA. Compared with the 1980s isoline and the pre-1980 isoline, the 5700-gpm isolines in JA in the 1990s and 2000s (Figure 1(b) and (c)) exhibit a northward shift between 80° and 120°E. The northward shift extends across more than 40° of longitude, which is larger than a synoptic-scale system and thus corresponds to a planetary system anomaly. A circulation anomaly of this scale would lead to anomalous droughts and floods.

To explore the northward shift in circulation, we analyse the planetary wave anomaly using the geopotential height and the STWJ at 200 hPa in the upper troposphere. The STWJ is a component of the planetary systems. The central locations of the STWJ over the past three decades are shown in Figure 1(d)–(f). Compared with which in the 1980s, the STWJ during the past two decades exhibits a northward shift in the west of 100°E and a southward shift between 100° and 130°E in June (Figure 1(d)). However, the STWJ shifts northward over the past two decades between 80° and 140°E in July (Figure 1(e)) and exhibits a northward shift between 85° and 113°E, and a southward shift between 110° and 130°E over the past two decades in August (Figure 1(f)). These changes indicate that the STWJ over the northern China exhibits a southward shift in June and a northward shift in JA, which explains the temporal difference in droughts and floods between June
Figure 1. Variation of the 5700-gpm latitude (left panels) and STWJ latitude (right panels) in summer in the past three decades. June is shown in the upper panels; July is shown in the middle panels; August is shown in the lower panels.

and JA (Zhang et al., 2015b). The shift extends across approximately 20° – 50° of longitude, reaching synoptic and planetary scales. In this study, the circulation anomaly in JA is analysed due to consistent shift in 5700-gpm isolines and the STWJ.

3.2. Relationship between the northward shift in circulation and the SAH

The northern edge of the planetary wave in the Asian mid-latitudes is located in a unique position. The TP, the largest plateau on Earth, is located on the south side of STWJ, and the strongest monsoon circulation in the lower and middle troposphere occurs to the south and east of the TP. This circulation also corresponds to the strongest SAH in the upper troposphere over TP. Therefore, this study further explores the northern border of the SAH (Figure 2) to illustrate the northward shift in the STWJ. The height of the SAH centre at 200 hPa is indicative of the SAH intensity, it increases since 1997 (Figure 2(a)). The 12 200-gpm isoline at 200 hPa passing just the north of the TP and locating to the south of the STWJ, is selected to reflect the movement of the SAH ridge and its connection with the STWJ. The latitudes of the SAH centre and northern ridge of the 12 200-gpm isoline increase with time (Figure 2(b)), illustrating the northward shift in SAH, and these shifts have the same annual variability. Does the SAH intensity lead to the northward shift in SAH and the jet to the north of the SAH? To address this question, the relationships between the jet and the SAH intensity, the latitude of the SAH centre and northern ridge are shown in right panels. The jet locations show positive correlation with SAH intensity, centre and northern ridge; the correlation coefficients are 0.1, 0.42 and 0.47, respectively. However, only the latter two relationships passes Monte Carlo tests, indicating that the northward shift in the STWJ is consistent with the northward shift in the SAH position, however, the increasing SAH intensity is not the main contributor to the northward shift in the STWJ.

Qu and Huang (2012) demonstrate that the SAH exhibits a decadal eastward shift. Is the northward shift associated with the eastward shift? To explore this relationship, the 12 300-gpm isoline is selected to investigate the zonal shift of the SAH over the TP. The 12 300-gpm isoline is used instead of the 12 200-gpm isoline because the former is continuous and can be used to visualize the eastern ridge over the Asian continent. In addition, because the 12 300-gpm isoline is located over the TP, its movement clearly shows the shift in the SAH and the relationship with the thermal anomaly over the TP. The decadal changes in the 12 200- and 12 300-gpm isolines in two critical regions (85° – 105°E, 36.5° – 39.5°N and 85° – 105°E, 31° – 35°N) are analysed for a northward shift. The eastern ridge of the
12 300-gpm isoline, including its latitude and longitude, is also analysed (Figure 3). The northern ridges of both the 12 200- and 12 300-gpm isolines have shifted to the north (Figure 3(a)), particularly in the 2000s. The mean value of the northward movement exceeds 1°, and the largest movement of the 12 300-gpm isoline is 4°. The trend of 12 200-gpm isoline is consistent with the latitude of the eastern ridge of the 12 300-gpm isoline (Figure 3(b)) but differs from the longitude (Figure 3(c)), which indicates that the eastward shift in SAH is not the main cause of the northward movement of the northern ridge. However, the northward shift in SAH centre is related to the northward shift in the SAH northern ridge. As with the STWJ, the SAH exhibits northward shift and extension, which favours northward shifts in the STWJ and the mid-latitude circulation system.

3.3. Land surface temperature in the critical region over the TP

Figures 2 and 3 illustrate the relationship among the northern STWJ, the 5700 gpm and the northward shift in the SAH’s northern ridge. To explore the mechanism of the northward shift in the circulation and its response to the SAH, SAH’s northern ridge, SAH position and SAH intensity is analysed further. Because SAH is thermal high-pressure, its position and extension reveals thermodynamic anomaly on land and atmosphere, furthermore, decadal planetary wave anomalies are generally influenced by thermodynamic factors. Therefore, it is important to explore thermodynamic factors influencing SAH variation. The northward shift of SAH may be caused by forces, which include external forcing, local forcing and interactions between circulation systems and/or internal dynamical variability. To determine the forcing source of the northward shift in the SAH, the correlations between the northern ridge of the 12 200-gpm isoline in JA and the JA LST from the CRU data (Figure 4(a)) and the JA SST data from the Hadley Centre (Figure 4(b)) are analysed. Three positive correlation centres are identified: North America (30°–65°N, 120°–65°W), Eastern Europe (30°–65°N, 10°–60°E), the region between the northern TP and Lake Baikal (27°–53°N, 85°–125°E). The correlation coefficients exceeded 90% confidence level. LSTs can quickly respond to atmospheric circulation; therefore, these high correlations indicate that the northward shift in SAH leads to increasing temperatures via wave train. However, the higher temperatures in above three centres also could exert wave motion and SAH anomaly. Therefore, further study is necessary to distinguish the relationship between increasing LST and the northward shift in the SAH. Anomalous
SSTs can also alter atmospheric circulation. Figure 4(b) presents the correlation between the northern ridges of the SAH and SST over the past 34 years. Weak positive correlation centres are located in the northwest Atlantic, northern Pacific and southern Pacific, and weak negative centres are located in the equatorial Atlantic and the eastern equatorial Pacific, with less than 90% significant, indicating a weak La Nina mode and negative Pacific Decadal Oscillation (PDO) mode, which possibly shows weak and potential forcing of the La Nina SST and negative PDO mode on the SAH. In all these forces, the LST over TP (Figure 5) illustrates the LST trend in TP region. Most areas exhibit positive trends with 90% confidence level (black line). Three trend centres are apparent: south of Lake Baikal, northwest of the TP and east of the TP, which has the highest trend and is the most critical region. The temperature and temperature gradient are thermodynamic factors. Figure 5(b) compares the zonal mean LST anomaly in the TP region (85°–105°E) in the 2000s to the LSTs before 2000. The northern TP (33°–40°N) and western Lake Baikal (45°–55°N) feature dramatically increasing temperatures, which may result in a weak temperature gradient with the southern TP and the Indian Ocean. Figure 5(c) presents the normalized mean LST in the northern TP (33°–40°N, 85°–105°E, hereafter called the critical TP) and the central SAH in the southern TP (28°–31°N, 85°–105°E, hereafter called the southern TP); these phenomena illustrate the trend of increasing temperature and the trend in the northern TP is greater than that in the southern TP. This trend leads to a weak temperature gradient, which widens wave movement and finally contributes to the northward shift in the STWJ and the northward extension of the SAH.

3.4. How does the increasing LST over the northern TP affect the SAH to the north and circulation in the mid-latitude?

The mechanism of the LST affects atmospheric circulation is complex. In this study, we first identify the direct factors associated with the northward shift in the SAH and then explore the thermodynamic mechanisms associated with the surface temperature and temperature gradient effects.
NORTHWARD SHIFT IN CIRCULATION SYSTEM

Figure 4. Correlation coefficients between the 12200 gpm northern ridge of the SAH in the critical region in the northern TP in JA and the LST in JA from the CRU data (a) and the JA SST data from Hadley Centre (b). The region highly correlated with LST around the SAH is also shown (c). All data are from 1979 to 2013. The thick line is the 95% confidence level.

On the dynamic factors and the northward shift in the SAH and circulation.
From the relation between the locations of the 12 200-gpm northern ridge and the height anomaly at 200 hPa (Figure 6(a)), and the locations of the 5700-gpm and height anomaly at 500 hPa (Figure 6(b)) in the critical region (33°–40°N, 85°–105°E), we find that the northward shift in the northern ridge of the SAH is consistent with the increasing height in the critical region. With global warming, the atmospheric layer will increase due to increasing LSTs and air temperatures in the lower troposphere (Lorenz and DeWeaver, 2007). Does the increasing height over TP correspond to rising atmospheric layer under global warming scenarios? To address this question, Figure 6(c) presents the vertical height anomaly in the critical region. The positive height anomaly in the lower troposphere (600–500 hPa) is weak. The centre contains a 50-gpm anomaly between 400 and 100 hPa in the mid-upper troposphere after 1999, which indicates that the increasing height is not directly caused by increasing surface temperature responding to global warming, but by other factors such as the change of turbulence heat transfer due to changing surface conditions and so on.

To explore the mechanism of the increasing height over the TP, Figure 7(a) and (b) presents the northern ridge series and the temperature anomaly distribution at 200 and 500 hPa over the TP. This comparison is performed because the northern ridge is located in the high-temperature region (33°–40°N, the critical region and north of 40°N); the positive temperature anomaly occurred after 1999, corresponding to obvious northward shifts, which demonstrates that the increasing temperature in the mid-upper troposphere related to the northward shift in SAH ridge and the increasing height. Figure 7(c) presents the vertical temperature anomaly over the critical region. The positive temperature anomaly appeared from the surface to 200 hPa, but the positive temperature centres occurred between 200 and 400 hPa, which indicates that the increasing LST over TP helps increase the temperature over the upper troposphere. The increasing LST may lead to an ascending motion that produces latent heat of condensation, thereby contributing to the increasing temperature. In addition, we observed a negative temperature anomaly above 200 hPa. It is that the interaction between the troposphere and the stratosphere and the cause of the increasing temperature in the troposphere merit further exploration. Vertical and horizontal advection also contributes to local changes in temperature. Figure 7(a) and (b) shows that the northward shift of the northern ridge does not match well to the positive temperature anomaly, indicating that thermodynamic processes are only one of several influencing factors. In addition, dynamic factors are important to
the northward shift of the SAH ridge and the increase in height.

Figure 8 shows the meridional profile (90°–100°E) of the composite flow, vertical velocity and temperature anomaly, which could show eddy stream anomaly. Because the TP terrain is inconsistent, this study separately analyses three parts of the profile (80°–90°E, 90°–100°E, 100°–105°E). The anomaly circulation is consistent; thus, 90°–100°E is discussed as a representative section. The composite flow demonstrates that the ascending motion over the TP (north of 33°N) increases after 1999 and that the ascending motion sloped to the north with height. The north wind is present between the northern TP and 50°N before 1999 (Figure 8(a)) but subsequently became a south wind (Figure 8(b)). The vertical velocity (Figure 8(a) and (b)) and the vertical velocity anomaly (Figure 8(c)) exhibit an ascending motion over the northern TP, the middle latitudes (approximately 50°N) and north of 63°N, with descending motions between these areas. A positive vertical velocity anomaly (Figure 8(c)) also forms on the north of the regions of ascending motion. The ascending and descending regions all extend to the north, which indicates a northward shift in the eddy. The negative vertical velocity in the mid-latitude is weakened after 1999, and the ascending motion over 50°N is also weakened.

Higher SSTs over the TIO lead to a high north-to-south SST gradient and ITCZ shift (Weller et al., 2014). The vertical velocity and composite flow demonstrate that the ascending motion to the south of the TP (south of 28°N) increased after 1999, which shows positive effects due to the increasing SST and northern ITCZ. Such a positive anomaly occurs only over the region with maximum ascending motion, whereas an ascending anomaly is located over the southern TP (28°–32°N). These features indicate that the northward shift in ITCZ does not influence ascending motion over the southern TP. Therefore, the northward shift in circulation and the planetary system over the northern TP and in the mid-latitude are separated from the northward shift in the tropical systems, but associated with the circulation and thermal anomaly over the TP.

To support our inferences from Figures 6 to 8, the temperature and vertical velocity anomalies (recent minus previous) are plotted in Figure 8(c). Similar to Figure 6, except for the positive temperature anomaly on the south side of the TP, there are two positive centres: one is in the lower troposphere over the northern TP and the mid-latitudes (40°–53°N), the other is in the mid-upper troposphere over the northern TP and the north of the TP (33°–50°N). The increasing temperature in the lower troposphere corresponds to a positive ascending motion.
over the northern TP and the descending motion in the mid-latitudes. Positive ascending motion over the northern TP results in secondary circulation to the north in the middle troposphere, with a south wind anomaly in the middle-upper troposphere and descending motion between 42° and 45°N. Surface heating leads to increased adiabatic heating in the lower troposphere, which enhances the ascending motion because convection further increases the latent heat of condensation (figure not shown) and stratification instability. This increasing of latent heat of condensation finally contributes to increasing air temperatures due to adiabatic cooling. These processes also heat atmosphere over the north of the TP with weakening ascending motion and warm advection with south winds. Circulation patterns similar to those shown in Figure 8 are apparent at 80°–90°E and 100°–105°E (figure is not shown), demonstrating the consistent patterns.

3.5. How does the dynamic process affect the north and circulation in the mid-latitude?

The circulation over three key regions may explain the northward shift. The three key regions are the northern TP (33°–40°N), the divergence region in the mid-latitudes (approximately 45°N) and the convergence region in the mid-latitudes (approximately 52°N). Corresponding to three key regions, the key circulation include increasing ascending motion over the northern TP, the positive ascending anomaly in the divergence region, and decreasing ascending motion in the convergence region, exhibiting a northward shift in eddy and weak previous eddy. Increasing ascending motion over the northern TP leads to secondary circulation and a south wind in the middle troposphere, and the strengthening SAH has a positive effect on the northward divergence flow in the upper troposphere. By contrast, decreasing ascending motion over the convergence region in the mid-latitudes leads to weak southward divergence flow in the middle troposphere, and the positive upward flow anomaly over the divergence region in the mid-latitudes weakens the downward motion. All these factors contribute to the south wind anomaly, which is one of the dynamic factors for the northward shift. The circulations over these three key regions are associated with the northward shift in the climate zone.

The atmospheric baroclinicity is the main driving factor of atmospheric motion in the mid-latitudes, To investigate the thermal effects of the TP on planetary wave motion, Figure 9 shows the zonal wind velocity difference between the 200 and 500 hPa anomalies (recent minus
pre-1999), the pre-1999 distribution and its correlation coefficient with surface temperature (abbreviation Ts) in the critical region in the northern TP. We selected 500 hPa because it represents the lower troposphere around the TP. A large baroclinicity centre is present over the TP (30°–42°N, 70°–120°E) before 1999, indicating that a baroclinicity system existed over the TP with cyclonic flow in the lower troposphere and anticyclonic flow in the upper troposphere. A baroclinicity anomaly is present to the north of 33°N between 80° and 115°E, and its centre is located more northerly than previous centre, demonstrating the northward shift in the baroclinicity system. The correlation with surface temperature in the critical region on the northern TP (Figure 9(b)) shows clear positive correlation coefficients between 33° and 50°N, demonstrating that the increasing temperatures over the TP could result in increasing baroclinicity and planetary wave motion on the north of 33°N, due to heterogeneously increased temperatures and the thermal wind. Because positive thermal wind and baroclinicity lead to mismatching of temperature and pressure field and destroying quasi equilibrium, which further results in wave motion so as to tend to quasi equilibrium. The motion difference between the upper troposphere and the lower troposphere is indicative of the atmospheric baroclinicity component due to thermodynamic processes, and it final affect dynamical process and northward shift in eddy and circulation.

3.6. CAM5 simulation of increased TP heating and its effects on the northward shift in circulation

To simulate the circulation shift caused by the pronounced increase in temperature over the TP that ultimately results in stronger ascending motion, we changed the surface characteristics of the TP and analysed the effects on heating and atmospheric circulation. The surface changes associated with climate warming include receding glaciers, permafrost degradation, desertification, decreasing soil moisture and vegetation degradation in the southern TP. We just performed the sensitivity experiments with a decrease in vegetation LAI by 30% in the study area (30°–40°N, 70°–100°E) because a similar decrease has occurred over the southwest TP in recent decades. The initial background data are the mean values from ECMWF for the past three decades (1980–2010), including relevant atmospheric and surface data. The control simulation (CTRL) and the sensitivity simulations (SEN) are performed for 60 a; the results for JA from the final 30 a are selected for analysis. Figure 10 shows the coupled CAM5 and CLM4 simulations of increase heating with vegetation degradation over the TP (30°–40°N). Figure 10(a) shows the zonal wind velocity difference between 200 and 500 hPa and the SAH.
NORTHWARD SHIFT IN CIRCULATION SYSTEM

Figure 8. Distributions of the flow field along 90°–100°E (arrow lines) and negative omega (shadow, −Pa s⁻¹) before 1999 (a) and after 1999 (b). Positive anomalies (thick lines) and negative anomalies (dashed lines) of T (°C) and the later-minus-earlier negative omega values are also shown (c). A profile of the terrain is shown at the bottom of each panel. The T and negative omega anomalies are calculated as the differences between the later values and earlier values.

(12 510 gpm) in the control simulation (CTRL) and the anomaly (SEN-CTRL). The anomaly centre shifts to the north compared to the centres of the zonal wind velocity difference in CTRL, indicating clear northward baroclinicity characteristics over the TP and in the mid-latitudes on the north of the TP. The SAH in SEN shifts to the north relative to the SAH in CTRL. All these results demonstrate that vegetation degradation over the TP results in a shift of the SAH and baroclinicity to the north, which affects the planetary wave motion, demonstrating the connection between the northward shift in the circulation system over the TP and mid-latitudes and TP heating.

Figure 10(b) shows the meridional distribution of negative omega in the region between 90° and 100°E in CTRL, the composite flow of the vertical wind velocity and the negative omega anomaly (SEN-CTRL). Figure 10(c) shows the air temperature anomaly, the negative omega anomaly (SEN-CTRL) and the total water flux anomaly contributing to the latent heat of condensation and air temperature. The negative omega in CTRL indicates ascending motion over the TP and the south of the TP. Another area of ascending motion is located at approximately 53°N. However, when vegetation degradation occurs over the TP (north of 30°N), the surface temperatures increase due to decreases of latent heat, which enhances positive sensible heat flux and ascending motion, as well as positive latent heat of condensation, ultimately contributing to higher air temperatures in the middle troposphere, even though ascending motion directly leads to decreased air temperatures, as indicated by the air temperature anomaly. The positive air temperature anomaly exhibits high centre in the middle troposphere to the north of the TP, which is also influenced by warming convection associated with the south wind anomaly. This
warming convection increases atmospheric baroclinicity in the northern TP and the mid-latitudes due to heterogeneously increased temperatures and the thermal wind. The composite velocity from the vertical velocity and negative omega anomaly (SEN-CTRL) indicates an ascending motion anomaly in the middle troposphere and positive divergence flow in the upper troposphere over the northern TP, which corresponds to descending motion, leading to a northward shift in the circulation system to the north of the TP. An ascending motion anomaly in the mid-high latitudes (from 40° to 70°N) occurred to the north of the previous ascending regions (CTRL), illustrating a northward shift in the eddy circulation system. Both the temperature anomaly and the composite velocity from the vertical velocity and negative omega anomaly exhibit increasing convergence in the lower troposphere, divergence in the upper troposphere and northward shifts in the circulation, which is consistent with previous results. The northward shifts in the circulation are the result of increased heating over the TP and increased baroclinicity over the northern TP and mid-latitudes.

4. Summary and conclusions
We examine the northward shifts in circulation in the Asian mid-latitudes by exploring the position of the 5700-gpm isoline at 500 hPa and the westerly jet at 200 hPa. The northward shift exceeds 40° of longitude in the Asian mid-latitudes (from 80° to 120°E), which show northward shift in the planetary system because of its scale reaching planetary scale. Such shifts in planetary system also exist over the NH. However, the direction and scale of the shifts differ; the scale of the shift ranges between 20° and 50° of longitude. Shifts in planetary systems can lead to extreme events of weather and climate, such as droughts and floods. Because the planetary system represents the background conditions and its movement is slow, therefore, synoptic systems can occur repeatedly under these conditions, and the northward shift in the planetary system warrants attention.

Because the planetary wave in the Asian mid-latitudes lies immediately on the north of the TP, the thermal anomaly, the circulation anomaly and the SAH over the TP are studied to explore the possible mechanisms underlying the northward shift in the planetary system and circulation. The northern ridge and SAH centre extend to the north and correlate well with the northward shift in the planetary wave. However, these parameters are poorly correlated with the SAH intensity, which demonstrates that the northward extension of the SAH differs from that of the SAH intensity. A previous study (Qu and Huang, 2012) reveals that the SAH exhibits a decadal eastward shift, meanwhile, the northern ridge of the SAH is poorly
Figure 10. CAM5 simulation of increased heating with vegetation degradation in the TP (30°–40°N, 70°–100°E). (a) Zonal wind velocity differences between 200 and 500 hPa in the control (CTRL, colours) and anomaly [isolines, sensibility (SEN)-CTRL] and the SAH in the CTRL and SEN. (b) Meridional distribution of negative omega in CTRL (Pa s⁻¹) and composite flow of vertical velocity and negative omega anomaly (SEN-CTRL, omega* (-1000)). (c) Air temperature anomaly (SEN-CTRL, °C) and total water flux anomaly (shadow, 10⁷ W m⁻²). A topographic profile of the region (90°–100°E) is shown at the bottom of (b) and (c). The $U$ anomaly interval in (b) is 1 m s⁻¹.

This study demonstrates that the circulation shifts to the north from the northern TP (north of 33°N) to 69°N between 80° and 120°E, but circulation anomaly is not significant in the southern TP and the tropical continent on the south of the TP. Therefore, the northward shift is distinct from the northward shift in the ITCZ, although the northward shift in the ITCZ increases moist convection to the south of the TP (Weller et al., 2014). To explore the source of the remote forcing to the northward shift in the circulation, the correlations between the northern ridge of the SAH and the critical region and the planetary wave, LST and SST in JA are analysed. The northward shift shows weak negative correlation with SST in the eastern Pacific, which represents the potential combined effects of a La Nina SST pattern and a PDO SST pattern (Wang et al., 2014). Positive correlation centres occur over three continents: the North America, Eastern Europe and then the northern TP to Lake Baikal. These results demonstrate that the northward extension and shift in the SAH, which potentially interacts with these three continental centres and the centre in the eastern Pacific.

The LST over the TP and the mid-latitudes on the north of the TP are analysed so as to better understand the local forcing source around the TP. The increasing temperatures and heating effect over the TP increase surface convection. These processes enhance positive ascending motion and the positive latent heat of condensation and contribute to increase in air temperature, even though ascending motion...
directly leads to decrease in air temperature, as evidenced by the air temperature anomaly. The positive air temperature anomaly also contributes to warming convection to the north of the TP via the south wind anomaly, which (1) further enforces the SAH and its northward extension; (2) increases atmospheric baroclinicity in the middle-upper troposphere over in the northern TP and the mid-latitudes due to heterogeneous temperatures and increases thermal wind, which helps northward shift in eddy and enforce planetary wave motion in the mid-latitudes and (3) encourages a secondary northward circulation, which strengthens the south wind anomaly in the middle troposphere and dynamic factors. The northward anomaly in ascending motion causes positive anomaly divergence flow in the upper troposphere over the TP and northward secondary circulation, which is helpful to warming convection in the middle troposphere. Because temperature and south wind anomaly is larger in the mid-lower troposphere than in the upper troposphere, it further increases atmospheric baroclinicity to the north of the TP. This phenomenon illustrates the thermal and dynamic contributions to the northward shift in atmospheric circulation in the mid-latitudes. In addition, the northward shift in the ascending motion in the convergence region in the mid-latitudes and the decreasing convergence leads to poor southward divergence in the middle troposphere over the convergence region, which decreases the north wind and contributes to the south wind anomaly and other dynamic factors. Therefore, increased TP thermal and decreased ascending in the convergence region in the mid-latitude contributes to a south wind anomaly and a northward shift in circulation patterns.

The study explored only the local forcing of LSTs over the TP on turbulence heat transfer (such as sensible heat flux), the planetary wave and atmospheric circulation. Other thermal factors such as latent heat flux and effective radiation are not analysed due to the limited length of the article, but these factors are important because they are directly associated with atmospheric heating, which will be explored further in future work. In addition, the north ridge of the SAH is related to the LSTs and potential sources of the La Nina SST and negative PDO SST patterns. These remote forcing anomalies are related to anomaly shifts in circulation. Beside, internal dynamic variability also plays a role. Therefore, the contribution rates of TP local forcing, remote forcing and dynamic variability are worthy of discussion. In addition, the parameterization scheme of CAM5 is necessary to be improved so as to well describe the land–air interaction, quantitative analysis and evaluation, because TP has complex surface conditions and altitude difference.

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