The Rossby wave train patterns forced by shallower and deeper Tibetan Plateau atmospheric heat-source in summer in a linear baroclinic model

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\textbf{ABSTRACT}

By using a linear baroclinic model (LBM), this study investigates the different Rossby wave train (RWT) patterns associated with the Tibetan Plateau (TP) upper-atmospheric heat source (TPUHS) that is anomalously shallower and deeper in boreal summer. Observational results indicate the different RWT patterns between the developing and decaying periods of synoptic TPUHS events, when the anomalous TPUHS develops from a relatively shallower to a deeper TP heat source. Based on the different vertical heating profiles between these two periods in observation, this study forces the LBM with prescribed TPUHS profiles to mimic a shallower and deeper summer TP heat source. The results show that the atmospheric responses to a shallower and deeper TPUHS do exhibit different RWT patterns that largely resemble those in observation. Namely, corresponding RWT pattern to a shallower TPUHS stretches from the TP to the west coast of America, while that to a deeper TPUHS extends from the TP region to Alaska.

\section{1. Introduction}

As the largest and highest topography in the world, the Tibetan Plateau (TP) serves as a strong heat source of the atmosphere in the summer season (Yeh, Lo, and Chu 1957; Flohn 1957), which has great influence on atmospheric circulation, weather, and climate through thermal dynamical effects (Ye and Gao 1979; Tao and Chen 1987; Ye and Wu 1998; Yanai and Wu 2006; Liu et al. 2012; Duan et al. 2012; Wang, Duan, and Wu 2014; Wu et al. 2016, Wu and Liu 2016). Due to the elevated surface sensible heating (SSH) of the TP in summer, an upward current and resulting convective activities prevail over the TP and its surrounding areas (Wu et al. 1997; Ye and Wu 1998). In addition, the formation and maintenance of the South Asian high is also largely attributable to the summer diabatic heating over the TP (Flohn 1960; Krishnamurti 1973; Reiter and Gao 1982; Yanai, Li, and Song 1992). Moreover, the Asian summer monsoon, acting as the strongest element of the global monsoon system (Flohn 1957; Chang 2004; Wang 2006), is also modulated by the thermal influence of the TP (Li and Yanai 1996; Yanai and Wu 2006; Wu et al. 2007; Romatschke and Houze 2011).

As a huge and elevated heat source, the TP plays an important role not only in the formation of summer circulation over the TP and surrounding Asian monsoon region, but also in the circulation anomalies over the whole Northern Hemisphere via a Rossby wave train (RWT). Model results reported by Wu et al. (1997) and Ye and Wu (1998) indicated that the elevated SSH of the TP is an efficient producer of negative vorticity in the upper troposphere in the midlatitude westerlies, which can also generate an RWT that influences the circulation anomalies across the Northern Hemisphere. Subsequently, based on reanalysis data, Liu, Li, and Wu (2002) investigated the relationship between the SSH and upper-level circulation anomalies in July, and observed a similar RWT. Previous studies consistently verified the existence of the RWT related to the forcing of the SSH over the TP in summer. However, the diagnostic results provided by Zhu, Ren, and Wu (2018)
indicated that the TP heat source is dominated by the upper-atmospheric heat source (TPUHS) (i.e. convective heating) rather than the SSH in summer. Besides, the RWT related to the TPUHS is also different from that related to the SSH over the TP. In particular, the RWT is different between the developing and decaying periods of the anomalous TPUHS, when the anomalous TPUHS develops from a relatively shallower to a deeper one (Zhu, Ren, and Wu 2018). Based on numerical experiments, the present study seeks to clarify if the TPUHS can really excite an RWT, and if the RWTs forced by shallower and deeper TPUHS are different.

Following this introduction, Section 2 introduces the data, method, and model; Section 3 shows the different RWT patterns between the developing and decaying periods of the anomalous TPUHS in observation, and investigates the different RWT patterns forced by the TPUHS that is relatively shallower and deeper in the model in boreal summer; and Section 4 provides a summary and discussion.

2. Data, methods, and model

The daily circulation data used in this study are from the National Centers for Environmental Prediction Reanalysis 1 product (NCEP1; Kalnay et al. 1996), with a horizontal resolution of 2.5° × 2.5° and 17 levels in the vertical direction. The period of analysis is from 1979 to 2014. As the climatological upper-level westerly over the TP region is weakest in the period of 20 July to 20 August (Zhu, Ren, and Wu 2018), the convective heating over the TP can heat the local atmosphere sufficiently. Hence, the present study focuses on the summertime (20 July to 20 August). Besides, the daily anomaly fields are obtained by removing the daily annual cycle of all variables.

The vertically integrated (from 100 hPa to the lowest pressure level, which is about 100 hPa away from the surface) atmospheric apparent heat source (< Q1>) is derived by residual budget analyses based on the thermodynamic equation (Yanai, Steven, and Chu 1973). By averaging the< Q1> over the TP region (25°–40° N, 70°–105° E) and above the altitude of 1500 m, we further define a daily TPUHS index. The Student’s t-test is used to examine the significance of the results, and the effective degrees of freedom for the significance test are calculated based on the method provided by Bretherton et al. (1999).

We employ a linear baroclinic model (LBM) (Watanabe et al. 1999; Watanabe and Kimoto 2000) to investigate the large-scale circulation responses to TP heat sources. Also, we choose the dry version of the LBM because the dry version is more applicable for investigating the atmospheric responses to regional heat sources (Lu and Lin 2009). The detailed model description can be seen in Watanabe and Jin (2003). Specifically, we take the summer (20 July to 20 August) climatology obtained from the NCEP1 reanalysis during 1979–2014 as the basic state. In each experiment, the model is integrated for 30 days with fixed diabatic heating forcing. Since a steady state can be reached in 15 days because of the dissipation terms employed in this model (Watanabe and Jin 2003), we use the model results averaged from day 16 to day 30 for our analysis.

3. Results

In observation, the RWT pattern, associated with shallow convective heating of the TP during TPUHS-developing period, fully forms at day(−3), stretching from the TP to the west coast of North America (Figure 1(a)). Meanwhile, that associated with deep convective heating of the TP during TPUHS-decaying period occurs at day(8), emanating from Lake Baikal and propagating downstream to the northeastern Pacific (Figure 1(b)). It should be noted that, associated with the different RWT patterns between the TPUHS-developing and TPUHS-decaying periods are the different vertical heating profiles over the TP between these two periods. During the TPUHS-developing period, the temperature anomaly center is located at 300 hPa and the warmest center occurs at day(−6) (Figure 2(a)), indicating shallow convective heating over the TP. Meanwhile, during the TPUHS-decaying period, the temperature anomaly center is located at 150 hPa and becomes the strongest at day(1) (Figure 2(b)), indicating deep convective heating over the TP. Observational results indicate that a different RWT exists during the developing and decaying periods of synoptic TPUHS events, when the anomalous TPUHS develops from a relatively shallower to a deeper TP heat source.

To demonstrate that the TPUHS can indeed excite an RWT, and the RWTs forced by shallower and deeper TPUHS are different, we perform two numerical experiments using the LBM. From the different vertical heating profiles between the TPUHS-developing and TPUHS-decaying periods in observation shown in Figure 2, the maximum of the temperature anomalies in the shallow and deep convective heating stages is 0.32 K and 0.25 K, respectively. In order to obtain a more obvious circulation anomaly signal, we quadruple them when we design the numerical experiments. The first experiment is named the ‘shallow’ experiment, where we set the maximal TP heating (1.28 K d⁻¹) at about the 300-hPa level in the LBM, to mimic the shallow convective heating (Figure 3(a)). The second experiment is named the ‘deep’ experiment, where the maximal TP heating (1 K d⁻¹) is set at about the 150-hPa level, to mimic the deep convective heating (Figure 3(b)).
The 200-hPa geopotential height responses to the ‘shallow’ forcing clearly show an RWT pattern stretching from the TP to the west coast of America, with the three anomalous high centers over the TP, over the Okhotsk Sea and over the west coast of America, and the two anomalous low centers near the Korean peninsula and Alaska (Figure 4 (a)). The successive weakening of the anomaly centers in the LBM with the increase in their distance from the TP forcing region may be related to the linearity of the model. It should also be noted that warm temperature center will be located below 200 hPa because the prescribed maximal heating over the TP is below 200 hPa, thus leading to the formation of an anomalous high at 200 hPa over the TP. Also, this anomalous high acts as a wave source that

Figure 1. The Rossby wave train patterns associated with the (a) shallow and (b) deep convective heating of the TP obtained by the lead/lag regressions of the 200-hPa geopotential height anomalies (units: gpm; interval: 4; black dots indicate significance at 0.1 level) against the TPUHS index when the TPUHS index leads for −3 days and 8 days, respectively.

Figure 2. The (a) shallow and (b) deep convective heating profile obtained by the lead/lag regressions of the area-mean air temperature (units: K) over the TP against the TPUHS index when the TPUHS index leads for −6 days and 1 day, respectively. The abscissa is the amplitudes of the area-mean heating over the TP (units: K d\(^{-1}\)); the ordinate is the pressure level (units: hPa) in (a) and (b).
generates an RWT pattern. The 200-hPa geopotential height responses to the ‘deep’ forcing also present a clear wave train pattern, which extends from the TP region to Alaska with the three anomalous low centers, respectively, over the TP, Japan, and near Alaska, and two anomalous high centers over the south of Lake Baikal and the east of Kamchatka peninsula (Figure 4(b)). It is clear that, dominating the TP is an anomalous low in the ‘deep’ experiment, which differs from that in the ‘shallow’ experiment. As the prescribed maximal heating over the TP is above 200 hPa, the warm temperature center will occur above 200 hPa, which is favorable for the formation of concave isobars at 200 hPa, thus resulting in an anomalous low over the TP at 200 hPa. Furthermore, due to the different response of local circulation anomalies over the TP in these two experiments, the corresponding RWT patterns also differ.

These model results show that the atmospheric responses to a shallow and deep TPUHS do exhibit different RWT patterns that largely resemble those in observation. Besides, the model results also indicate that the TPUHS can indeed excite an RWT, and the shallow/deep TPUHS can force different RWTs that have different effects on the circulation anomalies in boreal summer.

4. Summary

This study investigates the different RWTs associated with the TPUHS that is relatively shallower and deeper in boreal summer. The results in observation manifest the different RWT patterns between the developing and decaying periods of synoptic TPUHS events, when the anomalous TPUHS develops from a relatively shallower to a deeper TP heat source. Moreover, based on the results of the atmospheric response to idealized shallow and deep convective heating in the LBM, we can see that the shallow convective heating over the TP can induce an RWT pattern stretching from the TP to the west coast of America, with the three anomalous high centers over the TP, over the Okhotsk Sea and over the west coast of America, and the two anomalous low centers near the Korean peninsula and Alaska; the atmospheric responses to the deep convective heating over the TP also present a clear wave train pattern,
which extends from the TP region to Alaska, with the three anomalous low centers over the TP, Japan and near Alaska, and the two anomalous high centers over the south of Lake Baikal and the east of Kamchatka peninsula. These model results indicate that the TPUHS can indeed excite an RWT, and the shallow and deep TPUHS can force different RWTS, which have different influences on the circulation anomalies in boreal summer. Furthermore, different diabatic heating (deep/shallow convective heating) over the TP can cause a different response of the temperature anomaly over the TP, thus resulting in a different geopotential height anomaly over the TP. Therefore, due to the different response of local circulation anomalies over the TP, the corresponding RWT patterns also differ. But beyond the diabatic heating process, the adiabatic cooling process related to the RWTS may also contribute to the temperature anomaly over the TP. Therefore, in the future, more complex models are needed to further understand the physical processes and mechanisms involved in the effects of the TPUHS on circulation anomalies, because of the limitations of the LBM.

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Disclosure statement

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