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An important mechanism sustaining the atmospheric "water tower" over the Tibetan Plateau

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Abstract. The Tibetan Plateau (TP), referred to as the "roof of the world", is also known as the "world water tower" because it contains a large amount of water resources and ceaselessly transports these waters to its surrounding areas. However, it is not clear how these waters are being supplied and replenished. In particular, how plausible hydrological cycles can be realized between tropical oceans and the TP. In order to explore the mechanism sustaining the atmospheric "water tower" over the TP, the relationship of a "heat source column" over the plateau and moist flows in the Asian summer monsoon circulation is investigated. Here we show that the plateau's thermal structure leads to dynamic processes with an integration of two couplings of lower convergence zones and upper divergences, respectively, over the plateau's southern slopes and main platform, which relay moist air in two ladders up to the plateau. Similarly to the CISK (conditional instability of the second kind) mechanism of tropical cyclones, the elevated warm–moist air, in turn, forces convective weather systems, hence building a water cycle over the plateau. An integration of mechanical and thermal TP forcing is revealed in relation to the Asian summer monsoon circulation knitting a close tie of vapor transport from tropical oceans to the atmospheric "water tower" over the TP.

1 Introduction

It has long been known that the Tibetan Plateau (TP) as the third pole and "the world water tower" (Xu et al., 2008; Qiu, 2008) plays an important and special role in global climate and energy–water cycle. In particular, due to its elevated land surface and thus enhanced sensible heating, the TP becomes a unique heat source, nonexistent in any other part of the world (Flohn, 1957; Yeh et al., 1957; Yanai et al., 1992; Webster et al., 1998; Wu and Zhang, 1998; An et al., 2001; Sugimoto and Ueno, 2010). From its topographic structure, we know that the TP possesses steep slopes with dramatic rising of land surfaces on its south and east rims. Over the plateau, however, the TP extends into the north and west extensively in a relatively flat fashion; thus being presented as an oversized "mesa", although there are large mountains over the TP triggering convective cloud formations. In the boreal summer, this massive "mesa" is strongly heated by solar radiation. One of the consequences of this thermal structure is its virtual functionality serving as an "air pump", which attracts warm and moist air from low-latitude oceans up to the north into the Asian continent (Wu et al., 1997, 2012). During boreal winter, this flow pattern reverses with the TP's cooling source (Ding, 1994). Hence, the TP's role in the world's largest monsoon system is explained.

Furthermore, classic studies (Flohn, 1957; Yeh et al., 1957; Luo and Yanai, 1984; Wu and Zhang, 1998; Yanai et al., 1992; Hahn and Manabe, 1975; Webster et al., 1998; Xu et al., 2010; Ye and Gao, 1979) also indicate that the rising

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warm and moist air from the tropical oceans tends to be deflected predominantly to the right (carried along the mid-latitude westerlies), once they encountered the sharply elevated plateau. The deflected warm and moist air forms the well-known "southwesterly monsoonal flows", transporting water vapor down to southeastern China, plausibly explaining the abundant water resources in these areas (Xu et al., 2010, 2012; Zhao and Chen, 2001) (see the small rectangle in the low reach of the Yangtze River basin in the upper panel of Fig. 1). The lower southwesterly driving warm and wet air transport from tropical oceans to these areas of southeastern China in the summer season could also be induced by the conjunction of the TP and Eurasia continental thermal forcing (Duan and Wu, 2005).

However, many environment resource surveys (Lu et al., 2005; Yao et al., 2012; Qiu, 2008) confirm that the TP itself contains a large amount of water resources in the form of snowpack, glaciers, lakes, rivers and aquifers (the large rectangle over the TP in the upper panel of Fig. 1). The TP region contains one of the richest water resources and constitutes one of the densest hydrological systems in the world. Xu et al. (2008) identified the role of TP as the world water tower, and elucidated how a hydrological cycle is completed over the plateau and its surrounding areas, and how atmosphere is able to supplement and reinforce the water that has been continuously transported away from the TP. These studies certainly indicate that despite the fact that a large amount of water vapor is deflected to southeast China, there must be an appreciable amount of moist flows that are able to climb over the TP, supplying and depositing necessary amounts of water onto the TP, to make up the depleting surface flows.

In this study focusing on the climate mean in boreal summer, we investigate the mechanism in which a portion of moist air reaches over the TP to maintain the atmospheric "water tower", as shown with high vapor contents over the TP in the lower panel of Fig. 1. The mechanism depicts an understanding of dynamic and thermodynamic processes forcing the moist air up to the plateau. In particular, a coupling of two "dynamic pumps" with the CISK (conditional instability of the second kind) mechanism similar to the typhoon's thermal forcing, contiguous horizontally but staggered vertically, are revealed. The two "water connected pumps" will mutually support each other in such a way that they ladder and relay the moist air over the elevated plateau.

2 Data and method

In this study, we used the reanalysis meteorology data of years 2000–2009 from the Research Data Archive at the US NCEP (National Center for Atmospheric Research), Computational and Information Systems Laboratory (doi:10.5065/D6M043C6) for all atmospheric variable analyses, and the cloud cover fraction data derived from the Chinese meteorological satellite FY-2F for convective cloud analyses. Following the studies of Yanai (1961), Yanai and Johnson (1993), Yanai and Tomita (1998), the apparent heat source (Q_1) and apparent moisture sink (Q_2) are calculated. Atmospheric heat sources and moisture sinks are respectively gauged with the Q_1 and Q_2. As Q_1 includes Q_2 and radiative heating, here we concentrate only on the collective effect of apparent heating (Q_1) over the TP. The heat source column (in units of $\mathrm{W\,m^{-2}}$) over the TP is obtained with both horizontal and vertical integration of Q_1 over the TP area of 78–103° E and 28–38° N covering the most region with the altitude higher than 3000 m (see the large TP rectangle in the upper panel of Fig. 1) to form a one-dimensional variable representing the TP thermal forcing. The correlation coefficients between the TP heat source column and the meteorological variables (divergence, U, V and W components of wind and vapor transport flux) are calculated to build their horizontal and vertical distributions of correlations. Zonal, meridional and vertical components of the correlation vector are respectively derived through the correlation coefficients of the TP heat source column to U, V and W components of vector of wind and vapor transport flux, indicating the variations in wind and vapor transport flux induced by the TP thermal forcing.

3 Results

3.1 Elevated heat and wet islands over the TP

The upper panel in Fig. 2 depicts the vertical distribution in zonal differences of air temperature and specific humidity averaged along 93–94° E around and over the TP, and these differences are calculated respectively by subtracting air temperature and specific humidity in summer (June, July and August) averaged over 2000–2009 from their zonal means in the Northern Hemisphere. A "warm–wet island" elevated in the middle troposphere over the TP is identified from the positive differences of air temperature and humidity over the TP (upper panel of Fig. 2). On average, the urban temperature is 1–3 °C warmer than surrounding rural environments (Voogt and Oke, 2003; Zhao et al., 2014), while air temperatures over the TP is 4–6 °C and even up to 6 °C higher than its surrounding atmosphere at the same altitude in summer (upper panel of Fig. 2). This heat island over the massive TP exceeds that of any urban agglomerations in the world in both intensity and area.

A high total solar irradiance of 1688 $\mathrm{W\,m^{-2}}$, 23 % higher than the solar constant was observed over the TP (Lu et al., 1995), as the plateau absorbs a large proportion of solar radiation. Because the TP is the region with strong solar radiation exceeding the solar constant in the world, air temperatures over the TP could be 4–6 °C and even up to 10 °C higher than its surrounding atmosphere at the same altitude in summer (Yeh and Chen, 1992). The high solar radiation on the TP could result in a strong sensible heat exchange in

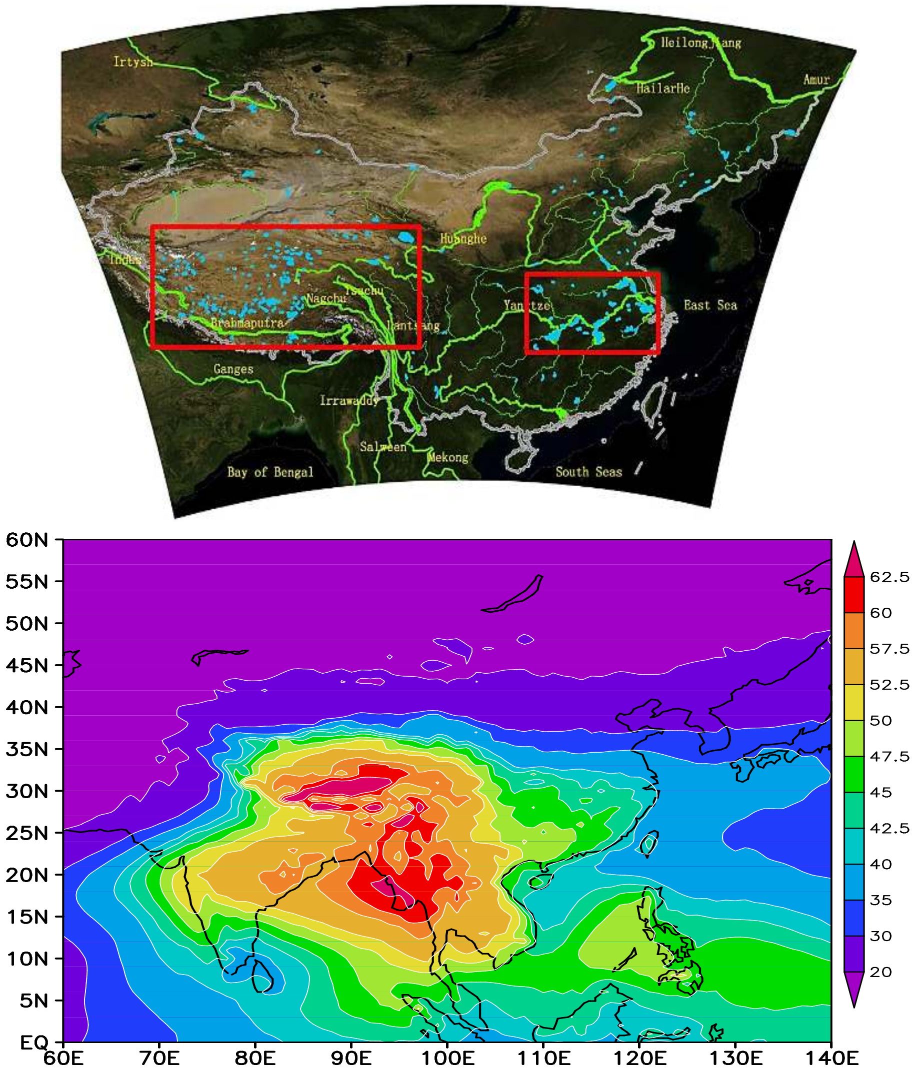

Figure 1. Geographical distribution of water sources in glaciers (snowpack), rivers and lakes over China with white, green and light blue colors, respectively. Two major lake groups are marked by two red rectangles in the TP and eastern China (upper panel). Column vapor content (10^{-2} g cm^{-2}) over 500 hPa in summer averaged over 2000–2009 (lower panel).

the surface layer. Air temperature is a measure of the sensible heat content of the air. A good positive correlation between surface air temperature and vertical velocity at 500 hPa over the TP (lower panel of Fig. 2) reflects an important role of the surface sensible heating and its vertical transfer in building the heat and wet islands over the TP. The surface heating from the plateau could trigger the air ascent driving the vertical water vapor transport up to the free troposphere. Even if the surface heat fluxes from the plateau have a negligible impact on the South Asian summer monsoon circulation strength (Boos and Kuang, 2010), they could greatly impact the convective precipitation over the TP. As shown in the upper panel of Fig. 2 for the vertical structures of the elevated heat and wet islands, a heat source column reaching the upper troposphere over the TP could be visualized from the distribution of positive temperature differences with two high cores, respectively, within near-surface layers and between 200 and 400 hPa (upper panel of Fig. 2). Due to a monotonic decrease in surface sensible heating with increasing elevation, the "hollow heat island" with a warm core at 200–400 hPa could be dominated by the latent heating released from the convective cloud and precipitation processes over the TP in association with the vertical structure of air vapor in the wet island over the TP (upper panel of Fig. 2).

The elevated land surface with a strong radiative heating could make the massive TP "mesa" more favorable for initiating a large number of convective cells. These convective cells over the plateau often give rise to precipitation over the TP and its surroundings in the boreal summer (Xu et al., 2012; Sugimoto and Ueno, 2010). In fact, the annual

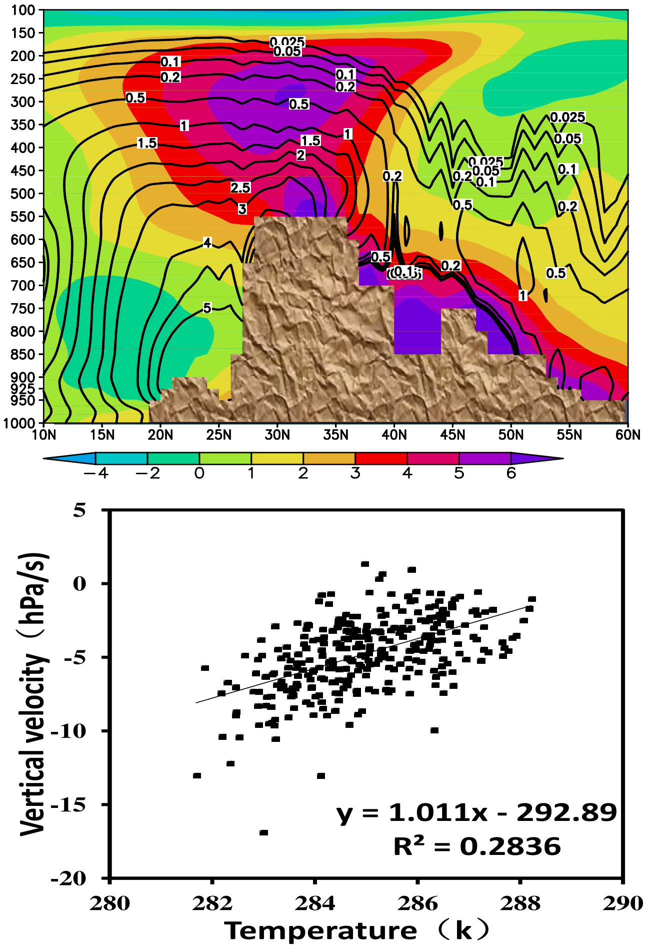

Figure 2. Vertical sections of air temperature (°C; filled contours) and specific humidity ($\mathrm{g\,kg^{-1}}$; contour lines) differences relative to the zonal means along 93–94° E in summer averaged over 2000–2009. The plateau section is marked with soil color (upper panel). A scatter plot of surface air temperature and vertical velocity at 500 hPa in the TP region in July 2000–2009 (lower panel).

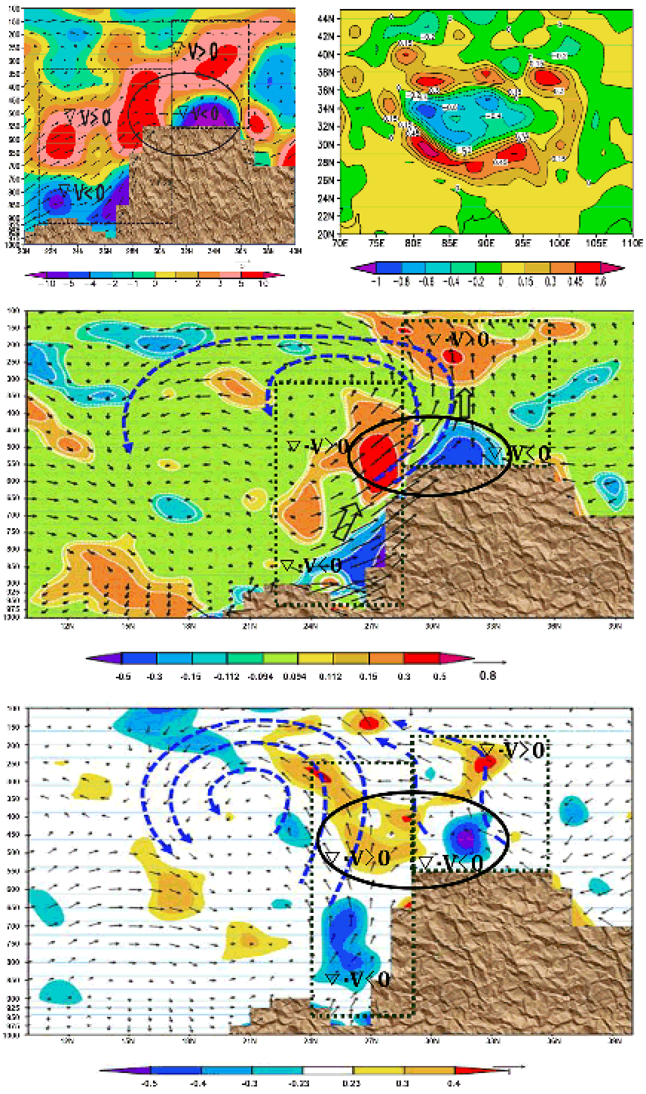

Figure 3. Vertical sections of wind vectors and divergences (filled contours) for summer averaged over 2000–2009 along 93–94° E (left upper panel); Distribution of summertime 500 hPa divergence averaged over 2000–2009 (right upper panel). Vertical sections of the correlations of the daily TP heat source column Q_1 to the divergences (filled contours) and the correction vectors of daily Q_1 to V- and W-wind components in July 2000–2009 along 93–94° E with the meridional circulations and the uplifting vapor transport denoted by blue dash lines and black arrows, respectively (middle panel). Vertical sections of the lag-correlations of TP heat source column Q_1 at 10 prior days to divergences and the lag-correlation vectors in the meridional circulations in July 2000–2009 along 93–94° E (lower panel). In all panels, two couplings of lower convergence zones (LC) and upper divergences (UD) are denoted with $\nabla \cdot V < 0$ and $\nabla \cdot V > 0$ in two dotted rectangles and the interaction of LC in the TP and UD over the southern slopes in the black ovals. The plateau section is marked with soil color.

occurrences of convective clouds (cumulonimbus) over the TP are observed with 2.5 times of the regional mean over the other areas of China (Xu et al., 2002), and the TP region is regarded as a high frequency center of cumulonimbus or mesoscale convective systems (MCSs) in China (Sugimoto and Ueno, 2012), which is also confirmed by the mean distribution of convective clouds over the TP (see Sect. 3.3) in the plateau low vortex region (upper panel of Fig. 4).

3.2 Processes of water vapor transport upward the TP

Based on the differences of temperature and humidity at a given pressure level of the atmosphere over the TP and over adjacent non-elevated areas in boreal summer, the vertical structures of heat source column and wet island on the TP are characterized in Fig. 2 (upper panel) with the particularly surprising "hollow heat island" between 200 and 400 hPa in

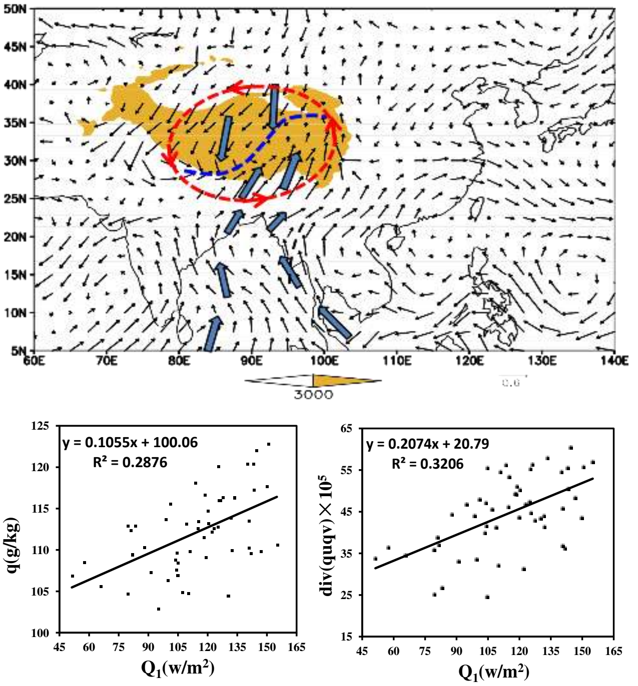

Figure 4. Correlation vectors of the TP heat source column strength Q_1 to the horizontal moisture transport flux components over summer of 1957–2009. A shear line between southward and northward air flows (light blue arrows) and the plateau low vortex over the TP are marked with blue and red dash lines, respectively. The TP region with the altitude of higher than 3000 m is shaded in yellow contour (upper panel). Correlations of the heat source strength Q_1, total water vapor q and net vapor transport flux divergence (div) in the TP air column in summer of 2000–2009 in scatter plots of Q_1 to q (left lower panel) and div (right lower panel).

the shape of “warm core” and “mushroom cloud” (high zonal air temperature deviation) over the TP. The vertical structure of the elevated wet island over the TP can also confirm that the large TP topography prevents dry and cool extratropical air from “ventilating” the moist and warm tropics and subtropics (upper panel of Fig. 2). It is particularly interesting that the TP “hollow heat island” structure is similar to the warm core of Typhoon-CISK process (Charney and Eliassen, 1964; Smith, 1997) in the company of the elevated wet island (upper panel of Fig. 2) and the meridional circulation with a strong convection (left upper panel of Fig. 3). The “CISK-like process” relaying warm–moist air up to the TP in two ladders is identified between two couplings of tropospheric lower convergence zones (LC) and upper divergences (UD) corresponding to (1) the LC in the South Asian monsoon regions and the UD over the southern TP slopes as well as (2) the LC on the TP main platform and the UD in the middle and upper troposphere over the TP (left upper panel of Fig. 3).

The strength of “heat source column Q_1” could be represented by the atmosphere column integration of apparent heat source Q_1 over the TP region. The middle panel of Fig. 3 presents the correlation vectors of the TP heat source column strength Q_1 over the TP to the W- and V-wind components at the vertical sections around the TP averaged in July 2000–2009. In this study, zonal, meridional and a vertical components of the correlation vector are derived through the correlation coefficients of the Q_1 to U- ,V- and W-wind (or transport flux) components, respectively, where the arrow length denotes the correlation combination with a longer arrow implying a better correlation, and the arrow direction means the direction of anomalous wind (or transport flux) induced by the TP thermal effect. Therefore, the middle panel of Fig. 3 indicates that the air ascent motions induced by the TP heating are profound over the TP during the summer monsoon period. The large topography of TP with the “hollow heat island” can force a water vapor pump with the strong upward air flows. A meridional circulation produced by the thermal effect of “hollow heat island” and the mechanical impact of the TP topography can not only result in the Asian summer monsoon circulations but also enhance the water vapor transport from the oceans crossing the Asian monsoon areas up to the TP (middle panel of Fig. 3). The strong divergences of the South Asian high in the upper troposphere are collocated with the near-surface convergence zones associated with the plateau low vortex, which is a favorable pattern for vertical circulation enforcing a strong water vapor uplift over the TP (left upper and middle panels of Fig. 3; upper panel of Fig. 4). The TP surface sensible heat and the latent heat release from the convective cloud and precipitation may maintain the vertical circulation driving the vapor transport up into the atmospheric “water tower” over the TP (lower panel of Fig. 2; Figs. 3–5). A water vapor pump with cloud convective activities is motivated in the near-surface air convergence zones over the TP, driven by the plateau heating (upper panel of Fig. 4; Fig. 6). The atmospheric “water tower” is set up by the air pump forced with the TP heating (Xu et al., 2008).

A coupling of two “dynamic pumps” with the CISK-like mechanism, contiguous horizontally but staggered vertically, are revealed with the cooperative interaction of the “heat source column” and the elevated wet islands over the roof of the world (see two dotted rectangles in the middle panel of Fig. 3). This interaction could be achieved with a positive feedback, when the forcing effect of the “heat source column” drives the water vapor flows climbing up the TP in the vertical motion, in turn, and the phase changes of water vapor to clouds and precipitation in the moist convection release latent heating intensifying the “heat source column” and especially the “warm core” in the upper troposphere associated with the South Asian high (Sugimoto and Ueno, 2012). The “heat source column” could enhance convergence zones at lower levels and divergences at upper levels in the troposphere for pushing the moist air up the TP (middle panel of Fig. 3; Fig. 4). There could be a mutual feedback between the UD on the southern plateau slopes and the LC on the TP platform through the dynamical interaction of the horizontally contiguous UD and LC (right upper and middle panels

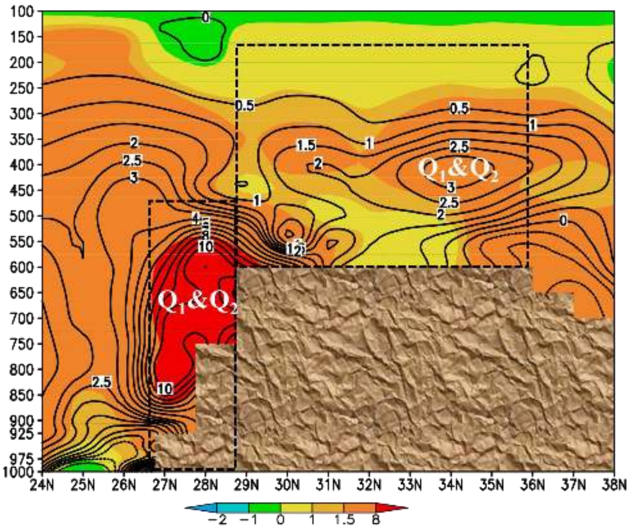

Figure 5. The vertical distributions of apparent heat source Q_1 (filled contours) and apparent moisture sink Q_2 ($\mathrm{W\,m^{-2}}$) averaged between 85 and 100° E in summer over 2000–2009. The Q_1 and Q_2 in two dash rectangles are produced with two ladders of CISK-like process respectively over the TP's southern slopes and main platform. The plateau section is marked with soil color.

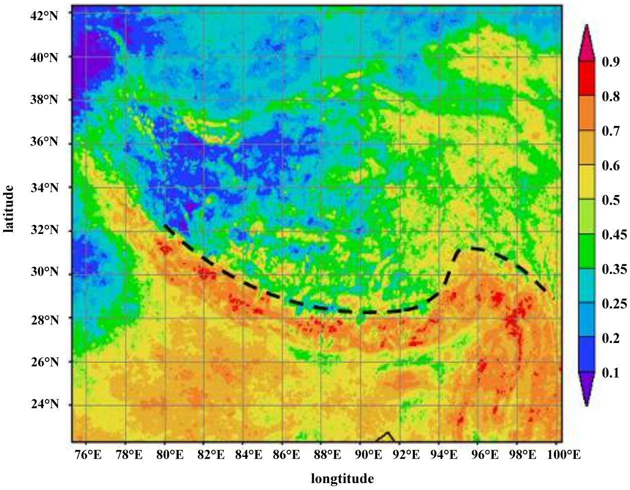

Figure 6. Mean distribution of cloud cover fraction in July 2008 (06:00 UT) derived from the Chinese meteorological satellite FY-2F. The black dash line separates the high and low amounts of cloud cover over the TP.

of Fig. 3). The UD over the southern TP slopes and the LC on the TP platform could be contributed by the water vapor flow acceleration at the inflection point between the steep southern slopes and the southern edge of TP platform with the mechanical TP impact on the air pump on the platform (upper and middle panels of Fig. 3).

The two ladders of "CISK-like process" over the South Asian summer monsoon region and the TP knit a close tie of vapor transport from tropical oceans to the atmospheric "water tower" over the TP (Fig. 3). The South Asian summer monsoon precipitation is produced in the first ladder of air vapor transport toward the TP atmosphere, which could be attributed to the TP topographical block at the steep southern slopes with less thermal impact (Boos and Kuang, 2010). The second ladder resulting in convective cloud precipitation over the large TP platform with less terrain obstacles for water vapor flows is dominantly controlled by thermal forcing of the "hollow heat island" in a large scale (Wu et al., 2012). The pump of the "hollow heat island" over the TP could not only attract air vapor transport from tropical oceans to the TP but also intensify the dynamic lift of air vapor on the southern slope of the TP for the Asian summer monsoon (middle and lower panels of Fig. 3). The dynamic structures of two couplings of tropospheric LC and UD with their interaction build up a meridional circulation in a two-ladder pump of moist air along the plateau (left upper and middle panels of Fig. 3), which could also be explained with the vertical distribution of apparent heat source Q_1 and apparent moisture sink Q_2 around the TP (Fig. 5). In Fig. 5 two couplings of high Q_1 and Q_2 areas are found between two couplings of tropospheric LC and UD, respectively, on two ladders in the process of water vapor transport up to the TP atmosphere (Fig. 3).

The convective clouds and precipitation of the plateau low vortex or cyclone are triggered by the plateau heating. The CISK-like process is found to play an important role in the local low vortex development for the TP precipitation (Qiao and Zhang, 1994).

The good correlations of the strength of "heat source column" Q_1 to the total water vapor and to the net transport flux divergence over the TP (two lower panels of Fig. 4) further interpret a large-scale effect of "CISK-like mechanism" with a positive feedback among the heat source column, the vertical convection and the water vapor supply for the atmospheric "water tower" over the TP. The two ladder "CISK-like mechanism" is a key process attracting water vapor toward the TP for building the TP's "water tower" in Asian water cycle. To further discover the process initiating the upward transport of water vapor flows over the TP, the lag correlations of the TP's heat source column Q_1 at 10 prior days to the divergences and the meridional circulation are analyzed in the lower panel of Fig. 3, which reflect that the plateau heating could initiate and trigger the vertical circulations for the "hollow heat island" process with a leading effect of the heat source column on water vapor transport toward the TP.

3.3 Cloud distribution over the TP

The TP region is identified as a frequent occurrence center of MCSs in China (Sugimoto and Ueno, 2012). In association with Asian summer monsoons, the summertime convective clouds bring the precipitation over the TP and its surroundings (Xu et al., 2012; Sugimoto and Ueno, 2010). To further clarify the atmospheric "water tower" over the TP in Asian water cycle, Fig. 6 presents the spatial distribution of total cloud cover over the TP and its surrounding area averaged in July 2008.

During the Asian summer monsoon period, the dense cloud covers exist over the regions from the Bay of Bengal, South Asian monsoon region, to the southern TP (Fig. 6). As characterized with the correction vectors of the column heat source over the TP to the moisture transport over and around the TP (middle panel of Fig. 3), two convergence zones of moisture transport fluxes $(\nabla\cdot qV < 0)$ are found on two ladders over the plateau's southern slopes and main platform during the moisture transport from the oceans up to the TP, resulting in these regions of dense cloud covers shown in Fig. 6. It is noteworthy that the high cloud amounts are zonally concentrated between the steep southern plateau slopes and the shear line of the plateau low vortex over the TP (upper panel of Fig. 4; Fig. 6) with the monthly mean cloud cover fractions up to 90 %, which could resulted from the "CISK-like mechanism" for building the TP's atmospheric "water tower" (Fig. 3). Over the large TP platform with relatively plain terrain, the monthly mean cloud covers of around 45 % are mostly observed on the central-eastern region with less cloud cover over the northwestern TP, depending on the moisture transport across the TP. The plateau low vortex over the TP and the southward air flows with less moisture on the north of the shear line could lead to the less cloud cover in the northwestern platform of TP (upper panel of Fig. 4).

The observed cloud distribution over the TP confirms that the "CISK-like mechanism" is an important mechanism sustaining the atmospheric "water tower" over the TP. Connecting with the cloud and precipitation in the atmospheric "water tower", the plausible hydrological cycles could be realized between tropical oceans and the TP.

4 Conclusions and discussions

The present analyses clearly indicate that the TP presents itself as a "warm–wet island". The surface heating over the plateau leads to a low-pressure center causing flow convergence at low levels of the plateau and subsequently triggers vertical motion. This convective system will result in plateau clouds and precipitation, which would explain abundant water storage in the atmosphere over the TP and its surrounding regions.

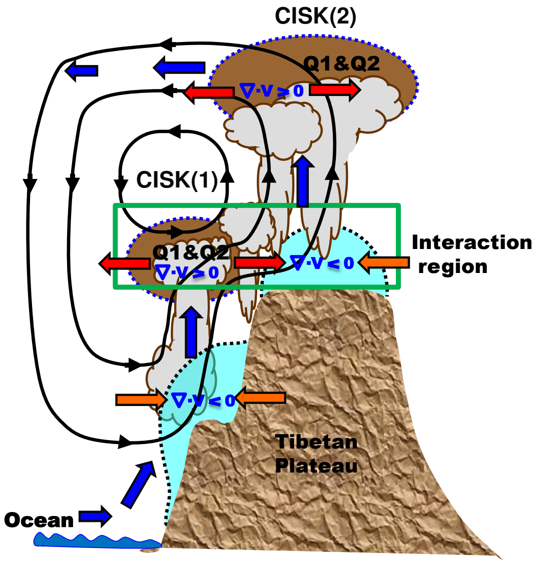

Figure 7. A diagram of the summary on two ladders of CISK-like processes with two couplings of heat source Q_1 and moisture sink Q_2 over the TP's southern slopes and main platform in forcing water vapor flows climbing up the TP, which is marked with soil color.

The classic Asian summer monsoon theory elucidated an "air pump" mechanism in relation to the TP. The warm–moist air from the low-latitude oceans is drawn toward the plateau by this air pump. Our analysis on the relationship between the "heat source column" over the TP and warm–moist air transport in the present study further reveals a CISK-like mechanism on water vapor suction up the plateau. An appreciable portion of warm–moist air converges at the foot of the south rim of the plateau. The convergence of the warm–moist air ascends along the plateau's slope and diverges at about the altitude of the plateau top. This divergence flow enforces the convergence at the heated low-pressure center over the TP and feeds in the convective system with warm–moist air, which results in the clouds and precipitations for the atmospheric water tower over the TP.

These dynamic and thermodynamic processes depict a coupling of two CISK type systems, both with convergence at low levels and divergence at upper levels, but the systems are horizontally contiguous as well as vertically staggered. The two systems display a mutually supportive mechanism with the mechanical and thermal TP impact between the southern slopes and the platform of the TP in the interaction region marked in Fig. 7. It is this coupling that ladders the moist air up to the plateau building the atmospheric "water tower" over the TP.

In this study, the mean climate of air vapor transport to the TP is investigated based on the summertime averages over the past years, and a two ladder "CISK-like mechanism" is identified as a key process sustaining the atmospheric "water tower" over the TP. The role of intraseasonal variability, synoptic-scale system activities and diurnal variation in the atmospheric heat source and moisture over the TP (Sugimoto et al., 2008; Fujinami and Yasunari, 2004) will be considered in a future study on the warm–moist air transport up to the plateau. It should be emphasized that considering the quality of reanalysis data over and around the TP, a comparison between NCEP/NCAR and some other reanalysis data sets such as JRA-25, ERA-Interim, or MERRA is necessary in further work. Furthermore, the two CISK type system revealed from this observational analysis need to be further studied with numerical models to understand the mechanism to work.

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