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Atmospheric Chemistry and Physics Discussions
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A vertical transport window of water vapor in the troposphere over the Tibetan Plateau with implication for global change

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Abstract

By using the multi-source data of meteorology over recent decades, this study discovered a summertime "hollow wet pool" in the troposphere with a center of high water vapor over Asian water tower (AWT) on the Tibetan Plateau (TP), where is featured by a vertical transport "window" in the troposphere. The water vapor transport in the upper troposphere extends from the vertical transport window over the TP with the significant connections among the Arctic, Antarctic and TP regions, highlighting an effect of TP's vertical transport window of tropospheric vapor in the "hollow wet pool" on global change. The vertical transport window was built by the AWT's thermal forcing in associated with the dynamic effect of the TP's "hollow heat island". Our study improve the understanding on the vapor transport over the TP with an important implication to global change.

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1. Introduction

The Tibetan Plateau (TP) is the largest high terrain in the world, known as "the roof of the world" with an averaged altitude over 4,000 meters. The rivers, such as the Yangtze River, Yellow River, Lancang River and Ganges River, are all originated from the TP, which is regarded as the "Asian Water Tower" (AWT) (Xu et al., 2008). The Three-River-Source (Yangtze, Yellow, and Lancang Rivers) region (TRSR) in the eastern TP is the core area of the AWT (Xu et al., 2014). The observed "CISK-like mechanism" is an important mechanism sustaining the atmospheric "water tower" over the AWT. Connecting with the cloud and precipitation in the AWT, the plausible hydrological cycles could be realized with the transport of water vapor from tropical oceans up to the TP (Xu et al., 2014).

Water vapor plays an important role in global environment and climate changes (Tian et al.,2009; Solomon et al.,2010). The ratio of strong convective clouds to total clouds over the Tibetan Plateau (TP) is about 5 times to the global ratio, and the frequent occurrences of strong convective clouds could be largely attributed to the TP's large topography (Luo et al.,2011; Su et al.,2006). The water vapor in the tropical upper troposphere is mainly originated from the tropical lower troposphere through convective transport and evaporation of convectively transported or in situ produced cloud ices (Tian et al.,2004; James, et al.,2008). Water vapor was first lifted by convection over the Bay of Bengal and the South China Sea and then transported upwards the tropical tropopause layer via the monsoon anticyclonic circulations towards Northwest India (Yanai, et al.,

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1973; Chen, et al., 2012). TP is a moisture sink in summer, having a net moisture convergence of 4 mm/day, where the convergence was enhanced from 1979 to 2018 (Feng and Zhou, 2012; Xu, et al., 2020). In general, Asian monsoon circulation provides an effective pathway for regional water vapor transport to the TP (Wang, et al.,2017). An important role of the anticyclone over the TP is verified in the exchange of water vapor between the troposphere and stratosphere (Garny, et al., 2016; Fu, et al., 2006) . Many studies have been focused on the transport of water vapor into upper troposphere and lower stratosphere from the tropical oceans to the TP (Chen, et al., 2012; Wang, et al.,2017; Xie, et al.,2018; Randel, et al.,2013) . However, not enough attention has been paid to the vertical transport of water vapor in the troposphere over the TP.

The following questions are also of great concern in the TP' vertical transport of water vapor study with implication for global change, for example, what is the forcing mechanism forming the vertical transport window of water vapor in the tropophere on the TP? How is the AWT's special column constructor built for the vertical transport of water vapor in the TP' troposphere? From the perspective of global atmospheric energy and water vapor exchanges, this study characterizes a window of water vapor vertical transport within the troposphere over the TP and the implication for global change.

2. Data and Methods

The daily meteorological data of cloud amount are provided by the meteorological observatories in the TP in the period of 1979 to 2016. The AIRS remote sensing products of water vapor and the ECMWF-interim data of meteorology are used in this study.

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In this study, the inverse algorithm is used to calculate the apparent heat source Q1, and the formula is as follows(Su et al.,2006) :

$$Q_1 = C_p[\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T + (\frac{p}{p_0})^k \overline{\omega}\frac{\partial \theta}{\partial p}] \qquad (1)$$

where T is air temperature; ω is the vertical velocity at the p coordinate, P0 = 1000 hPa; $k = {}^{R}/_{C_p}$; V is the horizontal wind vector; θ is the potential temperature.

Vertical integration of Q_1 is expressed as:

$$\langle Q_1 \rangle = \frac{1}{g}\int_{p_t}^{p_s} Q_1\, dp \qquad (2)$$

where p_s is the surface air pressure, p_t is the top air pressure, here taken as 100hpa.

In order to analyze the relationship between water vapor source tracing and its channels in the atmospheric water cycle over the TP, the correlation vector calculation was used to calculate the temporal and spatial variations of the water vapor transport channel. The expression is:

$$\vec{R}(x,y) = R_u(x,y)i + R_v(x,y)j \qquad (3)$$

where $\vec{\boldsymbol{R}}(\boldsymbol{x},\boldsymbol{y})$ represents the correlation vector in which R_u *(x, y)* represents the correlation coefficients between rainstorm or precipitation frequency and the component of latitudinal water vapor flux qu, and R_v *(x, y)* represents correlation coefficients between rainstorm or precipitation frequency and longitudinal water vapor flux components qv.

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3. Results and discussion

3.1 The structures of vertical transport window of water vapor over the TP

With the use of satellite remote sensing productions from 2003 to 2016, the global distribution of the total water vapor from 500 hPa to 300hPa was calculated and shown in Figures 1a . The results indicate that there is a high value center of the water vapor in the mid- and upper troposphere over the TP, extending southwards to the Bay of Bengal, India and Northern Southeast Asia. It is worth noting that the fraction of strong convective cloud to the total cloud ranges from 4.0 % to 21.0 % in the TP, and the TP during the summer season is dominated by the latent heat release (Fu et al.,2006; Dessler et al.,2006; Gao et al.,2014). The intense mesoscale convective activity and the "massive chimney effect" of huge cumulonimbus cloud continue to transport heat and water vapor to the upper troposphere(Fu et al.,2006; Xie et al.,2018) . Based on Chinese Third Tibetan Plateau Experiment-Observation of Boundary Layer and Troposphere (2014–2017), it is observed that the mean cloud-top height was around 11.5 km (a.s.l.), and its maximum value exceeded 19 km, and the mean cloud-base height was 6.88 km (a.s.l.) during the observation period, reflecting the deep convection and its impact on the upper troposphere.

3.2 Global effect of the vertical transport window over the TP

The vertical section of the correlation coefficients along the south-north direction between the low cloud cover on TP and the global water vapor are presented in Figure 1b. It could be noticed that there exists the structures similar with the massive chimney

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between the convective cloud and the water vapor on TP (Figures 1b and 2a). It is remarkable that the high correlation area exceeding the 95 % confidence level expand towards the polar region of the southern and the northern hemisphere (Figure 1b), and the relation between the convective clouds and the global water vapor in the upper troposphere across the northern and southern hemispheres could be depicted.

The distributions of high positive correlation coefficients between low cloud cover over the TP and the global the water vapor in the upper troposphere are calculated by ECMWF-interim reanalysis data (Figure 3a). It can be found that there is a region with highest values of correlation coefficients in the upper troposphere (500 hPa-300 hPa), covering a banded area from the plateau to the lower latitude tropical zone to the polar regions, which could indicate the significant correlations between convective cloud activities on the TP and the global water vapor in the upper troposphere especially in the polar region of the southern hemisphere area (Figure 3a).

The Indian continent heats up in spring and summer, convection draws moisture northwards from the Bay of Bengal, Arabian Sea and Indian Ocean, leading to precipitation in the Himalayas and beyond (Yanai et al., 1973). In Figure 3b, it could be found that, driven by the strong apparent heat source, the warm and wet water vapor flows on the Asian water tower (AWT) over the TP coming from the low latitude ocean could build a remarkable channel. The key entrance to the water vapor passage is just the intersection of the Himalayas on the southern slope of the TP. This region constitutes a special canyon pass in the plateau with deep valleys, making a perfect entrance zone for

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the oceanic warm-wet water flows (terrain in the lower right corner of Figure 3c). According to the correlation analysis of water vapor transport, the water vapor source of the AWT can also be traced back to the ocean surface water vapor source region with water vapor positive correlation extreme value region in the Chagos archipelago of the Central Indian Ocean near 10°S south of the equator (Figure 3d), revealing that the TP is the confluence area of across hemispherical water vapor from the southern Indian Ocean.

3.3 The transport window of water vapor driven by the AWT

Through the correlation analysis of the whole layer of apparent heat source Q_1 over the plateau region, the three-dimensional structure of vorticity and divergence, it can be found that the apparent heat source Q_1 in TP are an important forcing factor (Figure 4). The results show that the air heat island over the AWT is located at 300-500 hPa (Figure 5). The Q_1 is significantly related to the convective cloud and its strong ascending movement (Figures 3b-3d), and there exists also a strong high-level anticyclone in the region of the AWT in the southeast of the plateau (Figure 3d). In addition, the lower troposphere is the center of strong convergence and strong vorticity (Figure 4). All these results reveal the effective "pumping effect" of the vertical configuration with low-level cyclonic circulation and high-level divergence with anticyclone circulation in TP (Figures 3b-3d). The strong confluence effect could be driven by the elevated heating on the TP in the middle troposphere with the water vapor flow, making a strong warm wet vapor transport channel connecting the water vapor source in the low latitude tropical ocean with the water vapor center over the core area of AWT.

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4. Conclusion

By using the multi-source data of meteorology over recent decades, this study discovered a summertime "hollow wet pool" in the troposphere with a center of high water vapor over AWT on the highly elevated TP, where is featured by a vertical transport window with the transport flux columns of water vapor in the troposphere. Driven by the strong TP's heat source, water vapor flows are connected the AWT over the TP with the low-latitude oceans. Significant correlations exist between convective activity on the TP and water vapor in the upper-troposphere especially in the polar region of the southern hemisphere. The water vapor transport from the TP's vertcial window in the upper troposphere extends globally towards the northern and southern hemispheres from the TP with the significant connections among the three poles of Arctic, Antarctic and TP regions, highlighting an effect of TP's vertical transport window of water vapor on global change. The vertical transport window was built by the AWT's thermal forcing in associated with the dynamic effect of the TP's "hollow heat island" as well as the effective "pumping effect" of low-level convergence with cyclonic circulation and high-level divergence with anticyclone circulation over the TP.

In this observational study, a conceptual model of the comprehensive relation of the TP region with the global energy and water cycles under the thermal forcing in the core region of the AWT was put forward for the vetical transport window of vapor (Figure 6), where the "core area" of AWT is the key entrance of the low-latitude warm and moist air, and the water vapor source was traced back to the Southern Hemisphere. The heat driving effect on the TP could contribute to the maintenance of vertical upward transport of the energy and water vapor. The water cycle in the AWT clearly displayed the connection

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with the warm-wet vapor source in the tropical oceans and the southern Indian Ocean. Our study depicted a comprehensive understanding on the vertical water vapor transport in the atmosphere over the TP with an important implication to global change.

Data availability

ERA-Interim (

ECMWF, https://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=pl/) reanalysis daily and monthly data are part of the European Center for Medium-range Weather Forecasts. AIRS Science Team/Joao Teixeira (2013), AIRS/Aqua L3 Daily Standard Physical Retrieval (AIRS-only) 1 degree x 1 degree V006, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: [Jan. 2019], 10.5067/Aqua/AIRS/DATA303.The low cloud data used in this study are derived from the Data Sets of Surface Meteorological Elements in China released by the National Meteorology Information Center, China Meteorological Administration， which can be found at

https://zenodo.org/record/5121157#.YPkRHqjitPY

(http://doi.org/10.5281/zenodo.5121157).

Author Contributions

Xiangde Xu, Chan Sun and Tianliang Zhao conducted the study design. Deliang Chen, Jianjun Xu and Shengjun Zhang analysed the observational data. Juan Li, Bin Chen,

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Yang Zhao, Lili Dong, Xiaoyun Sun, and Yan Zhu assisted with data processing. Xiangde Xu and Tianliang Zhao wrote the manuscript. Xiangde Xu, Chan Sun, Tianliang Zhao, and Jianjun Xu were involved in the scientific interpretation and discussion. All authors provided commentary on the paper.

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Conflict of interest

Xiangde Xu, Chan Sun, Deliang Chen, Tianliang Zhao, Jianjun Xu, Shengjun Zhang, Juan Li, Bin Chen, Yang Zhao, and Lili Dong declare that they have no conflict of interest.

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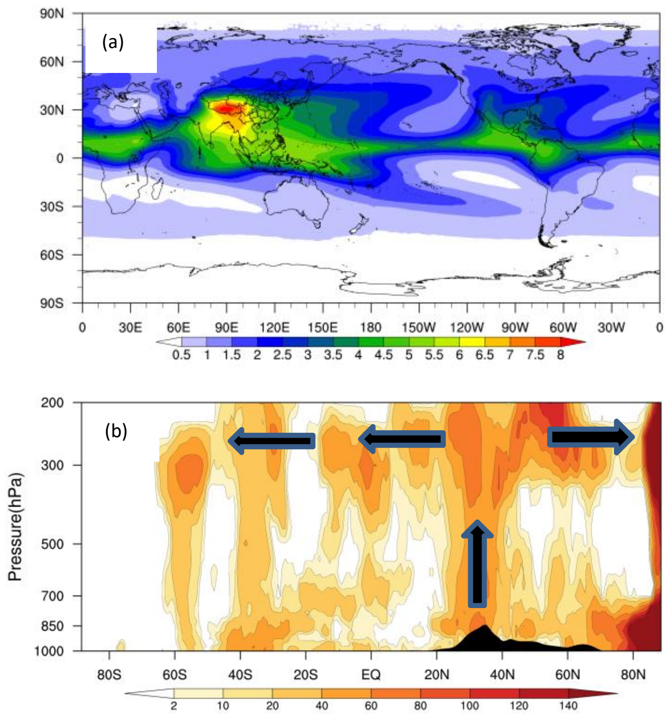

Figure 1.(a) the global distribution of the total water vapor from 300 hPa to 500 hPa based on the summertime AIRS data from 2003 to 2018, (b) the vertical section of the frequency (shaded) of the correlation coefficients passing the level of 90% confidence between summertime TP's low cloud cover and the water vapor at different vertical levels along the meridional direction averaged over 60oE - 180oE for 1979-2016 with the black arrows indicating the connections of TP's low clouds to global water vapor in the upper troposphere with high frequencies.

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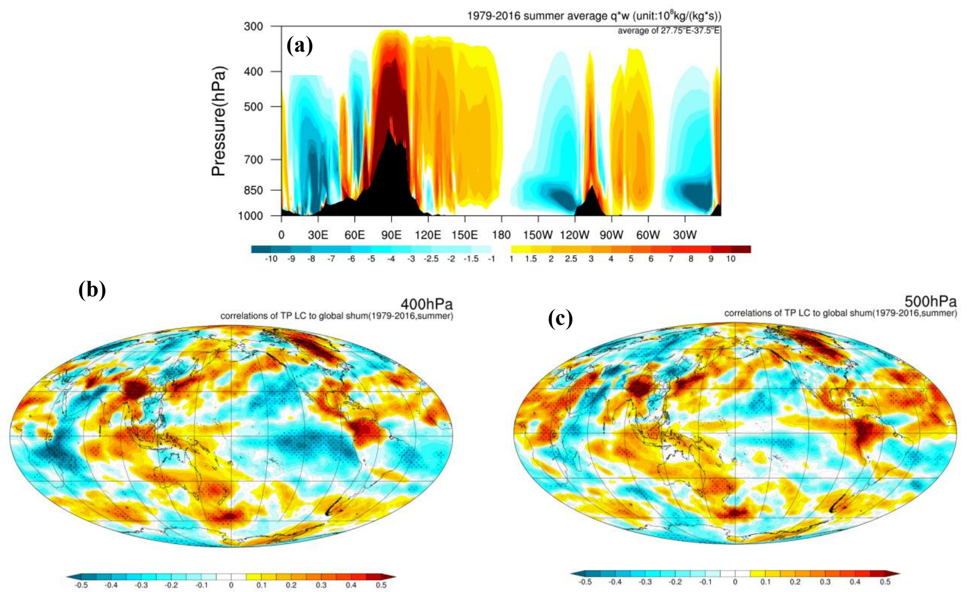

Figure 2 (a) Vertical section of vertical vapor transport flux averaged over 27.5-32.0°N in summers of 1979-2016; the spatial distributions of lag correlation coefficients of low cloud cover over the TP during May, June and July with the global specific humidity of the ECMWF-interim data in Summer from 1979 to 2018 at (b) 400 hPa and (c) 500 hPa.

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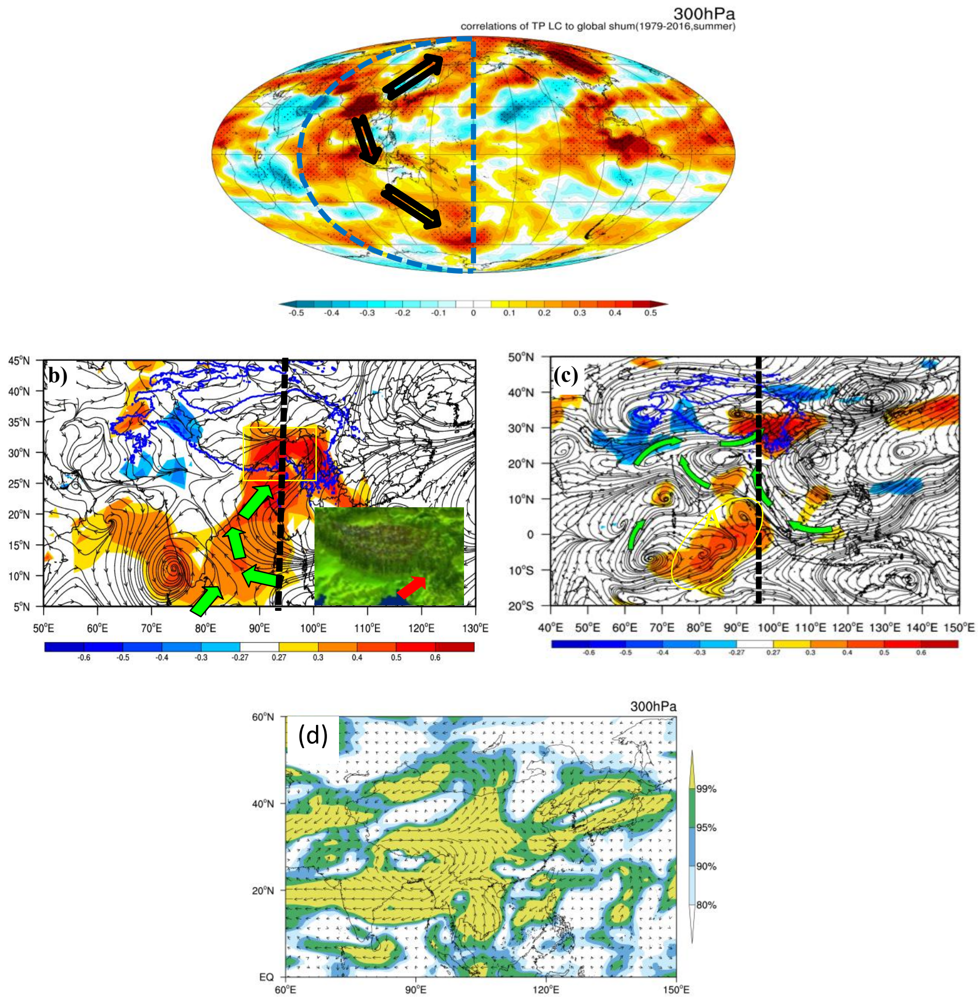

Figure 3. (a)The spatial distributions of correlation coefficients of low cloud cover over the TP with the global specific humidity of the ECMWF-interim data at 300 hPa in summers of 1979-2016 with the pathways of convective air to the troposphere, (b) the fields of correlation vectors (stream lines) of the TP-column Q_1 integrated over the TP region (80-102°E; 30-37.5°N) with the water vapor fluxes near the surface layer (the yellow rectangle frame denoting the AWT), (c) the water vapor fluxes at 500 hPa, (d)

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correlation vectors of TP-column Q1 integrated over the TP region (80-102°E; 30-37.5°N) to 300hPa vapor transport flux in July 2014-2016.

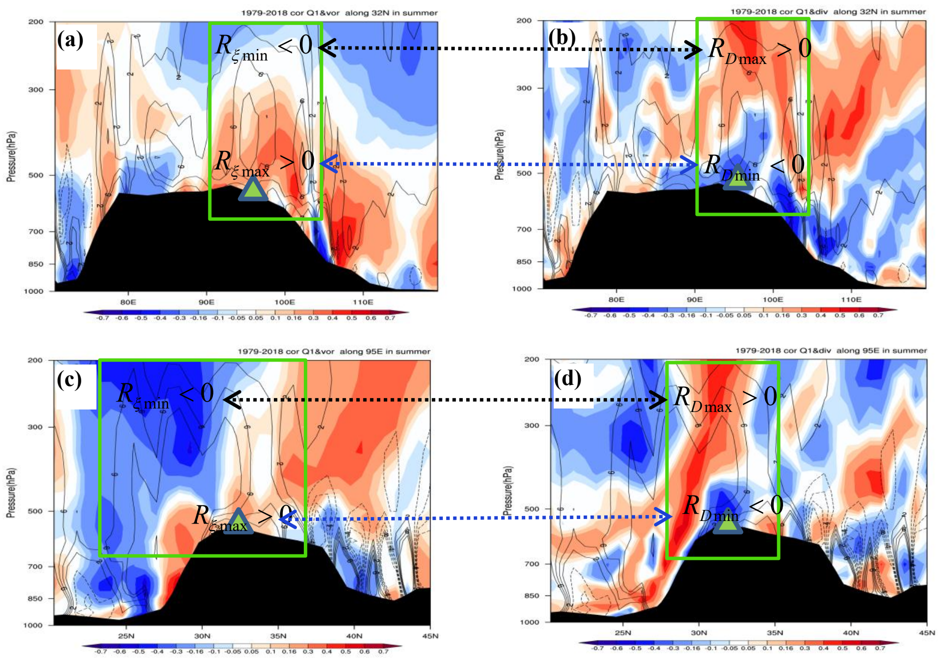

Figure 4. The vertical sections of (a) vertical motion (contours, in unit: 10^{-2} Pa·s^{-1}) and (c) correlation coefficients (shaded) between Q_1 and the vorticity as well as the correlation coefficients between Q_1 and the divergence (b, d) separately in the core region of the AWT, in which, a, b is along 32 °N, and c, d is along 95 °E. The green triangle is the AWT.

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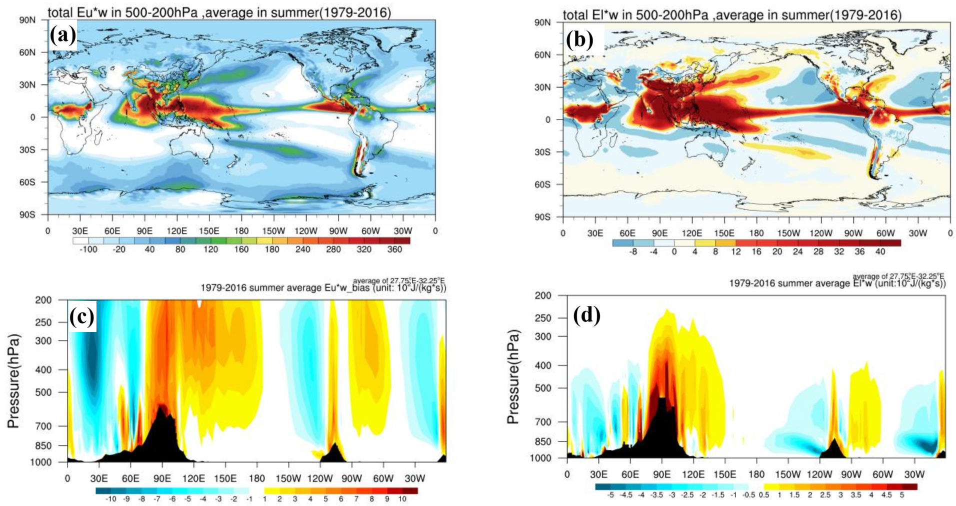

Figure 5. The summertime average distribution of (a) the total inner energy and (b) latent heat energy, as well as the vertical profiles of (c) the inner energy and (d) latent heat energy transporting upward from 1979 to 2017 along the east-west direction (27.5ºN-32.0ºN) over the TP.

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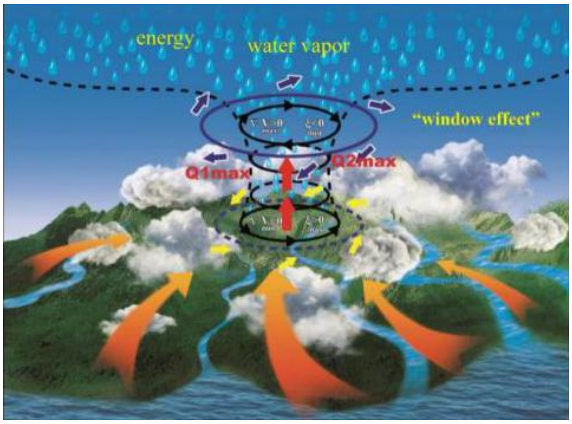

Figure 6. a diagram of water vapor transport to the troposphere driven by the thermal forcing of AWT over the TP.