Structure of the Western Tibetan Vortex inconsistent with a thermally-direct circulation

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Abstract

The Western Tibetan Vortex (WTV) is a large-scale circulation pattern identified from year-to-year circulation variability, which was used to understand the causal mechanisms for slowdown of the glacier melting over the western Tibetan Plateau (TP). A recent argument has suggested the WTV is the set of wind field anomalies resulting from variability in near-surface air temperatures over the western TP (above 1500 m), which, in turn, is likely driven by the surface net radiation. This study thereby evaluates the above putative thermal-direct mechanism. By conducting numerical sensitivity experiments using a global atmospheric circulation model, SAMIL, we find a WTV-like structure cannot be generated from a surface thermal forcing imposed on the western TP. A thermally-direct circulation generated by the surface or near surface heating is expect to cause upward motions and a baroclinic structure above it. In contrast, downward motions and a quasi-barotropic are observed in the vertical structure of the WTV. Besides, we find variability of the surface net radiation (sum of the surface shortwave and longwave net radiation) over the western TP can be traced back to the WTV variability based on ERA5 data. The anti-cyclonic (cyclonic) WTV reduces (increases) the cloudiness through the anomalous downward (upward) motions, causes more (less) input shortwave net radiation and thereby more (less) surface net radiations, resulting in the warmer (cooler) surface and near-surface air temperature over the western TP. The argument is constructive in encouraging examination of the radiative balance processes that complements previous studies.

Keywords Western Tibetan Plateau · Western Tibetan Vortex · Near-surface air temperature · Cloudiness · Surface net radiation · Thermally direct circulation · Generating mechanism

1 Introduction

A thermally-direct circulation is usually caused by a heating source in the lower- or mid-troposphere that warms up the air above/around it (e.g., Halley 1687; Ye and Wu 1998; Wu and Liu 2000; Holton 2004). The warm air then expands,

becomes less dense and then rises, resulting in a classic baroclinic structure, featuring as lower pressure in the mid-lower troposphere and at the near-surface level, but higher pressure in the upper troposphere (e.g., Holton 2004). In the mid- to high latitudes, where there is a stronger Coriolis force, these higher and lower pressure areas are usually associated with anti-cyclonic and cyclonic wind anomalies, respectively (e.g., Wu and Zhang 1998; Ye and Wu 1998). In reality, a thermally-direct circulation can involve more complex thermodynamic processes and features, such as condensing and latent heat release due to rising motions (e.g., Cornejo-Garrido and Stone 1977; Wu et al. 2007, 2015) and the stirring up of extra sub-vertical-circulations at its east and west edges due to vertical wind shears caused by its baroclinic structure (Wu et al. 2007, 2015). Its features may also vary under different background climates (e.g., Gill 1980; Jin and Hoskins 1995; Parker and Thorpe 1995). Thermally-direct circulations widely exist in Earth's atmosphere, the classic examples are the rising branches of

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the Hadley circulation (e.g., Halley 1687; Hadley 1735; Ferrel 1856; Thomson 1892) and the Walker circulation (e.g., Bjerknes 1969; Lau and Yang 2003). In short, the basic features of a thermally-direct circulation are: (1) anomalous rising motions and (2) a baroclinic structure (lower pressure at the ground surface and mid-lower troposphere, but higher pressure at the upper troposphere).

Forsythe et al. (2017) and Li et al. (2018) (hereafter collectively cited as FL1718) identified an atmospheric pattern or mode over the western TP in all four seasons and annual mean—termed the Karakoram/Western Tibetan Vortex (WTV, as shown in Fig. 1). Its intensity is measured by the Karakoram Zonal index (KZI). In the horizontal wind field, the WTV is shown as an evident anti-cyclonic (cyclonic) pattern with anomalous sinking (rising) motions at the center during its positive (negative) intensity phase (Fig. 1a, b). The WTV is identified in year-to-year circulation variability in all four seasons and annual mean (FL1718); the annual mean WTV on the mid-higher (250 hPa level) and the mid-lower (500 hPa level) troposphere extends from $\sim 50^\circ$ E to $\sim 105^\circ$ E (equivalent to ~ 5500 km, spanning 3–4 times the west–east breadth of the Indian Peninsula), centering at the head of the western TP with its eastern flank covering nearly the entire

TP (Li et al. 2018), also see Fig. 1a, b. So, the WTV is a large-scale circulation pattern; and it is generally different from the synoptic-scale or meso-scale systems prevailing on daily and sub-monthly time scales over the western TP, such as the western disturbance (Pisharoty and Desai 1956; Ramanathan and Saha 1972; Dimri 2004; Feng et al. 2014; Hunt et al. 2017, 2018) and the Tibetan Plateau vortices (e.g., Tao and Ding 1981).

The WTV is suggested (Li et al. 2019) not likely a thermally-direct circulation, as it has opposing vertical features (Fig. 1c) to a thermally-direct circulation: the anti-cyclonic WTV has a “warm high” structure at the near surface levels (Fig. 1b and Fig. 1c) above the western TP topography (i.e., the anti-cyclonic WTV is associated with warmer air temperature and higher pressure in the near-surface and the mid-lower-troposphere); and the cyclonic WTV, in contrast, has a “cool low” structure at the same levels (i.e., the cyclonic WTV is associated with cooler air temperature and lower pressure in the near-surface and the mid-lower-troposphere). Rather, FL1718 showed that its summer behaviour is likely influenced by both adiabatic heating, its coupling with the thermally-driven monsoon circulation and the subtropical westerly jet, which is in line with findings on the interactions

Fig. 1 Horizontal and vertical structures of the anti-cyclonic WTV (with positive intensity) in annual mean for 1979–2016. Horizontal structure (left panels: **a**, **b**) of the anti-cyclonic WTV is represented by correlations between the KZI and air temperature (T, colour-shading) and and vertical wind (arrows) vectors (V,W) at the **a** 250 hPa and **b** 500 hPa level (the near surface level of TP). Vertical structure (right panel: **c**) is represented by correlations between the KZI, T (colour-shading), geopotential height (HGT, contour) and vertical wind

(arrows) vectors (V, W) along a latitudinal profile (across 70° E– 80° E). Only the correlations significant at 0.05 level after taking account of the efficient numbers of degrees of freedom are colour-shading (Zar 1984; Li et al. 2013a, b); a significant vector denotes either one of its components is significant. Grey shading in left panels denote topography above 1500 m, black shading in (c) denote the topography. The black dots in left panels and green triangle in right panel denote the central Karakoram (36° N, 75° E)

between the circumglobal teleconnection (CGT) and the monsoon described above (e.g., Saeed et al. 2011).

Intuitively then, the anti-cyclonic trending in the WTV was used to explain (Forsythe et al. 2017; Bhambri et al. 2019) the development or maintenance of the “Karakoram Anomaly” (Hewitt 2005), an unusual glacier melting behaviour over Karakoram, i.e. the glaciers over the Karakoram and some neighbouring ranges did not show rapid retreats under the widespread warming and glacier retreat over Himalaya during recent decades (e.g., Hewitt 2005; Gardelle et al. 2012; Jacob et al. 2012; Kääb et al. 2012; Pratap et al. 2016; Bolch et al. 2017; Brun et al. 2017; Zhou et al. 2017; Farinotti et al. 2020). The “Karakoram Anomaly” is associated with that the summer temperatures have not been rising in the Karakoram (Fowler and Archer 2006; Khattak et al. 2011; Forsythe et al. 2012; Hasson et al. 2017), and the river flows in heavily glaciated basins of the Karakoram—a proxy for glacier melt in energy-limited catchments—have been stable or even declined (Fowler and Archer 2006; Sharif et al. 2013).

A few of studies have highlighted both the importance of a WTV-like circulation anomaly in this location in summer and its relationship with the interplay and mutual feedbacks between mid-latitude westerly and South Asian summer monsoon systems (e.g., Ding and Wang 2005; Krishnan et al. 2009; Saeed et al. 2011; Syed et al. 2012; Mölg et al. 2017). In particular, the WTV in summer shows marked similarities with the west-central Asian centre of action in a northern hemisphere summer CGT, which is principally located within a waveguide associated with the westerly jet stream (Ding and Wang 2005). Using a CGT index, Mölg et al. (2017) showed how a west–east (cold–warm) dipole in summer near-surface temperature anomalies across High Asia is associated with a southward shift in the upper-tropospheric westerly circulation, which is entirely consistent with the patterns linked to the WTV. The two-way interaction between the CGT and the South Asian summer monsoon proposed by Ding and Wang (2005) was also recently demonstrated using causal effect networks (Di Capua et al. 2020). It was found that mid-latitude circulation potentially exerts a larger causal influence on monsoon rainfall, although the latter system does feed back to the CGT, albeit more weakly.

However, de Kok and Immerzeel (2019, hereafter cited as dKI19) have recently raised a couple of arguments. The primary one is that the WTV is the change of wind field resulting from changes in near-surface temperature gradients in geostrophic flow. There are significant positive correlations between the intensity of the WTV and 2 m air temperature variability centring at the western TP (Fig. 2), which shrink to just over the western TP (above the altitude of 1500 m) in summer and autumn (FL1718; Li et al. 2019). In other words, dKI19 suggested the WTV is a thermally-direct

circulation generated from near-surface thermal forcing centring at the western Tibetan Plateau. Furthermore, dKI19 have assumed that surface net radiation likely drives near-surface temperature variability, especially in summer and autumn, which in turn generates the WTV. In short, dKI19 believes that summertime surface net radiation causes changes of near-surface temperature variability, which, in turn, drives the WTV, basically opposing to previous studies (FL1718; Li et al. 2019).

If the WTV is indeed a thermally-direct circulation generated from the near surface heating, then it’s hard to use the WTV or the WTV-like circulation variability to explain the glacier melting conditions and the near surface air temperature changes over the western TP, as did in Forsythe et al. (2017) and Mölg et al. (2017). In this study, we thereby carefully examine dKI19’s putative thermal-direct mechanism by conducting a set of model sensitivity experiments, revisiting the radiation processes over the western TP. The remainder is arranged as the follows. Section 2 presents data, model and prescriptions of modeling experiments. The modeling results and their comparisons with the observed WTV are given in Sect. 3. In Sect. 4, we analyzed the radiation processes related to the WTV and surface air temperature variability in summer over the western TP based on the ERA 5 data. Then, the results and discussions are presented in Sect. 5.

2 Data and model

2.1 Data

We use the ERA-Interim reanalysis (Dee et al. 2011) on both isobaric and sigma surfaces to present features of the observed WTV, as it has been shown to well represent near surface climate over the western TP high mountain areas (Forsythe et al. 2017). The use of the sigma surface is to remove the influence of topography in the lower troposphere. In plotting, we use a reversed Omega (Pa s^{-1} , vertical velocity in the isobaric system) to represent vertical wind velocity, so a positive value of the vertical wind velocity denotes upward motion, and vice versa. This is a common way in plotting Omega in meteorology. The monthly Karakoram Zonal Index (KZI) is calculated following the formulations in Li et al. (2018), which is the measure of the intensity of the WTV originally defined in Forsythe et al. (2017). A positive KZI represents the anti-cyclonic phase of the WTV, which is associated with warmer air temperatures at both the near-surface and the mid-lower troposphere over the western TP. The observed positive KZI events during 1979–2010 used here are defined as same as Li et al. (2019).

We also employ the same surface net radiation scheme and the same KZI calculations (at the 300 hPa level) for

Fig. 2 Anomalous 2 m air temperature (T_{2m} , K) at the anti-cyclonic WTV in four seasons, represented by linear regression of T_{2m} on standardized KZI (intensity index of WTV) using ERA-Interim reanalysis data. Color-Shading denotes significance at the 0.05 level after taking account of the efficient numbers of degrees of freedom

(Zar 1984; Li et al. 2013a, b). Grey-shading denotes the topography above 1500 m. Black rectangle is the region where the sensible heating is added on the TP topography surface (above 1500 m) in sensitivity experiments of SAMIL. The black dots in left panels and green triangle in right panel denote the central Karakoram (36° N, 75° E)

the ERA5 analysis used by dKI19 to test their arguments on radiation processes. It is important to note that further evaluations of the skills of the newly-released ERA5 dataset in representing atmospheric and thermal conditions over the western TP are still needed.

The anomalous circulation is then calculated as a departure from the climatological mean circulation during the reference period of 1979–2010 for consistency with FL1718. The climatological mean is separately assessed for each month of the annual cycle.

3 Numerical model and experiments

To examine the putative thermal-generating mechanism for the WTV proposed by dKI19, we employ SAMIL (version R42L26), a well-known (Wu et al. 2003; Wang et al. 2004) spectral atmospheric model developed at the State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS). It has 26 pressure levels, $2.5^{\circ} \times 2.5^{\circ}$ in horizontal resolution and covers the global domain. SAMIL has been intensively used for Tibetan climate simulations (e.g., Wu et al. 2003).

We conduct sensitivity experiments using SAMIL. We choose summer to conduct the numerical experiments, as the WTV's impacts are more focused on the western TP topography (above 1,500 m) in summer relative to other seasons (Fig. 2; also see Li et al. 2018). Additionally, a thermally-direct circulation is also likely easier to develop in the warm season. Both the sensitivity and control runs are executed for 60 months with the solar zenith angle fixed at 15 July, so each month is equivalent to one summer in the model.

Sensitivity run A constant sensible heat flux (3 times the climatological mean of July) is added at the topography surface (with elevation higher than 1500 m) over the western TP within the rectangular area in Fig. 3 (28° N– 42.5° N, 62° E– 87.195° E).

Control run Same as the sensitivity run, except that no extra sensible heat flux is added.

The simulated atmospheric circulation response to the surface thermal forcing is calculated as the mean difference of circulation in the sensitivity run minus the control run for the last 30 summers. Figure 3 shows the warmer near-surface air temperature over the western TP produced in SAMIL by adding a surface sensible heat flux; this mimics the thermal forcing conditions needed for the thermal-generating mechanism proposed by dKI19.

Fig. 3 The near-surface air temperature (SAT: colour-shading, K) response to near-surface sensible heat forcing in SAMIL, represented by the SAT differences between the thermal forcing sensitivity run and the control run. The sensible heat flux is added at the topography surface with elevation higher than 1500 m within the black rectangle area (28°N – 42.5°N , 62°E – 87.195°E)

4 Modelling results

We find that the response of the atmospheric circulation over the western TP to the surface thermal forcing maintains the structure of a classic thermally-direct circulation, featuring anomalous rising motions and a baroclinic structure; the opposite structure to the WTV. The details of horizontal and vertical structures of the WTV can be retrieved in Li et al. (2018).

4.1 Simulated rising motions

Figure 4a shows that significant upward motions (warm-color shading) occur above ground surface of the western TP as a response to the addition of a surface sensible heat flux in SAMIL. This extends up from the ground surface to near the tropopause at ~ 200 hPa. In contrast, the observed WTV (Fig. 4b) features anomalous downward motions (cold-color shading) within the central column of the WTV above the western TP, centred on the mid-upper troposphere around 400 hPa. The simulated response to surface heating in the vertical velocity is therefore the reverse of what occurs in the observed central column of the WTV.

4.2 Simulated baroclinic structure in pressure and wind fields

The baroclinic structure of the simulated thermally-direct circulation above the ground surface of the western TP is seen in both the pressure and wind fields. Higher pressure (represented by the higher geopotential heights of isobar surfaces) at the upper troposphere and lower pressure (represented by the lower geopotential heights of isobar surfaces)

at the bottom of the troposphere above the ground surface of the western TP—a classic baroclinic feature in the pressure field—is observed in the vertical profile of the thermally-direct circulation driven by the near-surface thermal forcing in SAMIL (Fig. 4c). In contrast, the pressure in the observed WTV is high at both the mid-low and mid-high troposphere, but centred on the mid-high troposphere, exhibiting as a quasi-barotropic structure (Fig. 4d).

The baroclinic structure of the thermally-direct circulation can be seen more clearer in the wind field. Figure 4e shows a significant anti-cyclone in the mid-high troposphere, but a significant cyclonic wind anomaly in the mid-low troposphere. The anti-cyclonic (cyclonic) winds at the mid-high (mid-low) troposphere are evidenced by both the significantly greater (smaller) stream function and greater (smaller) anomalous zonal wind shear at the according isobaric surfaces. In contrast, anti-cyclonic wind anomalies exist in both the mid-high and mid-low troposphere in the observed WTV (Fig. 2f), but are centred at the mid-high troposphere.

4.3 Simulated surface pressure

Classic theory tells us that surface-thermal forcing should to cause lower surface pressure (Holton 2004), which is consistent with a baroclinic structure of a thermally-direct circulation in pressure fields. We therefore also examine the surface pressure fields (Fig. 5). Comparing Fig. 5a, b, we can see significantly lower surface pressure and anomalous cyclonic winds near the ground surface occur in response to the sensible surface heat flux over the western TP in SAMIL, but non-significant surface pressure variability and cyclonic wind anomalies exist in the observed WTV. Furthermore, in spring and winter, the surface pressure (see Fig. 6) associated with warmer T_{2m} (Fig. 2) over the western TP is significantly increased rather than decreased. This discrepancy between the simulation and the observations implies that the surface pressure anomalies in the observed WTV are not directly driven by surface heating.

In summary, we find that the thermal forcing experiment produces (1) anomalous rising motions with (2) a classic thermally-direct circulation structure in the pressure, horizontal wind fields above the western TP topography, the opposite of a WTV-like structure. These experiments demonstrate that surface (or bottom of atmosphere) thermal forcing cannot generate a WTV-like structure.

Although the thermal forcing does not generate the WTV, we find the surface thermal forcing does impact the WTV. It enhances the anti-cyclonic WTV at the upper troposphere by amplifying the pressure (Fig. 4c) and the zonal wind shear (Fig. 4d), but weakens the anti-cyclonic WTV at the lower troposphere by reducing the pressure (Fig. 4c) and the zonal wind shear (Fig. 4d). This means that the surface thermal forcing may contribute as a key factor in the feedback

Fig. 4 Comparison of the meridionally-averaged (70° E– 80° E) vertical profiles between simulated thermally-direct circulation (left column: **a**, **c**, **e**) in SAMIL (sensitivity-control) and the observed WTV (right column: **b**, **d**, **f**) in its anti-cyclonic phase (which is associated with warmer T_{2m}) in ERA-Interim. **a**, **b** Vertical velocity anomalies, **c**, **d** are geopotential height anomalies, **e**, **f** are zonal wind (U, contours) and stream function (SF, colour-shading, only shows the values significance at 0.05 level). Vertical velocity anomalies in **a**, **b** are represented by the reversed omega but are amplified to similar magnitudes for better comparison. Colour shading denotes significance at the 0.05 level, after considering the equivalent sample size (Zwiers and von Storch 1995). Black shading denotes the smoothed western TP topography (across the 75° E)

processes causing the WTV to present as a quasi-barotropic rather than an ideally barotropic structure. This potential feedback mechanism merits further investigation, but such analyses are beyond the scope of this study.

5 Impacts of the WTV on radiation processes

We now further examine impacts of the WTV on variability in surface net radiation and near-surface air temperature (T_{2m}) over the western TP, moving beyond the simple theory proposed by dKI19 that surface net radiation likely drives near-surface air temperature due to significant correlation between surface net radiation and T_{2m} over the western TP. We find that the surface net radiation (positive value means incoming net radiation) itself may be modulated by the WTV through cloudiness over the western TP.

The significant positive correlation between surface net radiation (sum of surface net shortwave radiation and surface net longwave radiation) and T_{2m} over the western TP (as documented by dKI19) is verified well in Fig. 7a. Moreover, our further analysis reveals that this positive correlation mainly comes from a positive correlation between the surface net shortwave (or solar) radiation and the T_{2m} (Fig. 7c vs b). Net surface shortwave radiation is known as a major driver (e.g., Wan and Dozier 1996; Sobrino et al. 2004; Li et al. 2013b) of land surface temperature changes, and a warmer or cooler ground surface, in turn, impacts the T_{2m} by direct heat conduction, longwave radiation and evaporative cooling processes. Therefore, the surface net shortwave radiation is a key influence on T_{2m} .

Surface net shortwave radiation is heavily influenced by cloudiness. We now examine how modes of the WTV affect total cloud cover over the western TP and the Karakoram (Fig. 8). We find that an anti-cyclonic (cyclonic) WTV reduces (increases) the cloudiness over the western TP (Fig. 8d), causes more (less) net surface shortwave radiation (Fig. 8c) and net surface radiation (Fig. 8b), resulting in higher (lower) land surface temperature and T_{2m} (Fig. 8a) over the western TP. And the impacts of the anti-cyclonic

(cyclonic) WTV on the cloudiness are likely primarily due to its associated anomalous sinking (rising) motions over the western TP. In short, the variability of surface net shortwave radiation and T_{2m} can be traced back to WTV variability.

Bold values marked by “*” and “+” respectively denotes significant at 0.05 and 0.10 level, after considering the efficient numbers of degrees of freedom.

Over the Karakoram (shown as a green box in Fig. 8), we find that reduced (increased) cloud is responsible for greater (smaller) surface net shortwave radiation, as their correlation is -0.53 , significant at the 0.05 level (Table 1). Variability of the surface net shortwave radiation provides the majority of explained variance ($> 72\%$ variance) of the surface net radiation, as they are tightly covariant to each other (Fig. 8e) with their correlation reaching as high as 0.85 (Table 1). Because the KZI is also significantly correlated (-0.38 , see Table 1) with the total cloudiness in ERA5 data, we conclude that the WTV may impact the T_{2m} over Karakoram by modulating the cloudiness and therefore the surface net shortwave radiation.

In short, the WTV appears to impact T_{2m} through modulating cloudiness over sub-regions of the western TP, including the Karakoram area, but more numerical experiments are needed to verify this hypothesis based on observational analysis. This complements previous work which found that adiabatic sinking-compression (rising-expansion) provides the overwhelming control on middle-to-lower tropospheric temperature variability in the region, but that diabatic heating has localized importance over the edges of the western TP (Li et al. 2019). We also note that surface net radiation has no significant correlation with T_{2m} over southwest parts of the western TP (Fig. 7a), where T_{2m} is still significantly influenced by the WTV (Fig. 7a). This means that radiation does not drive T_{2m} variability there, and multiple mechanisms exist for the WTV to influence T_{2m} over sub-regions of the western TP, which have already been emphasized by Li et al. (2019).

6 Conclusions and discussions

An analysis of the thermal wind equation can hardly provide a definitive attribution of whether wind drives temperature or the reverse. Because the thermal wind equation reflects only an internal balance/relationship between the (horizontal gradient of) temperature and the (vertical shear of) geostrophic wind in geostrophic flows (see Holton (2004) for the basic theory). The thermal wind equation is often used to check analyses of observed wind and temperature fields for consistency in large-scale extratropical systems, and to estimate the mean horizontal temperature advection in a layer (Holton 2004). In the mid- to high latitudes, “the comparatively large-scale atmospheric

Fig. 5 The surface pressure anomalies (color shading and contours) and anomalous near-surface wind vector (at 0.92 sigma level) **a** in response to near-surface thermal forcing in SAMIL (sensitivity-control), and **b** composited in observed WTV's anti-cyclonic phase (which is associated with warmer near-surface air temperature) in

ERA-Interim. Color shading denotes significance at the 0.05 level, after considering the equivalent sample size (Zwiers and von Storch 1995). Only anomalous wind vectors significant at 0.05 level are plotted. Black rectangle area represents the area adding the sensible heating in the SAMIL

Fig. 6 Observed surface pressure anomalies (hPa) at the anti-cyclonic WTV in four seasons, represented by linear regression of surface pressure on the standardized KZI (intensity index of WTV) using ERA-Interim reanalysis data. Color-shading denotes significance at 0.05 level after taking account of the efficient degrees of freedom

(Zar 1984; Li et al. 2013a, b). Grey-shading denotes the topography above 1500 m. Black rectangle is the region where the sensible heating is added on the TP topography surface in sensitivity experiments of SAMIL

motions are fundamentally quasi-geostrophic" (Yeh 1957), so the large-scale wind and temperature fields are generally consistent and satisfy the thermal wind equation, which explains the generally high correlations between them in the extra-tropics. It's thereby hard to use this generally existing consistency to assert that temperature drives wind changes or the reverse, as the two 'directions

of causality' are both possible. For example, the Ferrell Cell in each hemisphere is driven by eddy forcing (Holton 2004) rather than the meridional temperature gradient at the mid-latitudes, but its temperature and wind fields still satisfy the thermal wind equation. So numerical experiments are needed and carried out in this study to assess the putative thermal-direct mechanism of the WTV.

Fig. 7 Pearson correlations between KZI and **a** T_{2m} , **b** surface net radiation (sum of the surface shortwave net radiation and longwave net radiation), **c** surface net shortwave radiation during summer (JJA) season in the period of 1979–2018 in ERA5 monthly data. The stippling denotes significance above the 0.10 level, after taking account of the efficient number of degrees of freedom (Zar 1984; Li et al. 2013a, b). The green star denotes the central position (36°N , 75°E) of the Karakoram focus area, the green square denotes area of 35°N – 37°N , 74°E – 76°E . The bold-black-outline denotes topography above 1500 m

Here, we note the numerical experiments with a surface sensible heat flux imposed over the ground surface of the western TP (above 1500 m within the area of 28°N – 42.5°N , 62°E – 87.195°E) using a global atmospheric circulation model, the SAMIL (version R42L26), however, were unable to produce circulation anomalies exhibiting the key characteristics of the WTV. On the contrary, these simulations produced only classical thermally-direct circulations right above the thermal forcing, featuring

1. anomalous rising motions, and
2. a baroclinic structure above the ground surface of the western TP (above 1500 m), is basically the opposite to the WTV structure, as shown as Fig. 9.

These simulations are reasonable according to the basic theory of the thermally-direct circulation (e.g., Halley 1687; Ye and Wu 1998; Wu and Liu 2000; Holton 2004), and are also in line with previous thermal-forcing simulations conducted over different parts of the TP (e.g., Wu et al. 2007; Wang et al. 2018).

Instead of generating the WTV, we find surface thermal forcing over the western TP may impact the WTV, which needs more discussions. The surface thermal forcing seemingly enhances the WTV at the mid-high troposphere but weakens it at the mid-low troposphere. Further analysis may be needed to establish whether it can provide an explanation for why the WTV has a quasi-barotropic rather than a barotropic

structure. It should also be noted that the vertical structure of the WTV extends downward from the upper troposphere to the near surface level over the topography of the western TP all year around, but it is generally shallower in summer and autumn seasons than in winter and spring seasons (Li et al. 2018). This arises another interesting question about what is the role played by the surface thermal forcing over the plain areas nonboring the western TP, which deserves further study.

But, the arguments of dKI19 do encourage the further explorations on radiation processes relevant to the WTV that is constructive. Our further explorations based on ERA5 data suggest the WTV may impact near-surface temperature and net radiation through the modulation of cloudiness over the western TP. Under the anti-cyclonic WTV, the anomalous sinking motions cause less cloudiness and more input shortwave (solar) radiation, which warms the (skin) surface temperature and near-surface air temperature. Under the cyclonic WTV, however, the anomalous rising motions cause more cloudiness and less input shortwave (solar) radiation, which cools the (skin) surface temperature and near-surface air temperature (Fig. 10). We note that the correlation between surface temperature and total cloud cover is not significant over the central Karakoram area (as shown in Table 1), which suggests the total cloud cover is not the only factor influences the radiations. The contribution of land surface ice/snow cover in response to the WTV may be another important force in modulating the surface

Fig. 8 Pearson correlations (upper panel) between KZI and **a** T_{2m} , **b** surface net radiation, **c** surface net shortwave radiation, **d** total cloud cover during summer (JJA) season, and **e** the area mean of the standardized time series (bottom panel) of the latter three variables over the central Karakoram (green square in **a–d**), in the period of 1979–2018 in ERA5 monthly data. The stippling denotes significance above the 0.10 level, after taking account of the effective number of degrees of freedom (Zar 1984; Li et al. 2013a, b). The green star denotes the central position (36° N, 75° E) of the Karakoram focus area, the green square denotes area of 35° N– 37° N, 74° E– 76° E. The bold-black-outline denotes topography above 1500 m

Table 1 Cross correlations among variables over the central Karakoram area (35° N– 37° N, 74° E– 76° E) during summers of 1979–2018 in ERA5 data

	KZI	T_{2m}	Surface net radiation	Surface net short-wave radiation	Total cloud cover
KZI	1	0.47*	0.35*	0.43*	– 0.38*
T_{2m}		1	0.64*	0.64*	– 0.11
Surface net radiation			1	0.85*	– 0.30⁺
Surface net shortwave radiation				1	– 0.53*
Total cloud cover					1

Bold values marked by “*” and “+” respectively denotes significant at 0.05 and 0.10 level, after considering the efficient numbers of degrees of freedom.

Fig. 9 Comparison of the conceptual vertical structures of the simulated thermally-direct circulation (left panel) and the observed anti-cyclonic WTV (right panel) within the troposphere (below ~150 hPa). Left panel is very close to an idealized thermally-

direct circulation depicted at the Page 78 of Holton (2004). Right panel is summarized from the seasonal profiles presented in Li et al. (2018). Thick black shading at the bottom of each panel denotes the western TP topography

radiative balance and requires more discussion in the future. It is also important to note that further evaluations of the skills of the newly released ERA5 dataset in representing atmospheric and thermal conditions over the western TP are still needed, as considerable bias in ERA5 reanalysis has been reported recently neighbouring the western TP (e.g., Jiang et al. 2021).

Previously, by diagnosing the classic thermal energy equation, a tendency equation of the air temperature, using the ERA-Interim reanalysis data, Li et al. (2019) demonstrated that adiabatic processes—i.e. the sinking-compressing-warming/rising-expanding-cooling—are the dominant contributor through which the WTV impacts the air temperature in the mid-lower troposphere and at the near-surface level (500 hPa) over the western TP. Li et al. (2019) found that two other types of major thermodynamic processes: diabatic processes (i.e. sensible heating, radiative heating and latent heating processes) and horizontal temperature convection (i.e. warm/cold currents) are also important in sub-regions of the western TP. Li et al. (2019) then proposed that the thermodynamic processes at the near-surface level over the western TP at around 500 hPa can generally explain the T_{2m} responses over the western TP high mountain areas. Further investigation of the radiation processes central to this study complement and enhance our understanding of the mechanisms through which the WTV influences the western TP's surface climates, including the T_{2m} changes. Of course, substantial additional verification work especially the numerical simulations will be needed for this to come to fruition. For example, whether high-resolution regional

Fig. 10 Assumed physical diagram of anti-cyclonic WTV's influences on 2 m air temperature (T_{2m}) over the western TP through modulating the surface radiation processes

climate or weather models can reproduce the radiative processes related to the WTV variability needs further examination. A specific unresolved research question concerns what proportion of WTV influence on T_{2m} is through the cloud radiative effects related to direct thermodynamic processes (including adiabatic processes and horizontal temperature convection). Meaningfully answering this question will

depend greatly on the accuracy of the sparse observational data over the western TP. Another interesting question concerns whether the cloud radiative effects play the same role at higher surface elevations where there is semi-permanent or permanent snow packs versus at lower elevations with intermittent snow cover on the western TP that far above the sea level.

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