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The Out-of-Phase Variation in Vertical Thermal Contrast Over the Western and Eastern Sides of the Northern Tibetan Plateau

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Abstract—The upper tropospheric thermal contrast over the northern Tibetan Plateau and the Tianshan Mountains during the peak summer monsoon is found to have experienced a significant change since the late 1990s, and the change is out of phase on the western and eastern sides of the northern Tibetan Plateau. Using the National Center for Environmental Prediction (NCEP)–DOE AMIP-II reanalysis daily data sets, we found that in the late 1990s, there was an increase/decrease in the tropospheric temperature (TT) at 100 hPa/300 hPa on the western side, whereas on the eastern side the TT changed in the opposite fashion. Associated with the TT change is an increase (decrease) in convection in the west (east). This is in agreement with the patterns of humidity fluxes and ascending/descending favorable winds, and has been further substantiated in a causal inference, which identifies a dominant causality from the TT variation over the western side of the northern Tibetan Plateau to the longwave and shortwave fluxes through the top of the atmosphere. The lack of causality from the eastern TT variation suggests a reduction in convection, hence cloudiness, over that region, which may account for the flash drought over China during the recent global warming hiatus.

Key words: Upper tropospheric temperature (TT), thermal contrast, peak summer monsoon, convection, causal distribution.

1. Introduction

The East Asian monsoon is the most notable monsoon system in the world, and is believed to be remarkably sensitive to climate change. It has been connected to the thermal contrast between the largest continent, Eurasia, and the surrounding oceans as well as the elevated heat source, namely the Tibetan Plateau (Wang et al. 2006; Vaid and Liang 2018a), anthropogenic factors (Xu 2001; Menon et al. 2002), tropospheric temperature (TT) variation (Dai et al. 2013; Vaid and Liang 2018b), and the El Niño–Southern Oscillation (ENSO) (Wu and Wang 2002; Huang et al. 2003; Vaid and Liang 2019). Among these, the TT variation has been regarded as a key mechanism, particularly for the summer monsoon variation in the same region, and has received growing scientific attention during recent decades (Zhou and Zou 2010; Dai et al. 2013; Vaid and Liang 2018b, 2019); it has also been considered one of the important signals characterizing climate change, as seen in the recent record of dramatic change over East Asia (Vaid and Liang 2015, 2018b). For example, it is revealed to undergo an abrupt change over East Asia during the seasonal transition period of the late 1990s, which has direct influences on the Himalayan glaciers and snow packs, and the hydrological cycle over much of South Asia (Vaid and Liang 2018b). Correspondingly, evidence has also demonstrated that the climate over East Asia has shown different or even opposite changes in response to the climate change observed during the late 1990s (Si et al. 2009; Liu et al. 2012). In a recent observation, Chung and Li (2013) found that sea surface temperature (SST) gradients across the equatorial Pacific underwent a regime change in 1998–1999 due to significant cooling (warming) over the tropical eastern (western) Pacific in the latter period. Significant changes were also seen after the late 1990s over the Pacific Ocean due to an anomalous wind divergence in the central Pacific that caused a shift in the anomalous atmospheric convection westward, leading to a westward shift of the anomalous westerly response, thereby preventing the eastward propagation of the SST anomaly after the late 1990s (Xiang et al. 2013). One naturally

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wonders how TT may respond, as it is noted that the TT is largely influenced by one of the largest sources of Earth's climate variability, namely ENSO (Vaid and Liang 2015, 2019). Many studies have highlighted the importance of the TT variation and its role in the East Asian monsoon system, one of the most influential monsoon systems in Asia (Wu 2005; Zhang et al. 2006; Chen et al. 2010; Vecchi et al. 2013; Vaid and Liang 2015, 2018b, 2019). For example, over China, the upper TT cooling during 1958–2001 has been implicated in the weakening of the East Asian summer monsoon (Yu et al. 2004), and the northward progression of the southerly monsoon winds may become weak because of the upper tropospheric variation, giving rise to a mid-lower Yellow River Valley (34°–40°N) drought and excessive rain in the Yangtze River Valley (Yu and Zhou 2007). The role of TT variation has significantly altered precipitation patterns (particularly over East Asia) highlighted during recent summers (Vaid and Liang 2015), and the TT gradient during the seasonal transition period is found to have undergone a sudden change in the late 1990s (Vaid and Liang 2018a, b). In addition, the impact of TT variation on the local precipitation over East Asia during boreal wintertime monsoon periods was also identified (Vaid and Liang 2019). These studies, among numerous others, testify to the relationship between the TT variations and the East Asian monsoon. However, none of the previous studies focused on the upper tropospheric thermal contrast between the vertical pressure levels and its associated impact on East Asia in the context of a changing climate, particularly in the late 1990s.

In this study, we will continue our previous research along the same lines (Vaid and Liang 2015, 2018b, 2019), but with a focus on the upper TT variation between 400 and 50 hPa during the peak summer monsoon, i.e., during the months of July and August. The remaining part of this paper is organized as follows. In Sect. 2, we introduce the data and analysis methods. The TT variation and its associated relationship with atmospheric convection during the peak monsoon months are revealed in Sect. 3. We summarize this study in Sect. 4.

2. *Data and Methodology*

We derive the wind fields, air temperature, geopotential height and relative humidity (Kanamitsu et al. 2002) from the National Centers for Environmental Prediction–Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP)-II reanalysis daily data sets for the period 1982–2017 (http://www.esrl.noaa.gov/psd/). Other data include the longwave flux (LWF) and shortwave flux (SWF) at the top of the atmosphere and the surface, and total cloud area (TCA) fraction data which are acquired from the Modern-Era Retrospective analysis for Research and Applications (MERRA) data set (Rienecker et al. 2011).

To study the changes in the moisture flux over the region in the late 1990s, the total horizontal mean transport components (zonal and meridional) of water vapor are calculated using the following formula:

$$Q_{\lambda} = \frac{1}{g}\int_{P_{\mathrm{b}}}^{P_{\mathrm{t}}} \mathrm{rh}u\mathrm{d}p,$$

$$Q_{\emptyset} = \frac{1}{g}\int_{P_{\mathrm{b}}}^{P_{\mathrm{t}}} \mathrm{rh}v\mathrm{d}p,$$

where rh (relative humidity) is the ratio of the partial pressure to the equilibrium vapor pressure of water vapor, (u, v) is the velocity vector, g is the acceleration due to gravity, and P_{b} and P_{t} are the pressure at the bottom (400 hPa) and top (50 hPa) levels of the integration volume, respectively.

To quantitatively examine the measurable impact of the upper TT thermal contrast on the atmospheric variables, for example, longwave flux (LWF) and shortwave flux (SWF), over East Asia during the peak summer monsoon, we use a newly developed theory and methodology for rigorously identifying the causality between time series (Liang 2014, 2015, 2016, 2018). We adopt a modified version of that methodology, the "composite causality analysis", as detailed in Vaid and Liang (2019), for the applications in this study. For a brief but comprehensive introduction from a user's point of view, see Vaid and Liang (2019). The following just gives the formula for the computation.

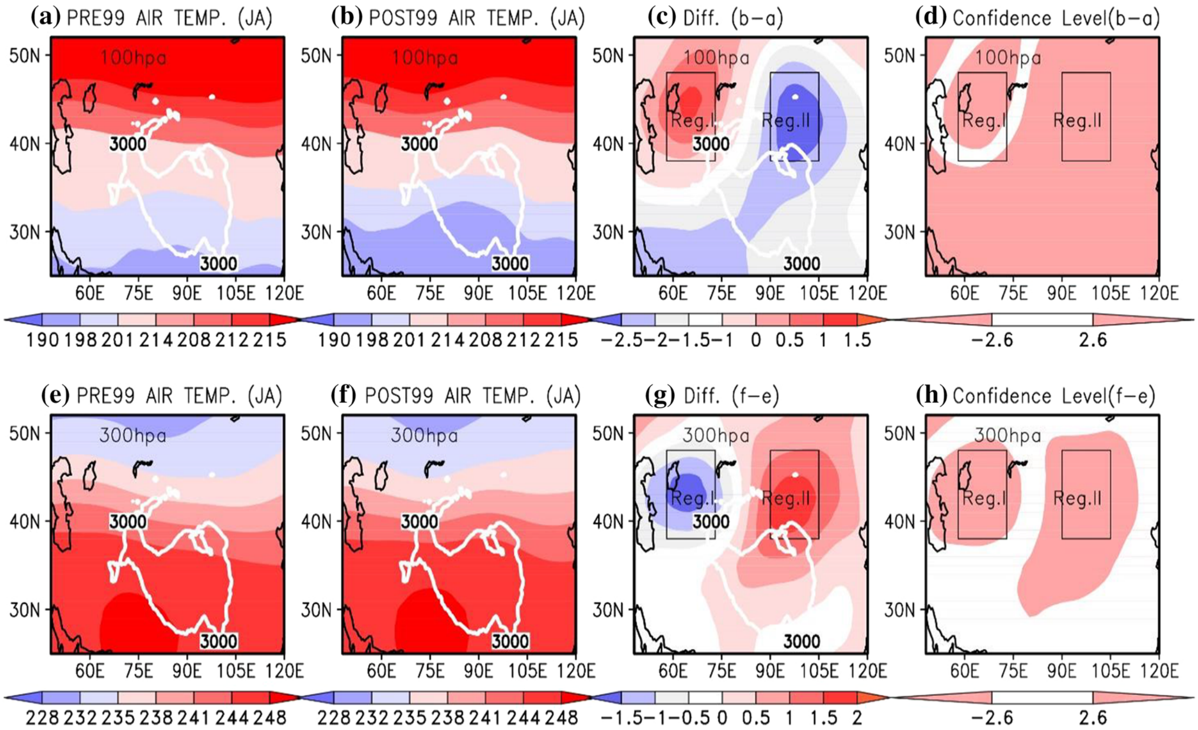

Figure 1
JA TT (in K) over the 100 hPa during the PRE99 (**a**) and POST99 (**b**) periods. **c** The difference between **b** and **a**, i.e. **b** − **a**. **d** Regions (shaded) showing that **c** is significantly different from zero at a 99% level. **e**–**h** Same as **a**–**d**, but for the 300-hPa level. The contour marks the 3000-m topographic isoline

The causal inference by Liang (2014) uses information flow to quantify the causality between time series. In the linear limit, the maximum likelihood estimator (MLE) of the causality from X_2 to X_1 (units: nats per unit time) is:

$$T_{2\to 1} = \frac{C_{11}C_{12}C_{2,d1} - C_{12}^2 C_{1,d1}}{C_{11}^2 C_{22} - C_{11}C_{12}^2},$$

where C_{ij} is the sample covariance between the time series X_i and X_j (i, j = 1, 2), and $C_{i,dj}$ the covariance between X_i and the series

$$\dot{X}_j = \frac{X_j(t + k\Delta t) - X_j(t)}{k\Delta t},$$

i.e., a series derived from X_j(t) using the Euler forward differencing scheme, with Δt being the time step size and $k \geq 1$ some integer. For details about the derivation and applications (in climate science and financial economics, among others), see (Liang 2014, 2015, 2016, 2018), among many others. It is worth noting that the causalities obtained this way are asymmetric in direction; that is to say, they are from the upper TT thermal contrast to the aforementioned atmospheric variables, which has nothing to do with that from the other way around.

3. Results

We mainly examine the upper TT variation (i.e., between the pressure level 400–50 hPa) over East Asia during peak monsoon months in relation to the convection. In the time dimension, we will deal with the periods 1982–1998 and 1999-2017 separately, and the former (latter) will be henceforth referred to as PRE99 (POST99). This distinction is motivated by the observation that the global and regional temperatures have probably undergone a period of abrupt warming hiatus since the late 1990s (Trenberth and Fasullo 2013; Kosaka and Xie 2013; England et al. 2014; Ying et al. 2015; Vaid and Liang 2015, 2018b). Figure 1 shows the July–August (JA) averaged TT

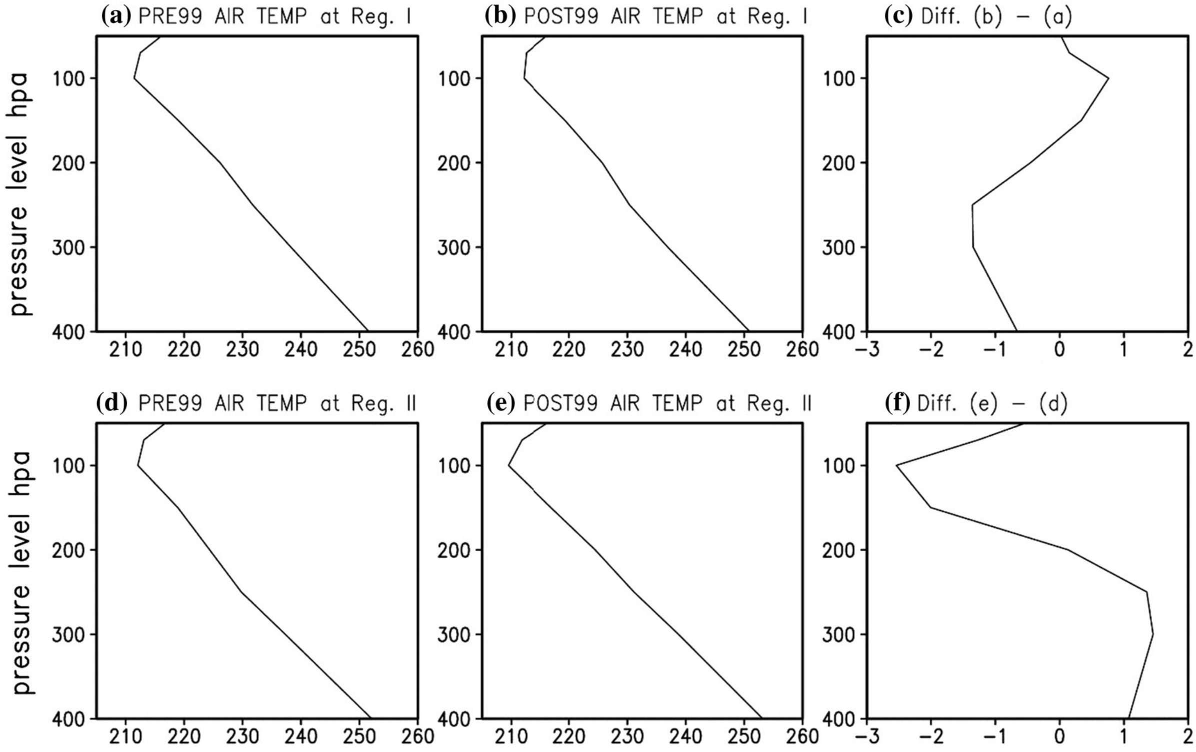

Figure 2
Vertical variation in JA air temperature over region I during **a** PRE99 and **b** POST99. **c** The difference between **b** and **a**, i.e. **b** − **a**. **d**–**f** are the same as **a**–**c**, for region II

for the periods PRE99 (a, e) and POST99 (b, f) over the 100 hPa and 300 hPa, respectively. The difference and associated confidence level are displayed in (c) and (d), respectively. To check the statistical significance of the difference as observed, Student's *t* test is performed. It can be seen that 300 hPa TT and 100 hPa TT underwent substantial change in the late 1990s. Interestingly, the difference between the TTs for POST99 and PRE99 is organized into a dipolar pattern, with one pole sitting over the western side of the northern Tibetan Plateau and Tianshan Mountains (Tianshan Mountains may also be taken as a part of the northern Tibetan Plateau; cf. Tang et al. 2013) and the surrounding area (Long. = 58°E–73°E, Lat. = 38°N–48°N; hereafter region I), and the other over the eastern side (Long. = 90°E–105°E, Lat. = 38°N–48°N; hereafter region II). In addition, the dipole has a clear vertical structure. At 100 hPa, it is positive in the west and negative in the east, while at 300 hPa, it reveals a west negative-east positive pattern.

The Tibetan Plateau is the highest plateau in the world, with an average altitude over 3000 m. Owing to its elevated topography, it receives a large amount of direct solar energy and becomes a strong heating source for the atmosphere in summer, which greatly affects the climate and environmental processes over Asia (e.g., Ye and Gao 1979). Several studies have revealed that atmospheric heating over it, and the meridional temperature gradient in the upper troposphere between the Plateau and its surrounding oceans, is closely connected to the Asian summer monsoon (e.g., He et al. 1987; Wu and Zhang 1998; Duan and Wu 2005) and the amount of monsoon rainfall (e.g., Hsu and Liu 2003; Duan et al. 2013). Here it is found that the TT changed abruptly in the late 1990s; the PRE99-POST99 TT change over the rectangular regions (I and II) in Fig. 1c, g are significantly different from zero at a 99% level (see Fig. 1d, h). That is to say, there actually exists a thermal contrast between 300 and 100 hPa over the regions I and II. Considering the role the Tibetan

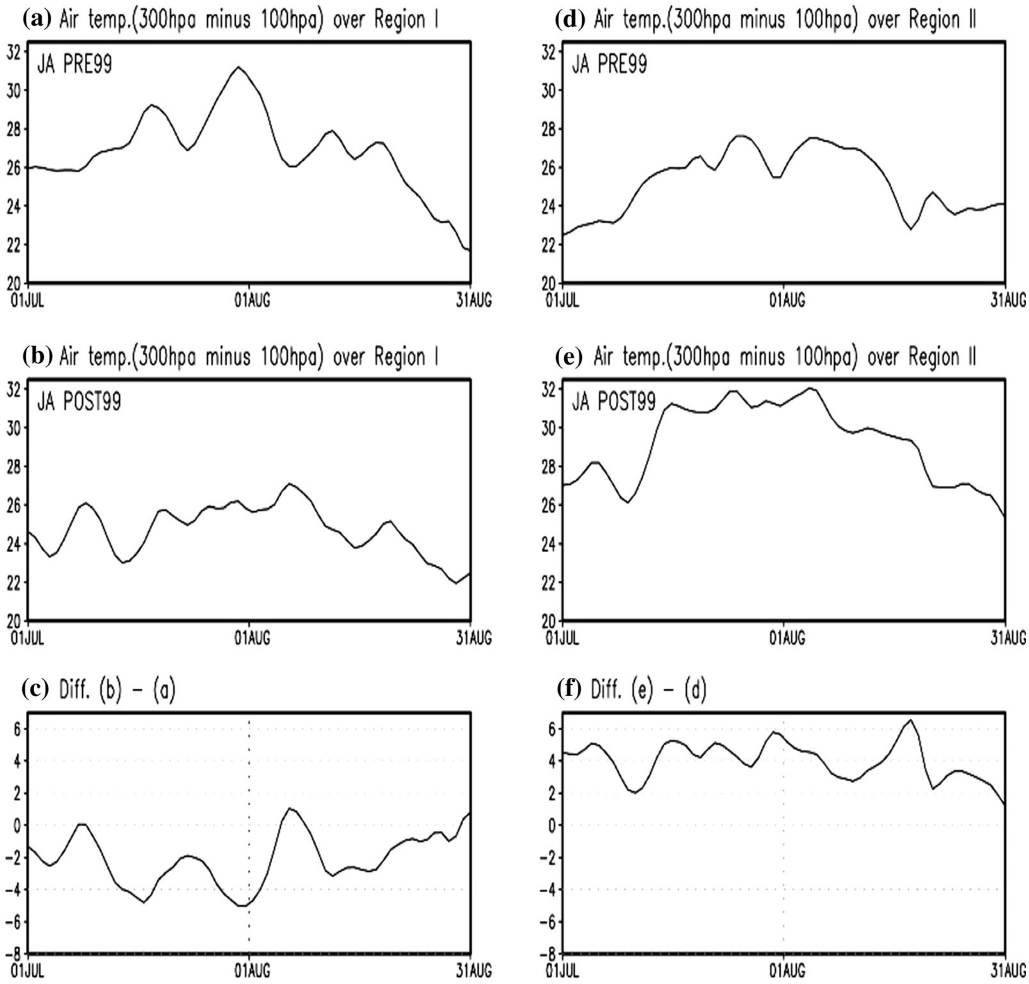

Figure 3
Air temperature (300 hPa minus 100 hPa) over region I for periods **a** PRE99 and **b** POST99. **c** The difference between **b** and **a**, i.e. **b** − **a**. **d**–**f** Same as **a**–**c**, but for region II

Plateau plays in the monsoon system, we speculate that the TT variations over these regions (I and II) may modulate the monsoon circulation as well as the convection over these regions, and thereby influence the climate variability over East Asia. More specifically, it is speculated that the upper TT variation may play a potential role in foreshadowing the convection over the regions (I and II) during the peak summer monsoon.

To see more about the thermal contrast that occurred in the upper troposphere over the two regions (I and II) in the late 1990s, the vertical profiles of the average air temperature during peak summer monsoon are plotted. Shown in Fig. 2 are the profiles for the PRE99 and POST99 periods and the difference between them (Fig. 2c, f). A closer look reveals that the thermal contrast takes the maxima at 300 hPa and 100 hPa. Clearly, over the two regions the variations in thermal contrast are out of phase.

To quantify the thermal contrast in the upper troposphere, we subtract the mean JA TT at 300 hPa from that at 100 hPa. The resulting differences for region I and region II are plotted in Fig. 3. The JA mean is taken separately over the two periods, namely PRE99 and POST99, respectively. Obviously, the thermal contrast experienced a substantial variation in the late 1990s (approximately +2° and −4° over 200 hPa for regions I and II, respectively).

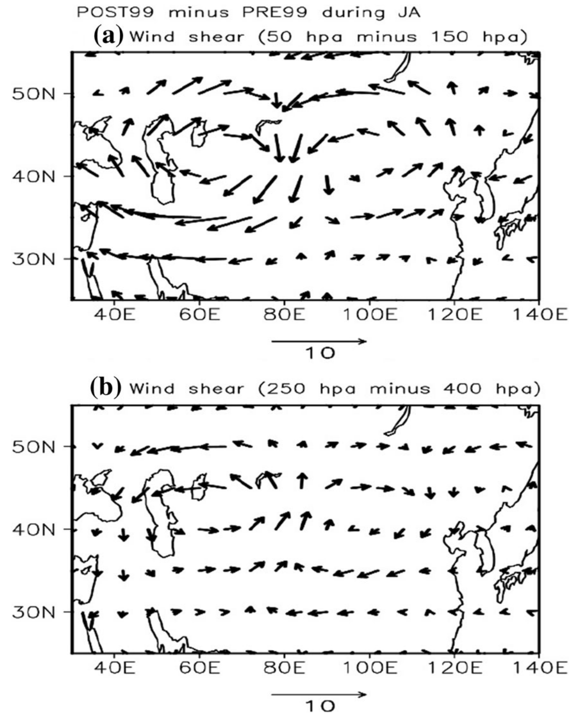

Figure 4
Increase in JA averaged wind shear (in m/s) around 100 hPa and 300 hPa since the late 1990s (POST99 minus PRE99): **a** 50–150 hPa; **b** 250–400 hPa

Moreover, if we compare Fig. 3c–f, we see that, remarkably, the thermal contrast varies out of phase over the western and eastern sides of the northern Tibetan Plateau.

Considering the relation between thermal contrast and convection, the above observed variation will inevitably exert influence on the local climate in the context of the East Asian monsoon. In the following, we first look at how the upper troposphere circulation may of changed before and after 1999. For this purpose, we compute the vectors of wind shear around 100 hPa and 300 hPa by subtracting the wind vectors at 100 hPa from those at 50 hPa, and subtracting those at 400 hPa from those at 250 hPa. We then take their respective averages over the PRE99 and POST99 periods, and then subtract the former from the latter. The resulting difference field is drawn in Fig. 4a, b. Clearly, the results are well correlated with the TT difference pattern (Fig. 1g). Particularly, the closed-loop circulation structures are clearly seen over regions I and II: In upper layers, the one over region I is anticyclonic and the one over region II is cyclonic (Fig. 4a), while in the lower layers the opposite structure is revealed (Fig. 4b). By the continuity equation, this structure implies increasing ascending/descending favorable winds in the troposphere over regions I and II, respectively, since the late 1990s. To see this, we average the JA wind vectors over the latitudinal belt of 38°N–48°N for periods PRE99 and POST99, and subtract the latter from the former (Fig. 5a–c). Clearly, more noticeable ascending/favorable winds (a sign of the convection) are seen in the upper vertical levels over region I, while over region II, descending/favorable winds (a sign of subsidence) are observed (Fig. 5c). The cause of these ascending winds and descending favorable winds in the late 1990s was the thermal contrast (between the 300 and 100 hPa levels) as shown before. Geopotential height analysis and relative humidity analysis also result in consistent findings (Fig. 5f, i). Expectedly, an ascending/descending motion over region I/II is found to be associated with the increasing/decreasing relative humidity in the late 1990s (Fig. 5i). In fact, a variation of around 10% in the relative humidity can be identified in the late 1990s. Udelhofen and Hartmann (1995) found that a small change in relative humidity in the upper troposphere may play an important role in the radiative forcing. For example, a $\sim$ 10% variation could lead to $\sim$ 1.4 $\mathrm{Wm^{-2}}$ variation in radiative forcings (Udelhofen and Hartmann 1995). Besides these, we have also looked at the cloud change during the late 1990s. In Fig. 5j–l, a clear sign of cloud cover in agreement with the aforementioned discussion is revealed (Note that a sky is said to be cloudy if the cloud fraction $\geq$ 0.01; cf. Wu et al. 2014). This suggests that the TT variations can modulate the convection over the regions and thereby influence the East Asian monsoon.

To see more about this, drawn in Fig. 6 is the vertically integrated moisture flux between 400 hPa and 50 hPa. As shown in Fig. 6c, the change in the moisture flux is mostly negative over East Asia, implying a subsidence over that area, which may be indicative of drought-like condition over China during the recent global warming hiatus (Wang et al. 2016).

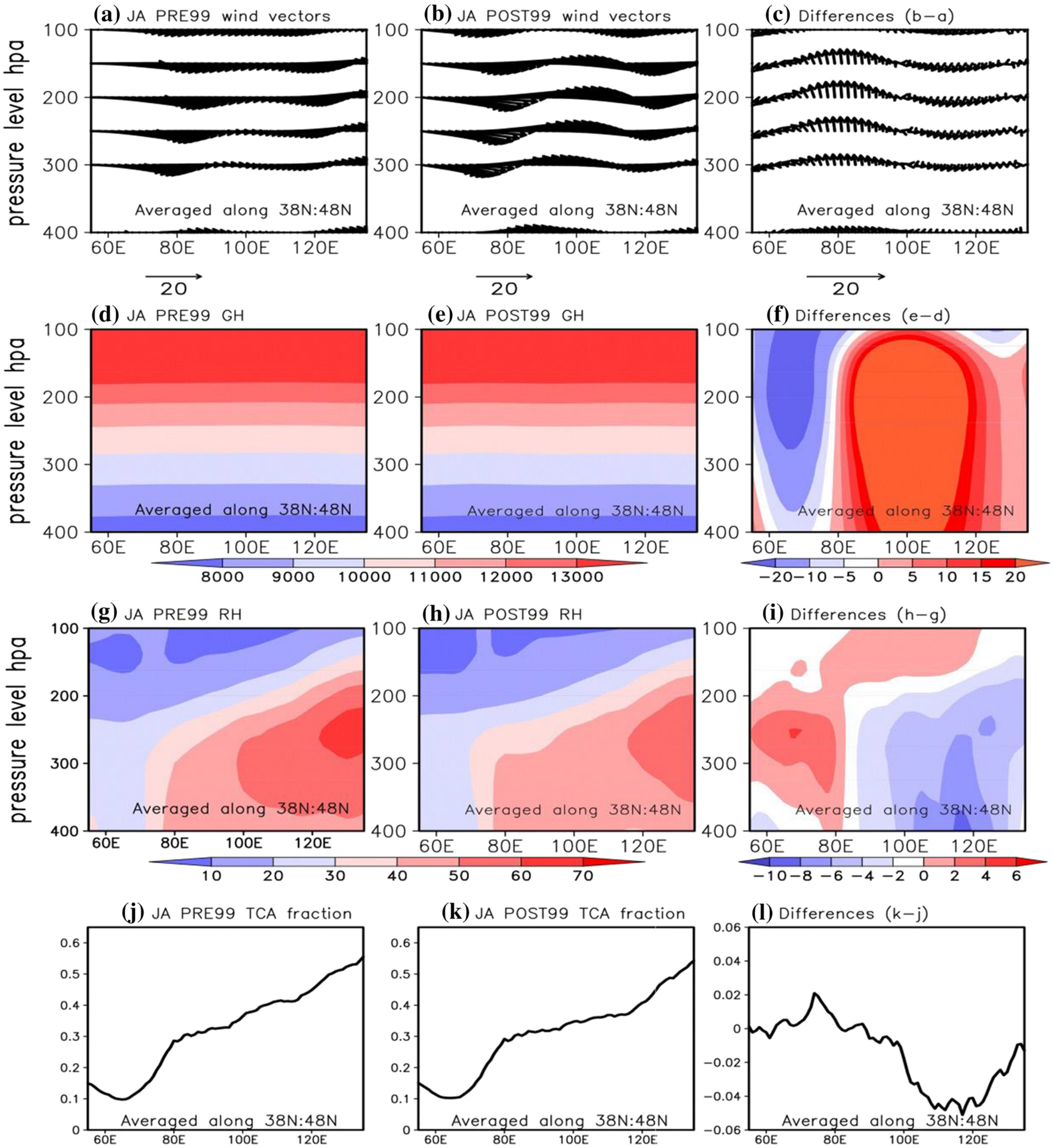

Figure 5

Vertical variation in the JA wind vectors averaged over the latitudinal belt 38°N–48°N during **a** PRE99 and **b** POST99. **c** The difference between **b** and **a**, i.e. **b** − **a**. **d–f** and **g–i** are the same as **a–c**, but for geopotential height and relative humidity, respectively. **j–l** are the same as those in **a–c**, respectively, but for TCA fraction

The longwave flux (LWF) and shortwave flux (SWF) in the late 1990s during the peak summer monsoon period also exhibit consistent variations. In Fig. 7, we plot the surplus (POST99 minus PRE99) upward LWF (Fig. 7a), downward SWF (Fig. 7b) and total forcing LWF plus SWF (Fig. 7c) through the top of the atmosphere (TOA). Also plotted are the respective meridionally averaged fluxes over the

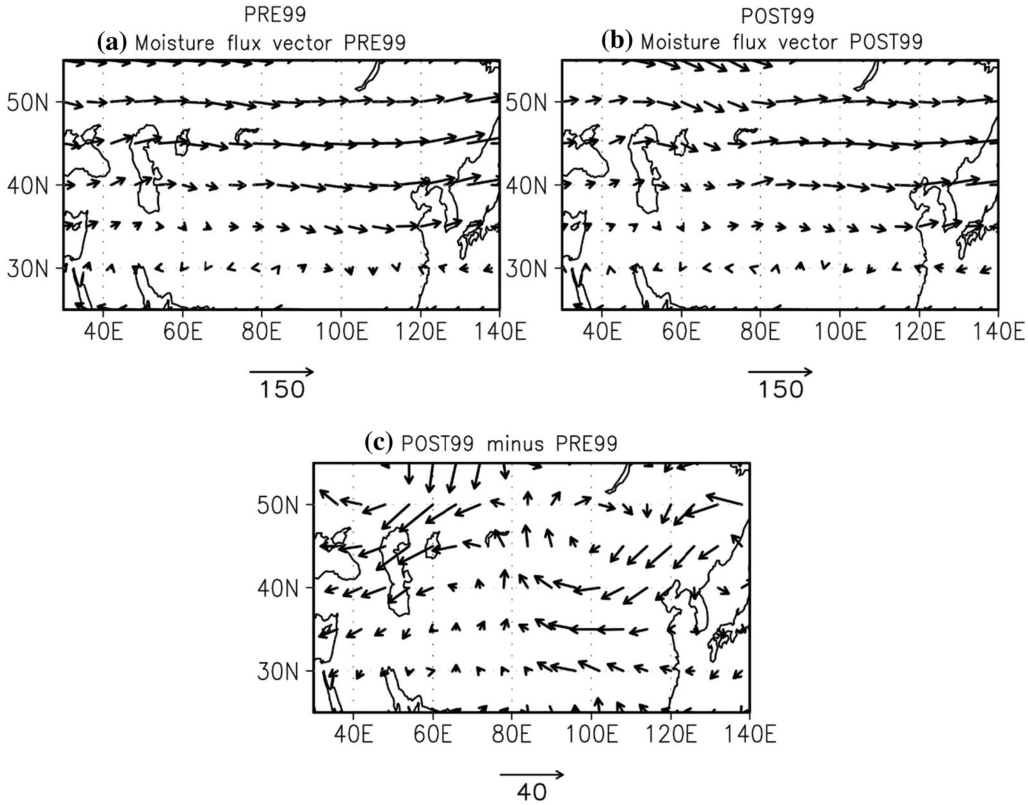

Figure 6
JA moisture fluxes integrated from 400 to 50 hPa for **a** PRE99 and **b** POST99. **c** The difference between **a** and **b**, i.e. **b** − **a**

latitudinal belt of 38°N–48°N (Fig. 7d–f), from which we see a clear decrease (increase) in LWF and SWF in the late 1990s over region I (region II). This is in agreement with the TT variation (Fig. 1c, g) and wind variation as observed above (Fig. 5c). Besides, we also looked at the change in the fluxes at the surface in the late 1990s (Fig. 7g–l). From Fig. 7, a clear variation in LWF and SWF fluxes at the TOA and the surface, respectively, is evidenced. The difference in the fluxes between the TOA and surface indicates that the absorption or reduction of the radiation might be due to the changes in aerosol concentrations (or dust) over the region. Since dust is considered a major source of tropospheric aerosol loading, it constitutes a key parameter in radiative forcing studies in influencing regional/global climate (Huang et al. 2006; Slingo et al. 2006). Note East Asia is considered to be one of the main dust sources in the world (e.g., Formenti et al. 2011; Wu et al. 2016). We feel that before making a conclusive statement regarding the role of dust, a detailed study on the long-term dust change using climate models is necessary. We leave this subject open to future studies.

To further examine the direct relationship between the TT variation and LWF and SWF, we construct a series of the vertical gradient of TT (the difference of TT between 100 and 300 hPa) for the two regions, and then apply to it and the series of LWF/SWF a newly developed “composite causality analysis”, which was briefly introduced in Sect. 2 and detailed in Vaid and Liang (2019). We have tried different time window sizes (31, 41, 51 days, etc.), and the resulting causal patterns are similar. The results are shown in Fig. 8. As can be seen, the TT gradient variation is causal to LWF and SWF. It is worth noting that the causalities obtained here are asymmetric in direction; that is to say, they are from the TT thermal contrast to LWF/SWF, which has nothing to do with that from the other way around.

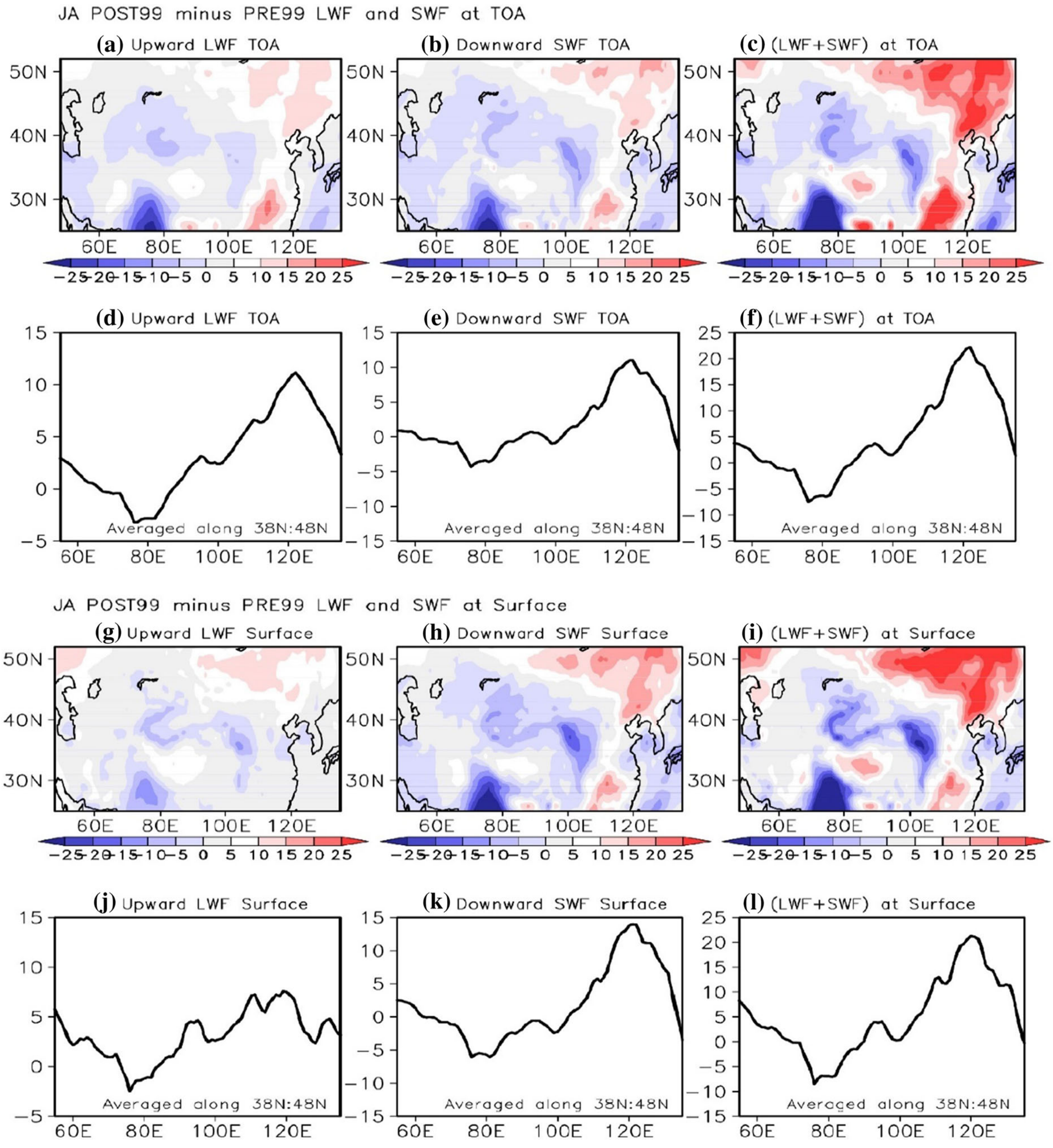

Figure 7

a The upward JA mean LWF (Wm^{-2}) through the top of the atmosphere since the late 1990s (POST99-PRE99). **b** Same as **a**, but for downward SWF. **c** Same as **a**, but for LWF + SWF. **d–f** are those in **a–c**, respectively, averaged over the latitudinal belt of 38°N–48°N. **g–l** are similar to **a–f**, but with fluxes through the surface

For the TT variation over region I, the impact is most pronounced over the western side of the northern Tibet Plateau (i.e., the regions with large causality), whereas for the TT variation over region II, the overall impact is limited over the eastern side of the northern Tibet Plateau. This makes sense, as can be expected. A remarkable observation is that the impact of region I TT gradient is much more dominant, particularly for the LWF case. This is a reflection of the fact that the increasing ascending motion on the

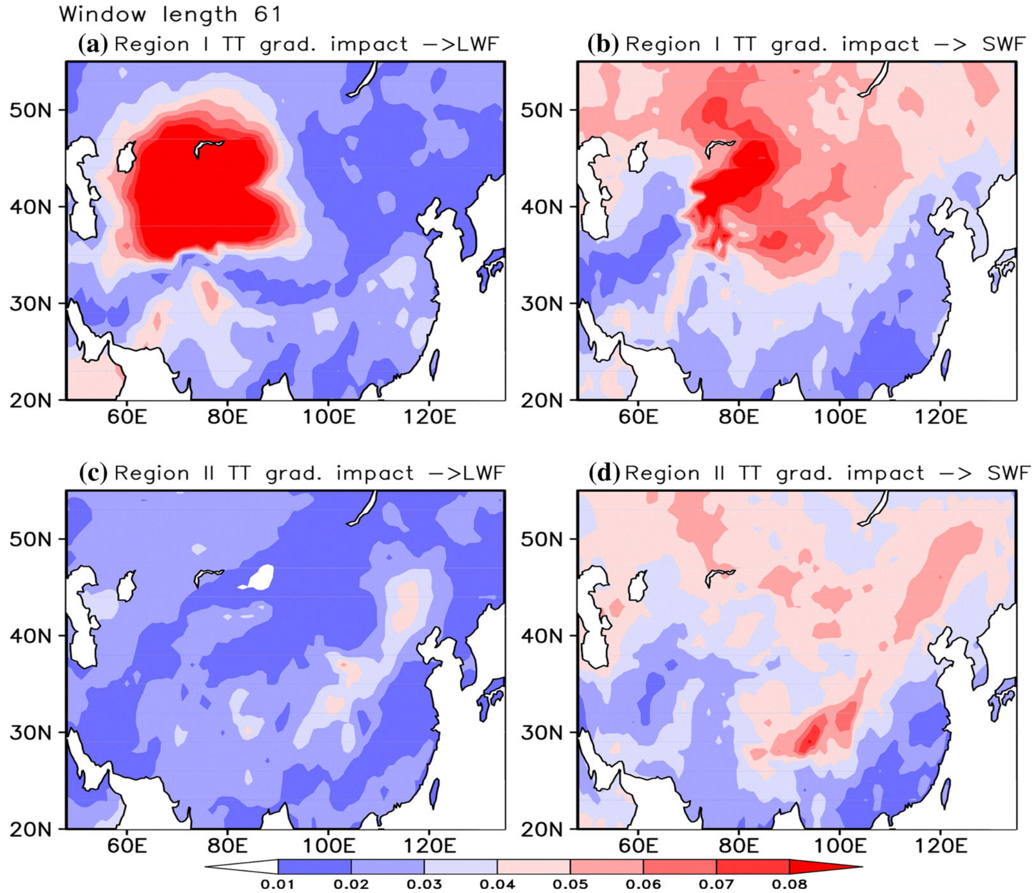

Figure 8

The causality (information flow in nats/day) from the TT thermal contrast over region I to **a** LWF and **b** SWF, for a time window size of 61 days. **c**, **d** are the same as **a**, **b**, but for region II. Nat is the unit for entropy, which has the form of $\int \rho \log \rho$ (ρ is the probability density function) when the logarithm uses a base e

western side of the plateau favors convection, and the resulting clouds influence significantly the incoming and outgoing heat fluxes. This remarkable result from another aspect distinguishes the role of the vertical TT thermal contrast over regions I and II on the East Asian convection in the late 1990s.

4. Summary

The upper tropospheric thermal contrast variation is observed to be one factor driving the convection change since the late 1990s over East Asia during the peak summer monsoon. The variation in tropospheric temperature, or TT, is can be observed to increase and decrease ever since the late 1990s over the regions west and east of the northern Tibetan Plateau, respectively. This remarkable out-of-phase change in thermal contrast is in agreement with the change in circulation and humidity flux, and has been further substantiated in a causal inference, which identifies a dominant causality from the TT gradient over the western side of the northern Tibetan Plateau to the longwave and shortwave fluxes through the top of the atmosphere. It is observed to control the convection over the northern Plateau and its surrounding regions, and hence represents a cause of the East Asian summer monsoon variability. That is to say, the climate variation over East Asia in the 1990s could have largely arisen from the regional response. In the studies that follow, we will use climate models to conduct sensitivity experiments to obtain further clarification.

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