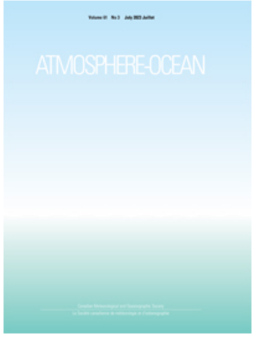

Atmosphere-Ocean

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tato20

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[Original manuscript received 11 November 2022; accepted 31 January 2023]

ABSTRACT *It has been recognized by the scientific community for many years that erratic monsoon attribution should be prioritized in order to meet the growing demand for reliable monsoon forecasts. It is believed that the severe 2009 drought in the South and East Asian regions was caused by an erratic monsoon season, which has sparked enormous interest in its cause. In this study, we have identified a factor in the upper troposphere, i.e. the large-scale upper tropospheric temperature, which may have potentially functioned as a new cause. We have observed that a major change in the upper tropospheric temperature occurred, with one region over Central Asia and another over the eastern Tibetan Plateau; also observed is the interaction between these two local systems. The thermal wind link suggests that the 2009 circulations over the two different regions at 250 hPa – are characterized by a cyclone and an anti-cyclone over Central Asia and the eastern Tibetan Plateau, respectfully, and that this could be the dynamic cause of the 2009 monsoon prediction failure. Subtropical jets provide a means of connecting the dynamical systems in the two different regions, which have enhanced the convection over Central Asia and reduced the convection over South and East Asia during that period. Also revealed is the role of the thermodynamic processes, specifically the role of the vertical thermal contrast (VTC) over Central Asia and the eastern Tibetan Plateau, which is responsible for changing the convective patterns during the 2009 monsoon season. This is further substantiated by the inferred causal relationship between the upper VTC and longwave fluxes (LWFs) at the top of the atmosphere.*

RÉSUMÉ *[Traduit par la rédaction] La communauté scientifique reconnaît depuis de nombreuses années que l'attribution des moussons erratiques doit être une priorité afin de répondre à la demande croissante de prévisions fiables des moussons. On pense que la grave sécheresse de 2009 dans les régions d'Asie du Sud et de l'Est a été causée par une saison de mousson erratique, ce qui a suscité un énorme intérêt pour sa cause. Dans la présente étude, nous avons recensé un facteur dans la haute troposphère, c'est-à-dire la température à grande échelle de la haute troposphère, qui a pu potentiellement fonctionner comme une nouvelle cause. Nous avons observé qu'un changement radical de la température de la haute troposphère s'est produit, avec une région au-dessus de l'Asie centrale et une autre au-dessus du plateau tibétain oriental; l'interaction entre ces deux systèmes locaux est également observée. Le lien entre les vents thermiques donne à penser que les circulations de 2009 sur les deux régions différentes à 250 hPa – sont caractérisées par un cyclone et un anticyclone sur l'Asie centrale et le plateau tibétain oriental, respectivement, et que cela pourrait être la cause dynamique de l'échec de la prévision de la mousson de 2009. Les jets subtropicaux permettent de relier les systèmes dynamiques des deux régions différentes, qui ont renforcé la convection en Asie centrale et réduit la convection en Asie du Sud et de l'Est au cours de cette période. Le rôle des processus thermodynamiques, notamment le rôle du contraste thermique vertical (CTV) sur l'Asie centrale et le plateau tibétain oriental, qui est responsable de la modification des schémas convectifs pendant la saison de mousson 2009, est également révélé. Cette hypothèse est étayée par la relation de cause à effet déduite entre le CTV en altitude et les flux d'ondes longues au sommet de l'atmosphère.*

KEYWORDS the 2009 erratic monsoon; upper tropospheric temperature; vertical thermal contrast; causal relationship

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1 Introduction

The regions of South and East Asia, which are located within a monsoon domain, are often subject to devastating natural hazards caused by anomalous monsoon patterns. There are a number of natural hazards that can be caused by monsoons' irregular behaviour, including droughts, floods, blizzards and heat waves, which brutally influence the local people and society. The South and East Asian monsoons, which varies remarkably from year to year from June through September, have a significant socioeconomic impact on the continent (Chen et al., 2019; Ghanekar et al., 2019; Li & Zhang, 2009; Qiu, 2010; Vaid & Kripalani, 2022a; Vaid & Liang, 2019a; Vaid & Liang, 2020; Yu et al., 2014). Over the Asian region, the monsoon evolution is primarily attributed to the land-ocean heat contrast, the south-to-north progression of the inter-tropical convergence zone due to the effect of changing solar insolation, jet streams, the heat source of the Tibetan Plateau, El Nino-Southern Oscillation (ENSO) (Dai et al., 2013; Gadgil & Joseph, 2003; Huang et al., 2003; Huang et al., 2012; Li & Yanai, 1996; Pant et al., 1988; Shukla & Mooley, 1987; Si & Ding, 2013; Vaid & Kripalani, 2021a, 2021b). These mechanisms, which have both atmospheric and oceanic causes, may make a monsoons extremely complex system erratic. It is not surprising that, despite the significant improvements in our understanding, the prediction of monsoon still remains a challenge and uncertain (Lau et al., 2000; Vaid & Kripalani, 2021a; Vaid & Liang, 2015; Wen et al., 2016). In order to meet the rising demand of trustworthy monsoon forecasts, the scientific community has, traditionally and presently, considered erratic monsoon attribution to be of high priority.

This situation happened in the 2009 monsoon, when a drought spell hit southern and eastern Asia causing predictions to be off. The drought was particularly severe in several parts of East and South Asia, where the reduction in total precipitation was most pronounced. The Ministry of Civil Affairs and the Office of State Flood Control and Drought Relief Headquarters in China both claimed that the drought had a significant impact on socioeconomic environments (Qiu, 2010). While in India, the monsoon claimed millions of people's lives, caused devastating agricultural losses, and affected the whole nation (Francis & Gadgil, 2009). To understand the drought, several investigations were conducted. The following factors were found to play a critical role in the aberrant 2009 monsoon. For instance, the 2008–2009 La Nina phase was found to modulate the East Asian drought (Gao & Yang, 2009). Evidence suggests that the long interruption in 2009 was driven by, for example, internal dynamics (Sikka et al., 2010), the intrusion of the West Asian desert air into the Central South Asian region (Krishnamurti et al., 2010), the reversal of the sea surface temperature gradient between the Bay of Bengal and the eastern equatorial Indian Ocean (Francis & Gadgil, 2010), and the warming in the Central Pacific, similar to the "El Nino Modoki" (Ratnam et al., 2010). It has been reported that, as a result, most of southern and eastern Asia experienced moderate to widespread droughts (source: www.imdpune.gov.in; http://www.chinadaily.com.cn/china/2010drought/index.html). Interestingly, none of the previous studies consider the importance of upper tropospheric temperature and how large-scale thermodynamical and dynamical systems interacted during the 2009 erratic monsoon. To the best of our knowledge, there has not been any research conducted on the role of the interaction between the large-scale processes in the upper atmosphere in generating the erratic 2009 monsoon.

Recently, a fresh viewpoint on the relevance and importance of large-scale interactions in the upper troposphere and its effects on South and East Asia was identified (Vaid & Kripalani, 2021a, 2021b, 2022a; Vaid & Liang, 2019a, 2019b). The objective of this study is to extend this point of view to explore additional possible causes for the failure of the monsoon. More specifically, the upper vertical change of tropospheric temperature during the 2009 monsoon and its effect on the erratic monsoon will be examined in the context of large-scale interaction. Section 2 is a description of the data and methodology, Section 3 presents the analysis and the findings, and Section 4 provides an overall summary and conclusion to the study.

2 Data and methodology

The National Center for Environmental Prediction (NCEP) – DOE AMIP 2 provides the daily wind fields, air temperature, and relative humidity, which we will be using for the study (Kanamitsu et al., 2002). Moreover, total cloud area (TCA) fraction, total surface precipitation flux (TSPF), and long-wave flux (LWF) at the top of the atmosphere (Rienecker et al., 2011) from the Modern Era Retrospective-analysis for Research and Applications (MERRA) of NASA will additionally be utilized. Note, this dataset has already been used to study monsoon variation over different regions, including South Asia (Vaid & Kripalani, 2022a, 2022b) and East Asia (Vaid & Liang, 2018b, 2019b). The daily climatology of the datasets is computed based on the 20-year (between 1996 and 2015) climatology (Vaid & Kripalani, 2021a). Besides, the rainfall data from the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie & Arkin, 1997) is also employed.

To quantitatively explore the measurable impact of the upper tropospheric temperature thermal contrast on the atmospheric variables, such as longwave (LWF) and total cloud area (TCA) fraction, over South and East Asia during the 2009 monsoon, we employ a newly established methodology for determining the causality between time series (Liang, 2014, 2015, 2016, 2018, 2021). Under a linear assumption, the maximum likelihood estimator (MLE) of the causality from X_2 to X_1 (units: nats per unit time) proves

 https://doi.org/10.1080/07055900.2023.2177136

to be:

$$T_{2\to 1} = \frac{C_{11}C_{12}C_{2,d1} - C_{12}^2 C_{1,d1}}{C_{11}^2 C_{22} - C_{11}C_{12}^2}, \qquad (A1)$$

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 stepsize and $k \geq 1$ some integer (usually chosen to be 1 for realistic or noisy series). This methodology is modified by us to form a "composite causality analysis." In the Appendix of Vaid and Liang (2019b) they show the methodological steps to be taken in performing such analysis. In order to examine the measurable impact of the upper tropospheric temperature thermal contrast on the atmospheric variables, such as longwave (LWF) and total cloud area (TCA) fraction, over South and East Asia during the 2009 monsoon period, we compute the causalities on a running window for all the time steps, and then make composites for those during June to September (JJAS) 2009. More specifically, for time series of length N (with time steps 1, 2, 3, … , N), suppose we consider a time window of length M, with $M<N$. We first perform the analysis for the sub-series on steps 1, 2, … , M, and take the resulting value as the causality at time step $1 + \frac{1}{2}(M - 1)$. We then slide the window forward by 1 and repeat the analysis for the sub-series on steps 2, 3, … , M+1, and so forth. In the end, we will obtain a series of causality on time steps centred at these sliding windows (no value at the beginning M/2 steps and the last M/2 steps). In the present case, an analysis is performed on the causal patterns produced by various time window sizes, including 41, 51, 61, and 71 days, and the resulting causal patterns are similar. After this is done, the composite causalities for JJAS 2009 are obtained.

3 Results

Changes in the 2009 summer monsoon rainfall from the long period average can be demonstrated by displaying the spatial pattern of precipitation during JJAS 2009 minus and climatology (Fig. 1a and Fig. 1b). During the 2009 summer monsoon, a contrasting pattern in the rainfall variations over the Asian region is exhibited, i.e. a deficit of rainfall over South and East Asia and a surplus of rainfall over Central Asia (Fig. 1). As discussed in Section 1, several previous studies have attempted to explain why there was a rainfall deficit, especially over South and East Asia, during the summer 2009 monsoon. However, the complex system is controlled by many mechanisms, with both atmospheric and oceanic causes, making the diagnostic study of the erratic 2009 monsoon challenging. Moreover, the upper tropospheric temperature, which is of utmost importance to the Asian monsoon (Liu & Yanai, 2001; Zhou & Zhao, 2010; Zuo et al., 2012; Vaid & Kripalani, 2021a, 2021b; Vaid & Kripalani, 2022a, 2002b), has not been considered. In the following, the daily upper air temperature (i.e. the temperature between 400 hPa and 50 hPa) during JJAS of 2009 and its departure from the long-term average (i.e. JJAS 2009 minus Climatology) over the Asian region regions are analysed.

This investigation shows that there exists a substantial large-scale air temperature variation between 100 and 250 hPa (Fig. 2a and Fig 2b). The upper air temperature experiences a significant change (99% confidence level) over two regions: Central Asia (Long. = 25°E–80°E, Lat. = 25°N–50°N; hereafter referred to as region I) and the eastern Tibetan Plateau (Long. = 85°E–130°E, Lat. = 20°N–40°N; hereafter referred to as region II). Central Asia was revealed to have a noticeable vertical dipole pattern in the upper troposphere, with negative anomalies at 250 hPa and positive anomalies at 100 hPa. Over the eastern Tibetan Plateau, positive anomalies at 250 hPa and negative

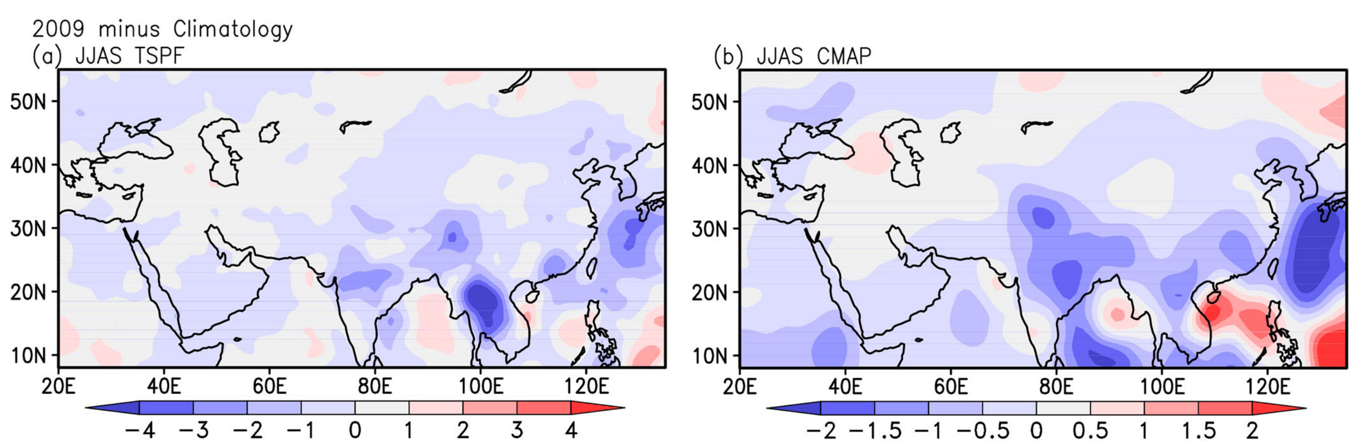

Fig. 1 The JJAS total surface precipitation flux (TSPF) and rain rate in 2009 (with climatology removed): (a) TSPF, and (b) Rain rate from CMAP (mm/day).

anomalies at 100 hPa are observed to be prevalent (Fig 2a and 2b). Over Central Asia and the eastern Tibetan Plateau regions, the air temperature at 100 and 250 hPa is shown to vary more than 2 K. Further findings show that the troposphere at 100 hPa/250 hPa appears to be much warmer or cooler over Central Asia, while it appears the opposite over the eastern Tibetan Plateau. It is revealed that the interaction between the large-scale upper tropospheric thermos-dynamical properties – which has not yet been completely explored – is what causes the dissimilarity between the 2009 monsoon and the long-period average. We speculate that it may have played a role in the drought-like conditions that prevailed over South and East Asia during the summer monsoon of 2009. Importantly, the connection between the eastern Tibetan Plateau and Central Asia has not yet been examined in previous studies. Given the supremacy of Central Asia and the Tibetan Plateau, also known as the Asian water tower (Dong et al., 2007; Fekete et al., 1999; Peng et al., 2018; Xu et al., 2002; Zhao & Zhang, 2016), these findings are unexpected.

In the following, we first examine the possible existence of a vertical thermal contrast (VTC) in the upper troposphere, particularly over Central Asia and the eastern Tibetan Plateau region. To explore the VTC, the vertical profiles of the average air difference over regions I and II for the 2009 period, minus climatology, are presented separately in Fig. 3a and 3b. Interestingly, the VTC over Central Asia is observed to be 3 K, and over the eastern Tibetan Plateau region it is observed to be approximately 1.5 K. The upper tropospheric temperature variabilities higher than 0.1–0.3 K are thought to be of considerable consequence in climate change and its drivers (Shangguan et al., 2019; Steiner et al., 2020; Vaid & Kripalani, 2021a, 2021b, 2022a, 2022b). Importantly, relative to the long period average, an increase of approximately 1.3 K and decrease of 1.9 K in the upper troposphere temperature at 100 and 250 hPa over Central Asia is observed. Whereas over the eastern Tibetan Plateau a noticeable decrease of 0.8 K at 100 hPa and increases of approximately 0.7 K at 250 hPa in the upper tropospheric temperature have been identified. It testifies to the

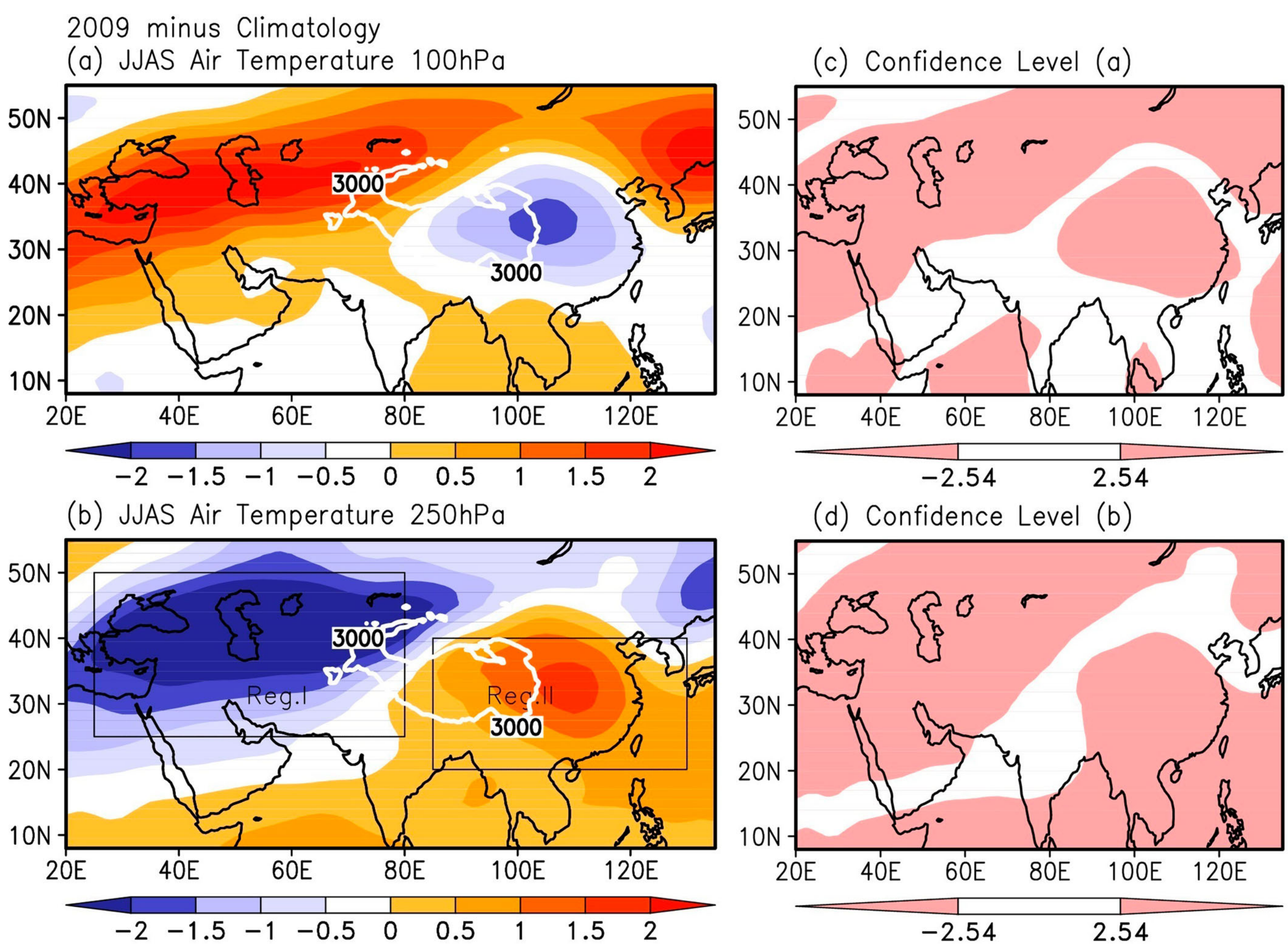

Fig. 2 The JJAS fields in 2009 (with climatology removed): (a) Air temperature (in K) above 100 hPa.; (b) As (a) but for 250 hPa. The isoline represents the 3000-meter topographical contour line, shown in white. (c) and (d) indicate that the abnormalities are statistically different from zero at the 99% level. (e) and (f) are the vertical variations of the JJAS air temperature over region I and region II, respectively.

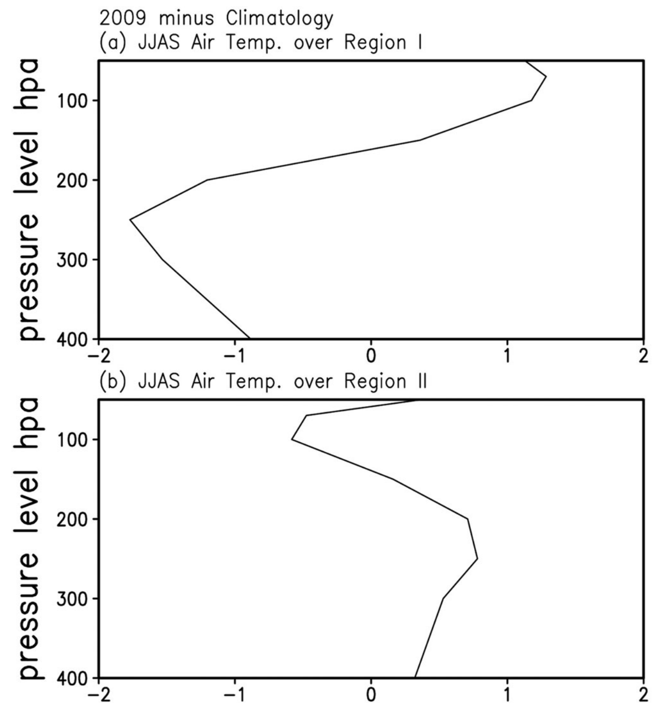

Fig. 3 (a) Vertical variation of the JJAS air temperature over region I. (b) Same as (a) but for region II. As before, the climatology is removed a priori.

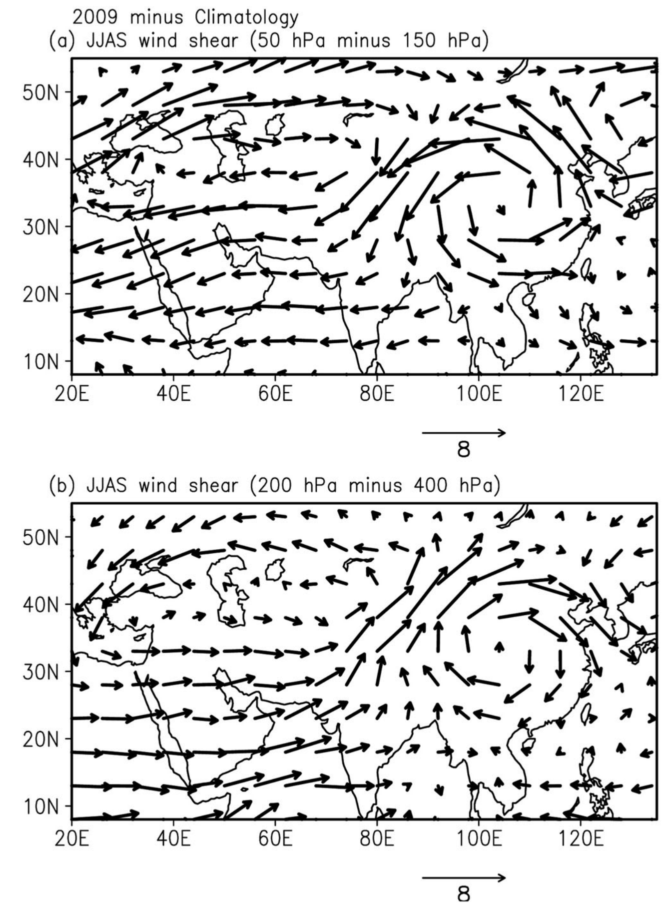

Fig. 4 Result of the change in climatology from 2009, averaged wind shear during JJAS: (a) 50–150 hPa; (b) 200–400 hPa.

existence of VTC between the pressure levels 400 hPa to 50 hPa (Fig. 3a and 3b). Recall that the interaction between the upper tropospheric temperature variations over a large scale tends to modulate the convection (Vaid & Liang, 2020). Therefore, it will impact the summer monsoon variation, depending upon the tropospheric temperature variations (Vaid & Kripalani, 2021a, 2021b; Vaid & Liang, 2015; 2018a; 2018b; 2019a, 2019b, 2020).

We then examined the dynamics related to the vertical temperature contrast over regions I and II. To accomplish this, the wind vector shear anomalies around 100 and 250 hPa were plotted (Fig. 4a and Fig. 4b). The annotation delineates the interaction between the anomalous cyclonic circulation centred over Central Asia and the anomalous anticyclonic circulation over the eastern Tibetan Plateau during the 2009 monsoon (Fig. 4b). Further analysis highlights its potential influence on the monsoon dynamics through the thermal wind relation (Fig. 4). An examination of Fig. 4a and 4b illustrates that the circulation features that have been disclosed coincide with the out-of-phase vertical variation in tropospheric temperature that is visible across both Central Asia and the eastern Tibetan Plateau in Fig. 2a and 2b. Clearly, an anomalous cyclonic/anti-cyclonic circulation is discernible over Central Asia, in agreement with the vertical variation in tropospheric temperature at 250 hPa/100 hPa. Whereas over the eastern Tibetan Plateau, the tropospheric temperature variation is found to be consistent with an anomalous anti-cyclonic/cyclonic circulation observed at 250 hPa/100 hPa (refer to Figs. 2b and 4b for more details). Notably, the horizontal advection features are found to be compatible with the tropospheric temperature variation depicted in Fig. 2b (for further information on the significant correlation between horizontal advection and temperature variation, see Vaid & Kripalani, 2021a, 2021b; Vaid & Liang, 2020). As implied by the thermal wind relation, we can infer that the 2009 monsoon drought over South and East Asia is dynamically controlled by distinct differences in circulation patterns at 250 hPa (Fig. 2b and Fig. 4b), which are characterized by a cyclonic circulation and anticyclonic circulation over the regions I and II, respectively.

We speculate that induced thermal wind factors may affect convection in the Asia region as a consequence of the strong thermal contrast between these two distinct geographical regions (He et al., 2007; Holton, 2004; Webster, 1987). The impact of distinct differences in circulation pattern and its interactions, i.e. the interactions of the anomalous cyclone and anti-cyclone over Central Asia and the eastern Tibetan Plateau respectively, on the mega-drought in Asia in 2009 can be understood using the wind motion interaction (Fig. 4b) via thermal wind relation and humidity pattern (Fig. 5). With "T" as the temperature between two pressure levels (here 250 and 100 hPa), "R" as the universal gas constant, and "f" as the Coriolis parameter, then the geostrophic velocity difference between the two pressure levels 250 and 100 hPa can be derived from the thermal-wind relation

$$\frac{\partial V_g}{\partial \ln P} = \frac{-R}{f}\hat{k} \times \nabla_p T$$

where ∇_p signifies the gradient operator on the pressure surface. Integrating from pressure level P_o to P_1, we get

$$V_T = V_g(P_1) - V_g(P_0) = -\frac{R}{f}\int_{P_0}^{P_1} (\hat{k} \times \nabla_P T) d \ln P$$

$$= -\frac{R}{f}\nabla_p T \ln\left(\frac{P_0}{P_1}\right),$$

This tells us that a northeasterly wind anomaly can be found in the 2009 monsoon (Figs. 2b and 4b,). Notably, in the present case, the northeasterly wind does not bring humidity (Fig. 5) to South and East Asia from the sea towards the east during this period (Fig. 4b). Recall here, relative humidity over the sea is observed to be significantly less than long term average (Fig. 5). Therefore, it is reasonable to assume that the lower humidity caused by the interaction between the large-scale features over Central Asia and the eastern Tibetan Plateau ultimately plays a role in decreasing the amount of vapour over South and East Asia (Fig. 6). Therefore, the interaction between these local systems will cause fairly widespread to widespread drought activity over most parts of South and East Asia, and thus support the break in the monsoon.

With the above observation, it is important to investigate the potential connection between the eastern Tibetan Plateau and the circulation patterns across Central Asia. Previously, the subtropical jet stream was seen to act as a bridge connecting various parts of the globe through atmospheric teleconnections (e.g. Branstator, 2002; Li et al., 2008; Vaid & Kripalani, 2021a, 2022b; Vaid & Liang, 2020). Therefore, we studied the subtropical jet stream over the Asian region. We have examined the 200-hPa zonal winds, which serve as a substitute for the subtropical jet stream (Fig. 7). A closer examination of the contrasts (JJAS 2009 minus Climatology) across Central Asia and the eastern Tibetan Plateau reveals important dynamical shifts, specifically over the subtropical jet stream (Fig. 7). It is observed that the variation in the subtropical jet steam over the distinct regimes is a cause for the anomalous cyclone and anti-cyclone over Central Asia and the eastern Tibetan Plateau respectively (Fig. 4b and Fig. 7). Specifically, the map (Fig. 7) indicates that there is a westerly wind over the southern part of Central Asia in association with an easterly wind over the northern part of Central Asia. Additionally, an easterly wind over the southern part of the eastern Tibetan Plateau in association

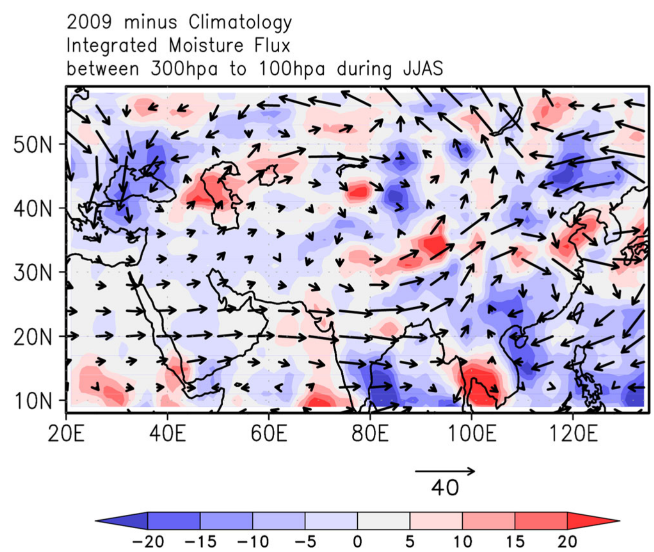

Fig. 6 The JJAS 2009 moisture fluxes integrated between 300 and 100 hPa (with climatology removed). Moisture fluxes are shown as vectors, and the shaded is divergence ($\times 10^{-6}$ rh s^{-1}).

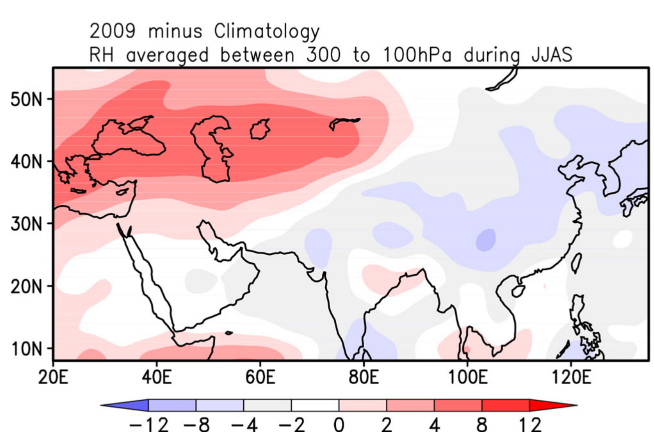

Fig. 5 The JJAS relative humidity (in %) averaged between 300 and 100 hPa (with climatology removed).

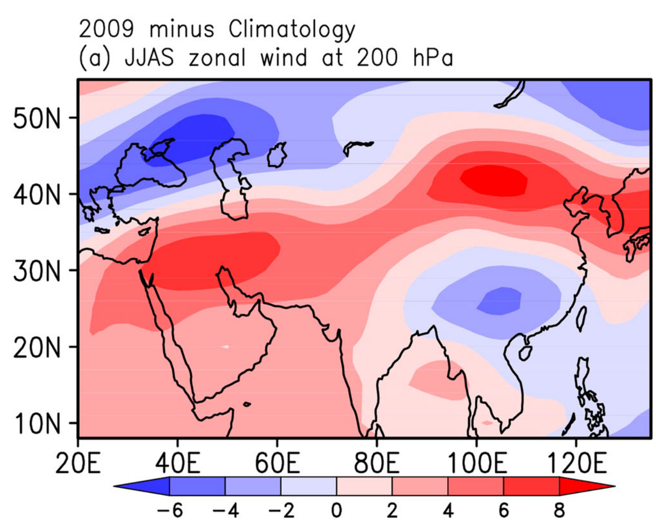

Fig. 7 The zonal wind (in m/s) at 200 hPa calculated based on the JJAS 2009 velocity anomaly (with climatology removed).

with the westerly wind over the northern part of the eastern Tibetan Plateau is depicted. This distribution suggests the formation of a cyclonic circulation over Central Asia and an anticyclonic circulation over the eastern Tibetan Plateau. Thus, it implies that the subtropical jet steam acts as a possible cause of the anomalous cyclone and anti-cyclone over Central Asia and the eastern Tibetan Plateau, respectively (Fig. 4b and Fig. 7). Apart from this, it also indicates that subtropical jet steams act as a possible atmospheric pathway (or teleconnections) through which the anomalous cyclone and anti-cyclone over Central Asia and the eastern Tibetan Plateau, respectively, are connected (Fig. 4b and Fig. 7). Nevertheless, it is too early to make a conclusive statement. A further detailed study using adequate atmospheric general circulation models is needed in the future.

The ideal gas equation, Pressure × Specific Volume = Temperature × Constant, means that temperature drops as air pressure lowers, given a specific volume. Low pressure causes cyclonic wind, which in turn causes low temperatures, and vice versa (cf. Figs. 2b, 4b, and 7 for these conspicuous features). Recall that such potential physical processes are viewed as a sign of convection change in this context (refer to Vaid & Liang, 2018a). Therefore, it suggests an increase in convection over region I and a decrease over region II during 2009.

We examine the variations in the upper relative humidity between 300 and 100 hPa during the 2009 monsoon. Upper humidity has been shown to have an impact on upper tropospheric convection in recent studies (Fu et al., 1997; Udelhofen & Hartmann, 1995; Vaid & Kripalani, 2021a, 2021b; Vaid & Liang, 2019a, 2019b). For instance, Udelhofen and Hartmann (1995) discovered that a 10% change in tropospheric relative humidity causes a change in radiative forcing of the order of 1.4 $\mathrm{W m^{-2}}$. Amazingly, a variation of around 10% in upper relative humidity between 300 and 100 hPa is exhibited during 2009 over Central, southern, and eastern Asian regions (refer to Fig. 5). A surplus of humidity flux over Central Asia, and a lack of humidity flux over South and East Asia, including the South China Sea was exhibited in 2009. The large-scale pattern of relative humidity, lower over the South and East Asia region and higher over the Central Asia region, is found to agree with the thermal contrast and wind circulation (Figs. 2b, 4b, and 7). The aforementioned finding explicitly shows the interaction of the large-scale wind motion with the relative humidity.

It is well known that relative humidity governs LWF and TCA (a proxy for clouds) and plays a leading role in radiation and water cycle balances (Fu et al., 1997; Udelhofen & Hartmann, 1995; Zhou et al., 2007). Notably, LWF and cloud cover have often been used as indicators of large-scale deep convective activity (Murakami, 1980; Yanai et al., 1973). Recall here that LWF is the total amount of thermal radiation emitted from the earth to interplanetary space. Low values of LWF are associated with clouds, as radiation from the low-temperature cloud top is weaker than that from the surface (Murakami, 1980; Yanai et al., 1973). Therefore, the LWF and TCA fluctuations during the 2009 monsoon are investigated (Fig. 8a and 8b). Figure 8 shows JJAS 2009 minus Climatology for LWF and TCA. Particularly across Central Asia and South and East Asia, it is evident that LWF and TCA have increased/decreased. This is consistent with the above-mentioned features, i.e. the thermal wind circulation (Figs. 4b and 7) and the upper VTC (Fig. 2b).

To further substantiate this claim, the direct relationship between the upper thermal contrast (as described in Fig. 2b) and LWF and TCA is investigated. The association is quantified utilizing a recently developed "composite causality analysis." Refer to the appendix "Composite Causality Analysis" in Vaid and Liang (2019b) for the methodology. An analysis is performed on the causal patterns produced by various time window sizes, including 41, 51, 61, and 71 days. The outcomes are shown in Fig. 9, and the causality from the upper tropospheric temperature thermal contrast to LWF and TCA is expressed. The study shows that the upper tropospheric temperature variation over regions I and II is strongly related to LWF and TCA over the Asian region. As shown in Fig. 9, the impact of VTC over Central Asia is seen to be most pronounced not only over the

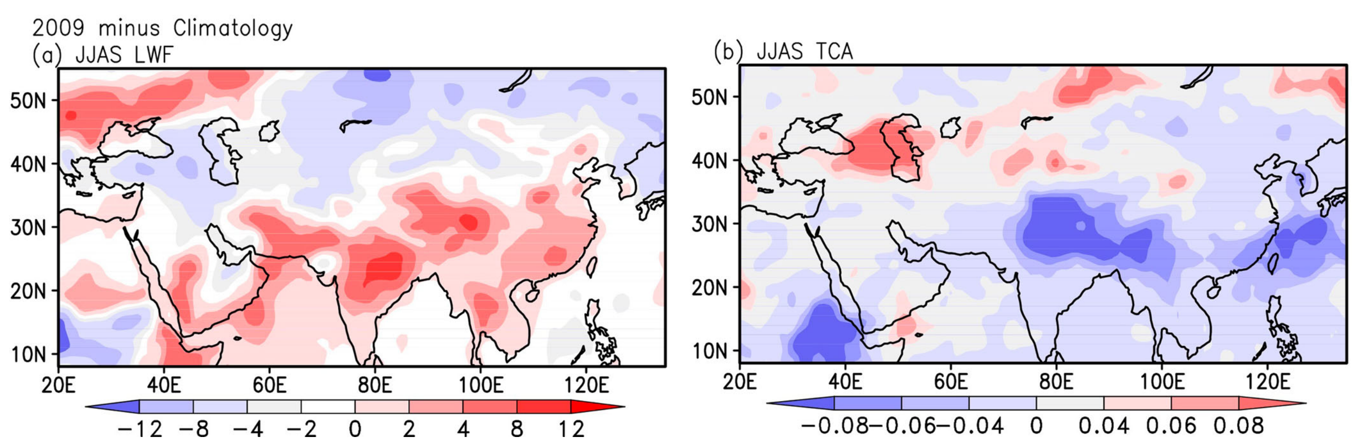

Fig. 8 Spatial distribution of the JJAS 2009 (a) LWF and (b) TCA fraction. The climatology is removed.

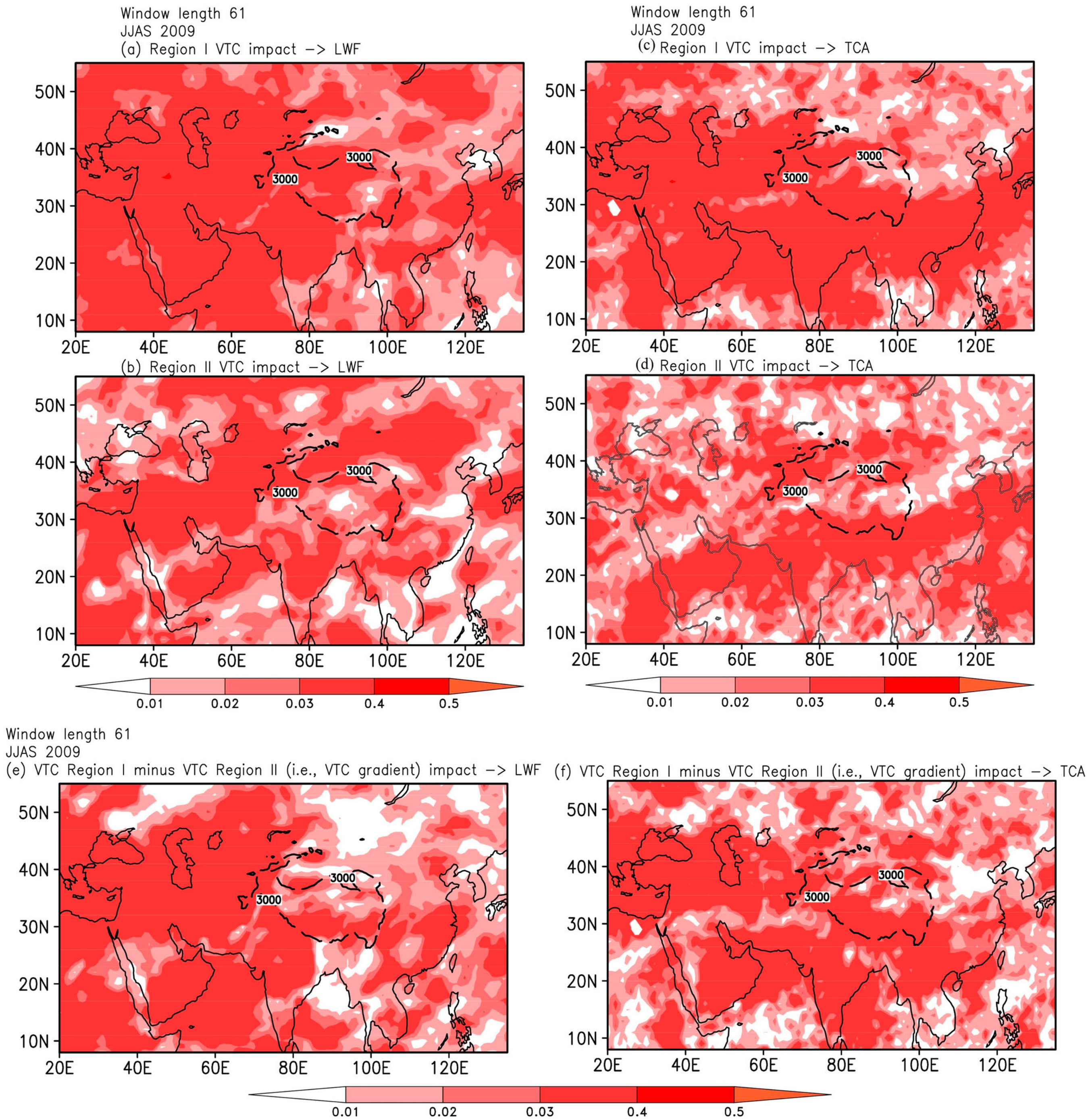

Fig. 9 (a) The causality (information flow, in nats/day) from the VTC over region I to the LWF at TOA for a time window size of 61 days. (b) The causality (information flow in nats/day) from the VTC region II to the LWF at TOA for a time window size of 61 days. (c) and (d) are the same as (a) to (b), respectively, but for the TCA. (e) the causality from the VTC region I minus VTC region II (i.e. VTC gradient) to the LWF at TOA, for a time window size of 61 days. (f) is the same as (e), but for the TCA. The 3000-m topographical isoline is shown by a black contour line (dashed).

Central Asian region itself, but also over the eastern Tibetan Plateau region. Similarly, the VTC over the eastern Tibetan Plateau is revealed to be casual to the Central Asian region. Interestingly, VTC over both the regions contribute to the LWF and TCA over the south and the east Asian regions in the 2009 summer monsoon. To substantiate the impact of VTC between the two distinct regimes (i.e. the VTC region I minus VTC region II: VTC gradient) on LWF and TCA over the south and east Asia, we analysed the causality from the VTC gradient to LWF (Fig. 9e) and TCA (Fig. 9f). The result demonstrates that VTC gradient is causal to the LWF and TCA over South and East Asia. This substantiates the finding that the VTC gradient between the two distinct regimes dynamically impacts LWF and TCA. Specifically, causality is identified from the upper tropospheric temperature thermal contrast to the LWF and TCA and is unrelated to those gained from the other direction. It is important to note that the causalities identified in this approach are asymmetric in direction. The impact of the upper vertical tropospheric temperature thermal contrast over regions I and II on the convection changes across South and East Asia is distinguished by this amazing observation. Based on this fact, we may also say that upper tropospheric temperature act as a key mechanism controlling the diversity of the South and East Asia monsoon.

4 Summary

Severe droughts increasingly impact societies in South and East Asia and are, therefore, of great socioeconomic importance. Previous studies have investigated the impacts of thermal contrasts, in terms of different definitions, on the Asian monsoon. These definitions include, for example, thermal contrasts at the surface and lower troposphere. Despite this, its dependence on large-scale dynamical and thermodynamic processes, particularly the upper tropospheric temperature variability, is yet to be understood. In this study, we have addressed the question of what caused the change in convection over South and East Asia during the 2009 erratic monsoon. It was found that the erratic monsoon was primarily caused by the vertical thermal temperature contrast of the upper troposphere and its interaction activities. We highlighted this as a factor that could have potentially contributed to the monsoon drought in the region. At a pressure level of 250 hPa, the significant warming and cooling of the upper air temperature in conjunction with the anti-cyclonic and cyclonic circulations, especially those across the eastern Tibetan Plateau and Central Asia, may be seen as a reflection of the thermal wind system (Figs. 2b and 4b). Large-scale thermodynamic and dynamic variables across Central Asia and the eastern Tibetan Plateau interacted during the 2009 erratic monsoon, causing substantial change to the convection pattern. According to the analysis, the subtropical jet stream connects the dynamical systems over the two different regions, leading to an increase in convection over the Central Tibetan Plateau and decrease over South and East Asia. Additionally, this study emphasized the relevance of the thermo-dynamical process in causing the variations in convection during the 2009 monsoons, namely the VTC over Central Asia and the eastern Tibetan Plateau. Additionally, a newly established methodology was used to exhibit the causal relationship between VTC and LWF and TCA, which presented further evidence for the role of VTC across Central Asia and the eastern Tibetan Plateau in the 2009 aberrant monsoon.

Acknowledgments

We are grateful to the editor and anonymous reviewers for their valuable comments and suggestions, which helped improve the manuscript in its present form. The data were visualized with GrADS. Datasets from the NCEP-DOE AMIP 2 reanalysis version 2, MERRA, and CMAP were utilized.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The National Science Foundation of China (42230105, 41975064) provided funding for this study.

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