Relationship between the thermal condition of the Tibetan Plateau and precipitation over the region from eastern Ukraine to North Caucasus during summer

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Abstract

Remarkable climate anomalies occurred in Europe in recent years, but the reasons are not entirely disclosed. This entails further exploring the physical mechanism of anomalous climate variability over Europe on the basis of previous studies. Using NCEP–NCAR reanalysis and CMAP precipitation datasets, we investigated the relationship between the thermal condition of the Tibetan Plateau (TP) and precipitation over Europe during summer and related mechanisms behind through observational analyses and simulation experiments. The results show that the summer TP surface air temperature (SAT) is significantly correlated with the simultaneous precipitation over the region from eastern Ukraine to the North Caucasus (EUNC; 43°–51° N, 34°–46° E) during the period 1979–2017. The effect of anomalous TP heating plays, to some extent, an active role in linking the summer TP SAT with EUNC precipitation. The variability of the TP SAT is a result of the anomalous TP heating, but it can reflect the variability in temperature of a thick tropospheric air column over the TP well. Corresponding to higher (lower) TP SAT, the higher (lower) temperature anomaly appears over the TP and extends westwards through the transport of anomalous temperature fluxes from the TP to the EUNC regions in the upper troposphere, resulting in the expansion (withdrawal) of the South Asian high (SAH) and associated less (more) precipitation over the EUNC region. Numerical simulations basically reproduce the above-mentioned physical process, which confirms that, through stimulating the variability of upper-tropospheric temperatures over the TP and a larger area to its west and associated upstream large-scale atmospheric circulation, the summer TP's thermal condition can modulate and expand the impact of the SAH to the EUNC region and therefore affect the concurrent precipitation in situ. This study implies an importance of the thermal anomaly of the TP to the variability of EUNC precipitation during summer.

1 Introduction

Europe has experienced remarkable climate anomalies in recent years. For example, severe wet anomalies appeared over Northern Europe (15° W–20° E, 45–60° N) during the summers of 2007, 2011, and 2012, which were the first, fifth, and sixth wettest years during the period 1979–2012, respectively

(Screen 2013). Meanwhile, in contrast to the positive precipitation anomalies over Northern Europe in recent summers, negative precipitation anomalies have prevailed over Mediterranean Europe and northwest Scandinavia (Screen 2013). The extreme drought and heat wave that hit Europe in the summer of 2003 had enormous adverse social, economic, and environmental effects (Beniston 2004; De Bono et al. 2004; Stott et al. 2004). Moreover, more than 70,000 additional deaths occurred in Europe during summer 2003 for the reference period 1998–2002 (Robine et al. 2008). In summer 2010, northeastern Europe and Russia also experienced an extended and extreme heat wave event, and its associated drought and high temperatures caused severe forest fires and crop failure (Barriopedra et al. 2011; Sedláček et al. 2011). Clearly, more studies are required to reveal the physical mechanisms of anomalous climate variability over Europe, in particular, variability of summer precipitation.

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Several factors are known to be important contributors to the variability of summer precipitation over Europe. As the principal pattern of interannual atmospheric variability over the North Atlantic–European sector, the summer North Atlantic Oscillation (NAO) strongly affects Northern European and Mediterranean precipitation by adjusting the position of the North Atlantic storm track (Folland et al. 2009; Bladé et al. 2012). Moreover, observational and numerical model results suggest that sea surface temperature anomalies (SSTAs) in the Atlantic Ocean, the Mediterranean Basin, and the North Sea modulate European climate anomalies, such as summer anomalous temperature and precipitation, on different timescales (Colman and Davey 1999; Cassou et al. 2005; Sutton and Hodson 2005; Feudale and Shukla 2011a, b; Sutton and Dong 2012).

In addition to the direct effect of adjacent Atlantic, Mediterranean Basin, and North Sea SSTAs and associated atmospheric modes, many studies (Ropelewski and Halpert 1987; Polonsky and Voskresenskaya 2003; Bulic and Kucharski 2012) have revealed that the climate variability over the Atlantic–European region is closely connected with El Niño–Southern Oscillation (ENSO). ENSO may exert a positive forcing on tropical Atlantic SSTs through modulating Walker circulation anomalies (Sutton et al. 2000; Saravanan and Chang 2000) or through exciting the propagation of Rossby-like wave disturbances (Nobre and Shukla 1996) and is also related to European precipitation (Lloyd-Hughes and Saunders 2002). Polonsky et al. (2004) further argued that, together, ENSO and the NAO form a complex interactive system, which contributes to a definite pattern of Euro-Asian climate variability. Moreover, the Indian Ocean Dipole (IOD), which is a dipole pattern of internal variability with anomalously low SSTs off Sumatra (i.e., in the eastern Indian Ocean) and high SSTs in the western Indian Ocean (Saji et al. 1999), also impacts the surface air temperature (SAT) and sea level pressure (SLP) over the Mediterranean and Black Sea region in summer, and the IOD-induced SAT/SLP anomalies can be clearly detected and are statistically significant (Polonsky and Basharin 2017).

Apart from the effects of SSTAs in different oceans and related anomalous atmospheric modes, snow cover and sea ice anomalies are, to some extent, responsible for the variation in European precipitation. For example, Overland et al. (2012) attributed recent wet summers in the UK to reduced spring snow cover over North America and decreased sea ice in the Hudson Bay. Wu et al. (2013) revealed a close relationship between winter–spring sea ice anomalies to the west of Greenland and Eurasian precipitation anomalies during the following summer. Wu et al. (2014) suggested that a west–east dipole pattern of Eurasian spring snow cover contributes to Eurasian temperature and precipitation anomalies during spring and the following summer.

The contributions of the thermal condition anomaly over the Tibetan Plateau (TP) to summer climate anomalies in different regions of the globe have been extensively studied. Using snow cover to measure the TP's thermal condition, Wu et al. (2012) revealed that the TP heating exerts a modulating effect on ENSO teleconnections and therefore affects the relationship between ENSO and the East Asian summer monsoon (EASM). The TP snow cover not only adjusts the EASM and related climate anomalies (Liu et al. 2014; Wu et al. 2015; Wang et al. 2018) but is also an important factor influencing the interannual variations of Eurasian heat wave frequency (Wu et al. 2016a). Employing surface or tropospheric air temperature data over the TP to reflect its thermal condition, many studies have shown that the TP heating anomaly can affect an extratropical large-scale atmospheric teleconnection over the Northern Hemisphere, i.e., the Asian–Pacific Oscillation (APO) during boreal spring and summer (Nan et al. 2009; Zhou et al. 2009; Liu et al. 2015, 2017a). The APO is linked to the variation of the NAO (Zhou and Wang 2015) and also measures the variability of monsoon rainfall over South Asia, East Asia, and extratropical North America (Zhao et al. 2012). This further implies that the TP heating may first affect the APO and then have a remote modulating effect on summer rainfall over different regions of the world. Recently, Nan et al. (2018) suggested that the TP heating may affect the variability of summer precipitation over central–eastern Sahel, West Africa, by modulating the upstream large-scale circulation. Using a fully-coupled climate model, Lu et al. (2018) uncovered a possible effect of the TP on the upstream climate over West Asia, North Africa, South Europe, and the North Atlantic. However, some issues remain unclear, such as, is the variability of the TP's thermal condition significantly correlated with the variability of summer precipitation over Europe? And if so, what is the physical process linking the TP's thermal condition with summer European precipitation? Can this process be captured by numerical experiments? In this study, these issues are explored.

The rest of this paper is organized as follows: The datasets, methods, and numerical model are described in Section 2. The relationship between the summer (June–July–August) thermal condition of the TP and the simultaneous precipitation over Europe is investigated in Section 3. Using observation and numerical simulation, a physical process that potentially explains the above relationship is presented in Section 4. Finally, a summary and a discussion are provided in Section 5.

2 Data, methods, and model

The present study primarily focuses on the region from eastern Ukraine to western Kazakhstan via Russia, which is located to

the north of the Black Sea and the Caspian Sea. For convenience, this region is called the Ukraine–Russia–Kazakhstan (URK) region (43° – 51° N, 34° – 46° E and 48° – 55° N, 46° – 58° E, as indicated by the black boxes in Fig. 1). Here, the left box represents the region from eastern Ukraine to the North Caucasus (in brevity, called the EUNC region hereinafter), and the right box denotes the Kazakhstan region. For the period 1979–2017, summer precipitation accounts for 28% of annual precipitation amount over the URK region.

This study uses monthly mean air temperature at 2 m and pressure-level geopotential height, air temperature, and u - and v -winds, which are obtained from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996). The spatial resolution of the NCEP surface data (e.g., 2-m temperature) is $1.875^{\circ} \times 1.915^{\circ}$, on Gaussian grids, while that of the NCEP pressure-level data (e.g., geopotential height) is $2.5^{\circ} \times 2.5^{\circ}$. The monthly values of the Climate Prediction Center Merged Analysis of Precipitation (spatial resolution: $2.5^{\circ} \times 2.5^{\circ}$; Xie and Arkin 1997) are also used in this study. The monthly extended reconstructed SST dataset (version 4) on $2^{\circ} \times 2^{\circ}$ grids (Huang et al. 2015) was obtained from the National Oceanic and Atmospheric Administration. The above data are extracted for the period 1979 to 2017.

Correlation and regression are used to examine the relationships between variables. The Student t test is employed to evaluate the statistical significance of correlation and regression analyses unless otherwise stated. Since the variation of

one variable may sometimes be caused by multiple factors, a linear fitting method is applied to show the independent effect of one factor after removing the variation of the other factor (Hu et al. 2012). For the two time series X_1 and X_2 , the X_2 -related variation (called X_1') of X_1 can be obtained through a linear fitting method, in which the variation of X_1 is regarded as a dependent variable and the variation of X_2 as an independent variable. The residual of the linear fitting (i.e., the difference X_1 minus X_1') can be used to reflect the individual variation of X_1 independent of X_2 .

Moreover, 10-year high-pass Lanczos filtering is applied in obtaining interannual components from the original variables. Lanczos filtering is a Fourier method of filtering digital data (Duchon 1979). After employing 10-year high-pass Lanczos filtering, high-frequency signals (i.e., interannual variabilities shorter than 10-year interdecadal timescale) have been retained and therefore the effect of linear trends/nonlinear interdecadal variabilities longer than 10-year timescale has been removed.

Referring to the doctoral thesis of Su (2006) in which temperature fluxes were used to measure heat transfer in the ocean, we calculated anomalous atmospheric temperature fluxes to demonstrate the reason for the expansion of temperature anomalies from the TP. The equation of temperature flux is as follows:

$$f = \rho c_p v T \quad (1)$$

Fig. 1 Regional map of Europe and northern Africa. The color shading denotes terrain altitude. The boxes indicate the study area of this study, i.e., the Ukraine–Russia–Kazakhstan (URK) region (43° – 51° N, 34° – 46° E and 48° – 55° N, 46° – 58° E). Here, the left box represents the region from eastern Ukraine to the North Caucasus (briefly called the EUNC region), and the right box denotes the Kazakhstan region

where f represents the temperature flux, ρ the density of air at some level, c_p the specific heat capacity of air, v the wind vector, and T the air temperature.

In this study, the hydrostatic equation was used to explain the link between the large-scale temperature and geopotential height anomalies. The hydrostatic equation is as follows:

$$\frac{dp}{dz} = -\rho g \quad (2)$$

where dp is the top pressure minus the bottom pressure just as dz is the top altitude minus the bottom altitude of an air column. ρ represents the density of the air column, and g is the standard gravity.

To further reveal the possible effect of the TP's thermal condition, two numerical experiments are conducted using the NCAR Community Atmosphere Model, version 3 (CAM3), with prescribed monthly SST (Collins et al. 2004). The first is CAM3-Tree, in which the surface vegetation type in each grid over the TP region (topographic height above 1500 m) is set to "broadleaf evergreen tropical tree." This vegetation type has a low surface albedo, which favors the absorption of solar radiation and, accordingly, results in a warmer TP. The second experiment is CAM3-Control, a "free run" experiment using the original vegetation type of CAM3, which generally has a higher albedo over the TP region than the configuration in CAM3-Tree and therefore leads to a cooler TP. As such, the difference between CAM3-Tree and CAM3-Control (the former minus the latter) can indicate the effect of TP thermal forcing. In both experiments, CAM3 is integrated for 20 years, and the outputs from the last 15 years are analyzed. Since we use the composite difference between CAM3-Tree and CAM3-Control to manifest the response of atmospheric circulation and precipitation to the TP heating, the significance of the results of the numerical experiments is tested through independent two-sample t tests.

3 Relationship between the summer TP's thermal condition and concurrent European precipitation

Correlation analyses show that, for the period 1979–2017, the summer SAT over the TP region (27°–40°N, 68°–104°E) is significantly and negatively correlated with the simultaneous precipitation from eastern Ukraine to western Kazakhstan via Russia, to the north of the Black Sea and the Caspian Sea (Fig. 2a). In turn, the summer precipitation over the URK region (as indicated by the black boxes in Fig. 2a) is also significantly and negatively correlated with simultaneous SAT over the TP region (see the lower black box in Fig. 2b).

The variation in SAT over the TP region is not definitely independent of that over its adjacent regions—in particular,

the Mongolian Plateau (MP). Here, the upper black box (44°–52° N, 84°–103° E) in Fig. 2b denotes the main body region of the MP. For convenience, the regionally averaged SAT over the TP (MP) region is referred to as the TP (MP) SAT index. During summer, the TP SAT index is highly correlated with the MP SAT index, with a correlation coefficient of 0.46, significant at the 99% confidence level, which implying that the TP and MP SATs tend to concurrently increase or decrease. In Fig. 2b, it should be noted that there are also significantly negative correlations over the MP region. The correlation coefficient between the MP SAT and URK precipitation indices is -0.43 , significant at the 99% confidence level. Therefore, we should further clarify the following issues. Are the TP and MP SATs both physically linked with the URK precipitation? Otherwise, is only one of them physically linked with the URK precipitation? Is the high correlation with the other one merely due to the concurrent and consistent variability between the TP and MP SATs?

To examine whether the individual variability of the TP (MP) SAT is still significantly correlated with the URK precipitation when the consistent variability of the MP (TP) SAT is absent, an individual TP (MP) SAT index is obtained through the method of linear fitting (Hu et al. 2012). Figure 3a presents the correlation between the summer individual TP SAT index and simultaneous SATs, in which significant positive correlations appear over the TP region, but no significant correlation is found over the MP region. This confirms that the individual TP SAT index eliminates the consistent variability of the MP SAT and only reflects the individual variation in SAT over the TP region. After removing the variability of the MP SAT, the individual TP SAT index is still highly correlated with precipitation over the URK region—in particular, the EUNC region (see the black box on the left in Fig. 3c). However, the relationship between the individual TP SAT and precipitation over the Kazakhstan region (see the black box on the right in Fig. 3c) becomes much weaker, with a non-significant correlation coefficient of -0.29 . The results indicate that, no matter whether the MP SAT varies consistently with the TP SAT or not, the individual variability of TP SAT is significantly related to the EUNC precipitation during summer.

Similarly, the individual MP SAT index can indicate the individual variation in SAT over the MP region after removing the consistent variability of the TP SAT, which can be revealed by Fig. 3b. Figure 3c shows that, over the URK region, there is no significant correlation between the individual MP SAT index and precipitation. This implies that the MP SAT is not really related with the URK precipitation during summer, and their high correlation may only be a manifestation resulting from the consistent variability between the MP and TP SATs. As such, the present study focuses on the relationship of the EUNC precipitation with the TP SAT rather than with the MP SAT.

Fig. 2 **a** Distribution of correlation coefficients between the summer TP SAT index and the simultaneous precipitation during 1979–2017. **b** As in **a** but between the summer URK precipitation index and the simultaneous SAT. Blue and purple shading denotes negative correlations significant at the 95% and 99% confidence levels, respectively and yellow shading positive correlations significant at the 95% confidence level. Black thick dashed contours indicate the area over 1500 m. The black boxes in **a** represent the URK area and those in **b** the TP and MP areas

Fig. 3 Distribution of the correlation coefficients of the individual TP SAT index with simultaneous **a** SAT and **c** precipitation. **b**, **d** As in **a**, **c** but for the individual MP SAT index. Yellow (red) shading denotes positive correlations significant at the 95% (99%) confidence level and

blue (purple) shading indicates negative correlations significant at the 95% (99%) confidence level. The black boxes in **a** represent the TP and MP areas and the black boxes in **b** the URK area. Black thick dashed contours indicate the area over 1500 m

Moreover, one may note that neither the individual TP nor the individual MP has a clear connection with precipitation over the Kazakhstan region (the right box in Fig. 3c, d). For the TP and MP SAT indices, the TP SAT-related component in the MP SAT variation can be obtained through a linear fitting method, in which the variation of the MP SAT index is regarded as a dependent variable and the variation of the TP SAT index as an independent variable. The TP SAT-related component in the MP SAT variation statistically represents the linear interaction part of the MP SAT associated with the TP SAT, which is called the linear MP SAT index. The residual of the linear fitting (i.e., the difference original MP SAT minus linear MP SAT) can be used to reflect the nonlinear interaction part of the MP SAT independent of the TP SAT, which is termed the nonlinear MP SAT index. The arithmetic mean of the TP and linear (nonlinear) MP SAT indices can be used to statistically indicate the linear (nonlinear) interaction between the TP and MP SATs, which is referred to as the linear (nonlinear) TP-MP SAT index. The correlation coefficient between the nonlinear TP-MP SAT and Kazakhstan precipitation indices is -0.52 , higher than that between the linear TP-MP SAT and Kazakhstan precipitation indices (-0.46). Numerical experiments disclosed that the thermal forcing of the TP and Iranian Plateau plays a dominant role in the generation and variability of the Asian summer monsoon (Wu et al. 2012a, b). Thus, it is more reasonable to think of the TP and Iranian Plateau as a whole to investigate their joint impacts (Wu et al. 2014). Our results suggest the importance of the nonlinear interaction between the TP and MP thermal conditions in adjusting precipitation over the Kazakhstan region during summer, implying that sometimes the TP and MP should not be considered as a whole. The effect of the nonlinear interaction between the TP and MP thermal conditions on summer precipitation over the Kazakhstan region is complicated and should be further investigated. However, it is beyond the scope of this study. The present study primarily focuses on the effect of the TP thermal condition on summer precipitation over the EUNC region.

Here, the EUNC precipitation index is defined as precipitation regionally averaged over the EUNC region. Figure 4a, b presents the comparisons of the EUNC precipitation index with the original and individual TP SAT indices during 1979–2017, respectively, which both show an out-of-phase variation. The correlation coefficient of the EUNC precipitation with the original TP SAT index is -0.52 (significant at the 99.9% confidence level), and that with the individual TP SAT index is still up to -0.44 (significant at the 99% confidence level).

One may notice that the summer TP SAT (EUNC precipitation) shows an increasing (decreasing) trend beginning in 2003. To examine whether the strong correlation between the summer TP SAT and EUNC precipitation indices still exists on interannual timescales, or is only a result of their opposite

linear trends, Lanczos filtering is employed to extract the interannual components from the two indices, and then the correlation coefficients are recalculated. The results show that the correlation coefficient between the original (individual) TP SAT and EUNC precipitation indices still reaches -0.43 (-0.37) on the interannual timescale, significant at the 95% confidence level. This suggests that a close and significant relationship between the summer TP SAT and EUNC precipitation also exists on the interannual timescale when the effect of linear trends/nonlinear interdecadal variabilities is absent.

4 Possible physical explanation

4.1 Anomalous circulation linking summer EUNC precipitation with TP SAT

Before investigating the physical link between the summer TP SAT and simultaneous EUNC precipitation, the anomalous atmospheric circulation associated with the summer EUNC precipitation is examined. Figure 5 shows the summer 100-, 500- and 850-hPa geopotential height anomalies obtained by regression on the summer EUNC precipitation index during 1979–2017, in which it can clearly be identified that a strong, significantly negative geopotential height anomaly from the upper to lower troposphere covers the EUNC region. The negative geopotential height anomaly indicates a deep low pressure, which can favor more and stronger deep convection over the EUNC region and, accordingly, result in more precipitation in situ. Conversely, when a strong high pressure (positive geopotential anomaly) governs this region, it can restrict convective activity and lead to less EUNC precipitation.

The summer geopotential height anomalies obtained by regression on the summer TP SAT index show significantly positive anomalies over the EUNC regions (Fig. 6). Corresponding to the higher (lower) TP SAT, a significantly positive (negative) anomaly appears over the EUNC region at the upper to lower tropospheric levels, forming a strong and deep high-pressure (low-pressure) anomaly contributing to less (more) precipitation over the EUNC region. In addition, Fig. 6a shows that a large-ranging belt of significantly positive anomalies appears at the upper-tropospheric (100-hPa) level, extending from the TP to the Mediterranean Sea, with two anomalous centers over the northern TP and over the Black Sea.

Along a vertical cross-section from the TP to EUNC regions (the green diagonal line in Fig. 6a), summer anomalous geopotential heights obtained by regression on the summer TP SAT index are presented (Fig. 7a). This figure further reveals that, corresponding to the higher (lower) TP SAT, a significant deep high-pressure (low-pressure) anomaly is established over the TP region. Meanwhile, a deep high-pressure (low-

Fig. 4 **a** Time series of the summer EUNC precipitation (blue line) and original TP SAT (red line) indices during 1979–2017. **b** As in **a**, but for the individual TP SAT index. The correlation coefficient of the EUNC precipitation with the original (individual) TP SAT index is -0.52 (-0.44)

pressure) anomaly also forms over the EUNC region, which is the direct reason for anomalous EUNC precipitation. The contribution of the deep pressure anomaly over the EUNC region to local precipitation can also be further revealed by the anomalous summer geopotential heights regressed upon the summer EUNC precipitation index along the same cross-section (Fig. 7b), in which a deep negative anomaly is present over the EUNC region, corresponding to a higher-than-normal EUNC precipitation index.

Moreover, Fig. 7a indicates that the deep pressure anomaly over the TP and that over the EUNC region seem to be linked with each other through significant geopotential height anomalies in the upper troposphere, which is also consistent with the upper-tropospheric belt of significantly positive anomalies from the TP to EUNC regions in Fig. 6a.

Summer anomalous geopotential heights obtained by regression on the individual TP SAT index also clearly show the upper-tropospheric belt from the TP to the Mediterranean Sea (Fig. 8a), which is clearer and has better continuity relative to Fig. 6a, in which there is a relatively lower significance to the west of the TP. Figure 8b further reveals that, corresponding to the variability of the individual TP SAT, this upper-tropospheric belt of significant geopotential anomalies links the deep pressure anomaly over the TP to that over the EUNC region. Note that the significance of geopotential height anomalies over the EUNC region decreases when extending downwards, but it is still over the 95% confidence level around the 500-hPa level and therefore may modulate precipitation in situ.

Climatologically, in the upper troposphere, there is a strong high-pressure system across Eurasia and Africa during boreal summer, which is called the South Asian high (SAH). The SAH is closely related to the Northern Hemispheric atmospheric circulation and Asian regional climate (Mason and

Anderson 1963; Tao and Zhu 1964; Hu et al. 2010; Cai et al. 2017; Wang et al. 2017). The variability of the SAH is closely linked with the TP thermal anomaly (Zhao et al. 2009; Nan et al. 2018). The upper-tropospheric belt of significant geopotential anomalies in Figs. 7a and 8a implies that the variability of the TP SAT is closely related to that of the SAH during summer.

To more intuitively exhibit the relationship between the TP SAT and the spatial structure of the SAH, we present composites of the 100-hPa geopotential height during the years of higher (1984, 1988, 1990, 2012, 2013, 2014, and 2016) and lower (1992, 1997, 2000, 2002, 2003, 2004, and 2005) TP SAT indices, respectively (Fig. 9). During the years of higher TP SAT indices, the composited 100-hPa geopotential heights (red contours) reflect a stronger and extended SAH. As shown by the 16,650-gpm contour (red contour), the SAH expands farther north between 34° E and 46° E (i.e., the longitude ranges of the EUNC region) and consequently affects the EUNC region. During the years of lower TP SAT indices, the SAH (blue contours) is relatively weaker and its north branch shows clear southward retreat between 34° E and 46° E.

The northward advance/southward retreat of the SAH's north branch can be measured by the latitude where the north branch of zonal mean 16,650-gpm height isoline between 34° E and 46° E is located, which for brevity, we refer to as the SAH-LAT index. Correlation analysis indicates that the correlation coefficient of the SAH-LAT index with the TP SAT index is 0.68 and that with the individual TP SAT index can still reach up to 0.54, both significant at the 99.9% confidence level. The correlations between the summer SAH-LAT index and simultaneous 100-, 500-, and 850-hPa geopotential heights (Fig. 10a–c) reveal that the location of the SAH's northern edge is a good representation of the variation in

Fig. 5 Summer **a** 100-hPa, **b** 500-hPa, and **c** 850-hPa geopotential height anomalies (unit: gpm) obtained by regression on the summer URK precipitation index during 1979–2017. Yellow (red) shading denotes positive anomalies significant at the 95% (99%) confidence level and blue (purple) shading indicates negative anomalies significant at the 95% (99%) confidence level. Black thick dashed contours indicate the area over 1500 m

geopotential height over the EUNC region, not only at the upper-tropospheric (100-hPa) level but also at the mid-tropospheric (500-hPa) and lower tropospheric (850-hPa) levels; that is, the SAH-LAT index is a robust indicator of deep pressure anomalies over the EUNC region. Therefore, the expansion and withdrawal of the SAH—in particular, the northern edge’s advance and retreat around the EUNC region—is closely connected with local precipitation in situ during summer (Fig. 10d). As such, the EUNC precipitation index is also highly correlated with the SAH-LAT index, with

a correlation coefficient of -0.51 , significant at the 99.9% confidence level. The aforementioned results imply that the SAH may be an important circulation system linking the TP thermal anomaly and precipitation over the EUNC region during summer. The variability of the SAH’s intensity and location, in particular, the advance and retreat of its northern edge around the EUNC region contributes to, at least partly, the variability of summer EUNC precipitation. However, this link does not clarify causality, which should be further explored in the next subsection.

Fig. 6 As in Fig. 5 but for regression on the summer TP SAT index. A vertical cross-section in this figure is displayed along the green diagonal line from 35° N, 100° E to 50° N, 20° E in **a**

4.2 Possible local and remote effects of the TP's thermal condition

Recently, several studies suggested that the TP heating may modulate the upstream large-scale circulation and related climate (Nan et al. 2018; Lu et al. 2018). Their results remind us that it should be investigated whether the anomalous TP thermal condition can stimulate the variation in the SAH and remotely affect the EUNC precipitation.

According to the theory of the TP sensible heating-driven air pump (Wu et al. 1997, 2007), the surface sensible heating

of the TP can generate convective precipitation over the TP and therefore produce condensational latent heating. Both the effect of sensible heating and that of condensational latent heating over the TP can enhance tropospheric temperatures in situ and result in a thick warm anticyclone (Wu et al. 2016b; Liu et al. 2017b). It should be emphasized that the variability of the TP SAT is only a result of anomalous TP heating and also that the TP SAT should be considered as the surface part of a thick air column with temperature anomalies resulted from the anomalous TP heating. Therefore, the correlation coefficients of 500–200 hPa mean air temperature

Fig. 7 Summer anomalous geopotential heights (unit: gpm) obtained by regression on the summer **a** TP SAT and **b** EUNC precipitation indices along a vertical cross-section from the TP to EUNC region (green diagonal line in Fig. 6a). Yellow (red) shading denotes positive anomalies significant at the 95% (99%) confidence level and blue (purple) shading indicates negative anomalies significant at the 95% (99%) confidence level. The black shaded area represents the terrain

averaged over the TP region with the original and individual TP SAT indices are both 0.76, significant at the 99.9% confidence level. The significant correlations indicate that the TP SAT can reflect the variability in temperature of the thick air

column over the TP region well. The high consistent variation between the TP SAT and the temperature of the thick air column above it can also be identified in Fig. 11a, showing the summer anomalous air temperatures obtained by

Fig. 8 **a** Summer 100-hPa geopotential height anomalies (unit: gpm) obtained by regression on the summer individual TP SAT index after removing the MP SAT-related variation during 1979–2017. **b** As in **a** but along a vertical cross-section from the TP to EUNC region. Yellow (red) shading denotes positive anomalies significant at the 95% (99%) confidence level and blue (purple) shading indicates negative anomalies significant at the 95% (99%) confidence level

Fig. 9 Composites of summer 100-hPa geopotential heights (unit: gpm) during the years of higher and lower TP SAT indices, which are denoted by red and blue contours, respectively. The green dashed vertical lines indicate 34° E and 46° E

regression on the summer individual TP SAT index along a vertical cross-section from the TP to EUNC regions. Corresponding to the higher TP SAT, significantly positive temperature anomalies appear from surface to the 200-hPa level over the TP (Fig. 11a). In the present study, we choose the SAT to measure the thermal condition over the TP and investigate its relationship with the EUNC precipitation, since the SAT in the reanalysis assimilates observation of gauge stations in the TP region, which may have a higher reliability than other calculated variables, such as sensible heat flux.

It is also seen that in Fig. 11a, corresponding to the higher (lower) TP SAT, the higher (lower) temperature anomaly extends westwards from the TP region to the EUNC region in the upper troposphere. The summer anomalous temperature fluxes at the 200-hPa level regressed upon the summer

individual TP SAT index (Fig. 11b), which were calculated through Eq. (1) in Section 2, showing that the anomalous temperature fluxes transfer westwards from the TP to the Mediterranean Sea along approximately 30° N and then move northeastwards to the EUNC region along the northwest flank of an anomalous anticyclone of temperature fluxes. This result signifies that the westward extension of temperature anomalies over the TP may be attributable to the westward atmospheric heat transfer in the upper troposphere. This is also supported by the response of high-level atmospheric circulation to reduced TP snow cover in a simple general circulation model (Wu et al. 2016a). The simulation result obtained by reducing the forcing effect of the TP snow cover revealed that a positive anomaly in geopotential height is induced at upper troposphere over TP on the third day since adjusting this

Fig. 10 Distribution of the correlation coefficients of the summer SAH-LAT index with simultaneous **a** 100-hPa, **b** 500-hPa, and **c** 850-hPa geopotential height anomalies. **d** As in **a–c** but for precipitation. Yellow (red) shading denotes positive correlations significant at the 95% (99%)

confidence level and blue (purple) shading indicates negative correlations significant at the 95% (99%) confidence level. The black box represents the EUNC region. Black thick dashed contours indicate the area over 1500 m

Fig. 11 **a** Summer anomalous air temperatures (unit: °C) obtained by regression on the summer individual TP SAT index along a vertical cross-section from the TP to EUNC regions. **b** As in **a**, but for anomalous 200-hPa air temperature fluxes (vectors; unit: W m^{-2}) and temperature (shadings; unit: °C). Yellow (red) shading in **a** denotes positive anomalies significant at the 95% (99%) confidence level. The black-shaded area in **a** represents the terrain. The dashed contours in **b** denote the areas over 1500 m

underlying surface thermal forcing, which develops and extends westward towards southern Europe from the third day through the 15th day (see Figure 7 in Wu et al. 2015a, b).

Note that this simulation conducted by Wu et al. (2016a) revealed the westward extension of geopotential height anomalies rather than that of temperature anomalies. In fact, the geopotential height–temperature link can be well explained through the hydrostatic equation. According to this equation (i.e., Eq. (2) in Section 2), pressure decreases by the increase in altitude, since the term in the right-hand side of the equation is negative. When the air column is warmed (cooled), its density decreases (increases) and consequently causes a smaller (larger) negative value of the term in the right-hand side. Correspondingly, the decrease in pressure slows down (accelerates) with the same increase in altitude. As such, the warmer (cooler) air column is in good agreement with higher- (lower-) pressure anomalies above it. Based on Eq. (2), we can conclude that the westward-extended belt of upper-tropospheric temperature anomalies (Fig. 11) leads to upper-tropospheric geopotential height anomalies (Fig. 8a) and related expansion or withdrawal of the SAH (Fig. 9) and eventually contributes to precipitation anomaly over the EUNC regions (Fig. 3c).

In short, through modulating the variability of upper-tropospheric temperatures over the TP and a larger area to its west and associated upstream large-scale atmospheric circulation (i.e., the SAH), the TP thermal anomaly seems to remotely affect the variability of precipitation over the EUNC region during summer.

4.3 Numerical experiments

To further demonstrate the influence of the TP's thermal condition, the effect of TP heating is simulated by adjusting the surface vegetation type over the TP using CAM3. With prescribed climatological mean SSTs, CAM3 excludes the potential influence of the atmosphere–ocean interaction. As such, the difference between CAM3-Tree and CAM3-Control (the former minus the latter) reflects the individual effect of TP thermal forcing.

The difference between the highest and lowest TP SATs is 2.86 °C, and the difference between the five highest and five lowest mean TP SATs is 1.74 °C. The composite difference in summer SAT between CAM3-Tree and CAM3-Control clearly shows high SAT anomalies of approximately 1–3 °C over the TP (Fig. 12a), which is comparable to the above

observation. That is, the experiments can reflect the observation-like anomalous surface thermal condition over the TP. Meanwhile, from the composite difference in summer precipitation (Fig. 12b), significantly negative precipitation anomalies can also be distinctly detected over the EUNC region, although the area of anomalous precipitation extends farther west relative to the observation associated with the summer individual TP SAT index (Fig. 3c). Generally speaking, the summer TP heating forces the simultaneous EUNC precipitation in CAM3.

The composite difference in summer temperature between CAM3-Tree and CAM3-Control along the vertical cross-section from the TP to EUNC regions (Fig. 13) basically resembles the vertical structure of regressed temperature anomalies based on the reanalysis data (Fig. 11), confirming that a stronger TP heating can enhance temperatures from surface to the 200-hPa level over the TP and the higher temperature anomaly can extend westwards from the TP to EUNC regions in the upper troposphere.

Accompanying the westward-extended belt of upper-tropospheric temperature anomalies (Fig. 13), the positive upper-tropospheric geopotential height anomalies over the

TP also extend westwards and eventually form the other center of positive geopotential height anomalies around the Mediterranean Sea and the Black Sea (Fig. 14a). In addition, the vertical structure of the composite difference in summer geopotential height anomalies along a vertical cross-section from the TP to EUNC regions (Fig. 14b) also shows that a significant and deep high-pressure anomaly appears over the TP, which extends westwards in the upper troposphere, and eventually forms a deep high-pressure anomaly over the EUNC region. In CAM3, although the center of geopotential height anomalies around the Mediterranean Sea and the Black Sea is slightly farther west relative to Fig. 8a, the anomalous geopotential height can still control the EUNC region and affect precipitation there and over its far west area (Fig. 12b).

It should also be noted that the composite difference in summer 100-hPa geopotential height anomalies (Fig. 14a) shows non-significant negative anomalies over the mid-high latitudes, around the West Siberian plain. Over this region, this simulation is different from the regressed geopotential height anomalies as shown in Fig. 8a, which may possibly be attributed to the lower simulation ability over higher-latitude regions and to the absence of air–sea interaction in CAM3. Although there are some differences between the simulation and observation over the mid-high latitudes, the simulation has a better reliability over the mid-low latitudes where the TP is located. CAM3 verifies to some extent that the TP heating can force a strengthened and northwestward-extended SAH through adjusting the variability of upper-tropospheric temperatures over the TP and a larger area to its west and therefore spreads the effect of the SAH to the EUNC region and affects precipitation in situ.

Observations and numerical experiments reveal that the warmer thermal condition in the TP can force a deep higher temperature anomaly from the surface to the upper troposphere in situ. The higher temperature anomaly extends westwards from the TP to EUNC regions in the upper troposphere through the westward transport of temperature fluxes along the latitudes of approximately 30° N, forming a large-scale westward-extended belt of upper-tropospheric temperature anomalies. Corresponding to such a westward-extended belt of temperature anomalies, a westward-extended belt of upper-tropospheric geopotential height anomalies appears, which modulates the SAH and spreads the effect of the SAH to the EUNC region and eventually affects precipitation over the EUNC region.

This potential mechanism explains the significant correlation between the TP SAT and EUNC precipitation indices during summer and suggests that the variability of summer precipitation over eastern Europe is not only governed by adjacent SSTAs in the Atlantic Ocean and the Mediterranean Sea (Colman and Davey 1999; Cassou et al. 2005; Sutton and Hodson 2005; Feudale and Shukla 2011; Feudal and Shukla 2011a, b; Sutton and Dong 2012) but also adjusted by the

Fig. 12 Composite difference in summer **a** SAT (unit: °C) and **b** precipitation (unit: mm) between CAM3-Tree and CAM3-Control (CAM3-Tree minus CAM3-Control) for the last 15 years of CAM3. Yellow and red (blue and purple) shading in **b** denotes positive (negative) anomalies significant at the 95% and 99% confidence levels, respectively. The black box in **b** represents the EUNC region. Black thick dashed contours indicate the area over 1500 m

Fig. 13 Composite difference in summer air temperatures (unit: °C) between CAM3-Tree and CAM3-Control (CAM3-Tree minus CAM3-Control) along a vertical cross-section from the TP to EUNC regions. Yellow and red (blue and purple) shading denotes positive (negative) anomalies significant at the 90% and 95% confidence levels, respectively. The black-shaded area represents the terrain

downstream TP thermal forcing. Clearly, the joint effect of the TP thermal condition and SSTAs is worthy of further discussion.

5 Summary and discussion

In this study, the relationship between the summer thermal condition of the TP and the simultaneous precipitation over Europe is investigated. The results indicate that the variation in summer TP SAT is highly correlated with the synchronous precipitation over the EUNC region during 1979–2017.

Moreover, this relationship is still significant on the interannual timescale.

The close relationship between the summer TP SAT and EUNC precipitation can be attributed to, to some extent, the impact of anomalous TP heating. The TP SAT should be regarded as the surface part of temperatures of a thick air column over the TP. The variation in the TP SAT shows a result of anomalous TP heating and can reflect the variation in temperatures of the thick tropospheric air column over the TP well. Corresponding to a higher (lower) TP SAT, the higher (lower) temperature anomaly appears over the TP and extends westwards through the transport of anomalous temperature fluxes along the latitudes of approximately 30° N from the

Fig. 14 **a** Composite difference in summer geopotential height (unit: gpm) anomalies at the 100-hPa level between CAM3-Tree and CAM3-Control (CAM3-Tree minus CAM3-Control). **b** As in **a** but along a vertical cross-section from the TP to EUNC regions, in which the cross-section is along the green diagonal line in **a**. Yellow and red (blue and purple) shading in **c** denotes positive (negative) anomalies significant at the 90% and 95% confidence levels, respectively. Black thick dashed contours in **a** and **b** indicate the area over 1500 m, and the black-shaded area in **c** represents the terrain

TP to EUNC regions in the upper troposphere, which leads to the expansion (withdrawal) of the SAH and associated less (more) precipitation over the EUNC region.

Although there are differences between the CAM3 simulation and observation, the simulation generally captures the characteristics of atmospheric circulation anomalies over the mid-low latitude region and confirms the physical process—through triggering the variability of upper-tropospheric temperatures over the TP and a larger area to its west and associated upstream large-scale atmospheric circulation (i.e., the SAH), the TP thermal anomaly can remotely affect the variability of precipitation over the EUNC region during summer. This study reveals the importance of the thermal condition of the TP to the variability of EUNC precipitation during summer.

The present study reveals the contribution of the TP thermal condition to summer precipitation over the EUNC region, other than the effect of SSTAs in the Atlantic Ocean. The joint effect of the TP thermal condition and SSTAs in the Atlantic Ocean should be further discussed. The summer EUNC precipitation index is significantly and negatively correlated with simultaneous SSTs in the mid-latitude North Atlantic Ocean (34°–45° N, 60°–80° W and 34°–40° N, 32°–60° W; for brevity, called MNAO; figure not shown). Here, the SST regionally averaged over the MNAO region is referred to as the MNAO SST index. The correlation coefficient between the summer EUNC precipitation and MNAO SST indices is -0.47 , significant at the 99% confidence level. The EUNC precipitation fitted commonly by TP SAT and MNAO SST is highly consistent with the observational EUNC precipitation, with a correlation coefficient of 0.56 , significant at the 99.9% confidence level. This correlation coefficient is higher than the one between the EUNC precipitation and TP SAT/MNAO SST indices, implying that the variability in the summer EUNC precipitation can be explained by the joint effect of the TP thermal condition and SSTAs in the North Atlantic, better than any one of the two factors.

Since SSTAs in other sea areas and snow cover and sea ice anomalies (Ropelewski and Halpert 1987; Polonsky and Voskresenskaya 2003; Bulic and Kucharski 2012; Overland et al. 2012; Wu et al. 2013; Wu et al. 2014) may also be responsible for, to some extent, the variability of European precipitation, all of the factors, together with the TP thermal condition, should be further investigated to demonstrate their common contribution to the variation of summer EUNC precipitation in the future. Furthermore, the preceding TP soil moisture anomaly may provide a precursor for predicting summer precipitation over the EUNC region, and due to that, the soil moisture anomaly may maintain from spring until summer and modulates the local land–air interaction and related thermal condition in the TP during summer (Liu et al. 2015). This also deserves further exploration in the future.

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