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The extremely wet spring of 2022 in Southwest China was driven by La Niña and Tibetan Plateau warming

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ABSTRACT

In the spring of 2022, an excessive amount of rainfall fell in Southwest China (SWC) under the background of frequent droughts in history. This extreme event occurred in the decaying phase of a La Niña event, and thus, presumably La Niña played a role in this extreme event. Based on observational diagnoses and model forecasts, the atmospheric circulation anomalies, contributions of remote forcing, and the predictability of this event were examined in this work. It is suggested that La Niña and the Tibetan Plateau upper-tropospheric warming are two major factors leading to the extreme event. In addition to the recognized impact of La Niña, the upper-tropospheric warming over the Tibetan Plateau modulates the Asian atmospheric circulation by inducing a northwest-southeast wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau. The meridional heat contrast associated with the Tibetan Plateau warming favors upward motion and excessive rainfall in SWC. The statistical connection between the SWC spring rainfall anomaly and the northwest-southeast wave pattern is confirmed by a climate model forecast. The model captured the wet pattern in SWC in spring 2022 in short (1–3 months) lead real-time predictions though there are biases in the area and severity. That may be due to that the model did not well capture the atmospheric circulation anomalies at the middle and high latitudes associated with the Tibetan Plateau upper-tropospheric warming. These results indicate that such an event is predictable to some extent if both the ENSO evolution and heat condition over the Tibetan Plateau can be well predicted.

1. Introduction

Southwestern China (SWC, the red rectangle in Fig. 1a, b, including Sichuan, Guizhou, Yunnan, Guangxi Provinces, and Chongqing municipality), being located on the southeast side of the Tibetan Plateau, is influenced by both southwesterly and southeasterly winds during the summer monsoon season. The climate in SWC has obvious dry and rainy seasons. Spring rainfall in SWC has decreased during the recent decades under the background of warming (Wang et al., 2015; Lu et al., 2021). Under the background of more frequent and severe droughts since 2006 (Qiu, 2010; Wang et al., 2015; Jiang et al., 2016; Ren et al., 2017; Yuan et al., 2019; Lu et al., 2021), SWC experienced an extremely wet spring in 2022, with a record-breaking amount of rainfall since 1961. Such an extreme event occurred in the decaying phase of a La Niña event (Fang et al., 2022) under the background of global warming, which has attracted the community's attention.

Previous studies have explored the role of persistent sea surface temperature anomaly (SSTA) in the central and eastern tropical Pacific in the rainfall variations in SWC. Statistically, the rainfall abundance (deficit) during spring and summer in SWC is concurrent with the decay phase of a La Niña (El Niño) event (Feng and Li, 2011; Yang et al., 2011; Wang et al., 2015; Liu et al., 2022). During an El Niño event, anomalous easterlies develop over the Arabian Sea and Bay of Bengal (BOB) in the lower troposphere accompanying an anomalous anticyclone over the BOB and a stronger western Pacific subtropical high (WPSH), and vice versa during a La Niña event. Atmospheric circulation anomalies, such as the westward shift and intensification of the WPSH (Li et al., 2011; Yang et al., 2012; Liu et al., 2019; Wang et al., 2021) and the northward

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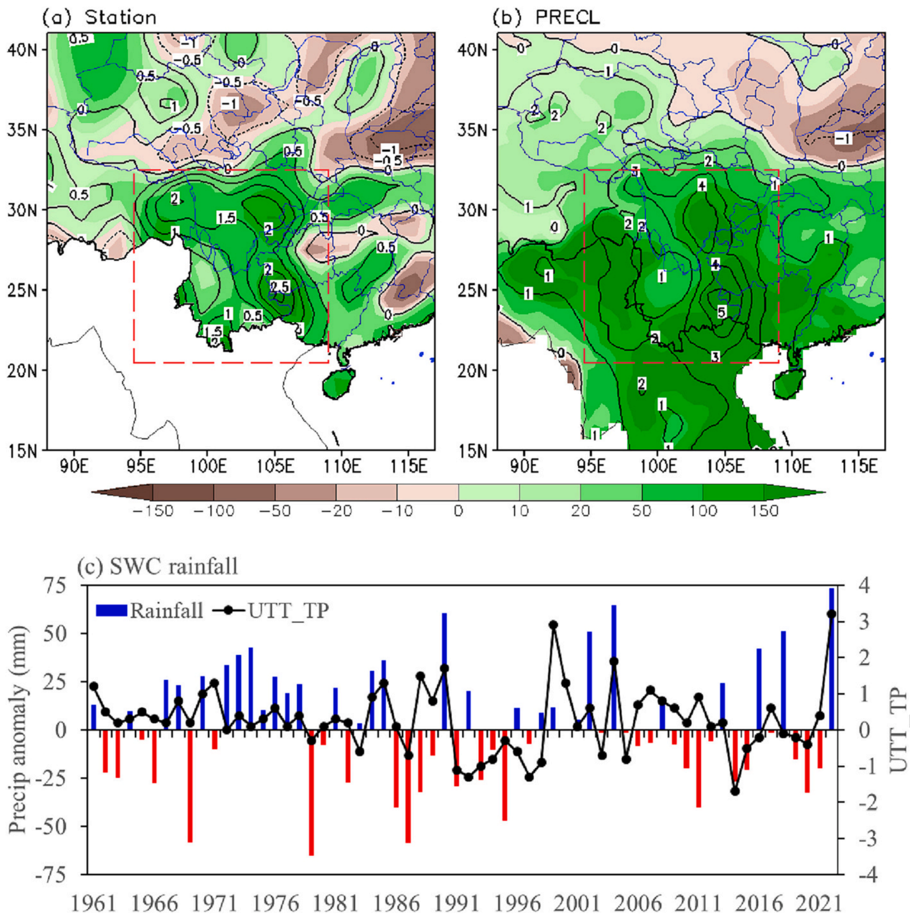

Fig. 1. Distribution of rainfall anomaly (shading, mm) and normalized anomaly (contour) in MAM 2022 based on (a) national station data of China and (b) PRECL data, respectively. (c) The time series of the accumulated MAM rainfall anomaly (bars, mm) in SWC (21°-32°N, 95°-108°E) based on the station data and the UTT_TP index (black line; °C) from 1961 to 2022. The red-dashed line rectangles in (a, b) represent the SWC region. The UTT_TP index is defined as the averaged zonal mean departure upper tropospheric temperature anomaly (UTT, 500–200 hPa) over the western Tibetan Plateau (20°-40°N, 60°-90°E). The correlation coefficient between SWC rainfall and the UTT_TP index is 0.41, exceeding the 0.01 significance level according to the *t*-test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shift of the mid-latitude westerlies (Sun and Yang, 2012), contribute directly to the rainfall deficit in SWC. In 2022, a moderate La Niña event evolved in the tropical Pacific since the previous autumn, which is the second-year La Niña following the first one of 2020/2021 (Li et al., 2022; Hu et al., 2014). This extreme event was presumably driven by La Niña. In contrast, in the spring of 2021, SWC experienced an unusual drought under the context of a La Niña event (Liu and Gao, 2021; Liu et al., 2022). It is still unclear to what extent the SSTA contributes to SWC rainfall anomaly, how robust the impacts of the El Niño-Southern Oscillation (ENSO) and WPSH are on the spring rainfall in SWC, and what the predictability of the drought is (Wang et al., 2021; Lu et al., 2021).

Concurrent with the remarkable SSTA in the central and eastern tropical Pacific associated with the La Niña event in 2022, persistent high upper-tropospheric temperature over the western Tibetan Plateau (UTT_TP) was observed, which broke the spring record since 1961 (Fig. 1c). It has been noted that the extraordinary upper-tropospheric warming may induce rainfall anomaly over East Asia (Nan et al., 2009; Zhao et al., 2012; Liu et al., 2018). The surface sensible heat over the Tibetan Plateau in spring drives ascending motion locally and modulates the Asian-Australian monsoon (Wu et al., 1997). As a remote forcing, the upper tropospheric temperature anomalies over Tibetan Plateau also have a significant impact on the precipitation anomalies over the central-eastern Sahel (Nan et al., 2019) and the region from eastern Ukraine to North Caucasus (Chen et al., 2020). Furthermore, the thermal condition of the Tibetan Plateau may be a part of an Asian-Pacific Oscillation (APO), a seesaw change in upper-tropospheric temperature between Asia and the North Pacific (Zhao et al., 2007; Fan and Zhou, 2022). The APO may result in anomalous precipitation in East Asia (Zhao et al., 2007; Zhou and Zhao, 2010; Zhou et al., 2018), and SSTAs in the tropical–extratropical North Pacific (Zhou et al., 2010; Zhou and Xu, 2017). Recently, Nan et al. (2021) argued that the anomalous high tropospheric temperature over the Tibetan Plateau in summer leads to a south-north temperature gradient, with anomalous easterly and westerly winds in the upper troposphere in the subtropics and higher latitudes, respectively. Those previous studies about the roles of UTT_TP mostly focus on summer, and it is unclear whether the Tibetan Plateau thermal condition has similar effects on the circulation and climate anomalies over East Asia in spring.

The above intriguing observations motivate us to further explore the factors leading to SWC rainfall extreme in spring 2022 and its predictability. We focus on the following two objectives: (1) What are the roles of ENSO and the upper-tropospheric warming over the Tibetan Plateau in spring? (2) What is the predictability of this event? The remainder of the paper is organized as follows. Section 2 describes the data and methods used in this study. The atmospheric anomalies associated with SWC spring rainfall anomaly, and predictability of the extreme event in spring 2022 are addressed in Sections 3 and 4, respectively. Section 5 is a summary and discussion.

2. Data and methods

Observations of monthly mean precipitation at ~2400 national meteorological stations in China are used in this work. The station data are rigorously quality-controlled and homogenized at the China National Meteorological Information Center (Yang and Li, 2014). In addition, the National Oceanic and Atmospheric Administration (NOAA)'s grid Precipitation Reconstruction over Land (PRECL) dataset with a 0.5° × 0.5° horizontal resolution (Chen et al., 2002), and the fifth-generation reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ERA5; Hersbach et al., 2020) with a 0.25° × 0.25° horizontal resolution are used in this work. Atmospheric variables analyzed in the

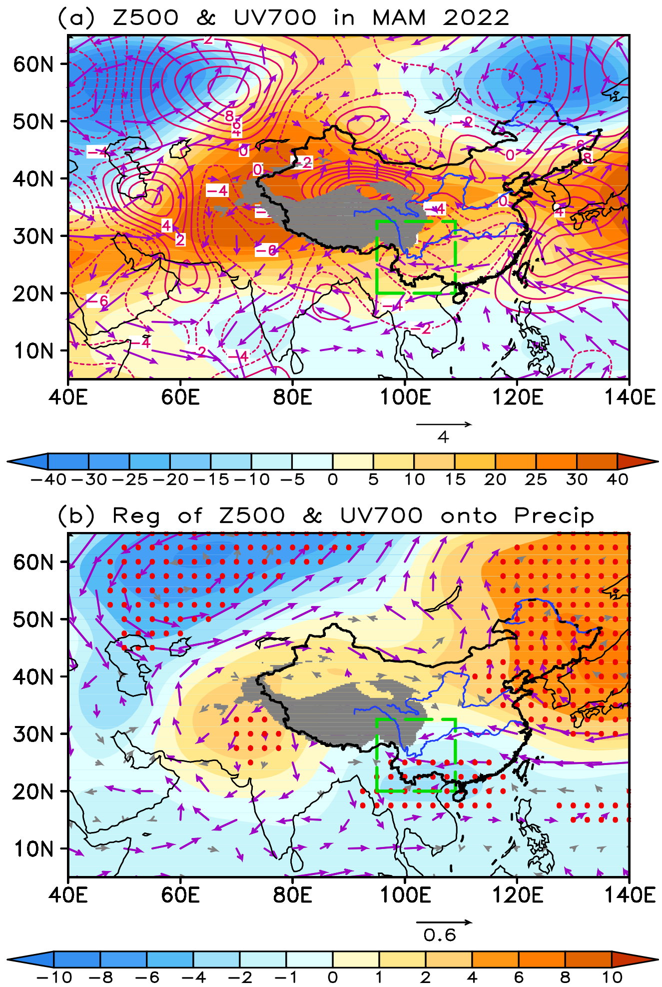

Fig. 2. (a) Observed Z500 (shading, gpm), uv700 (vector, m s^{-1}) anomalies and associated temperature advection (contour, 10^{-5} °C/s) in MAM 2022, and (b) regressions of Z500 and uv700 onto MAM rainfall in SWC during 1961–2022. Red stippling in (b) indicates the Z500 regressions reaching the 0.05 significance level based on the *t*-test. The grey shading denotes the Tibetan Plateau with an elevation exceeding 3000 m. The green-dashed line rectangles represent the SWC region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

present study include 500 hPa geopotential height (Z500), 700 hPa zonal and meridional winds (UV700), air temperature from 500 hPa to 200 hPa, downward surface solar radiation flux, medium and high cloud cover from ERA5. The UTT_TP index used in this study is defined using the vertically (500–200 hPa) and regionally (20°-40°N, 60°-90°E) averaged zonal-mean departure air temperature in ERA5.

Monthly mean SST on a 2°×2° resolution, which is extracted from NOAA Extended Reconstructed SST, version 5 (ERSSTv5; Huang et al., 2017), and Niño3.4 index, averaged SSTA in the region of 5°S-5°N and 170°-120°W, and the Indian Ocean basin mode index (IOBM, Chambers et al., 1999), averaged SSTA in the region of 20°S-20°N and 40°-110°E, are used to examine the contribution of SST forcing to the spring rainfall anomaly in SWC.

The present study focuses on the spring (March–April-May, MAM) season covering the period of 1961–2022. Anomalies of all variables are defined as the deviations from the climatological mean of MAM for the period 1991–2020. Correlation and linear regression are used in this study. The statistical significance of the correlation is estimated using the two-tailed Student's *t*-test. For the springs of 1961–2022, the correlation coefficients at the significance levels of 0.1, 0.05, and 0.01 are 0.21, 0.25, and 0.33, respectively. To focus on an interannual timescale, unless specified, the trends of all the variables and indices are removed in this study.

Ensemble means of predictions (hindcasts in 1982–2011 and real-time forecasts since 2012) initiated from January 1982–May 2022 from the NCEP Climate Forecast System version 2 (CFSv2) are examined in this study to assess the predictability of this SWC extremely wet event and to verify the statistical connection with remote forcings (Saha et al., 2014; Xue et al., 2013; Hu et al., 2017). The real-time predictions include 80 members within the last 20 days of each month and four forecasts per day, out to 9 months (Saha et al., 2014).

Furthermore, a numerical experiment with a linear baroclinic model (LBM) is conducted to investigate the response of the atmosphere to the upper-level heating over the Tibetan Plateau. The LBM is based on the hydrostatic primitive equations linearized on a basic state (Watanabe and Kimoto, 2000; Watanabe and Jin, 2003), and it can be used to simulate the linear response to a prescribed forcing (Lu and Lin, 2009; Wu et al., 2016; Henderson et al., 2017). In this study, the dry LBM provides a steady state of perturbation through adiabatic processes over the Tibet Plateau. The horizontal resolution is set to T42 with 20 sigma levels. The horizontal (vertical) diffusion, Rayleigh friction, and Newtonian damping are also included, and the specific details of LBM could be referred to Watanabe and Kimoto (2000). We integrate the LBM for 40 days. The model response approaches the steady state approximately after day 15. The results at day 20 are shown as the steady response to the prescribed heat forcing.

3. Extremely wet spring of 2022 and associated atmospheric circulation anomalies

The amount of rainfall in spring has a crucial impact on agriculture, industry, and life in SWC. Climatologically, the accumulated rainfall in MAM is about 210 mm in SWC, decreasing from southeast to northwest (not shown). In 2022, most SWC experienced the wettest spring since 1961, with the rainfall 100–150 mm more than the climatic mean, particularly in the eastern SWC (Fig. 1a). The rainfall anomalies in MAM 2022 based on PRECL data exhibit a similar spatial distribution and strength (Fig. 1b). The area-averaged (21°-32°N, 95°-108°E) rainfall amount in MAM 2022 is ranked highest since 1961, about 75 mm more than the climate mean, reaching 2.8 times of the standard deviation of rainfall over the period (Fig. 1c).

Persistent atmospheric circulation anomaly is the direct factor leading to droughts or wets in the region. Fig. 2 shows the contemporary atmospheric circulation anomalies in MAM 2022. There was a negative-positive-negative wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau (Fig. 2a), which favored a deepened trough over the Ural Mountains and led to the southward invasion of cold air along the northeastern flank of the Tibetan Plateau to southern China, with the noticeable negative temperature advection over SWC (Fig. 2a). On the other hand, the low latitudes from the eastern Arabian Sea to the Philippines were generally controlled by negative Z500 anomalies, which were usually related to an active India-Burma trough (Ding and Gao, 2020) and weak WPSH (Liu et al., 2013). Between those two negative Z500 anomaly regions, the Tibetan Plateau and the nearby regions were dominated by extraordinarily positive Z500 anomalies. Such a northwest-southeast wave pattern provided a favorable circulation condition for the abundant rainfall in SWC. The low-level southeasterly on the northern side of an anomalous cyclone from the Indochina Peninsula to the South China Sea, together with the flow around the southwestern flank of the WPSH, transported warm and humid air from the South China Sea and western Pacific to SWC. Meanwhile, the northerly cold air flow from the high latitude along the eastern flank of the Tibetan Plateau converge with the low latitude warm humid airflow in SWC, providing a favorable condition for the excessive rainfall there.

Accordingly, under such an anomalous circulation pattern, the water vapor transport by the easterly and northerly airflows formed a

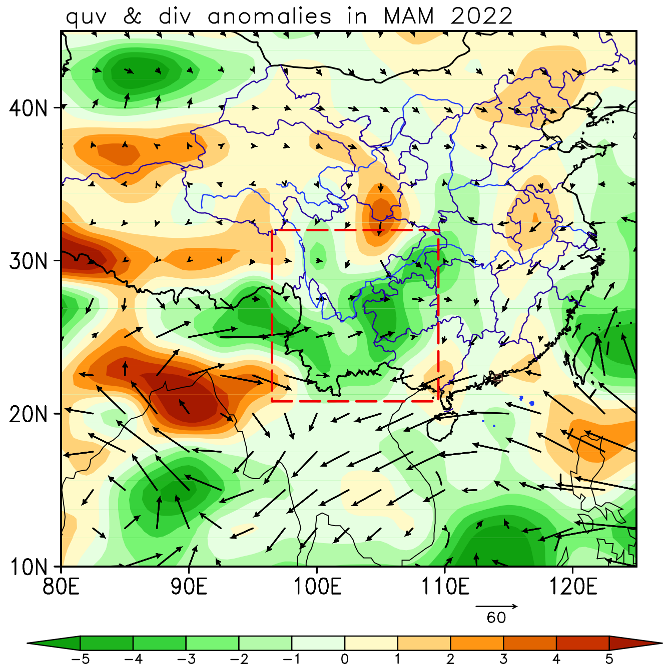

Fig. 3. Observed vertically integrated water vapor anomalies from surface to 300 hPa (vector, $kg \cdot m^{-1} \cdot s^{-1}$) and associated divergence (shading, 10^{-5} $kg \cdot m^{-2} \cdot s^{-1}$) in MAM 2022. The red-dashed line rectangles represent the SWC region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distinguished moisture convergence center over SWC (Fig. 3), which provided sufficient water vapor for rainfall there. In addition, an anomalous westerly water vapor transport is seen on the southern side of the Tibetan Plateau, which also strengthened the water vapor convergence at the southeastern foothills of the plateau.

The anomalous circulation conditions in the extremely wet spring in 2022 in SWC (Fig. 2a) fit the statistical relation, as displayed by the regressions of Z500 and 700 hPa wind (UV700) anomalies onto the time series of SWC spring rainfall (Fig. 2b). Both the observations in MAM 2022 and the regressions suggest the importance of the negative-positive-negative northwest-southeast circulation anomaly in SWC wet spring. Then, what kind of remote forcing led to such an anomalous circulation pattern? Is the anomalous circulation pattern predictable? We will make further analysis in the following section.

4. Predictability of the extremely wet spring in SWC

4.1. Impact of La Niña

The SWC extremely wet spring in 2022 occurred in the decaying phase of a La Niña event, with the MAM Niño3.4 index of −1.09 (Fig. 4c; Zhi and Zheng, 2022). In the regression of the SSTA onto the detrended MAM rainfall in SWC, a "warm west and clod east" SSTA pattern, a La Niña-like pattern, favors excessive rainfall in SWC (Fig. 4a) (e.g., Feng et al., 2014; Cao et al., 2017; Deng et al., 2022). Based on previous studies, the anomalous cyclonic wind anomalies at lower latitudes (BOB and southeast coast of China) likely result from a combined effect of negative SSTAs in both the central-eastern equatorial Pacific (Wu and Wang, 2000; Wang et al., 2000; Yang et al., 2011; Deng et al., 2022) and the tropical Indian Ocean (Xie et al., 2009; Ding et al., 2021). In MAM 2022, the La Niña event (Fig. 4b) coexisted with the cyclonic wind anomalies over BOB and the Philippine Sea, which is consistent with the historical statistics. In addition, the Indian Ocean SSTAs in MAM 2022 are small (the IOBM index is 0.17, Fig. 4c), and thus, it has a minor contribution to the observed anomalous circulation. The above analysis suggests that the SSTAs in the tropical Pacific Ocean may be the primary contributor to the circulation anomaly in the lower latitude. However, those SSTAs seem not to be a major contributor to the anomalous circulation in the middle and high latitudes, i.e., the northwest-southeast wave train from the Ural Mountains via the Tibetan Plateau to the Indochina Peninsula. As a result, the correlations of MAM rainfall in SWC with the Niño3.4 and IOBM indices are relatively low, with the correlation coefficient of −0.26 and − 0.08, respectively.

4.2. Impact of upper-tropospheric warming over the Tibetan Plateau

In addition to the role of oceanic forcing, the heating effect of the Tibetan Plateau is also important for the climate anomalies over Eurasia (Wu et al. 1997; Nan et al., 2009). Here, the UTT_TP, which reflects the synthesis of the sensible heat and condensation heating (Liu et al., 2001, 2004), is used to represent the tropospheric thermal condition of the Tibetan Plateau (Zhao et al., 2012; Nan et al., 2019). Nan et al. (2009) showed that the springtime UTT_TP can cause anomalous winds over the central-eastern tropical Pacific.

Fig. 5a is the correlation of the upper tropospheric temperature anomaly with the MAM rainfall in SWC. Significant positive correlations are located over the western Tibetan Plateau, meaning that the MAM rainfall in SWC is statistically related to the thermal condition of the Tibetan Plateau. In MAM 2022, the anomalous UTT_TP warming averaged in the high correlation region persisted for more than 3 months, and broke the record in spring since 1961 (Fig. 1c). The correlation coefficient between the UTT_TP index and the spring rainfall in SWC reached 0.41, exceeding the 0.01 significance level according to the Student's *t*-test. Furthermore, the anomalous UTT_TP warming is relatively independent of La Niña in spring, with a correlation coefficient of −0.12 during 1961–2022.

The linear regression of atmospheric circulation anomalies onto the UTT_TP time series is shown in Fig. 5b. Under the anomalous warming over the Tibetan Plateau, the northwest-southeast wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau is seen in both anomalous Z500 and UV700 fields (Fig. 5b). The positive tropospheric temperature anomaly over the Tibetan Plateau is associated with an anticyclone over the western plateau. The anomalous meridional temperature gradients between the Tibetan Plateau and its north and south flanks are accompanied by anomalous easterly and westerly winds in the subtropics and higher latitudes. To the north of the anomalous anticyclone, the meridional thermal gradient enhances the East Asian westerly jet, with an anomalous cyclone located over the Ural Mountains. Zhang et al. (2006) indicated that the seasonal evolution of the Eurasian westerly jet is associated with the meridional temperature contrast in the upper troposphere over the Eurasian continent. Subsequent studies confirmed the connection between the intensity and meridional shift of the westerly jet with heating over the Tibetan Plateau and temperature contrast between the Tibetan Plateau and the higher latitude of Eurasia (e.g. Kuang and Zhang, 2005; Zhang et al., 2019; Nan et al., 2021). In addition, to the south of the anticyclone over the Tibetan Plateau, the north-south temperature gradient strengthens anomalous easterly wind and an anomalous cyclone circulation, and SWC is under the control of the anomalous easterly flow (Fig. 5b). Such regressed atmospheric circulation onto the UTT_TP is consistent with that in MAM 2022 (Fig. 2a), implying an important role of the Tibetan Plateau heating in the extreme wet spring 2022 in SWC.

The persistent tropospheric warming over the Tibetan Plateau may be linked to positive feedback among cloud, solar radiation, and temperature (Nan et al., 2021). To examine the feedback, the composite fields of cloud and downward solar radiation in typical years of significant positive MAM UTT_TP anomaly are obtained (Fig. 6). Taking one standard deviation of the de-trended UTT_TP index as the criterion, nine positive springs of 1961, 1971, 1985, 1988, 1990, 1999, 2000, 2004, and 2007 are selected to make the composites. It is shown that the

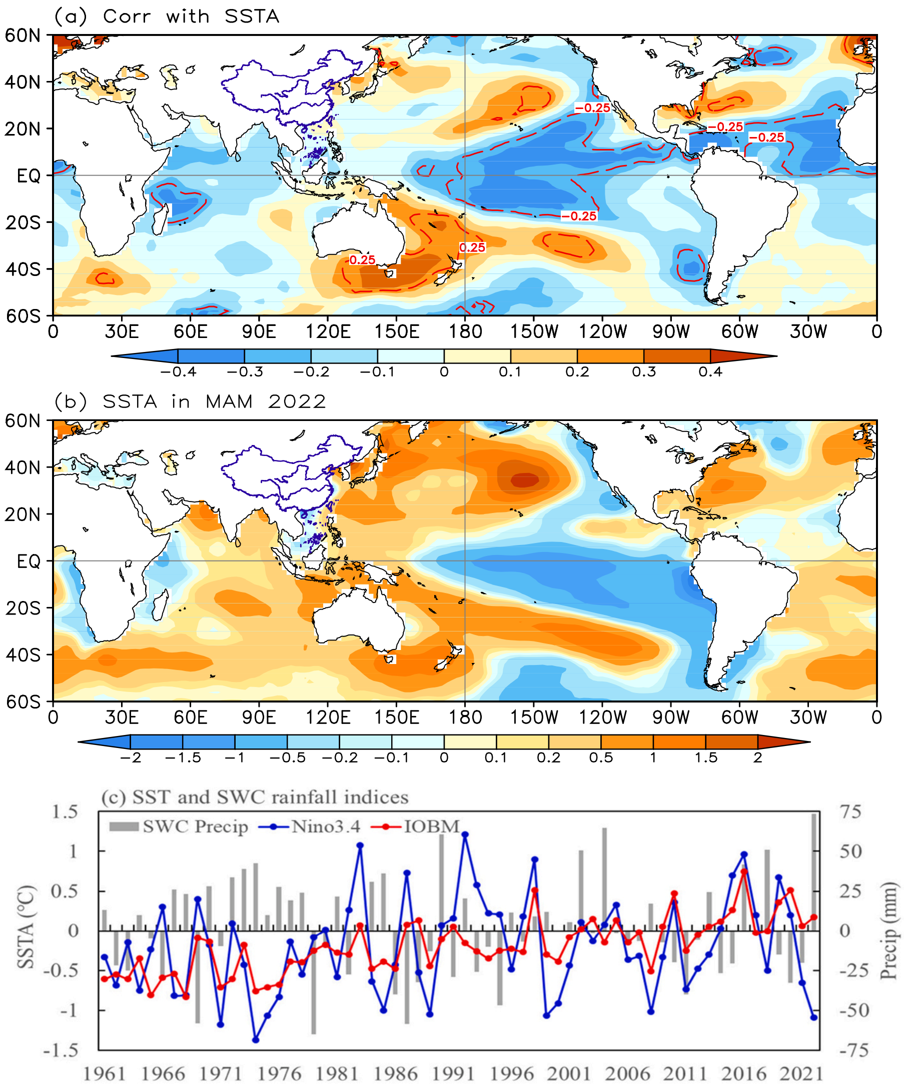

Fig. 4. (a) Correlation of MAM rainfall in SWC with SSTA, (b) distribution of SSTA in MAM 2022 (°C), and (c) time series of SWC rainfall (grey; mm), MAM Niño3.4 (blue; °C), and IOBM (red; °C) indices from 1961 to 2022. Dashed lines in (a) indicate the correlations reaching the 0.05 significance level based on the *t*-test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amounts of high and medium cloud cover decreased over the Tibetan Plateau with the UTT_TP warming, which allows more solar radiation reaching the surface (Fig. 6a and b) and enhances the warming, especially over the western Tibetan Plateau (Fig. 6c). That suggests positive feedback among cloud, radiation, and UTT_TP warming. By modulating the atmospheric circulation, such persistent warming over the Tibetan Plateau enhances ascent and rainfall over SWC and its surroundings (see the above-normal high and medium cloud cover and deep convection in SWC (Fig. 6a, b, d).

The above analysis suggests that the extremely wet spring in MAM 2022 was caused not only by the La Niña, but also by the UTT_TP warming through inducing a northwest-southeast wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau.

4.3. Reconstruction of the wet spring of 2022

To further quantify the contributions of the La Niña event and UTT_TP to the SWC extremely wet spring in 2022, we use the linear regression method to reconstruct the rainfall anomaly in SWC in MAM 2022. First, the MAM rainfall anomalies at each station are regressed onto the detrended Niño3.4 and UTT_TP indices. Then, the linear regression coefficients are multiplied by the corresponding values of each of the two indices in MAM 2022 to reconstruct rainfall anomalies in MAM 2022. The observed distribution of excessive rainfall in SWC is well reproduced using both indices (Fig. 7a and b), confirming the roles of the two factors in the extreme wet spring in SWC in 2022.

Nevertheless, the reconstructed rainfall anomaly based on either the Niño3.4 or UTT_TP index is smaller than the observed anomaly in MAM 2022. As the correlation coefficient of the UTT_TP with the SWC spring rainfall is higher than that of Niño3.4, and the UTT_TP index in the spring of 2022 is the largest since 1961, the spring rainfall anomaly in SWC reconstructed based on the UTT_TP index (Fig. 7b) is closer to the observations than that based on the Niño3.4 index (Fig. 7a). The reconstructed positive rainfall anomaly based on the UTT_TP index exceeds 50 mm in most areas of SWC and 100 mm in southern SWC, about 1/2 of the observed anomaly, and the reconstructed rainfall anomaly based on the Niño3.4 index is only about 1/4 of the observations (Fig. 1a, b). The reconstructed rainfall anomaly based on the combined role of La Niña and UTT_TP using the multivariate regression (Fig. 7c) is about 3/4 of the observed anomaly, which implies that other factors may contribute to the SWC rainfall anomaly in MAM 2022, such as internal dynamical variability (Liu et al., 2022). Thus, it is concluded that the upper-tropospheric warming over the Tibetan Plateau and the La

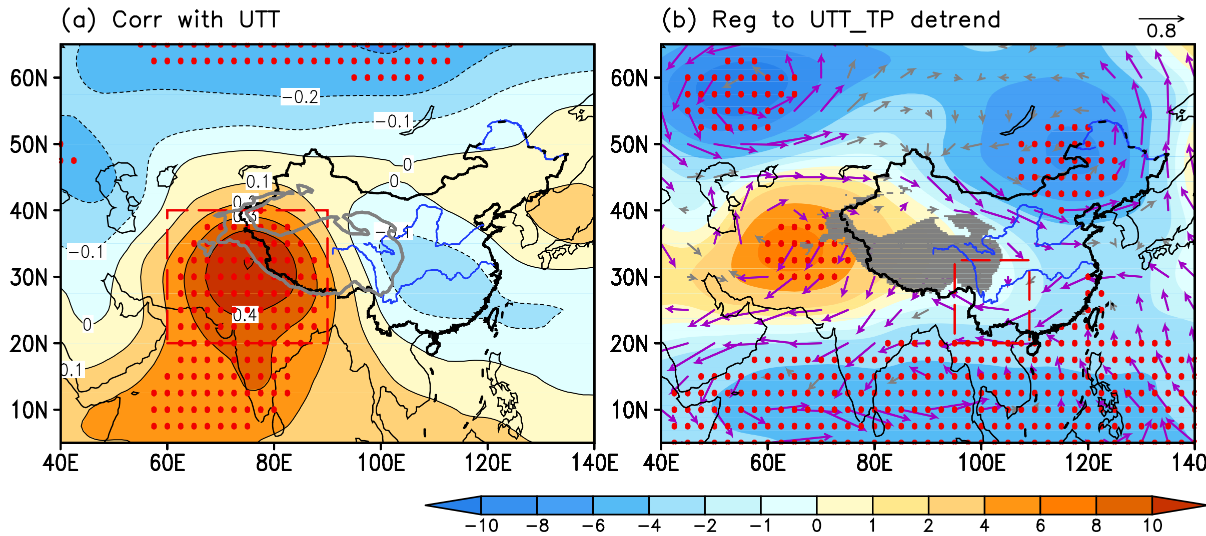

Fig. 5. (a) Correlation of MAM rainfall anomaly in SWC with the zonal-mean departure upper-tropospheric (500-200 hPa average) temperature (UTT) anomaly, and (b) Regression of Z500 (shading, gpm) and uv700 (vector, m s^{-1}) anomalies onto the UTT_TP index (20°-40°N, 60°-90°E; °C). Red stippling in (a) and (b) indicates the correlations/regressions reaching the 0.05 significance level based on the *t*-test. The bold grey contour in (a) and the grey area shading in (b) denote the Tibetan Plateau with an elevation exceeding 3000 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

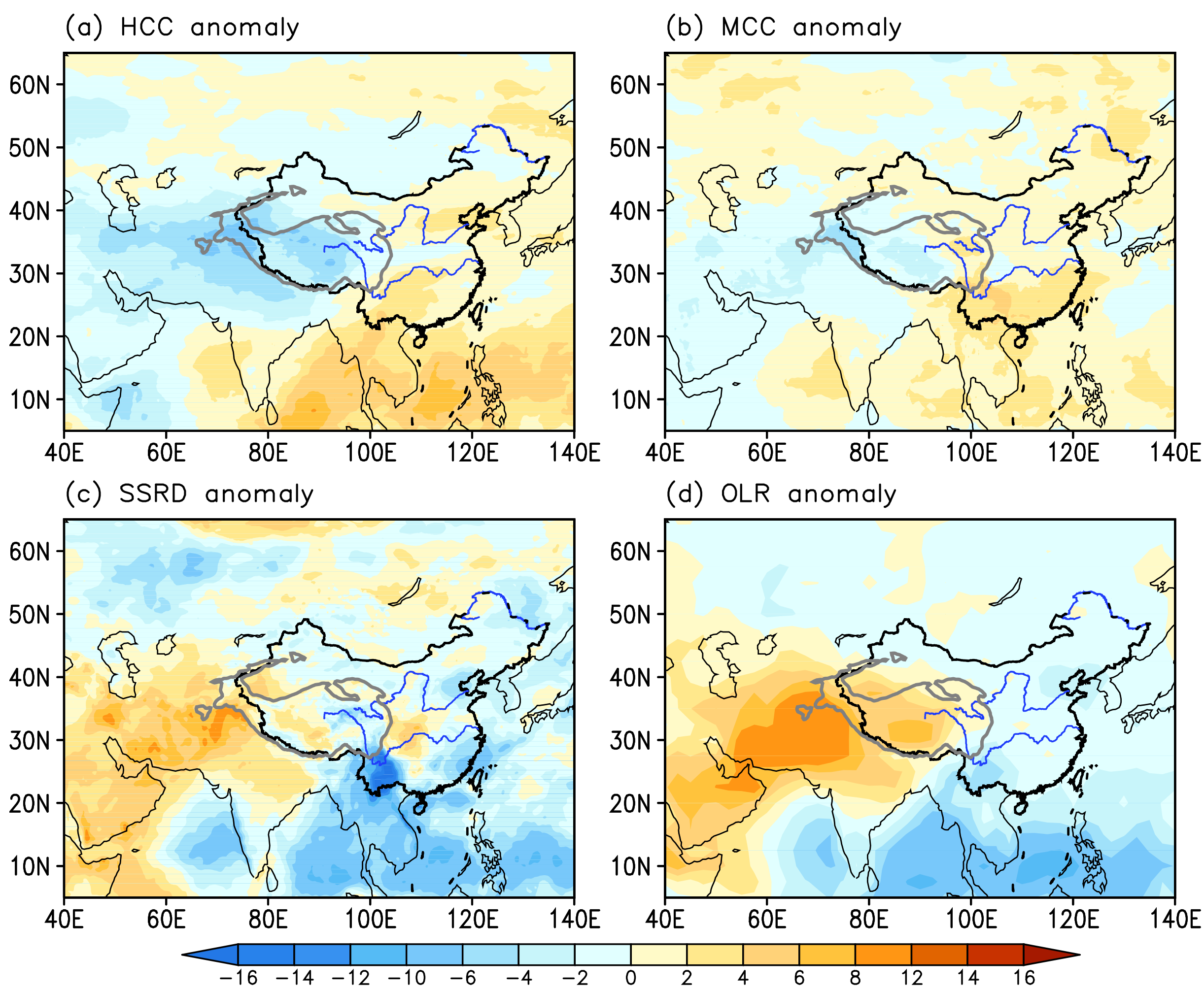

Fig. 6. Composites of (a) high cloud cover (HCC; %), (b) medium cloud cover (MCC; %), (c) downward surface solar radiation flux (SSRD; W m^{-2}), and (d) outgoing longwave radiation (OLR; W m^{-2}) anomalies in the typical positive MAM UTT_TP years. The bold grey contour denotes the Tibetan Plateau with an elevation exceeding 3000 m.

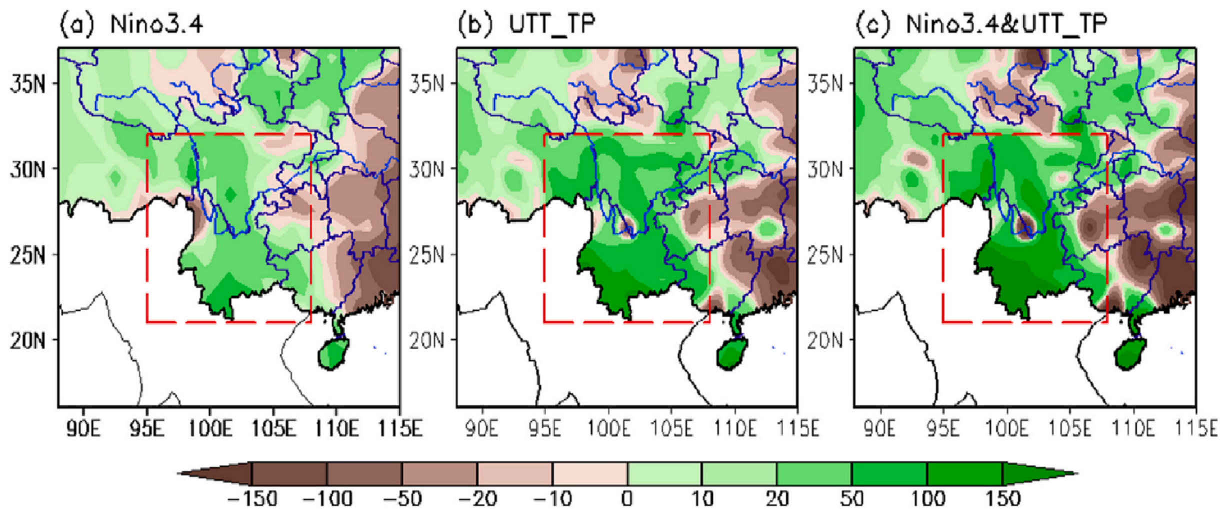

Fig. 7. Reconstructions of 2022 MAM rainfall anomaly (mm) based on the linear regression with the (a) Niño3.4 and (b) UTT_TP indices, and (c) Reconstructions of 2022 MAM rainfall anomaly (mm) based on multivariate regression with these two factors.

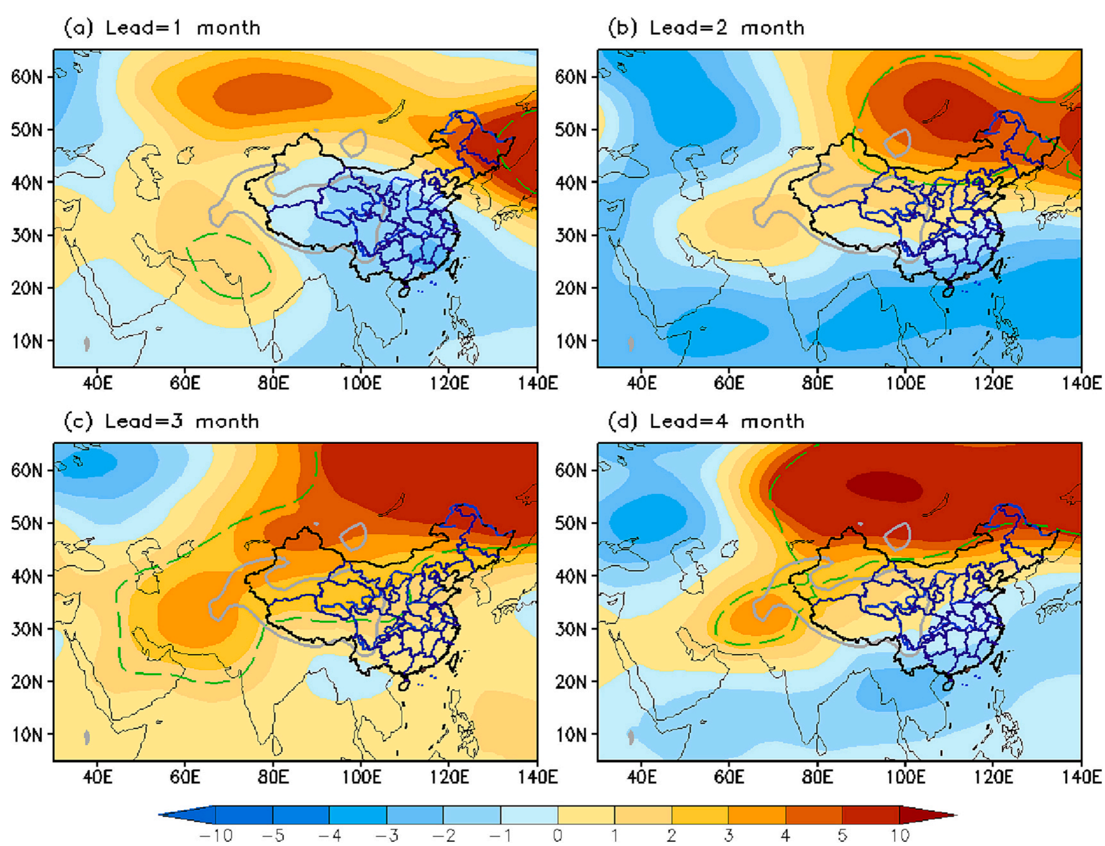

Fig. 8. The linear regression of Z500 anomalies onto the time series of spring rainfall anomaly averaged in SWC (21°-32°N, 95°-108°E) in the (a) 1-month, (b) 2-month, (c) 3-month, and (d) 4-month leads in CFSv2 predictions in 1982–2021. The green dashed lines indicate the significance level of 0.05 according to the *t*-test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Niña event are two major factors contributing to the observed SWC rainfall anomaly in MAM 2022 (Figs. 7c, 1a, b). Such two primary external/remote forcings may imply the predictability of this extreme event.

4.4. Model prediction and simulation

The predictability and possible causes of the SWC extremely wet spring are further assessed using the forecasts of the CFSv2 model. To verify the hypothesis derived from the observations that the extremely wet spring in MAM 2022 was influenced by both the La Niña and the UTT_TP warming (Fig. 5), Fig. 8 shows the linear regression of Z500 anomalies onto the time series of the SWC rainfall anomaly corresponding to different lead times in CFSv2. Such statistical connection of the spring rainfall anomaly in SWC with the northwest-southeast wave pattern is reproduced in CFSv2 with different lead times, which implies

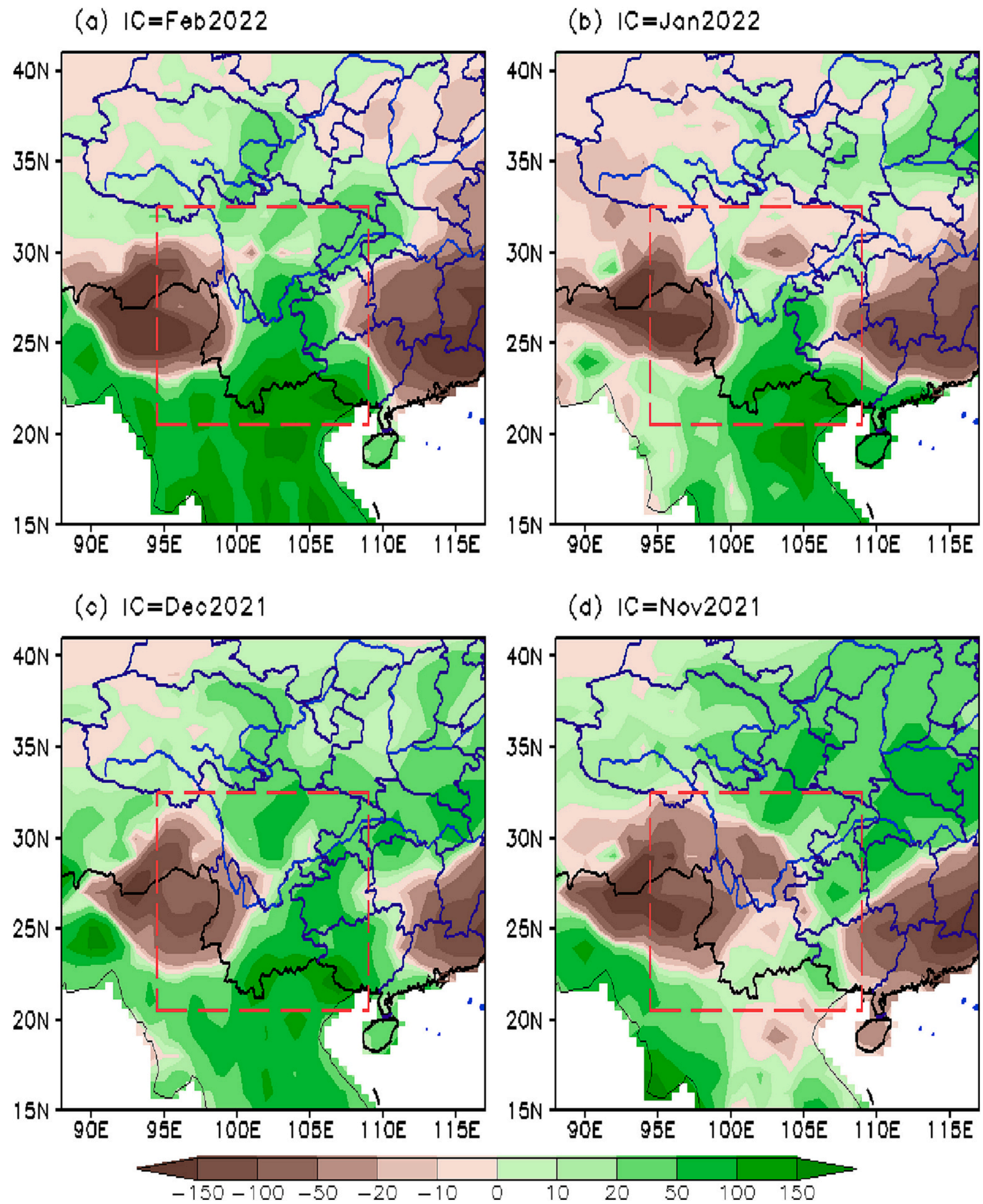

Fig. 9. CFSv2 real-time forecasts of rainfall anomalies (mm) in MAM 2022 with the initial conditions in (a) February 2022, (b) January 2022, (c) December 2021, and (d) November 2021. The forecasts are 80-member ensemble mean. The red-dashed rectangle represents SWC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the predictability of the SWC spring rainfall anomaly.

For the real-time predicted SWC rainfall anomalies, the ensemble mean predictions with 1–4 month leads show that the wet anomaly in SWC in MAM 2022 is partially captured (Fig. 9). The excessive rainfall was predicted mainly in the central and southern SWC, with an underestimation of the wet area and severity. Furthermore, the predicted anomaly amplitude declines with the lead-time increase. For the 4-month lead (Fig. 9d), the predicted anomalies are partially opposite to the observations.

The predicted Z500 anomalies with 1–4 month leads are shown in Fig. 10. The negative Z500 anomalies at lower latitudes were partially captured at different lead times (Fig. 10), which may be mainly caused by the La Niña event (Wu and Wang, 2000; Wang et al., 2000; Yang et al., 2011; Deng et al., 2022). At middle and high latitudes, however, there was obvious forecast bias of circulation pattern, with the obvious positive anomaly center over the north of the Ural Mountains, and relative low anomaly in the western Tibetan Plateau, which may be related to the upper-tropospheric heating condition over the Tibetan Plateau (Kuang and Zhang, 2005; Zhang et al., 2019; Nan et al., 2021).

It is implied that the predicted above-normal rainfall in SWC in MAM 2022 is probably due to the successfully predicted La Niña in 2021/2022 and La Niña-related atmospheric circulation distribution by CFSv2 (Li et al., 2022). However, as for the extremely wet spring of 2022 in SWC, the underestimated prediction anomaly may be largely due to that the model did not well capture the atmospheric circulation anomalies at the middle and high latitudes associated with the Tibetan Plateau upper-tropospheric warming from the perspective of predictability sources. Thus, the CFSv2 real-time prediction suggests that in addition to the impact of La Niña, the contribution of the UTT_TP warming to the SWC extremely wet event in MAM 2022 cannot be ignored. Otherwise, such extreme rainfall anomalies will be greatly underestimated.

In addition, the atmospheric circulation response to the UTT_TP warming is confirmed by a numerical experiment with the LBM (Watanabe and Kimoto, 2000). Fig. 11 shows the distribution of the

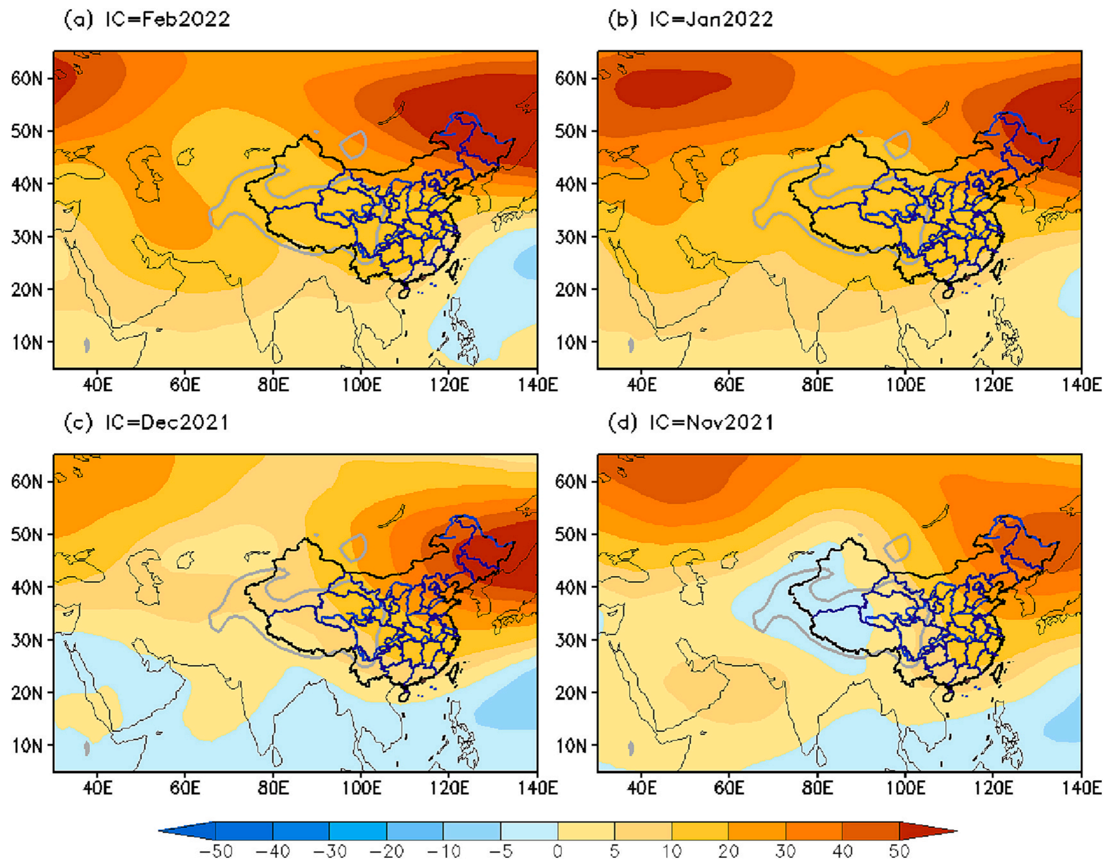

Fig. 10. Same as Fig. 9, but for Z500 anomalies.

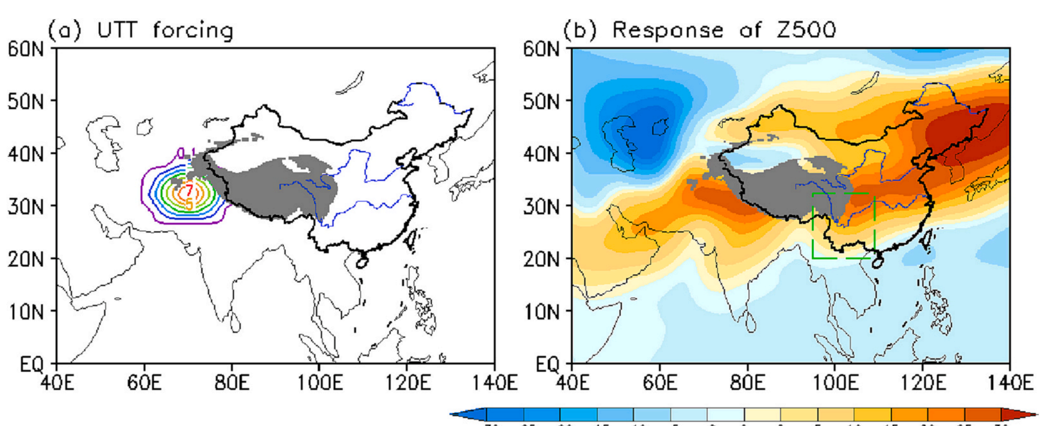

Fig. 11. (a) Distribution of the prescribed UTT_TP forcing (contour, °C/d) averaged from 500 hPa to 200 hPa, and (b) response of Z500 anomalies (shading, gpm) to the UTT_TP forcing. The grey area shading in (a) and (b) denote the Tibetan Plateau with an elevation exceeding 3000 m, and the green-dashed line rectangles in (b) represent the SWC region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prescribed UTT_TP forcing averaged from 500 to 200 hPa, and the simulated response of Z500 anomalies to the Tibetan Plateau upper-level warming in the LBM. The upper-tropospheric warming over the Tibetan Plateau induces a northwest-southeast wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau, which is consistent with the observation (Figs. 2a, 5b). Thus, both the observed analysis and the LBM experiment illustrate the role of the UTT_TP.

5. Summary and discussion

In 2022, SWC experienced an extremely wet spring under the background of frequent droughts in history. Such an extreme event occurred in the decaying phase of a La Niña event. In this work, observations and model forecasts were analyzed to investigate the causes and the predictability of this event. It is found that La Niña and upper-tropospheric warming over the Tibetan Plateau are two major factors of the extreme event. The impact of La Niña is through inducing an anomalous cyclone over the BOB and Philippine Sea that modulates the moisture transport to SWC. The upper-tropospheric warming over the

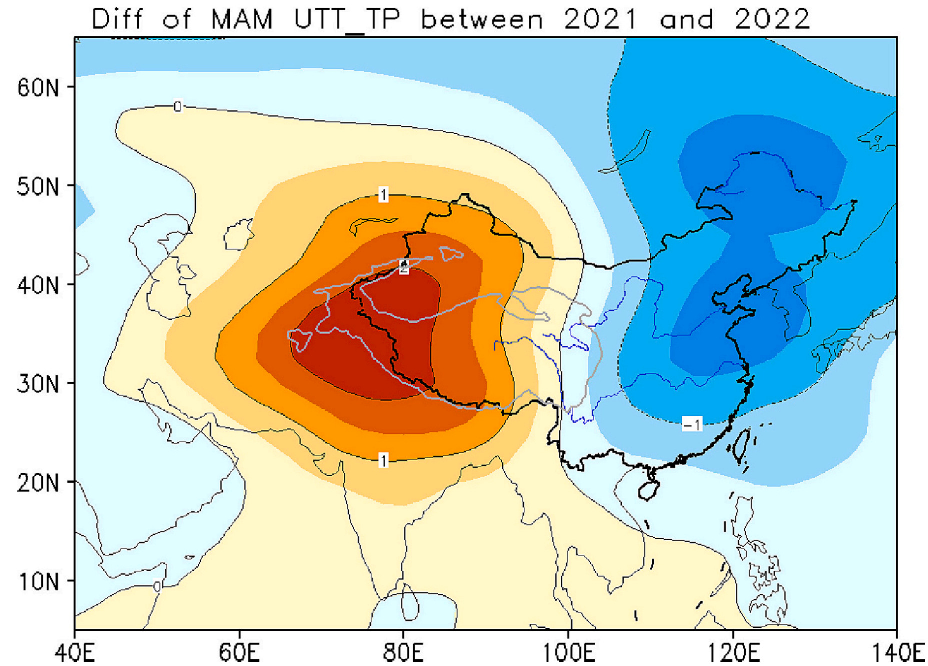

Fig. 12. Difference of MAM zonal mean departure upper-temperature anomaly between 2022 and 2021.

Tibetan Plateau induces a northwest-southeast wave pattern extending from the Ural Mountains to the Indochina Peninsula via the western Tibetan Plateau. The meridional heat contrast associated with the upper tropospheric warming over Tibetan Plateau favors upward motion and excessive rainfall in SWC.

The CFSv2 model largely reproduced the relationship between the SWC rainfall anomaly and the northwest-southeast wave pattern. Though the simulation of extreme weather and climate events from state-of-the-art climate models are mostly underestimated (Such as Liang et al., 2019; Liu et al., 2021), from the perspective of predictability sources, the real-time prediction underestimates the wet area and severity of SWC rainfall in MAM 2022 probably because the CFSv2 model only captured the impact of the La Niña, but not the atmospheric circulation at the middle and high latitudes associated with the UTT_TP warming. These results imply that the predictability of such an extreme event is linked to whether both the ENSO evolution and thermal condition over the Tibetan Plateau can be well predicted.

The spring of both 2021 and 2022 is under the decaying phase of a La Niña event, but SWC experienced remarkably different climate anomalies. In the spring of 2021, SWC, especially southern SWC, experienced a serious drought (Liu et al., 2022). Why did distinct climate features occur under a similar ENSO background? Liu et al. (2022) indicated that the SWC spring drought in 2021 occurred in the decaying phase of a La Niña event with negative geopotential height anomalies over the Philippine Sea, which is distinct from the historical perspective. Historically, spring drought over SWC is often linked to El Niño and strong western North Pacific subtropical high. The extreme drought in the spring of 2021 may be mainly driven by the atmospheric internal variability and amplified by the warming trend, while the forcing from the tropical central and eastern Pacific played a minor role in the occurrence of drought.

The remarkably different climate anomalies in SWC between 2021 and 2022 are more probably due to the differences in the thermal condition over the Tibetan Plateau between the two springs. Although both springs are in the cold phase of ENSO, the UTT_TP index in MAM (Fig. 1c) and the spatial distributions of the upper-level tropospheric temperature anomalies over the Tibetan Plateau and SWC (Fig. 12) are different. It appears that the Tibetan Plateau thermal condition may be a primary factor causing the difference of MAM rainfall in SWC between the two springs. It also implies the importance of the UTT_TP thermal condition in the variability and predictability of the spring rainfall in SWC.

Previous studies also indicated the influence of a tripole SSTA pattern in the North Atlantic Ocean on the spring East Asian climate by exciting an atmospheric teleconnection over the mid- and high-latitude Eurasia (Wu et al., 2011; Chen and Wu, 2017; Sun et al., 2022). Did the North Atlantic SST anomalies contribute to the wet condition in SWC in spring 2022? The correlation of the MAM rainfall in SWC with SSTA displays a tripole distribution of significant correlation in the North Atlantic Ocean (Fig. 4a). This suggests that the tripole SSTAs may play a role in the SWC spring rainfall variation from a historical perspective. However, the SSTAs in MAM 2022 are weak in the tropical and high-latitude North Atlantic (Fig. 4b). The reconstructed spring rainfall anomalies based on the North Atlantic spring tripole SST anomalies are small in SWC (not shown). Those results indicate that the North Atlantic SST anomalies are not a main contributor to the wet condition in SWC in MAM 2022.

Author contributions

Yunyun Liu conceived the idea in discussion with Duo Li, Zeng-Zhen Hu, Renguang Wu, Jie Wu, and Yihui Ding. Duo Li performed the observed analyses. Jie Wu conducted the LBM simulation. Yunyun Liu wrote the initial manuscript. Zeng-Zhen Hu, Renguang Wu and Yihui Ding contributed substantially to improving the research and presentation. All the authors contributed to the writing, editing, presentation, and reviewing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

PRECL precipitation data is downloaded from ftp://ftp.cpc.ncep.noaa.gov/precip/50yr/gauge/0.5deg/; HadISST from https://www.

metoffice.gov.uk/hadobs/hadisst/; and ERA5 from https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5; CFSv2 hindcast and forecast from https://rda.ucar.edu/datasets/ds094.2/.

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