Was the Extremely Wet Spring of 2022 in Southwest China Driven by La Niña?

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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 second-year of a double/triple dip La Nina event, and thus, presumably La Niña played a role in this extreme event. In this work, based on observational diagnoses and model forecasts, we examine the atmospheric circulation anomalies, contributions of external forcing, and the predictability of this event. It is suggested that La Niña and the upper-tropospheric warming over the Tibetan Plateau 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 with the upper tropospheric warming over the Tibetan Plateau favors upward motion and excessive rainfall in SWC. The 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 probably due to that the model did not well capture the atmospheric circulation anomalies at the middle and high latitudes associated with the upper-tropospheric warming over the Tibetan Plateau. 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 captured.

1. Introduction

Southwestern China (SWC, the red rectangle in Figs. 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 second-year of a double/triple dip La Nina 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 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; Wang et al. 2021) and the northward shift of the mid-latitude westerlies (Sun and Yang 2012) have been shown to 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 are (Wang et al. 2021; Lu et al. 2021).

Concurrent with the remarkable SSTA in the central and eastern tropical Pacific associated with a second-year La Nina event, persistent high upper-tropospheric temperature over the western Tibetan Plateau (UTT_TP) is observed, which broke the spring record since 1961 (Fig. 1c). The extraordinary upper-tropospheric warming induces 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). Furthermore, as an external forcing, the thermal condition of the Tibetan Plateau has 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). 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 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 $2° \times 2°$ 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 external/boundary 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 external factors (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).

3. Extremely Wet Spring Of 2022 And Associated Atmospheric Circulation Anomalies

Spring is the dry to wet transition season in SWC. The amount of rainfall in spring has a crucial impact on farming, production, and life in SWC. Climatologically, the averaged accumulated rainfall in MAM is about 210 mm in SWC, decreasing from southeast to northwest (figure not shown). In 2022, most SWC suffered the wettest spring since 1961, with the rainfall 100–150 mm more than the climatic mean according to the spatial distribution of MAM mean rainfall anomalies, 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 regional droughts or wet. Figure 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). A trough over the Ural Mountains favored the southward invasion of cold air along the northeastern flank of the Tibetan Plateau to southern China. On the other hand, the low latitudes from the eastern Arabian Sea to the Philippines were generally controlled by negative 500 hPa geopotential height (Z500) anomaly, which is 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 went down along the eastern flank of the Tibetan Plateau to 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 distinguished moisture convergence center over SWC (Fig. 3), which provided sufficient water vapor for rainfall here. 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 role of anomalous circulation conditions in the extremely wet spring in SWC is confirmed by a regression Z500 and 700 hPa wind (UV700) anomalies onto the time series of SWC spring rainfall (Fig. 2b). The distribution of obtained anomalies the regressions with the observations validates that the negative-positive-negative northwest-southeast circulation anomaly is a typical favorable circulation pattern for SWC wet spring. Then, what kind of external 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

a. Impact of La Ni*ñ*a

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, typical of the La Niña events, favors excessive rainfall in SWC (Fig. 4a) (e.g., Feng et al. 2014; Cao et al. 2017; Deng et al. 2022). From the historical perspective, the anomalous cyclonic wind anomalies are located at lower latitudes (BOB and southeast coast of China), likely resulting from a combined effect of negative SSTAs in both the central-

eastern equatorial Pacific (Wu and Wang 2000; Wang et al. 2000; Yang, 2011; Deng et al. 2022) and the tropical Indian Ocean (Xie et al., 2009; Ding et al., 2021). In MAM 2022, the second-year La Niña event, with negative SSTAs in the central-eastern equatorial Pacific and positive SSTAs in the northwestern tropical Pacific (Fig. 4b), is the primary contributor to the cyclonic wind anomalies over BOB and the Philippine Sea, which is consistent with the historical statistics. In addition, the Indian Ocean SSTA in MAM 2022 is small (the IOBM index is 0.17, Fig. 4c), which seems to have a minor impact on 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 cannot reproduce 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.

b. 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 measure 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.

Figure 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, which indicates that the MAM rainfall in SWC is statistically reated to the thermal condition of the Tibetan Plateau. In MAM 2022, the anomalous UTT_TP warming averaged in the high correlation region was persistent 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.

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 the 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 the anomalous easterly wind and an anomalous cyclone circulation, and SWC is just 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 in SWC.

The tropospheric temperature over the Tibetan Plateau is related to the amount of high and medium cloud cover and the surface downward solar radiation flux (Nan et al., 2021). Thus, the composite fields of these variables in typical years of the significant positive MAM UTT_TP anomaly are further conducted to investigate the maintenance mechanism of the upper-level tropospheric warming over the Tibetan Plateau and its impact on the spring rainfall in SWC (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 amounts of high and medium cloud cover decreased over the Tibetan Plateau with the UTT_TP warming, which allows more solar radiation to reach the surface (Fig. 6a and 6b). In turn, positive downward solar radiation anomalies lead to surface warming, especially over the western Tibetan Plateau (Fig. 6c). That suggests a positive feedback process among the clouds, radiation, and UTT_TP warming. By modulating the atmospheric circulation, such persistent warming over the Tibetan Plateau enhance ascent and rainfall over SWC and its surroundings (see the above-normal high and medium cloud cover and deep convectionin, 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.

c. 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 7b), 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 indice 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 (Fig. 1a, b). The reconstructed rainfall anomaly based on the Niño3.4 index is only about 1/4 of the observations, implying 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 Niña event are two major factors contributing to the observed SWC rainfall anomaly in MAM 2022 (Figs. 7c, 1a, b). Such two primary external forcings may imply the predictability of this extreme event.

4.4 CFSv2 prediction

The predictability and possible causes of the SWC extremely wet spring are further examined 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 well reproduced in CFSv2 with different lead times, which implies 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 mostly opposite to the observations.

A comparison of the predictions of associated Z500 anomalies with 1–4 month leads is 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, 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 MAM2022 is probably due to the well-predicted La Niña in 2021/2022 by CFSv2 (Li et al., 2022), rather than the upper-tropospheric warming. 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.

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 second-year of a double/triple dip La Nina

event. In this work, observations and model forecasts were analyzed to investigate the reasons 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 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 with the upper tropospheric warming over Tibetan Plateau favors upward motion and excessive rainfall in SWC.

The CFSv2 model reproduced the relationship between the SWC rainfall anomaly and the northwest-southeast wave pattern. The real-time prediction underestimates the wet area and severity of SWC rainfall in MAM2022 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 related to whether both the ENSO evolution and thermal condition over the Tibetan Plateau can be well captured.

The spring of both 2021 and 2022 is under the decay 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? That may be due to the differences in the thermal condition over the Tibetan Plateau between the two springs. Although the evolution and value of Niño3.4 indices are close in the two springs, the UTT_TP index values are different in MAM 2021 and 2022 (Fig. 1c), and the spatial distributions of the upper-level tropospheric temperature anomalies are also different in the western Tibetan Plateau and SWC (Fig. 11). It appears that the Tibetan Plateau thermal condition may be the primary contributor for 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 indicated the influence of a tripole SSTA pattern in the North Atlantic Ocean on the spring East Asian climate by atmospheric teleconnection over the mid- and high-latitude Eurasia (Wu et al. 2011; Chen and Wu 2017; Sun et al. 2022). Does the North Atantic 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 historical perspective. However, the SSTAs in MAM 2022 are not obvious in the tropical North Atlantic and small in the 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 appear to indicate that the North Atlantic SST anomalies did not have a large contribution to the wet condition in SWR in MAM 2022.

Declarations

Ethics approval and consent to participate (Not applicable)
Consent for publication (Not applicable)

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/.

Competing interests

The authors declare no competing interest.

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Author Contributions

Yunyun Liu conceived the idea in discussion with Duo Li, Zeng-Zhen Hu and Renguang Wu. Duo Li performed the data analyses and plotted the figures. Yunyun Liu wrote the initial manuscript. Zeng-Zhen Hu and Renguang Wu contributed substantially to improving the research and presentation. All the authors contributed to the writing, editing, presentation, and reviewing of the manuscript.

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Figures

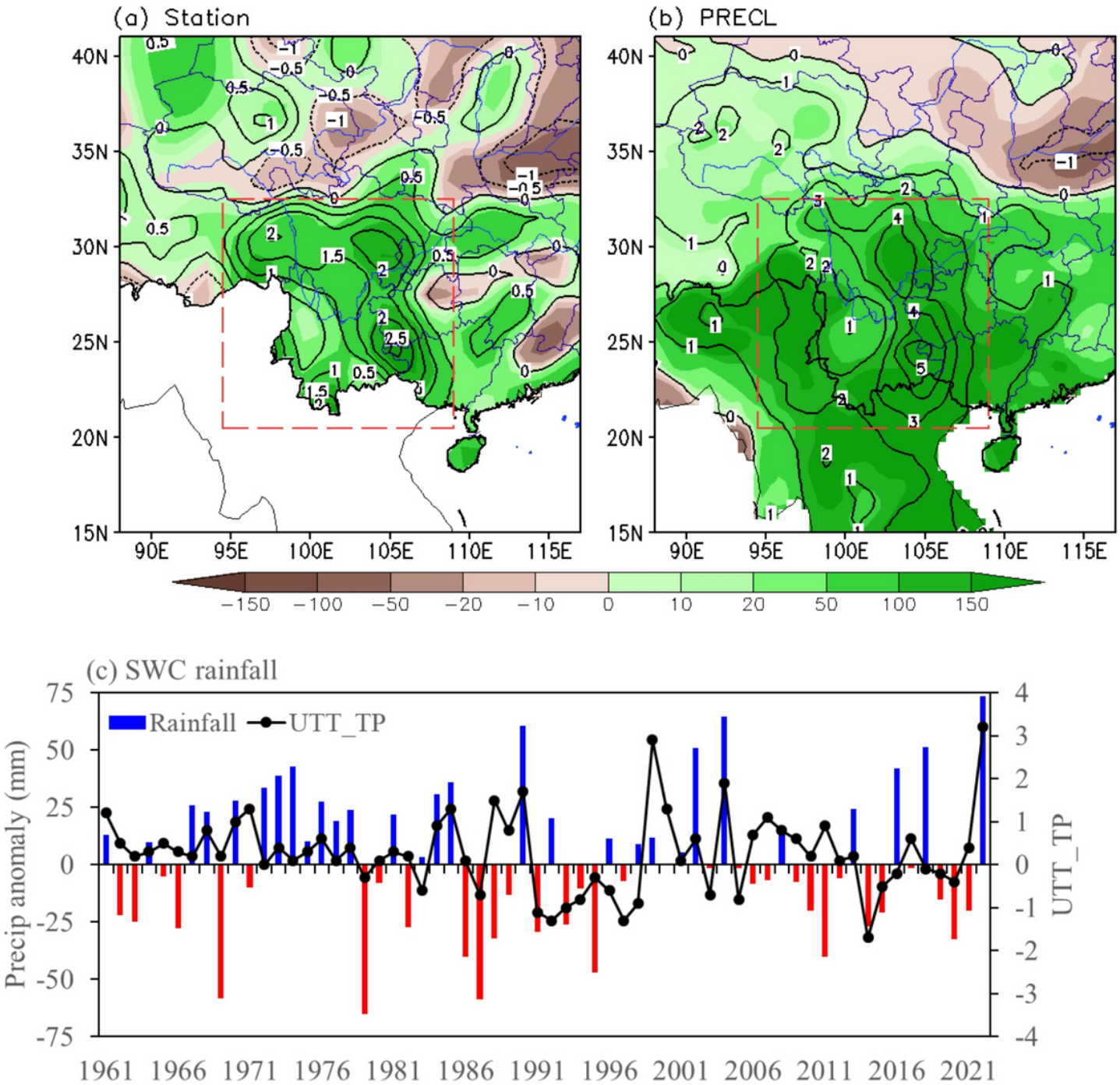

Figure 1

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 Student's *t*-test.

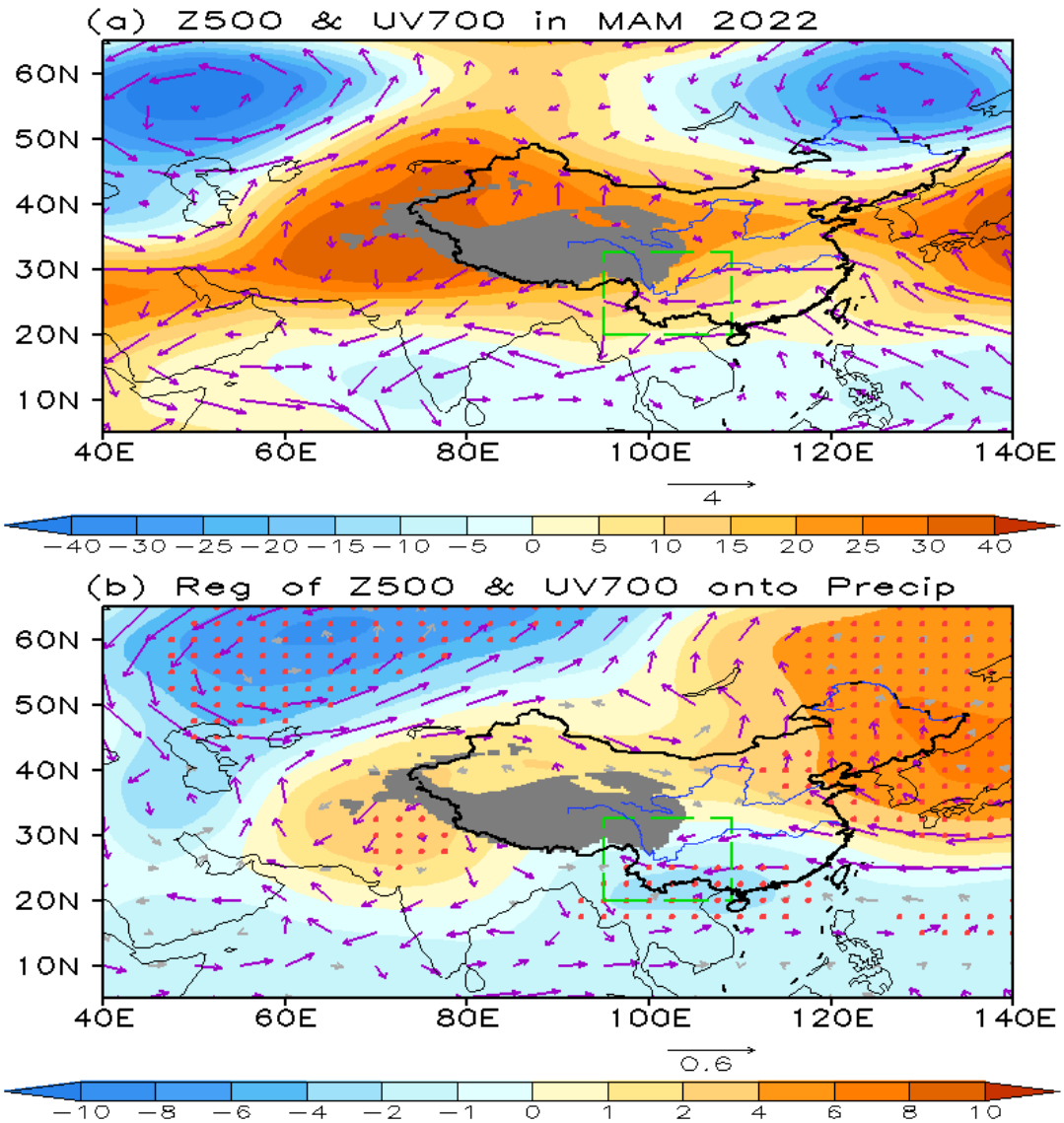

Figure 2

(a) Observed Z500 (shading, gpm) and uv700 (vector, m s^{-1}) anomalies in MAM 2022, and (b) regressions of Z500 and uv700 onto MAM rainfall in SWC during 1961-2022. Red stippling in (b) indicates the anomalies 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.

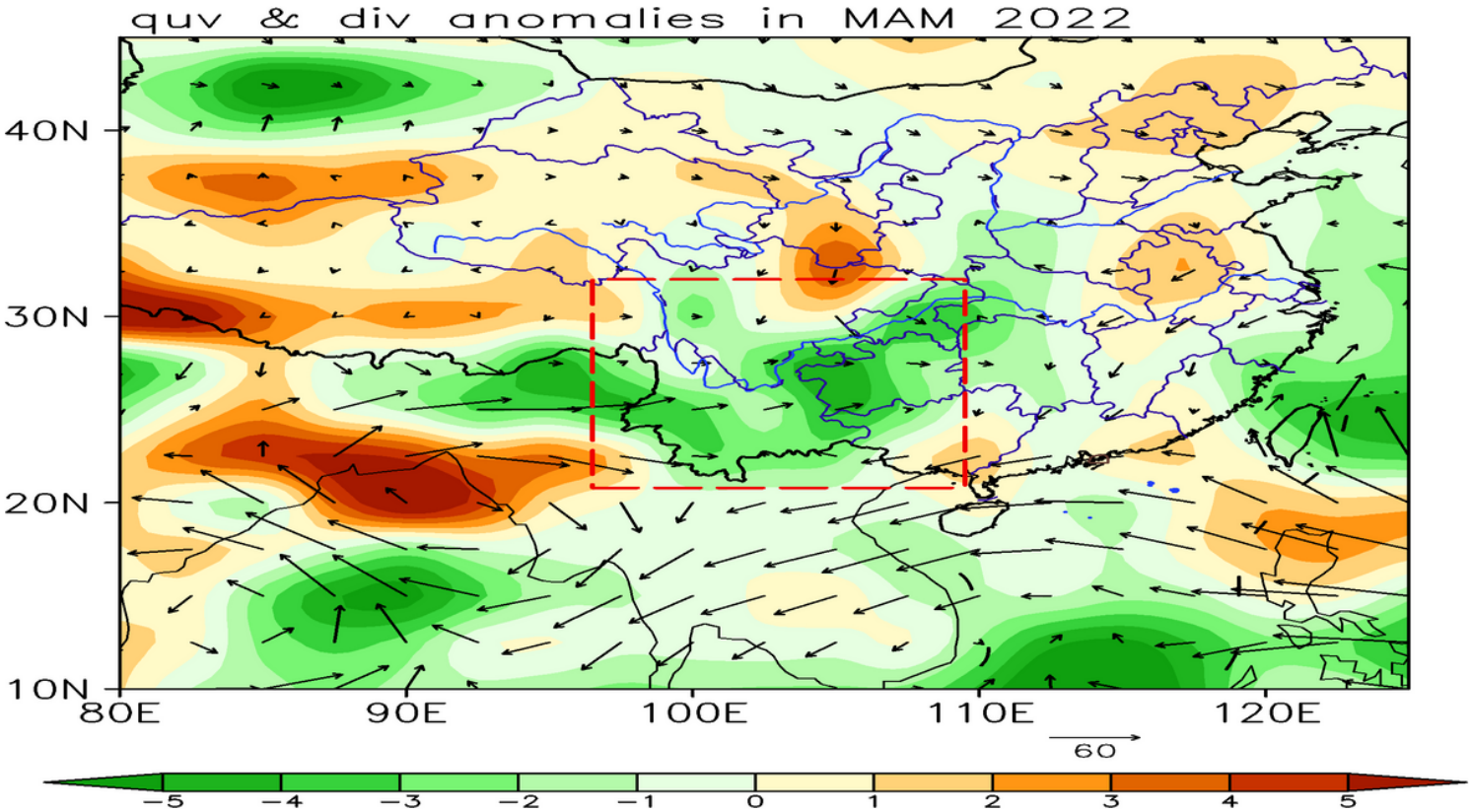

Figure 3

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.

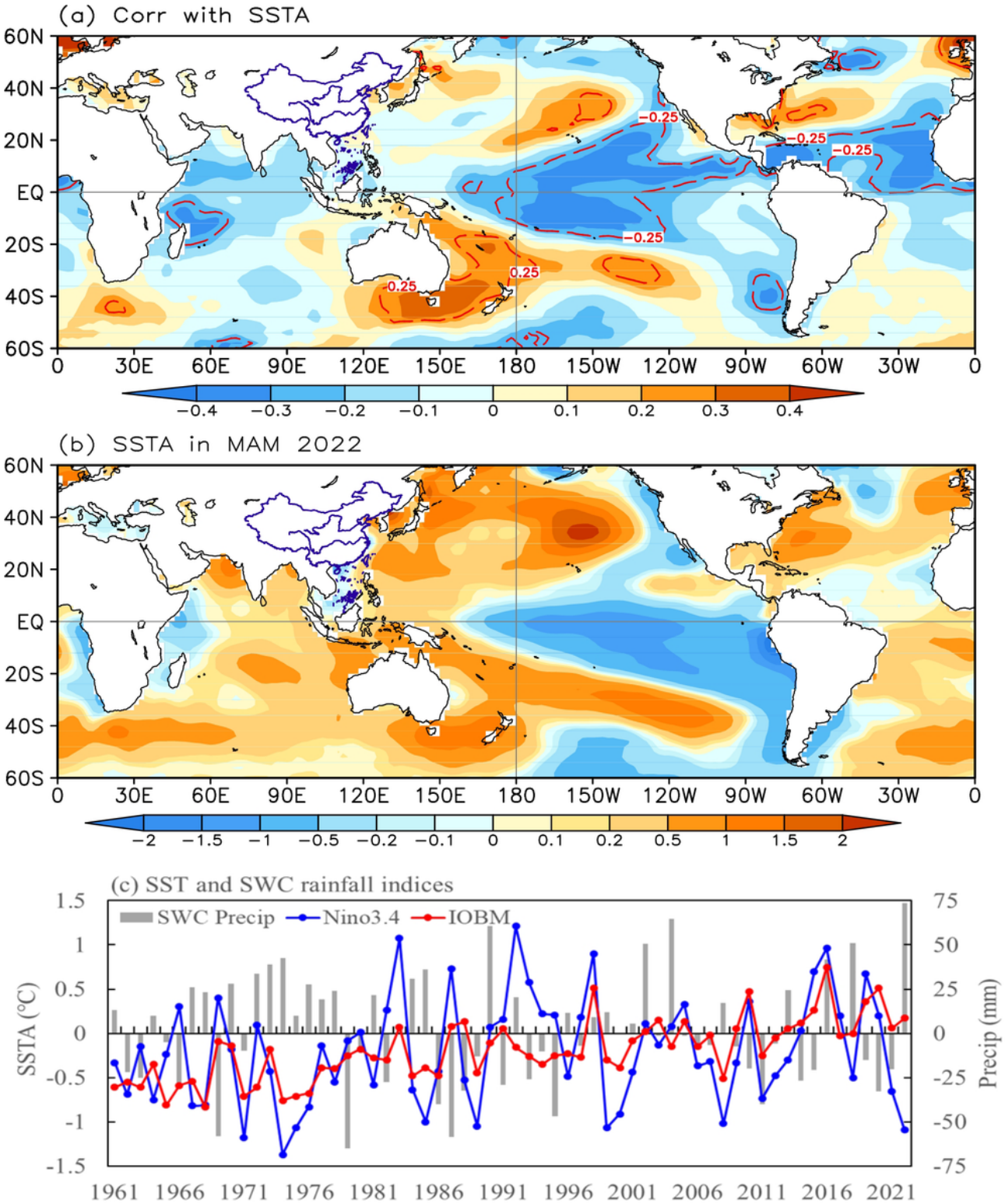

Figure 4

(a) Correlation of MAM rainfall in SWC with SSTA, (b) distribution of SSTA in MAM 2022 (°C), and (c) time series of SWC rainfall (gray; mm), MAM Niño3.4 (blue; °C), and IOBM (red; °C) indices from 1961-2022. Dashed lines in (a) indicate the correlations reaching the 0.05 significance level based on the *t*-test.

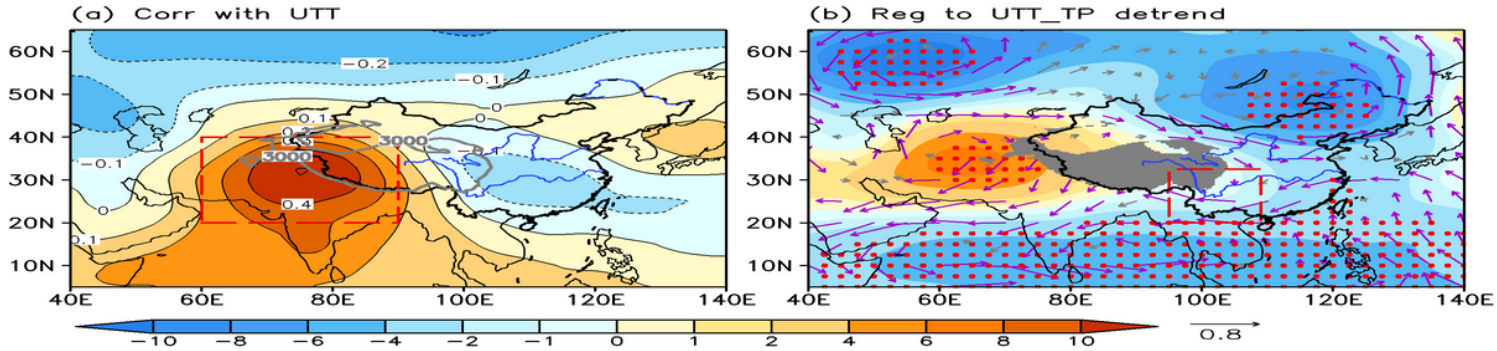

Figure 5

(a) Correlation of MAM rainfall anomaly in SWC with the zonal-mean departure upper-tropospheric (500-200hPa 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 (b) indicates the regressions reaching the 0.05 significance level based on the *t*-test. The grey area shading in (b) denotes the Tibetan Plateau with an elevation exceeding 3000 m.

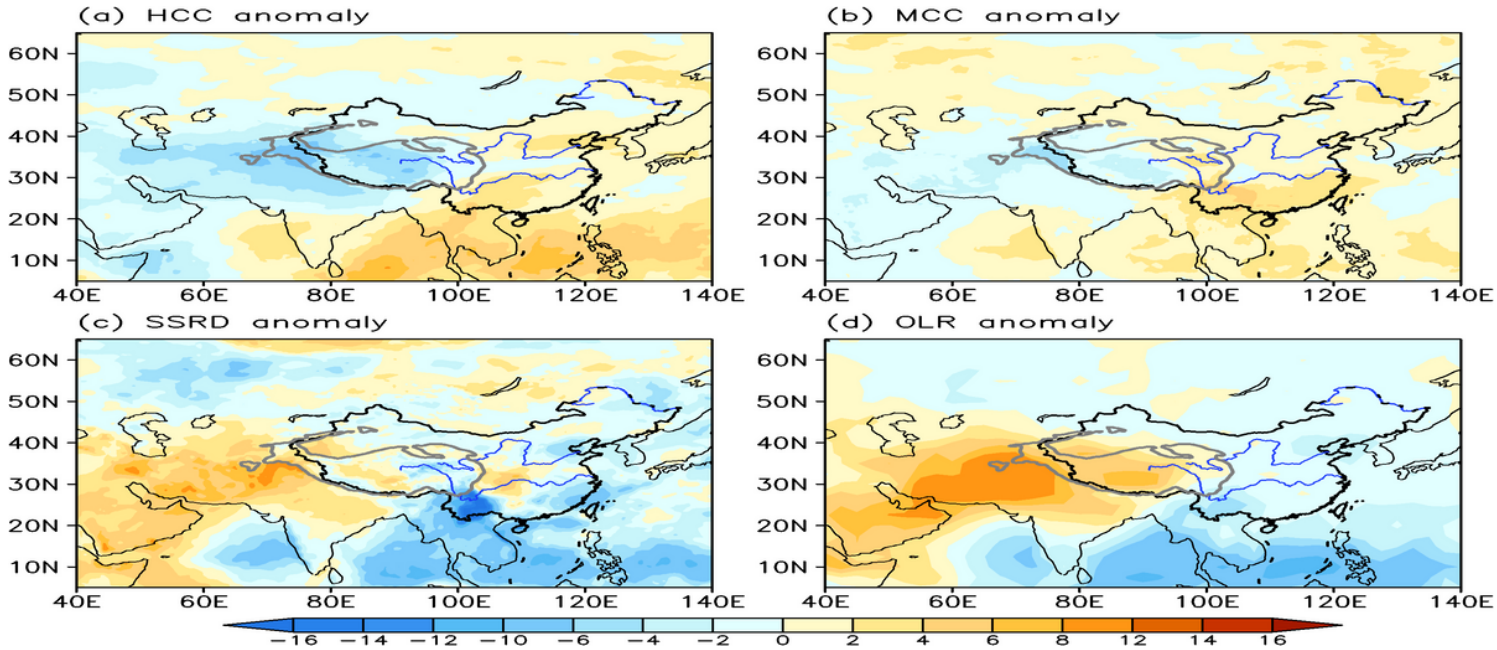

Figure 6

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.

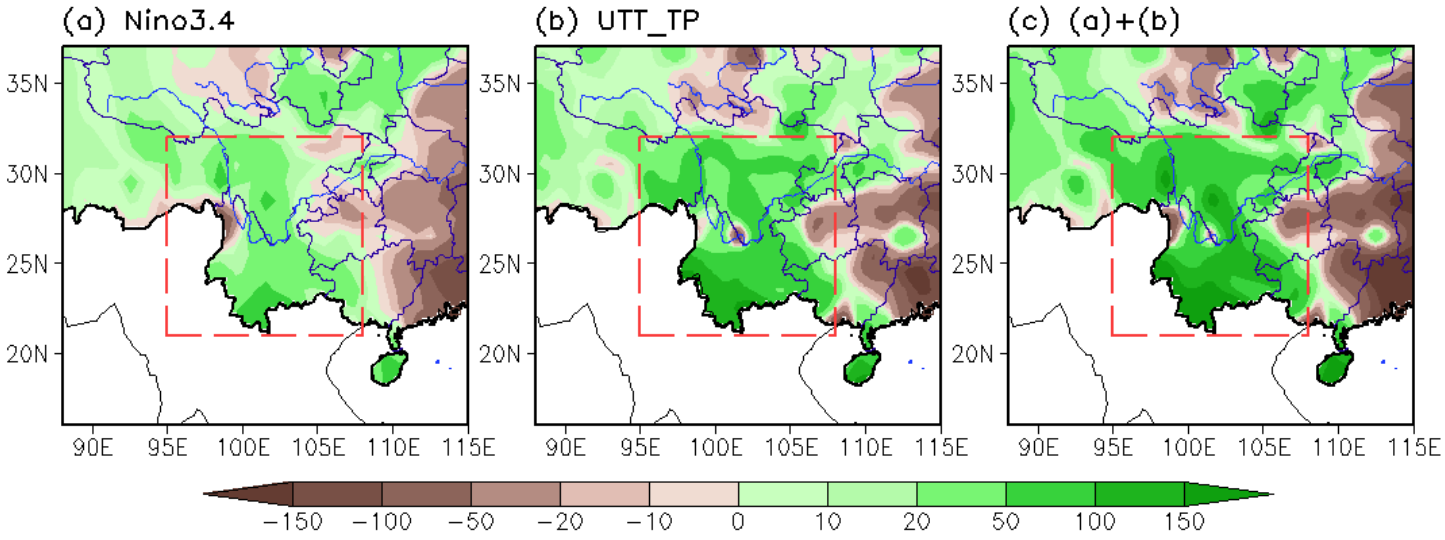

Figure 7

Reconstructions of 2022 MAM rainfall anomaly (mm) based on the linear regression with the normalized (a) Niño3.4 and (b) UTT_TP indices, and (c) the sum of (a) and (b).

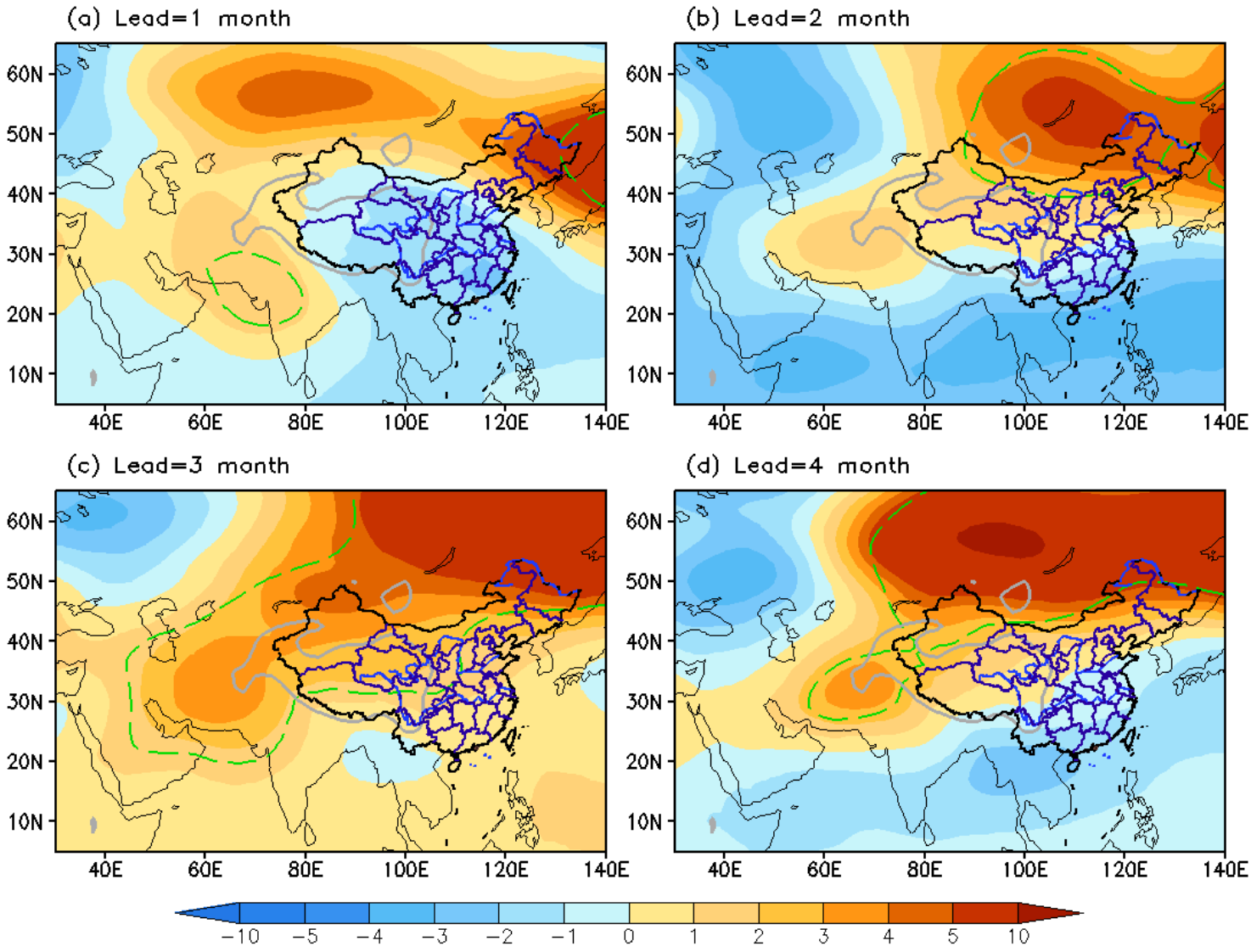

Figure 8

The linear regression of 500 hPa geopotential height 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.

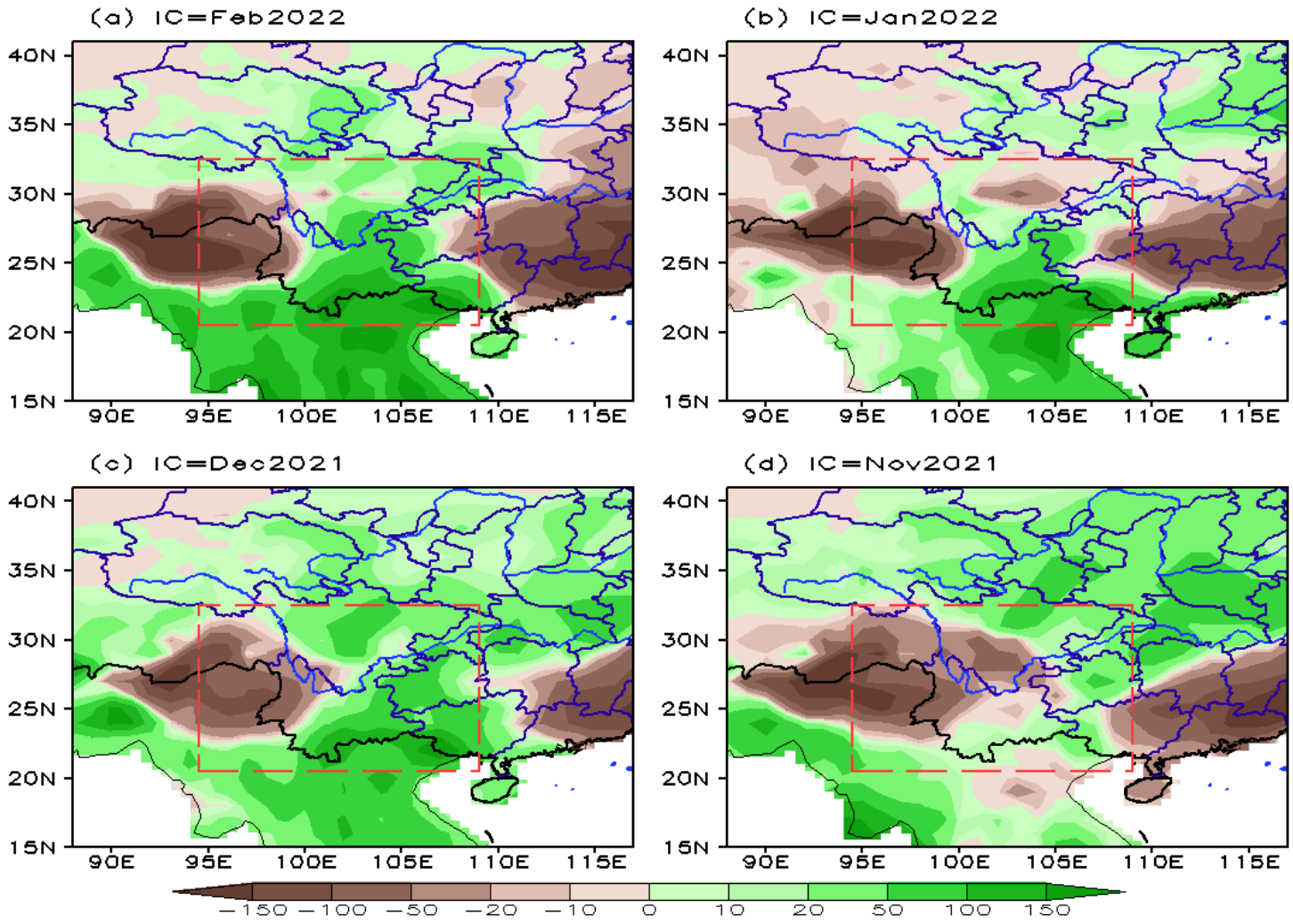

Figure 9

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.

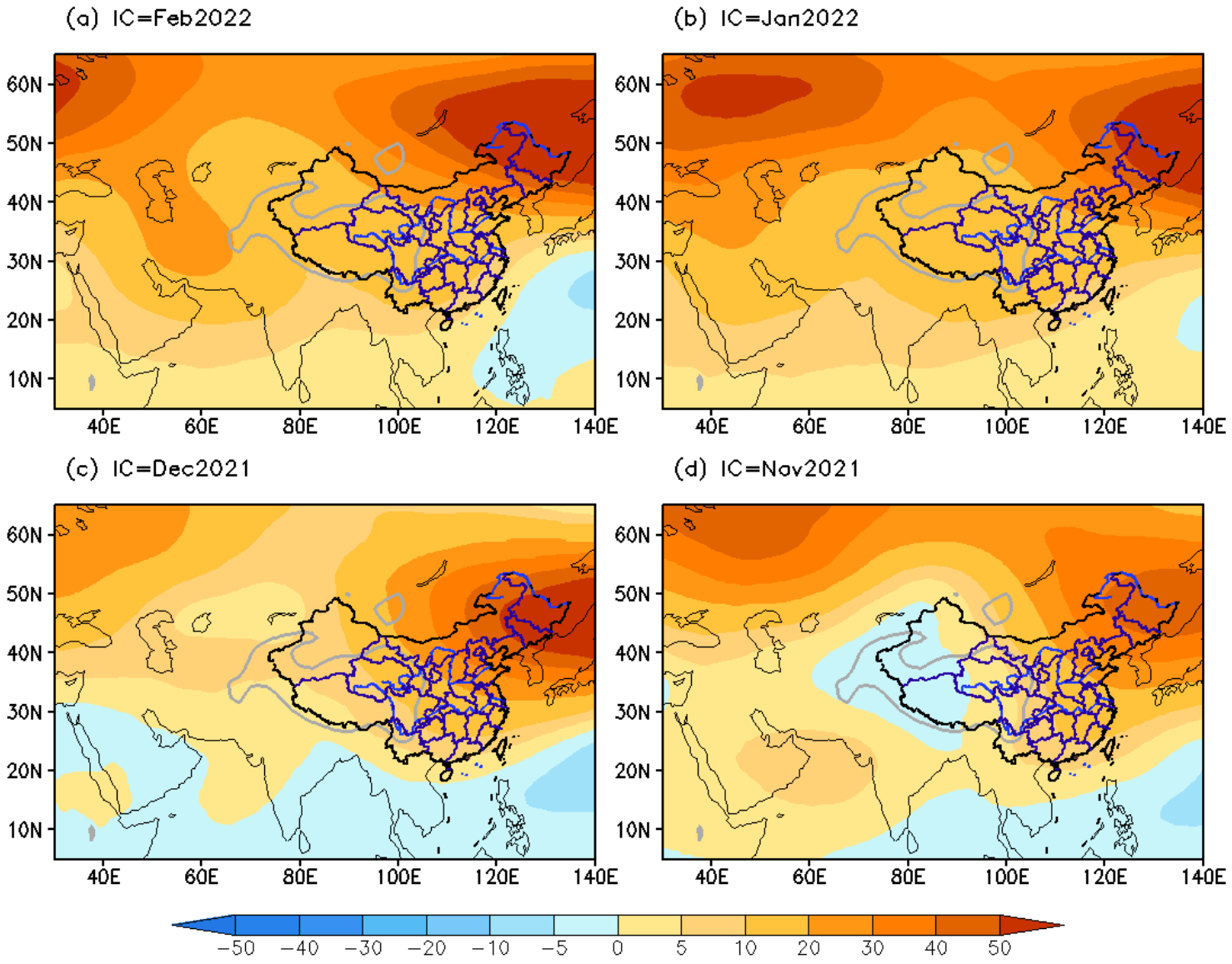

Figure 10

Same as Fig. 9, but 500-hPa geopotential height anomalies.

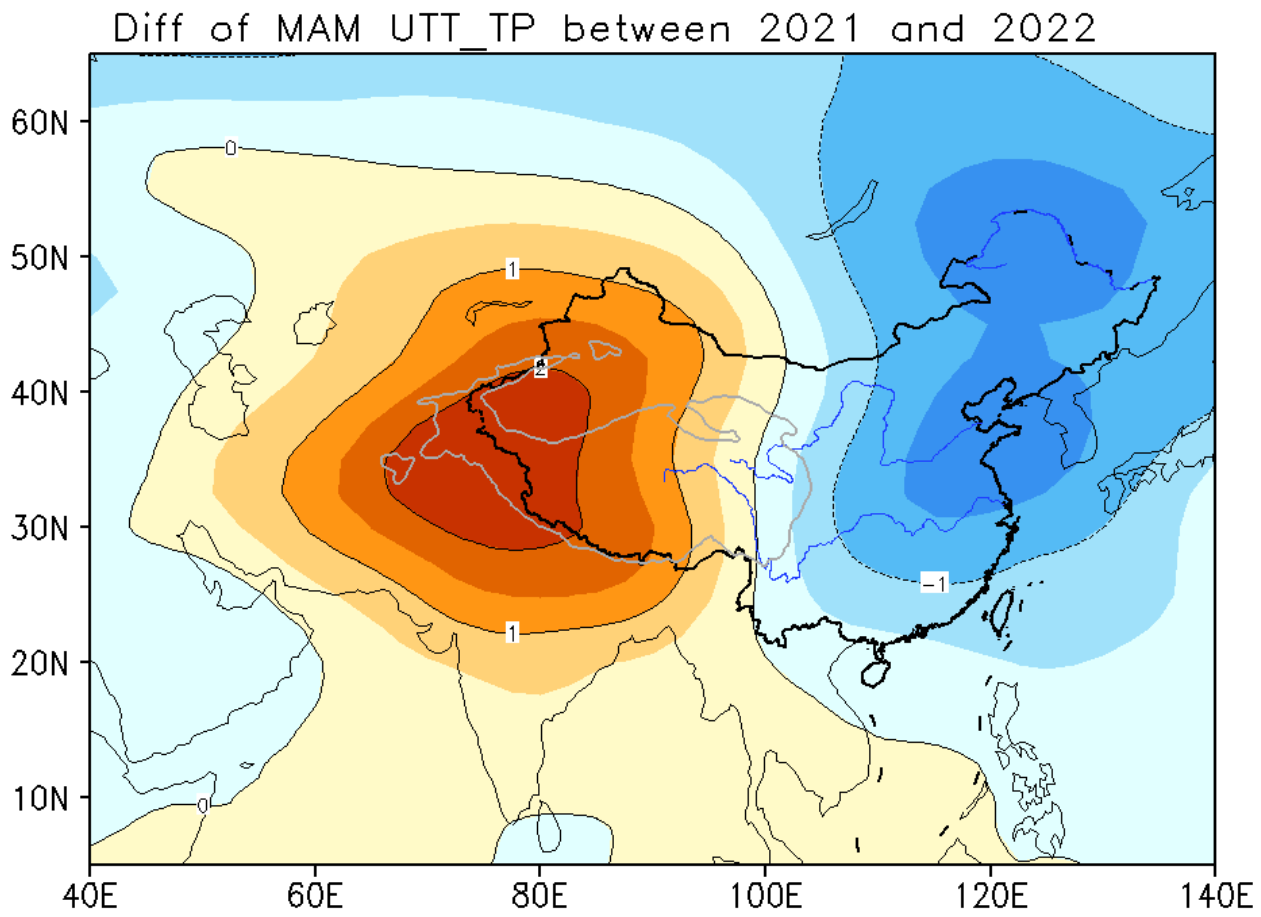

Figure 11

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