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Short Communication

Excessive Tibetan Plateau spring warming found to cause catastrophic June 2024 heavy rainfall in China

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In June 2024, southern China (S. China) experienced record-breaking rainfall events (Fig. 1c). According to the National Climate Center's June 2024 Climate Impact Assessment, since the start of the Meiyu season on June 10th, the precipitation in the Yangtze River Basin during June 10th-30th was 49.2% above the long-term average, marking the second highest rainfall in the basin since 1961 (The co-authors, QP. Li and G. Xu of CMA provide this information). The heaviest rainstorms occurred during June 9th-July 2nd, with the duration and impact range exceeding that of June 1998, when also experienced extraordinary June precipitation and flooding in S. China. Associated with these catastrophic rainfall events, a large number of geological disasters occurred, such as landslides and urban flooding. The cause of this catastrophic precipitation remains unidentified. It is, therefore, imperative to understand the underlying causes and make skillful predictions of such extreme hydroclimatic events for adequate monitoring, prevention, and mitigation efforts.

Unfortunately, subseasonal-to-seasonal (S2S) precipitation prediction for late spring and summer, which contains a substantial number of extreme hydroclimate events, has remained poor to date. The World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP) of the World Meteorological Organization (WMO) have launched a joint S2S Prediction Project to tackle predictions ranging from 2 weeks to 3 months [1]. To address the scientific challenges raised in the WCRP/WRRP project, the Global Energy and Water Exchanges (GEWEX)/Impact of Initialized Land Temperature and Snowpack on Subseasonal-to-Seasonal Prediction (LS4P) Project initiated a new approach, testing the impact of land surface temperature (LST) and subsurface temperature (SUBT) in high-mountain regions on S2S prediction by using Earth System Models (ESMs). Climate scientists from more than forty major climate research and prediction centers worldwide participated in this project [2]. Observational data analysis under LS4P revealed a lag correlation between spring land temperature over the Tibetan Plateau (TP) and downstream summer precipitation, i.e., when the spring TP was warm/cold, S. China was highly likely to have a wet/dry summer, respectively [2–4]. The correlation of the first principal components of May TP 2m-temperature (T-2m) and June precipitation in S. China from a Maximum Covariance Analysis over 1980–2015 was 0.58, with a significant level of $p < 0.05$ [3]. Such significant lag correlation was further confirmed in the latest analyses with another dataset from 1980 to 2022 [5]. Furthermore, LS4P conducted modeling studies to evaluate whether such lag correlations represent causal relationships. In LS4P Phase I (LS4P-I), 2003—a year with extreme drought in S. China following an unusually cold spring in the TP–was selected as the focal case. Multi-model ensemble means from this study demonstrated that cold spring LST/SUBT anomalies over the TP caused subsequent downstream summer drought in S. China, and the TP LST/SUBT effect is a first-order source of S2S precipitation predictability [4–6]. However,

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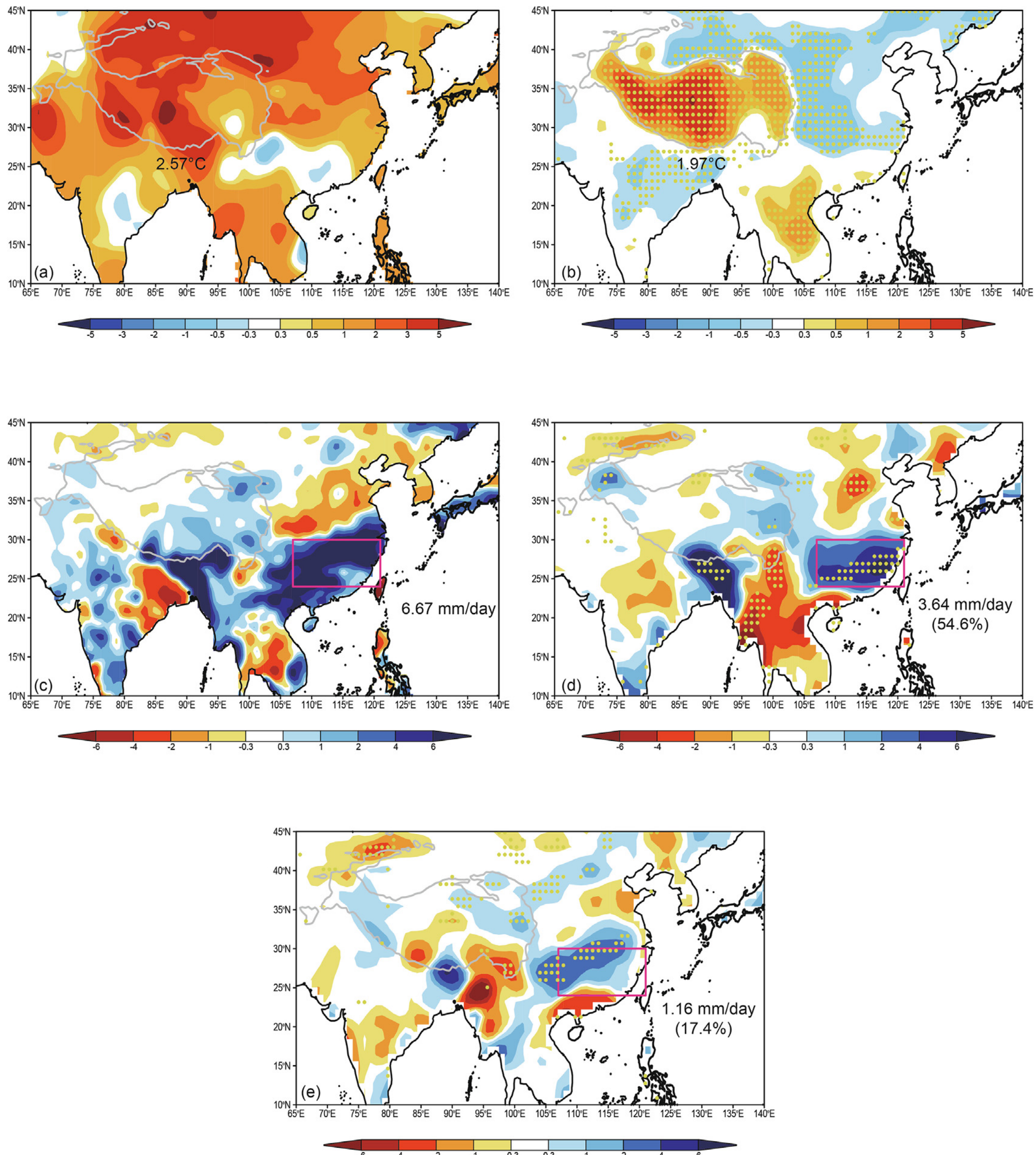

Fig. 1. Observed and simulated May 2024 T-2m anomalies (°C) and June 2024 precipitation anomalies (mm/day). (a) Observed May T-2m difference between 2024 and the climatology reference; (b) GFS/SSiB2 simulated May T-2m anomaly after soil temperature initialization over TP. (c) same as (a), but for the June 2024 precipitation anomaly. (d) Simulated June precipitation anomaly due to TP LST/SUBT effect. (e) same as (d) but due to the global SST effect. Note: (1). The dotted grids denote the statistical significance based on the Student *T*-test at the $p < 0.1$ level. (2). The grey bold 4000 m contour lines illustrate the approximate TP geographic location. (3). The numbers in panels are averages of corresponding variables over the TP in panels (a) and (b) and over the red box in panels (c)–(e).

as this is newly emerging research that is still in the early exploration stages, further investigations, including additional case studies of extreme hydroclimate scenarios, are necessary.

The TP had a very warm spring in 2024. The March and April TP T-2m were 2.05 °C and 1.61 °C higher, respectively, than their 1981–2010 means over the region (29°–37°N and 86°–98°E) at elevations above 4000 m. In May, the TP T-2m anomaly peaked (Fig. 1a) at 2.57 °C higher than the climatological mean. It was the warmest May since 1980, based on the statistics shown by Xue et al. [4], surpassing the 1.5℃ anomaly observed in May 1998. Since the warm spring in the TP and the abnormal June precipitation in S. China in 2024 align with the lag relationship discovered in previous LS4P-I studies, we decided to make a timely assessment of the potential causal relationship for the 2024 scenario and elucidate the underlying mechanism.

This study utilized the National Centre for Environmental Prediction—Global Forecast System (NCEP-GFS) from version 2 of the NCEP Climate Forecast System (CFSv2) model [7], a state-of-the-art global atmospheric model. The version used was coupled with the second generation of the Simplified Simple Biosphere biophysical model (SSiB2) [8] (hereafter referred to as GFS/SSiB2). A comprehensive description of GFS/SSiB2 and an assessment of its performance have been addressed in several studies [8]. GFS/SSiB2 has shown the capacity to predict extreme events, such as the 1998 floods and the 2003 droughts in S. China [3,9]. In addition, the T-2m data in this study were obtained from the second version of the Global Historical Climatology Network and the Climate Anomaly Monitoring System (GHCN_CAMS; hereafter CAMS) (https://psl.noaa.gov/data/gridded/data.ghcncams.html), which provide gauge-based gridded monthly T-2m data globally. Precipitation data were obtained from the Climate Prediction Center Global Unified Precipitation Dataset. It should be noted that anomalies in this paper, both in T-2m and precipitation, are relative to the 1981–2010 climatology.

Two sets of numerical experiments were conducted to assess the potential contribution of the extreme warm May T-2m anomaly over the TP to the disastrous June 2024 precipitation event in S. China (Table S1 online). In the control scenario case (referred to as Exp. CTRL), the initial and boundary conditions for the atmosphere, sea surface temperature (SST), sea ice, and land surface conditions were obtained from the 2024 NCEP CFS Reanalysis (CFSR) [10], a standard configuration for S2S prediction of initial and boundary conditions. Each experiment consisted of six ensemble members, initialized at 00Z on April 24th–29th, 2024, and ending at 00Z on July 1st, 2024. The simulation results presented in this study are based on the multi-member ensemble means. The differences between Exp. CTRL-simulated June precipitation and observations, i.e., the biases, are shown in Fig. S1 (online). Exp. CTRL failed to produce the heavy precipitation in S. China and exhibited a severe dry bias. Meanwhile, Exp. CTRL-simulated T-2m also failed to produce the observed homogeneous extreme warm temperature over the TP.

Our objective is to examine whether the observed extreme warm T-2m shown in Fig. 1a caused the catastrophic June precipitation in S. China, as shown in Fig. 1c. To produce the observed T-2m anomalies over the TP, relative to the Exp. CTRL, we conducted a second experiment (referred to as Exp. LST/SUBT). In this experiment, we applied an LST/SUBT initialization mask. The method to generate the mask was developed in LS4P, which is based on the observed T-2m anomaly and model biases over the TP [2]. This mask was imposed at Exp. LST/SUBT model initialization (only at the first timestep of model integration) over the TP, while all other configurations remained unchanged. We aimed to produce the May T-2m difference over the TP between Exp. LST/SUBT and Exp. CTRL, closely matching the observed May 2024 T-2m anomaly. Subsequently, we checked whether the June precipitation difference between these two experiments was also consistent with the observed anomaly. The experiments conducted in this study are summarized in the Table S1 online. Land initialization and configuration have been identified as one of the major potential avenues for improving S2S predictions in the WCRP/WRRP S2S project [1].

Before discussing the model results further, we will first clarify two relevant issues: (1) Fig. 1a shows that high T-2m anomalies can also be found across most parts of East and South Asia. However, through extensive testing, the LS4P groups found that only T-2m anomalies over high-elevation areas contributed to S2S prediction [11]. (2) Although T-2m interacts with the atmosphere by influencing surface heat and momentum fluxes and upward longwave radiation, leading to the modulation of atmospheric circulation and affecting S2S prediction, T-2m is not a prognostic variable but a diagnostic variable in the prediction model. It is determined by the land surface energy balance equation. Therefore, we cannot directly initialize T-2m. However, T-2m and LST are closely related through the energy balance equation, and measurements over the TP confirm that they are close in magnitude and variability. LST and SUBT are highly correlated and both have inertia, providing memory [12]. Given that T-2m has global and long-term observations with the highest quality among measured land variables, it was used as a proxy for initializing LST and SUBT. We expect that through the LST/SUBT initialization, the observed May T-2m anomaly could be reproduced for adequate land–atmosphere interactions. The detailed mathematical and technical aspects of the LS4P initialization method are presented in Xue et al. [2].

After imposing the T-2m mask for initialization in Exp. LST/SUBT, the ensemble mean difference between Exp. LST/SUBT and Exp. CTRL produced a 1.97 °C anomaly in May 2024 over the TP, representing about 77% of the observed May anomaly (Fig. 1b). To facilitate a quantitative assessment, we define a red box (24°–30°N and 107°–121°E) in Fig. 1c–e to focus on regions with the most intense precipitation anomalies. Within this box, the observed June precipitation anomaly was 6.67 mm/day, while the LST/SUBT effect (Exp. LST/SUBT–Exp. CTRL) produced a precipitation anomaly of 3.64 mm/day, contributing about 55% of the observed anomaly (Fig. 1d). Dotted grids in the red box indicate statistically significant values based on a Student's *t*-test at the $p < 0.1$. In this study, 33.7% of the grid points in the red box passed the *t*-test at $p < 0.1$. Since the *t*-test does not account for spatial correlation and temporal autocorrelation within the model simulations, a field significance test was conducted to address the effects of multiplicity and spatial correlation, thereby reducing the degrees of freedom in the point-wise statistical test and providing a robust evaluation of whether the significant differences occurred by chance [13]. This method is particularly valuable when the number of samples is small. The precipitation difference between Exp. LST/SUBT and Exp. CTRL in the red box area passed the field significance test at $p < 0.1$. This confirms that the statistical significance of the differences between Exp. LST/SUBT and Exp. CTRL did not occur by chance over the area with the most intensive anomaly. The results from each ensemble member are displayed in Figs. S2 and S3 (online) for reference. In addition to S. China, the LST/SUBT effect also produced dry anomalies in northern China and wet anomalies in the eastern TP, Bangladesh, western Myanmar, and southern Japan (Fig. 1d), consistent with observed anomalies.

Previous studies [6,9] comprehensively analyzed the mechanisms of how TP spring T-2m /LST/SUBT anomalies affect summer droughts and floods over the East Asian lowland plains. The circulation changes in this study are consistent with these studies, but with a clearer response due to the extraordinary warm temperature anomaly over the TP. The warm T-2m anomaly produced a positive sensible heat flux anomaly (Fig. S4a online), which heated the atmosphere around 35°N (Fig. S4b online). This, in turn, produced a positive meridional temperature gradient south of 35°N and a negative gradient to the north. According to the thermodynamics of atmospheric circulation, such horizontal temperature gradient changes strengthened/weakened the westerly zonal wind at 200 hPa in the northern/southern part of the westerly jet in May and June (Fig. S5 online). The geopotential height (GPH) difference at 200 hPa also underwent corresponding changes, as shown in Fig. S7 (online), linked by the quasi-geostrophic relationship between wind and GPH at mid-latitudes. Moreover, studies have demonstrated that T-2m perturbations over the TP lead to the eastward propagation of eddy kinetic energy anomalies on synoptic timescales toward eastern China [6,9] (Fig. S8 online), along with other perturbations induced by TP T-2m anomalies [14,15]. Overall, these results are consistent with those presented in Ref. [6], though with the opposite sign, as Xue et al. [6] discussed a cold TP case. One notable difference is the much stronger May GPH anomaly over the TP in 2024 (Fig. S7a online) due to excessive heating. This strong positive GPH, coupled with induced negative GPH anomaly to the east, favored a strong southward steering flow, similar to what was reported by Xue et al. [3] (Fig. S7a online), helping larger positive GPH anomaly in the upper troposphere to extend southeastward, contributing to record-breaking rainfall in S. China till southern coastal areas. In terms of the vertical baroclinic structure, there was divergence/convergence in the upper/lower atmosphere over S. China in June (Fig. S9a online). A low-level cyclonic structure that intensified the summer Meiyu monsoon flow from the Bay of Bengal and the South China Sea was produced (Fig. S9a online). Once this cyclonic perturbation reached S. China, ample moisture, convective instability, along with condensation heating, fueled strong positive feedback enhancing convective activity and contributing to the further growth of a strong cyclonic system. This inflow of moisture resulted in increased vertically integrated moisture flux convergence (Fig. S9b online). The above processes explain the effect of the 2024 May TP LST/SUBT anomaly on the East Asian monsoon system, which led to the catastrophic June rainfall in S. China. A schematic diagram illustrating these mechanisms is shown in Fig. 2. In fact, local amplification of extreme precipitation events can also be found over tropical land. Moisture continues to build up due to advection from nearby oceans, resulting in increased stored convective available potential energy (CAPE) in the atmosphere. When deep convection eventually breaks out, it tends to lead to the development of a mesoscale convective system (MCS), resulting in very extreme precipitation over land [16].

While this study demonstrates a significant relationship between excessive TP heating and downstream heavy precipitation, further improvements are still necessary. For instance, this study was only able to reproduce 77% of the observed May TP T-2m anomaly because the model was unable to hold the initially imposed LST anomaly. This limitation was observed across nearly all LS4P-I ESMs, and the plausible causes were discussed in several papers [2,5]. Further improvement of the LST/SUBT initialization and/or model parameterization could help address this issue. In addition, our previous study [3] suggested that regional climate downscaling improves the simulated intensity and spatial distribution of droughts and floods compared to global model simulations, which provide the lateral boundary conditions for regional downscaling. Such an approach is particularly important for enhancing the accuracy of S2S predictions and ensuring their practical applicability for societal planning purposes.

In addition to LST/SUBT, the impact of SST on climate prediction also needs to be considered for an event like this. We conducted SST experiments (referred to as Exp. SST), in which the 2024 daily SST forcing was replaced by the SST daily climatology (1981–2010), while other configurations remained unchanged (Table S1 online). The moderate El Nino event that peaked in December 2023 had receded in May 2024. By May and June 2024, there was only moderate warming in the western and northern Pacific and Indian Oceans (Fig. S10 online). The difference between Exp. CTRL and Exp. SST indicates that the SST effect produced a positive precipitation anomaly of 1.16 mm/day in S. China, which accounts for about 17% of the observed rainfall anomaly. However, these results failed to pass the field significant test, which is consistent with ensemble members' performance (Fig. S11 online). Despite this, we report the SST results, as SST plays a significant role in climate and weather systems, and scientific considerations should take precedence over statistical considerations when analyzing climatological data.

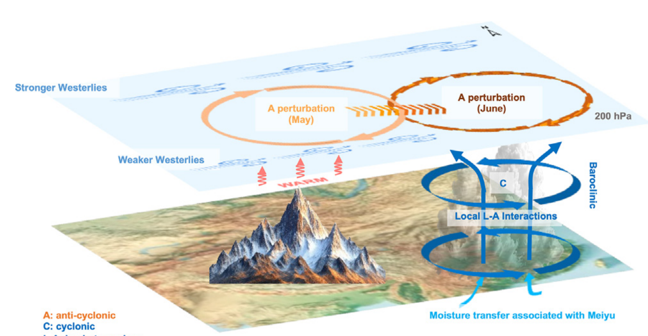

Fig. 2. Schematic diagram illustrating the subseasonal processes associated with the remote effect of Tibetan Plateau spring land temperature anomaly affecting downstream summer precipitation. It is based on Figs. S4–S9 and comprehensive analyses and discussions in Xue et al. [6] and Diallo et al. [9].

The root cause of extreme hydroclimate events lies in precipitation variability at S2S timescales. When the extraordinary rainfall event began to develop in June 2024, by checking the May TP T-2m anomaly, we realized that it was consistent with our previous LS4P studies, prompting us to initiate this investigation. Our timely results demonstrate the robustness of our approach, suggesting that TP spring land heating was the primary contributor to the catastrophic June 2024 precipitation in S. China. The objective of this paper is to provide timely insights to society and the scientific community regarding the cause of the extreme rainfall event in June 2024, and to spark the community's interest in broader and more comprehensive investigations into the various causes, such as LST/SUBT, SST, vegetation, and soil moisture, of extreme hydroclimate events, which are crucial for both scientific understanding and societal planning.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Qian Li made model simulation, data processing, and contributed to results analysis and manuscript writing. Yongkang Xue led this research and designed the experiments and contributed to results analysis and manuscript writing. Xianghui Kong contributed to model simulation, data processing, and results analysis. William Lau, Aihui Wang, Zhijiong Cao, and Weidong Guo contributed to results analysis. Zhijiong Cao also contributed to field significance test and technical assistance for the schematic diagram. Hara Nayak contributed to processing and analysis of the 2024 observational data. Ratko Vasic contributed to obtaining model initial conditions for late April 2024 in a timely manner. Qiaoping Li and Guoqiang Xu contributed to the information of the observed 2024 synoptical processes in China, assessment and analysis of model results, and provide information reported in the National Climate Center's June 2024 Climate Impact Assessment. In addition, all the co-authors contributed to the revision of the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.01.011.

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