Oki, T., and S. Kanae, 2006. Global Hydrological Cycles and World Water Resources. *Science* 313, 1068–1072.

Paiva, R.C.D., et al., 2013. Assimilating in situ and radar altimetry data into a large-scale hydrologic-hydrodynamic model for streamflow forecast in the Amazon. *Hydrol Earth Syst Sci* 17, 2929–2946.

Pedinotti, V., A. Boone, S. Ricci, S. Biancamaria, and N. Mognard, 2014. Assimilation of satellite data to optimize large-scale hydrological model parameters: A case study for the SWOT mission. *Hydrol Earth Syst Sci* 18, 4485–4507.

Polcher, J., et al., 2011. Hydrological modelling on atmospheric grids: Using graphs of sub-grid elements to transport energy and water. *Geosci Model Dev* 16, 2583–2606.

Pontes, P.R.M., et al., 2017. MGB-IPH model for hydrological and hydraulic simulation of large floodplain river systems coupled with open source GIS. *Environ. Model. Softw*. 94, 1–20.

Revel, M., D. Ikeshima, D. Yamazaki, and S. Kanae, 2019. A Physically Based Empirical Localization Method for Assimilating Synthetic SWOT Observations of a Continental-Scale River: A Case Study in the Congo Basin. *Water* 11.

Sadki, M., S. Munier, A. Boone, and S. Ricci, 2023. Implementation and sensitivity analysis of the Dam-Reservoir OPeration model (DROP v1.0) over Spain. *Geosci Model Dev* 16, 427–448.

Schwatke, C., D. Dettmering, W. Bosch, and F. Seitz, 2015. DAHITI – an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrol Earth Syst Sci* 19, 4345–4364.

Shepherd, A., et al., 2012. A Reconciled Estimate of Ice-Sheet Mass Balance. *Science* 338, 1183–1189.

Smith, L.C., 1997. Satellite remote sensing of river inundation area, stage, and discharge: A review. *Hydrol. Process*. 11, 1427–1439.

Swain, R., and B. Sahoo, 2017. Improving river water quality monitoring using satellite data products and a genetic algorithm processing approach. *Sustain. Water Qual. Ecol*. 9–10, 88–114.

Tavakoly, A.A., C.H. David, J.L. Gutenson, M.W. Wahl, and M. Follum, 2023. Development of non-data driven reservoir routing in the routing application for parallel computatIon of discharge (RAPID) model. *Environ. Model. Softw*. 161, 105631.

The Ad Hoc Group et al., 2001. Global water data: A newly endangered species. *Eos Trans. Am. Geophys. Union* 82, 54–58.

The Global Runoff Data Centre, 2023. *GRDC Data Portal*. https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser.

United Nations, 2010. *Resolution 64/292: The Human Right to Water and Sanitation*.

United Nations Environment Programme (UNEP), 2016. *Transboundary River Basins Status and Trends, Summary for Policy Makers, Volume 3, River Basins*.

United Nations Office for Disaster Risk Reduction, 2020. *The Human Cost of Disasters: An Overview of the Last 20 Years (2000–2019)*.

Vorosmarty, C.J., et al., 2010. Global threats to human water security and river biodiversity. *Nature* 467, 555–561.

Wongchuig, S., et al., 2024. Multi-Satellite Data Assimilation for Large-Scale Hydrological-Hydrodynamic Prediction: Proof of Concept in the Amazon Basin. *Water Resour. Res*. 60, e2024WR037155.

Yamazaki, D., S. Kanae, H. Kim, and T. Oki, 2011. A physically based description of floodplain inundation dynamics in a global river routing model. *Water Resour. Res*. 47, W04501.

Yao, F., et al., 2023. Satellites reveal widespread decline in global lake water storage. *Science* 380, 743–749.

Excessive Tibetan Plateau Spring Warming Found to Cause Catastrophic June 2024 Precipitation in Southern China and Bangladesh—A Typical LS4P Scenario

Yongkang Xue[1] and Aaron Boone[2]

[1]University of California, Los Angeles (UCLA), USA; [2]CNRM, Université de Toulouse, Météo-France, CNRS, France

In June 2024, relentless deadly rainfall lashed southern China and Bangladesh, threatening millions with severe flooding. The precipitation in the Yangtze River Basin from June 10th to 30th was about 50% above the long-term average, making June 2024 the wettest June in Southern China since 1980. The events drew worldwide attention due to their devastating societal and economic impacts (Figures 1, 2c).

No operational season prediction forecast system in the world predicted or simulated such extreme events last year. For instance, since sea surface temperature (SST) is traditionally considered as a key factor in climate and weather predictions, we tested the effect of May and June SST on the June 2024 events using the National Center for Environmental Research (NCEP) Global Forecast System (GFS) coupled with the Simplified Simple Biosphere Model (SSiB) land model (GFS/SSiB). We found that SST attributed only 17% of the observed rainfall anomaly in Southern China, and no heavy rainfall in Bangladesh was predicted (Li et al., 2025). There was no plausible explanation being openly proposed in the scientific community and reported in public for the events until the GEWEX initiative Impact of Initialized Land Surface Temperature and Snowpack on Subseasonal-to-Seasonal Prediction (LS4P, Xue et al., 2021) organized a study to explore the cause and mechanisms (Li et al., 2025). LS4P aims to explore a new approach for subseasonal-to-seasonal (S2S) prediction by utilizing spring land surface temperature/subsurface temperature (LST/SUBT) anomalies over high-elevation regions such as the Tibetan Plateau (TP) and the Rocky Mountains to predict late spring and summer downstream droughts or floods.

Since 2018, LS4P has conducted a series of investigations to identify a lagged relationship between spring land temperatures over the TP and Rocky Mountains and downstream summer precipitation over East Asia, North America, and other regions. Specifically, the findings indicated that when the TP experiences a warm or cold spring, southern China is likely to experience a wet or dry summer, respectively (Xue et al., 2022, 2024). In June 2024, as record-breaking rainfall began to develop in Southern China, LS4P scientists found excessively warm TP spring land temperatures, which were the warmest since 1980, and hypothesized the heavy June rainfall in Southern China was a typical scenario, established in previous LS4P findings (Xue et al., 2022, 2024). During the LS4P Side Meeting at the 2024 GEWEX Open Science Conference (July 7–12) in Sapporo, Japan, a group of LS4P scientists volunteered to collaborate on an investigation of the cause of the June 2024 extreme event in near real-time, aim-

Figure 1*. Relentless deadly June 2024 rainfall lashes southern China and Bangladesh as flooding threatens millions. Left and middle panels from China Hunan Meteorology; right panel from the* Dhaka Tribune

ing to provide a timely explanation to both the scientific community and the public.

Using the same atmosphere-land coupled model (i.e., the GFS/SSiB) for the SST study, near real-time experiments were conducted. The National Oceanic and Atmospheric Administration (NOAA) database provided timely initial and boundary conditions for the model simulations. However, the original model simulation was unable to reproduce the observed 2-m surface temperature (T-2m) anomalies over the TP and the extreme June precipitation. One of the biggest challenges in this study was to reproduce the observed extreme warm temperatures over the TP. LS4P Phase I (LS4P-I) research had previously shown that both global models and reanalysis data sets (which provide atmospheric and surface initial conditions for global models) systematically failed to capture May temperature anomalies over the TP, leading to underestimation of anomalous June rainfall in Southern China and exhibiting severe biases (Xue et al., 2021).

To address this, we adopted a land-state initialization approach, developed in LS4P-I and based on the observed T-2m anomaly and model biases over the TP (Xue et al., 2021). This approach successfully reproduced most of the observed May 2024 T-2m anomalies over the TP (Figures 2a and 2b): the model simulated approximately 55% of the observed extreme June rainfall anomaly in Southern China (Figures 2c and 2d). Moreover, the experiment realistically simulated the observed precipitation anomalies over other regions. Notably, about 90% of the observed heavy rainfall in Bangladesh was simulated—an important outcome, as Bangladesh experienced devastating June floods with widespread media coverage that reported an initially unclear cause. In addition, abnormally wet conditions over the eastern TP and southern Japan, and dry conditions over northern China, were also captured in the simulation (Figure 2d), which were consistent with the observations (Figure 2c).

The results over Southern China and Bangladesh passed a more stringent field significance test, which accounts for multiplicity and spatial correlation effects, indicating that these results did not occur by chance. A detailed discussion on these results was published in Science Bulletin (Li et al., 2025). The LS4P scientists finished the experiments in August 2024 and submitted the paper in September. The paper was accepted in December and published in January 2025. It typically takes years to identify the causes of climate-related catastrophic events. Our ability to determine the primary driver of the June 2024 extreme summer hydroclimate event in such a short timeframe underscores the robustness of the LS4P approach. A schematic diagram was developed to illustrate how subseasonal processes, influenced by remote TP spring land temperature anomalies, affect downstream summer precipitation (Li et al., 2025). This synthesis integrates findings from both this study and LS4P's previous comprehensive analyses (Xue et al., 2024).

S2S precipitation prediction skill has remained stubbornly low for years for late spring and summer, which encompasses a substantial number of extreme hydroclimate events. To tackle this challenge, the World Meteorological Organization (WMO) launched the S2S Prediction Project, which focuses on improving predictions for timescales ranging from 2 weeks to 3 months. Among various influencing factors, the combined effect of land initialization and configuration have been identified as one of the key elements with the potential to significantly enhance S2S predictions. While many land variables such as albedo, soil moisture, snowpack, and vegetation have been utilized for climate and weather predictions since the 1970s, the memory effect of land temperature on S2S predictions has been largely overlooked, despite the fact that the T-2m measurements have the highest quality among land variables, with the longest meteorological observational records, global coverage, and dense measurement networks.

The LS4P team, comprising leading climate and weather prediction and research centers from many different countries, has made great strides in demonstrating the critical role of high-mountain land temperature anomalies in S2S predictions. The project has published numerous peer-reviewed papers and contributed to a special issue in *Climate Dynamics* titled "Sub-seasonal to Seasonal (S2S) predictability and Land-induced Forcing", featuring 17 papers. Supported by GEWEX, LS4P's accomplishments represent a major contribution to advancing S2S prediction—a field that is scientifically challenging, yet critically relevant to society. The LS4P S2S work opens new avenues for improving S2S prediction for operational applications, which is increasingly important

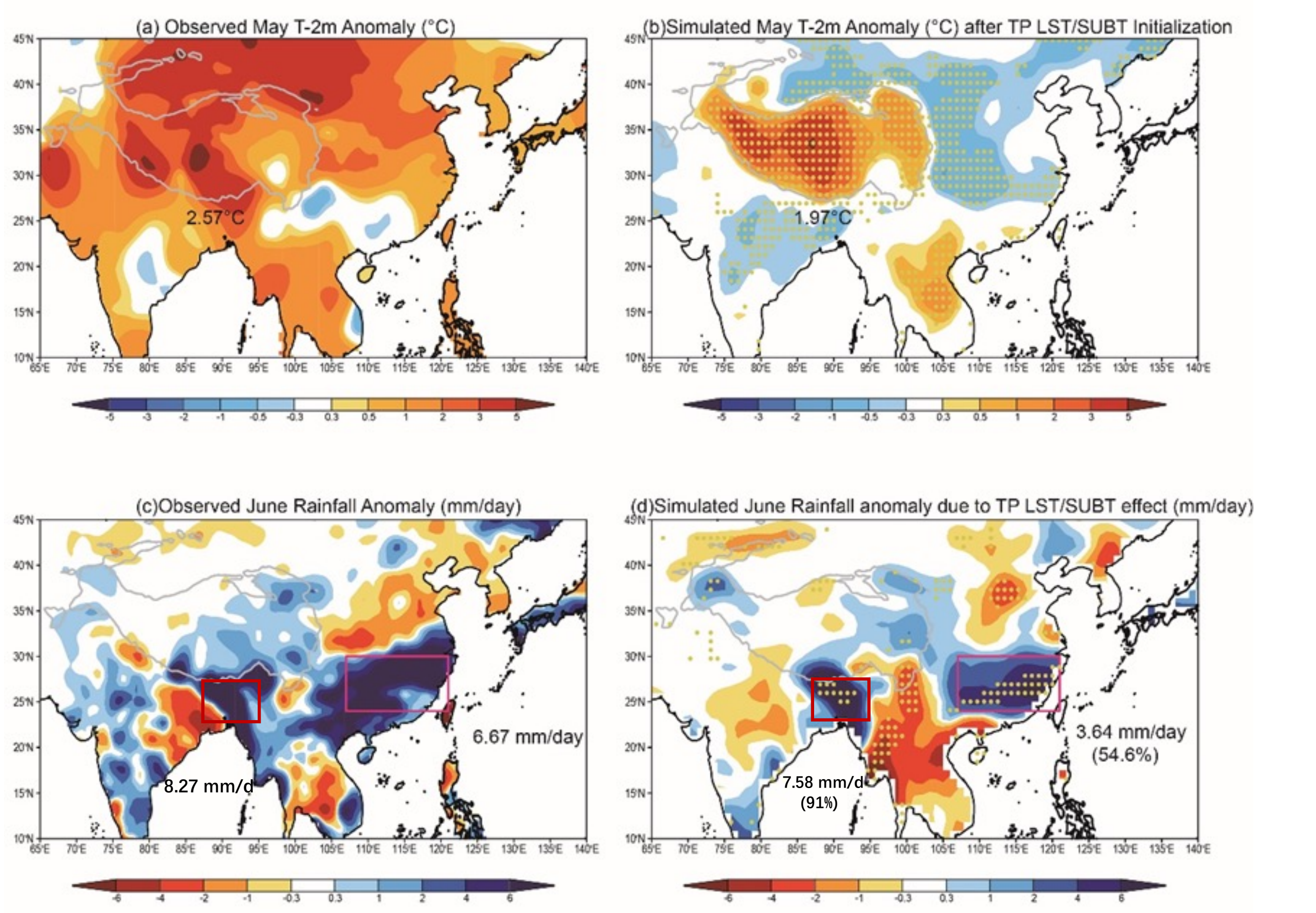

Figure 2. *Observed and Simulated 2m-temperature (T-2m, °C) and precipitation (mm/day) anomalies. (a) Observed May T-2m anomaly; (b) GFS/SSiB2 simulated May T-2m anomaly after soil temperature initialization over TP. (c) same as (a), but for the June 2024 precipitation anomaly. (d) Simulated June precipitation anomaly due to TP LST/SUBT effect. 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 4000m 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) - (d). The values in parentheses in (d) indicate the percentage anomalies produced by TP LST/SUBT anomalies*

given the rising frequency of anomalous meteorological events observed worldwide.

LS4P is currently working on the Phase-II experiments, which explore the effect of LST/SUBT in both the Rocky Mountains and the TP on droughts and floods across North America, East Asia, and other regions. Preliminary results from a few LS4P groups suggest that spring LST/SUBT anomalies in these high-altitude regions influenced both the catastrophic 1998 summer flood in Southern China and the severe drought in the Southern Great Plains of the U.S. We welcome new research groups to join this effort.

Despite its promise, the LS4P approach has yet to gain full recognition within the broader scientific community, where traditional SST-based methods still dominate. However, the 2024 extreme rainfall study reinforces LS4P's validity (Xue et al., 2024), demonstrating that excessive TP spring warming was the primary factor behind the catastrophic June 2024 rainfall in Southern China and Bangladesh. While many unresolved challenges still remain with its new approach, the LS4P team hopes their paper in *Science Bulletin* will stimulate further research using diverse methodologies to enhance S2S prediction of extreme hydroclimate events and increase public awareness of the latest advancements in this field made by LS4P scientists.

References

Li, Q., Y. Xue, X. Kong, W. K.-M. Lau, A. Wang, Q.P. Li, Z. Cao, H. Nayak, G. Xu, W. Guo, and V. Ratko, 2025. Excessive Tibetan Plateau Spring Warming Found to Cause Catastrophic June 2024 Heavy Rainfall in China. *Sci. Bull.*, https://doi.org/10.1016/j.scib.2025.01.011.

Xue, Y., T. Yao, A.A. Boone, I. Diallo, Y. Liu, et al., 2021. Impact of Initialized Land Surface Temperature and Snowpack on Subseasonal to Seasonal Prediction Project, Phase I (LS4P-I): Organization and Experimental design. *Geosci. Model Dev.*, 14, 4465–4494, https://doi.org/10.5194/gmd-14-4465-2021.

Xue, Y., I. Diallo, A.A. Boone, T. Yao, Y. Zhang, et al., 2022. Spring Land Temperature in Tibetan Plateau and Global-Scale Summer Precipitation – Initialization and Improved Prediction. *Bull. Am. Meteorol. Soc.*, 103, 12, E2756–E2767, DOI: https://doi.org/10.1175/BAMS-D-21-0270.1.

Xue, Y., I. Diallo, A.A. Boone, Y. Zhang, X. Zeng, et al., 2024. Remote effects of Tibetan Plateau spring land temperature on global subseasonal to seasonal precipitation prediction and comparison with effects of sea surface temperature: The GEWEX/LS4P Phase I experiment. *Clim. Dyn.*, 62, 2603–2628, DOI: 10.1007/s00382-023-06905-5.