Hot Spots of the Remote Effect of Tibetan Plateau Spring Temperature in Global S2S Prediction–GEWEX/LS4P Phase I Highlights and Phase II Initiation

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In 2018, the Global Energy and Water Exchanges (GEWEX) program launched an initiative, the "Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction" (LS4P, *https://ls4p.geog.ucla.edu*; Xue et al., 2021), as a community effort to test the impact of initializing land temperatures in high mountain regions in multiple Earth System Models (ESMs) on subseasonal to seasonal (S2S) prediction. The World Weather Research Program (WWRP) and World Climate Research Programme (WCRP) S2S project has listed the study of land initialization and configuration as one of its major activities (Merryfield et al., 2020). Climate scientists, especially climate modelers, from more than 40 institutions worldwide, many of which are major climate research and prediction centers, participated in this project.

The development and objectives of LS4P and evidence of land memory and persistence of land temperature anomalies in high mountains have been presented in Xue et al. (2021), which also introduced the LS4P phase I (LS4P-I) experimental protocol. LS4P-I focuses on the remote effect of the land surface temperature (LST) and subsurface temperature (SUBT) in the Tibetan Plateau (TP). The year 2003, when extreme summer drought/flood occurred to the south/north of the Yangtze River, respectively, after a very cold spring in the TP, is the focal case. The causes of the severe drought to the south of the Yangtze River in 2003 have never been identified. As such, LS4P is different from and complements other international projects that focus on operational S2S prediction (Kirtman et al., 2014; Pegion et al., 2019). Eighteen ESM groups have completed the LS4P-I experiment. The highlight of the LS4P-I results from sixteen ESMs[1] has been presented in the *Bulletin of American Meteorological Society* (Xue et al., 2022) to elucidate the new development in the S2S prediction.

LS4P-I has examined the LS4P models' bias in simulating the TP surface temperature. The analyses of LS4P-I resulting from the control simulation reveal that every ESM has a large bias in producing the observed TP May 2003 2-meter temperature (T-2m) cold anomaly, -1.4°C. Furthermore, the LS4P-I ESMs also produce large biases for June precipitation, not only over East Asia but over many parts of the world. To reproduce the observed TP May T-2m cold anomaly, initialization of the LST/SUBT was conducted to generate the observed T-2m anomaly in the model simulation. The LS4P hypothesis is that if the May land temperature anomaly in the TP contributes to the June precipitation anomaly, then by reducing May land temperature bias in the TP through initialization to produce the adequate temperature anomaly in the TP, the ESMs should produce better prediction of the June precipitation anomaly. LS4P-I has developed an innovative new land state initialization approach based on the observed surface T-2m anomaly and the model's bias over the TP (Xue et al., 2021). After using this initialization set up, the LS4P-I ESMs' ensemble mean has partially produced the observed TP May T-2m anomaly, which is -0.82°C.

The initial goal of LS4P was merely to test whether the preliminary results from one model (Xue et al., 2018), i.e., the spring TP LST/SUBT effect on the summer precipitation of the lowland plains of the Yangtze River Basin, could be confirmed by a multi-model ensemble. However, the statistical analyses and regression testing based on observational data reveal that the lag relationship between the May T2m anomaly over TP and the June precipitation anomaly not only exists over East Asia, but also over many parts of the world (Xue et al., 2022). Taking advantage of multiple state-of-the-art ESMs contributions, the LS4P-I participants promptly decided to evaluate the results beyond East Asia and compare the LS4P results with observations at global scale.

The observed and simulated June 2003 precipitation anomalies are compared in Fig. 1. In Fig. 1a, it is shown that in addition to the observed anomalies over East Asia, there were many other regions associated with large precipitation anomalies[2]. The most noticeable are the anomalies over North and Central America and the Eurasian continent. Meanwhile in parts of northern South America, West and East Africa, Australia, and many other areas, the precipitation anomalies are apparent. The precipitation anomaly produced by the LS4P-I ensemble mean after the May cold TP anomaly is displayed in Fig. 1b, which covers many regions in the world. We define the areas with a significant June precipitation impact due to the TP May cold temperature, which is also consistent with the observations (Fig. 1a), as hot spots.

Based on this definition, eight hot spot regions are identified with a significant precipitation difference (statistical significance at $p < 0.10$) (Fig. 1b). For those hot spot regions, the results of the ensemble mean suggest that observed lag relations represent cause and effect. To make quantitative assessments on the impact and uncertainty of the TP effect, we have made statistics for each hot spot region over the box area as shown in Fig. 1b. In addition to the expected difference in the southern Yangtze River Basin, the regions of the South Great Plains and Central America show the largest impacts. For these hot spots, very few models produce anomalies that are different in sign compared to the observations (inserted bar graphs in Fig. 1b). For some hot spot regions, such as the Sahel and East Africa, model uncertainties are relatively large. It should be pointed out that in the southern Yangtze River Basin, South Great Plains, and a few other regions, the TP LST/SUBT effect produces 25-50% of the observed anomaly.

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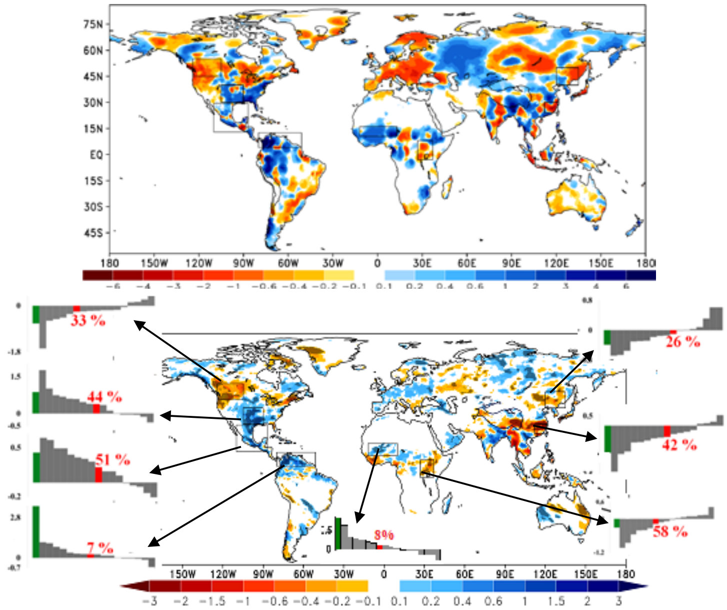
[1] Two model results were completed after the paper had been submitted

[2] The observed anomaly uses the climatology (the mean of 1981–2010) as a reference

Comparison of observed and Simulated June 2003 Precipitation Anomaly (mm/day)



Simulated June 2003 Precipitation Anomaly (mm/day) due to SST Anomaly

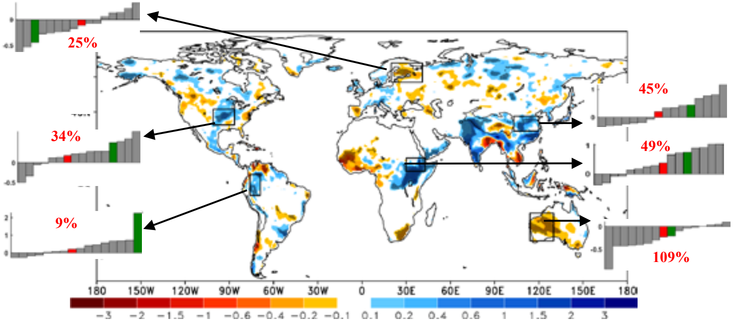


***Figure 1**. Comparison of Observed and Simulated June 2003 Precipitation Anomaly (mm/day). (A) Observed June 2003 anomaly. (B) Model-simulated precipitation anomalies due to the cold TP anomaly. Figure is from Xue et al. (2022,* BAMS*). (C) Model-simulated precipitation anomalies due to the global SST anomaly. Figure is from Xue et al. (2023,* Climate Dynamics)

Notes: (1) Boxes indicate the hot spots regions; (2) Gray bars denote different models and are arranged in a descending order for each region; green bar is observation and red bar is ensemble mean in each hot spot; (3) Simulated percentages of observed anomalies from the ensemble mean are shown in red color above or below the red bars.

LS4P-I has also conducted another experiment, in which the observed May and June 2003 sea surface temperature (SST) in previous experiments is replaced by the climatological SST to test the SST effect, which will be reported in a forthcoming paper in a special issue "Sub-seasonal to Seasonal (S2S) predictability and Land-induced Forcing" in Climate Dynamics, which is expected to be published in 2023. With the same definition for hot spots, the SST experiment has identified six regions where the SST has significant effect. They are the U.S. Great Plains, West Amazon Basin, Horn of Africa, northern Yangtze River Basin, Western Australia, and Northern Europe (Fig. 1c). Among them, the first three regions partially overlap with the TP LST hot spots, indicating both LST/SUBT and SST factors produce the same sign of forcing. In the northern Yangtze River Basin, central America, northwestern North America, and northeastern Asia, both factors produce the same sign of anomalies, but only one factor produces statistically significant results. In western Australia, Northern Europe, and the Sahel, the SST and LST/SUBT produce the opposite signs of anomalies, indicating their effects compensate each other there. Nevertheless, our study reveals for the first time that high mountain land temperature could be a first order source of S2S precipitation predictability, and its effect is probably as large as ocean surface temperature over global "hot spot" regions identified here.

The LS4P-I results also suggest a strong linkage between the TP spring LST/SUBT and summer precipitation over North America (Xue et al., 2022). To explore the relationship between North America and the TP, the Tibetan Plateau Index (TPI) and the Rocky Mountain Index (RMI) are defined as the averaged T2m observed anomaly over the region bounded by 29°N~37°N and 86°E~98°E, and 32°N~45°N and 110°W~125°W, respectively. The May TPI and May RMI from 1981 to 2015 have a correlation of -0.44 with $p < 0.01$. Furthermore, the existence of a wave train from the TP through the Bering Strait to the western part of North America, referred to as the Tibetan Plateau-Rocky Mountain Circumglobal (TRC) wave train, has also been identified based on the May TPI. The heating change over the high mountain TP region efficiently modifies the phase, strength, as well as the shape of the wave train, which may intrinsically exist in the midlatitude atmosphere along with the westerly jet, affecting the atmospheric circulation in its downstream region, such as the west coast of North America. Five hot spot regions are located along the TRC wave train or its extension.

With the completion of LS4P-I, we launched LS4P-II in 2023 to make further investigations to explore more outstanding S2S prediction issues that are associated with the high mountain LST/SUBT. A hybrid kickoff workshop was held on Sunday, December 11, during the 2022 American Geophysical Union (AGU) Meeting, and 57 participants attended the workshop either in person or remotely (Image I). Although the workshop occurred in the middle of the night to early morning in some time zones, some in those regions still attended the entire workshop. During the event, representatives from the GEWEX Scientific Steering Group, the WCRP/WWRP S2S Project, the GEWEX Global Land-Atmosphere System Studies (GLASS) Panel, the US-Regional Hydroclimate Project (US-RHP), and other organizations presented the latest developments in relevant fields. LS4P Phase I achievements were reported, including two LS4P-I group papers (Xue et al., 2021, 2022) and more than 10 papers from the individual LS4P group, most of which are in the Climate Dynamics LS4P special issue. The protocol for LS4P Phase II has also been discussed. LS4P Phase II will focus on the Rocky Mountain LST/SUBT effect and the interaction between TPI and RMI. The LS4P approach intends to explore a new and potentially far-reaching perspective to stimulate the community's interest in more follow-on explorations. With this new approach, many challenging issues have been discussed and identified and listed in the LS4P-II protocol:

1. Despite the improved initialization, the LS4P-I ensemble mean is still unable to produce fully the observed TP T-2m anomaly. It is imperative to further improve the initialization

procedure/methodology of LST/SUBT (Xue et al., 2021) and convert the methodology for use in operational applications.

2. In some regions, such as in the Eurasian continent and India, the statistical analysis revealed lag correlation between precipitation there and TPI (Xue et al., 2022), but models fail to produce such a relationship. The cause(s) of such discrepancies need to be explored.
3. In some regions, the TP LST/SUBT anomaly of the LS4P-I ensemble mean produces significant June precipitation anomalies (Fig. 1b), such as in western Australia and western Europe, but with the opposite sign compared to the observations. It is unclear whether this is a model deficiency, or if some other processes involved, such as SST interactions, are more dominant than the TP LST effect.
4. The causes of the LST/SUBT anomaly. The possible roles of snow, aerosols in snow, winter Arctic circulation, soil memory, and other factors in producing LST/SUBT anomaly in the high mountain regions need further investigation as was done in Zhang et al. (2019) and Liu et al. (2020).
5. So far, we have only focused on the TP and Rocky Mountains as the S2S predictability source regions. Recent studies have suggested that there are probably more regions such as the Central Asian highlands and West Asian highlands where LST/SUBT may produce remote effects (Z. Yang et al., 2019; J. Yang et al., 2021), which deserves more investigation. In particular, the LST/SUBT effect of the Southern Hemisphere mountains merits more attention for a possible LS4P-III.

For LS4P Phase II, we have selected the year 1998, which was a year with severe flooding in the Yangtze River (Diallo et al., 2022) and severe drought in Texas and Oklahoma (Hong and Kalnay, 2002). In addition, the year 1998 was a strong El Niño year. A strong SST effect is expected and will be compared with the mountain LSTs. The fully coupled model with land-ocean-atmosphere interaction is encouraged to be compared with specified SST. We have conducted pilot experiments with one ESM for this case (Diallo et al., 2022; Nayak et al., 2022), and the preliminary results are encouraging. We expect the LS4P experiment will further advance our understanding of the LS4P hypothesis, and some issues listed above will be tackled. Thus far, the focus of LS4P research is mainly on later spring to early summer (or at monsoon onset stage). We notice 2022's severe anomalies (droughts and floods) occurred in middle and late summer (or at late monsoon stage), and the preliminary analysis revealed that the year 2022's situation may be similar to 1998. The LS4P-II experimental design will take this into account. More detailed information for the LS4P-II workshop including files and recording for some presentations, as well as LS4P-II protocol can be found on the LS4P website (*https://ls4p.geog.ucla.edu/*).

Image 1. *Participants of the LS4P-II hybrid kickoff workshop*

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