



# Memory of land surface and subsurface temperature (LST/SUBT) initial anomalies over Tibetan Plateau in different land models

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## Abstract

This study applies three widely used land models (SSiB, CLM, and Noah-MP) coupled in a regional climate model to quantitatively assess their skill in preserving the imposed  $\pm 5^\circ\text{C}$  anomalies on the initial land surface and subsurface temperature (LST/SUBT) and generating the 2-m air temperature (T2m) anomalies over Tibetan Plateau (TP) during May–August. The memory of the LST/SUBT initial anomalies (surface/soil memory) is defined as the first time when time series of the differences in daily LST/SUBT cross the zero line during the simulation, with the unit of days. The memory of the T2m anomalies (T2m memory) is defined in the same way. The ensemble results indicate that the simulated soil memory generally increases with soil depth, which is consistent with the results based on the observations with statistic methods. And the soil memory is found to change rapidly with depth above  $\sim 0.6\text{--}0.7\text{ m}$  and vary slowly below it. The land models have fairly long soil memories, with the regional mean 1.0-m soil memory generally longer than 60 days. However, they have short T2m memory, with the regional means generally below 20 days. This may bring a big challenge to use the LST/SUBT approach on the sub-seasonal to seasonal (S2S) prediction. Comparison between the three land models shows that CLM and Noah-MP have longer soil memory at the deeper layers ( $> \sim 0.05\text{ m}$ ) while SSiB has longer T2m/surface memories and near-surface ( $\leq \sim 0.05\text{ m}$ ) soil memory. As a result, it is difficult to say which land model is optimal for the application of the LST/SUBT approach on the S2S prediction. The T2m/surface/soil memories are various over TP, distinct among the land models, and different between the  $+5^\circ\text{C}$  and  $-5^\circ\text{C}$  experiment, which can be explained by both changes in the surface heat fluxes and variances in the hydrological processes over the plateau.

**Keywords** Soil temperature · Soil memory · Land surface model · Tibetan Plateau · Sub-seasonal to seasonal (S2S) prediction

## 1 Introduction

Sub-seasonal to seasonal (S2S) prediction of extreme hydro-climate events such as droughts and floods is crucial due to their enormous social, economic, and environmental impacts (Merryfield et al. 2020). Extensive studies have shown that

sea surface temperature (SST) variability have predictive value for land precipitation (Barlow et al. 2001; Jia and Yang 2013; Seager et al. 2014; Ting and Wang 1997; Trenberth et al. 1988). However, SSTs alone only partially explain the phenomena of predictability (Mei and Wang 2011; Mo et al. 2009; Pu et al. 2016; Rajagopalan et al. 2000; Scaife et al. 2009; Schubert et al. 2004, 2009; Xue et al. 2018, 2016a, b). Recent studies based on climate observations and model simulations have suggested that the remote (non-local) effects of large-scale land surface/subsurface temperature (LST/SUBT) anomalies in geographical areas upstream on their downstream regions is probably as large as the more familiar effects of SST (Diallo et al. 2019; Shukla et al. 2019; Xue et al. 2016b, 2018). For instance, the spring warm 2-m air temperature (T2m)/LST/SUBT anomalies in western U.S. are demonstrated to have a causal relationship with the extraordinary 2015 flood in Southern Great Plains and

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adjacent regions, and combination of LST/SUBT anomalies and SST can fully explain the phenomena (Xue et al. 2016b, 2018).

To pursue a new gateway in improving the S2S prediction with the application of the LST/SUBT approach, the Global Energy and Water Exchanges (GEWEX) and GEWEX/Global Atmospheric System Study (GASS) have supported the establishment of a new Initiative called “Impact of initialized land temperature and snowpack on sub-seasonal to seasonal prediction” (LS4P, Xue et al. 2019). This project intends to test the impact of model initialization of LST/SUBT on the S2S prediction with multiple Earth System Models (ESMs) and regional climate models (RCMs). The Tibetan plateau region provides an ideal geographic location for the first phase experiment of LS4P owing to its relatively high elevation and large-scale area as well as the presence of persistent LST anomalies. Furthermore, numerous studies have reported that the Tibetan Plateau’s thermal and dynamic forcing drive the Asian monsoon through a huge, elevated heat source in the middle troposphere (Wang et al. 2008; Wu et al. 2007; Yanai et al. 1992; Yao et al. 2019; Ye 1981).

May and June 2003 are selected for the main tests in Phase I (Xue et al. 2021). The summer of 2003 was characterized by a severe drought/flood over the southern/northern part of the Yangtze River Basin in eastern China and an abnormally cold spring in Tibetan Plateau. To test the effect of May 2003 T2m/LST/SUBT anomalies in Tibetan Plateau on June 2003 precipitation, the climate models have to reproduce the observed May T2m anomaly. The previous practice suggested that the only way to produce the observed T2m anomalies in the model integration is imposing both LST/SUBT initial anomalies in Tibetan Plateau based on the observed T2m anomalies and model bias (Xue et al. 2021).

Ideally, the LST/SUBT initial anomalies in Tibetan Plateau may influence the lower and middle atmospheric layers and further affect the circulation pattern downstream through the wave train that is generated through the surface heating perturbation, which eventually plays an importance role in the occurrence of droughts and floods in late spring/summer over the eastern part of Asia (Diallo et al. 2021). However, the LS4P ESMs and RCMs with their land models are generally unable to hold the imposed LST/SUBT anomalies well during the model integration and thus have difficulty in generating the observed T2m anomaly over Tibetan Plateau (Xue et al. 2021). Our premise is that the current models’ deficiencies in maintaining the LST/SUBT initial anomalies are mainly rooted in their land parameterizations.

Previous studies have shown that the land models generally miss some key land surface processes in Tibetan Plateau (Liu et al. 2020; Yang et al. 2009). For instance, the abundant organic matter beneath the alpine meadows in the central and eastern Tibetan Plateau is generally not

taken into account in the land models. Less soil organic matter increases soil thermal conductivity and decreases soil heat capacity, which could cause the rapid loss of soil thermal anomalies in the models. In addition, high soil moisture and shallow soil layer depth in the land models also hamper the preservation of soil temperature anomaly in Tibetan Plateau (Liu et al. 2020; Su et al. 2011).

The low skill of the LS4P models in keeping the LST/SUBT initial anomalies and reproducing the observed T2m anomaly underscores the need to investigate the memory of LST/SUBT initial anomalies (referred as surface/soil memory) and the responses of surface air temperature to the anomalies over Tibetan Plateau in different land models. It is also imperative to understand the inherent mechanisms.

Thus, this study applies three widely used land models (SSiB, CLM, and Noah-MP, Table 1), which are coupled in the regional climate model Weather Research and Forecasting (WRF, Skamarock et al. 2008) and intends to address three questions:

- How long do the LST/SUBT initial anomalies last in these land models?
- How does T2m response to the LST/SUBT initial anomalies in each model?
- What are the major physical processes to regulate the surface/soil memories and the responses of T2m to the LST/SUBT initial anomalies?

Here we focus on quantitatively assessing the ability of different land models in preserving the LST/SUBT initial anomalies and generating T2m anomaly, which could help better understand the LST/SUBT approach for the S2S prediction and provide practical notes for the relevant numerical simulations. The rest of this article is organized as follows. Section 2 describes the data and methods. The results are presented in Sect. 3, followed by the mechanism explaining in Sect. 4. Major conclusions and some discussions are in Sect. 5.

**Table 1** Model structure of SSiB, CLM and Noah-MP

Model	Number of soil layers	Soil layers	Reference
SSiB	3	0, 0.05, 1.05	Xue et al. (1991)
CLM	10	0.01, 0.03, 0.06, 0.12, 0.21, 0.37, 0.62, 1.04, 1.73, 2.86	Oleson et al. (2010)
Noah-MP	4	0.05, 0.25, 0.7, 1.5	Niu et al. (2011)

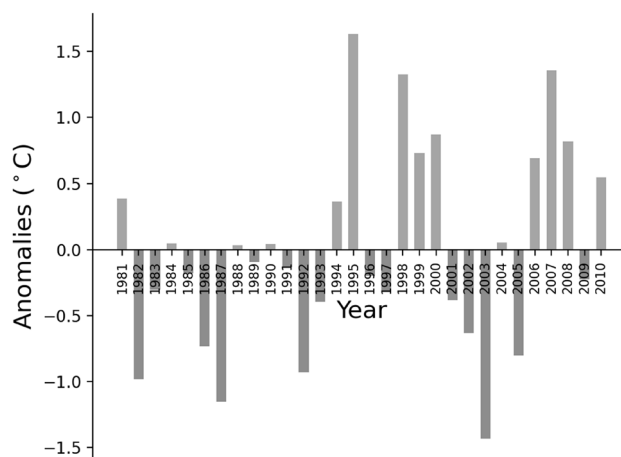
## 2 Data and methods

### 2.1 Experimental design

In this study, the WRF model is used in a single (non-nested) domain of  $25 \text{ km} \times 25 \text{ km}$  resolution covering East Asia (the blue area in Fig. 1). The model has 35 levels in the vertical direction with its top fixed at 50 hPa. Its initial and boundary conditions are from the ERA-Interim reanalysis data (Dee et al. 2011). In it, three land surface models (LSMs) are separately chosen to simulate the exchange of surface water and energy fluxes at the soil-atmosphere interface. They are the Simplified Simple Biosphere (referred as SSiB) Model, Community Land Model Version 4 (referred as CLM) and Noah-MP(multi-physics). SSiB and Noah-MP solve Richards equation to derive soil moisture for each soil layer, while CLM's soil moisture is estimated by adopting an improved one-dimensional Richards equation (Zeng and Decker 2009). The force-restore method is used to derive the soil temperature in SSiB, while CLM and Noah-MP calculate the evolution of the soil temperature by solving the thermal diffusion equation. Other main physical parameterizations in the WRF model are the New Simplified Arakawa-Schubert (SAS) cumulus scheme (Han and Pan 2011), the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006), the New Thompson microphysics scheme, and the RRTMG shortwave and longwave schemes (Iacono et al. 2008).

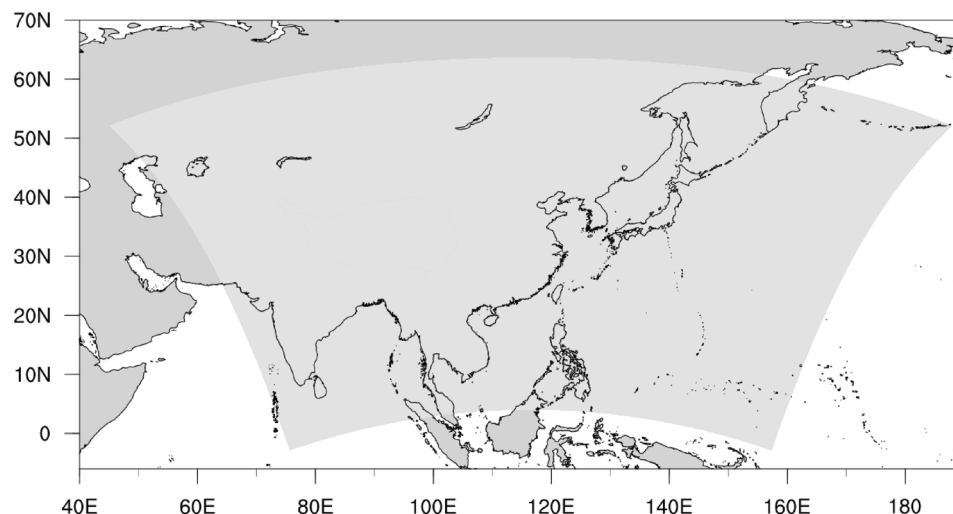
To assess the skill of the LSMs in maintaining the LST/SUBT initial anomalies, three experiments are designed for each LSM coupled in the WRF model. They are the control,  $+5^\circ\text{C}$  and  $-5^\circ\text{C}$  experiment. Compared with the control experiment, the only difference in the  $\pm 5^\circ\text{C}$  experiment is that air temperature at the bottom layer, land surface temperature and subsurface temperature of all layers

over Tibetan Plateau (the yellow area in Fig. 1) at the initial time are modified by adding  $\pm 5^\circ\text{C}$  to their original values. The initial soil moisture and snow conditions are from the driving data, the ERA-Interim reanalysis, and are consistent between all the experiments. May–August of 6 years (1987, 1991, 1996, 1998, 2003, and 2007) are selected for the simulation. Among them, 1987 and 2003 (1998 and 2007) have abnormally cold (warm) spring in Tibetan Plateau during 1981–2010 (Fig. 2). In addition, 1991 and 1996 are normal years based on a threshold of half standard deviation of the T2m anomaly variability ( $0.37^\circ\text{C}$ ). Thus, there are totally 54 ( $6 \times 3 \times 3$ ) runs in this study. Each run is from May 1 to August 31, as long as 123 days, which covers the simulation duration (May–June) of the LS4P models and meanwhile is long enough to assess the surface/soil memories.



**Fig. 2** May T2m anomaly averaged over Tibetan Plateau during 1981–2010 relative to the time mean based on the China Meteorological Forcing Dataset

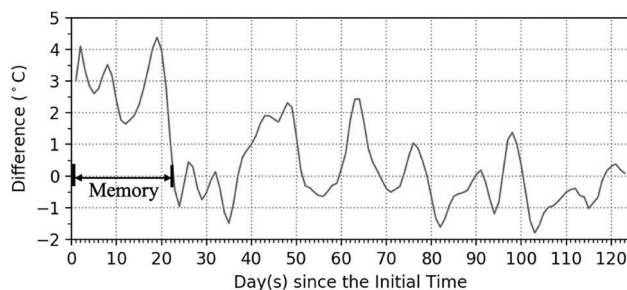
**Fig. 1** The simulation domain (the blue area) and Tibetan Plateau (the yellow area)



The reason why we use  $\pm 5$  °C instead of the anomalies calculated based on the observed T2m anomalies and model bias [see Eq. (1)a, b in Xue et al. 2021] is that imposing a uniform anomaly makes it possible to assess the surface/soil memories over areas of different weather/climate conditions and land surface features (such as vegetation, soil moisture, and snow) in Tibetan Plateau. Note that the objective of this study is to compare the T2m/surface/soil memories between different LSMs, not to reproduce the observed T2m anomalies as in Xue et al. (2021). The  $\pm N$  °C ( $N = 1, 3$ ) experiments for a single year (2003) are also conducted and it is found that the LST/SUBT perturbations in these experiments are so weak that the produced surface/soil memories are too short to do the comparison between the LSMs. Thus,  $N$  is set as 5 in this study. The ensemble means of the model results are presented hereafter.

## 2.2 Definition of the memory of the LST/SUBT initial anomalies

The memories of the LST/SUBT initial anomalies (surface/soil memories) are defined as how long the abnormal signals can last in the model integration, that is to say, the first time when the abnormal signals cross the zero line, with the unit of days. The abnormal signals are time series of the differences in daily LST/SUBT between the control and  $\pm 5$  °C experiment. And the three-point smoothing method is applied to erase the high-frequency oscillations in the time series. For instance, Fig. 3 illustrates the smoothed time series of the differences in daily soil temperature at the layer of 0.25 m between the control and  $+5$  °C experiment with the land model of Noah-MP on a randomly selected model grid ( $35.3^\circ$  N,  $88.4^\circ$  E) during 2003. The abnormal signal is above  $3^\circ$ C in the beginning of the simulation, gradually decreases to zero after  $\sim 22$  days since the initial time and then oscillates around the zero line. As a result, the soil memory at 0.25 m is  $\sim 22$  days on this model grid.



**Fig. 3** Time series of the differences in daily soil temperature at the layer of 0.25 m between the control and  $+5$  °C experiment with the land model of Noah-MP on a randomly selected model grid ( $35.3^\circ$  N,  $88.4^\circ$  E) during 2003. The three-point smoothing method is applied to erase the high-frequency oscillations in the time series

The memory of T2m anomaly (referred to as T2m memory) is defined in the same way, as an index to assess the responses of surface air temperature to the LST/SUBT initial anomalies.

Because of the various weather/climate conditions and land surface features over the Tibetan Plateau, the T2m/surface/soil memories are calculated on each model grid, instead of on the whole region. Since the land models have different soil layers (Table 1), the soil memories are also linearly interpolated to three specified layers (0.05, 0.50, and 1.0 m) based on their adjacent two original layers so as to do the comparison between the land models.

## 2.3 Validation data

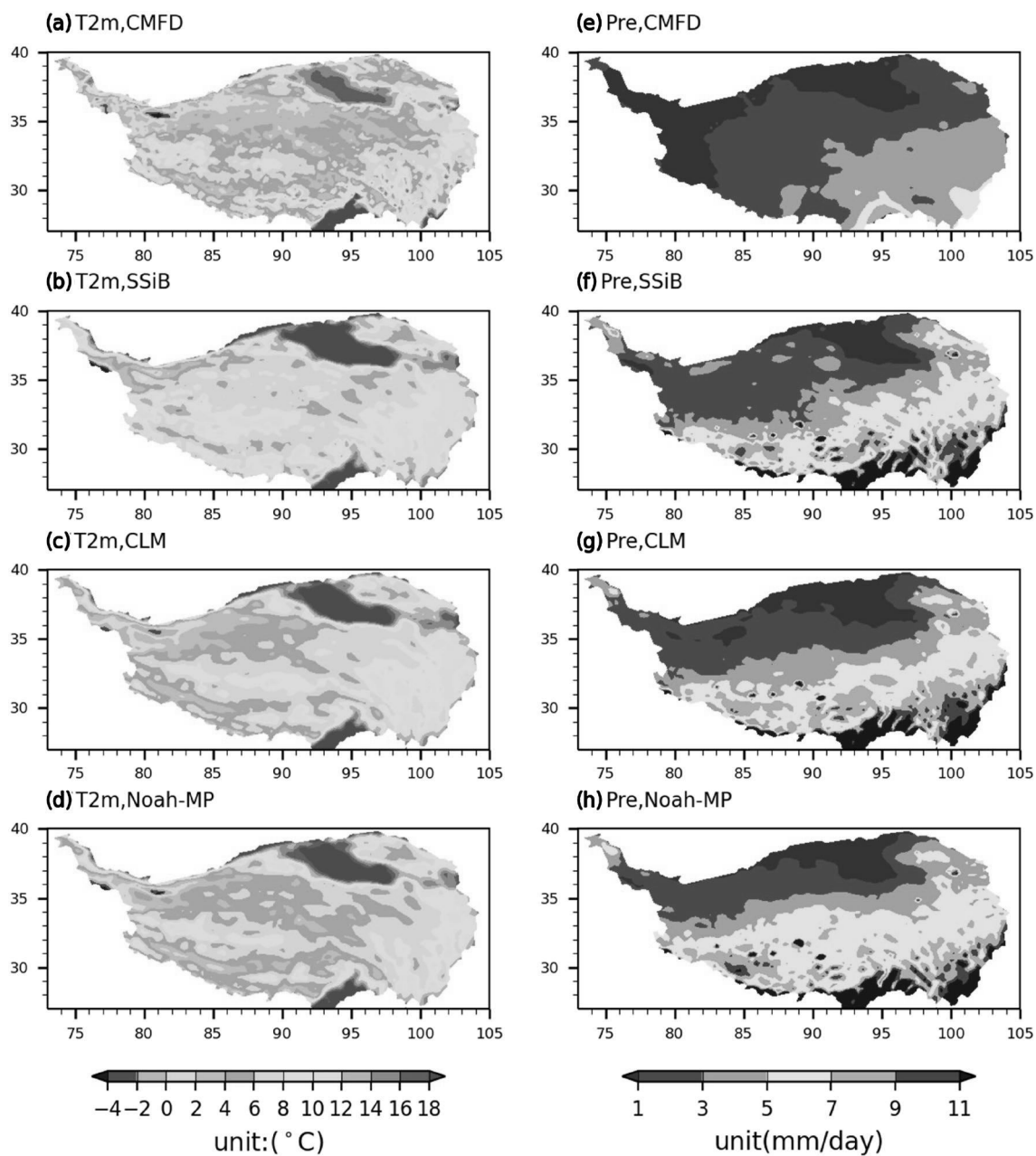
The T2m and precipitation data from the China Meteorological Forcing Dataset (CMFD, He et al., 2020) with a resolution of  $0.1^\circ$  are used as “observations” to evaluate the model performance over Tibetan Plateau. This dataset is the first high spatial–temporal resolution gridded near-surface meteorological dataset developed specifically for studies of land surface processes in China and made by merging various data sources (such as satellite products, reanalysis datasets, and in-situ station data), which is demonstrated to be of superior quality. Before the evaluation, the T2m and precipitation gridded data are bilinearly interpolated to the model grides.

## 3 Results

### 3.1 Model evaluation

Comparison with the validation data (CMFD) shows that all the simulations in the control experiments with different land models can well capture the spatial pattern of the observed T2m over Tibetan Plateau (Fig. 4a–d), with the spatial correlation coefficients in a range of 0.85–0.88 (Table 2). However, large positive biases of T2m are found over the plateau, especially in the simulation with SSiB whose mean bias over the plateau is  $2.87$  °C. The biases are reduced in the simulations with CLM and Noah-MP, whose mean biases are  $1.58$  °C and  $1.16$  °C, respectively. According to Wu et al. (2021), the longwave radiation term associated with the overestimated water vapor content is likely to contribute to the warm bias over Tibetan Plateau in our simulations. Note that the model-simulated T2m is not adjusted to the elevation height of the validation data before calculating the model bias.

All the simulations also overestimate the precipitation over Tibetan Plateau, especially in the southern part (Fig. 4e–h), which results in large deviations. For instance, the mean bias in the simulation with Noah-MP



**Fig. 4** Time averaged T2m (unit: °C) and precipitation (Pre, unit: mm/day) during May—August in the selected years (1987, 1991, 1996, 1998, 2003, and 2007) in the validation data (CMFD) and the control experiments with different land models

**Table 2** Spatial correlation coefficient (Cor) and mean bias of the simulated T2m (unit: °C) and precipitation (unit: mm/day) over Tibetan Plateau in the control experiments with different land models

Model	T2m		Precipitation	
	Cor	Bias	Cor	Bias
SSiB	0.85	2.87	0.62	2.71
CLM	0.88	1.58	0.66	2.71
Noah-MP	0.87	1.16	0.62	3.11

is as large as 3.11 mm/day. However, the precipitation gradient increasing from northwest to southeast over Tibetan Plateau in the validation data is fairly well simulated, with the spatial correlation coefficients all above 0.60 (Table 2).

To sum up, all the simulations with different land models can well simulate the weather processes over Tibetan Plateau despite some systematic biases, which provides a good base to the further analyses of the T2m/surface/soil memories.

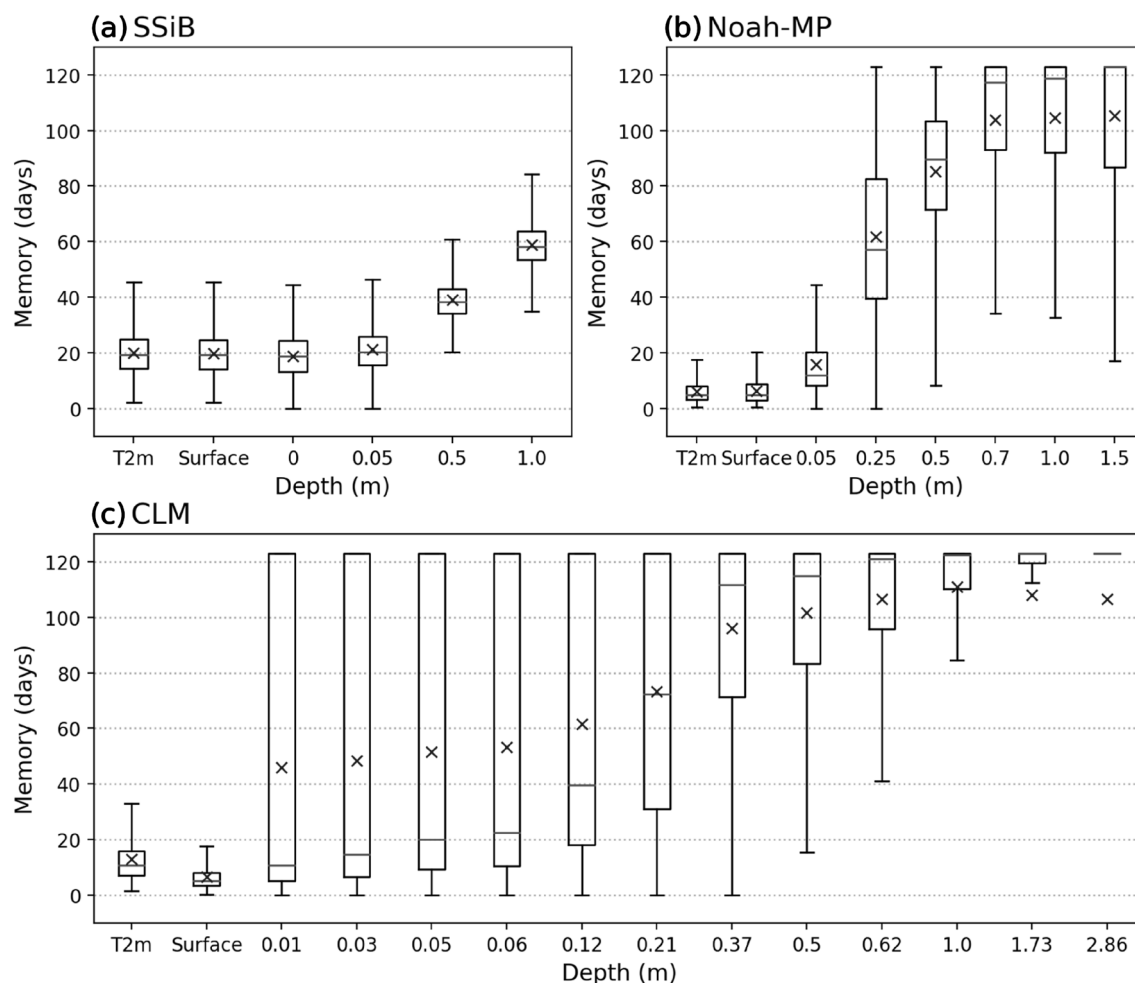
### 3.2 T2m/surface/soil memories

#### 3.2.1 The +5 °C experiments

Figure 5 shows boxplots of T2m/surface/soil memories on each model grid over Tibetan Plateau in the +5 °C experiments. Based on the means, medians, and interquartile ranges of the boxplots, it is easy to find that the simulated soil memory generally increases with soil depth, which is consistent with the results based on the observational data with statistics methods (Hu and Feng 2004; Yang and Zhang 2016). Figure 6a reveals that the regional mean soil memory changes rapidly with depth above ~0.6–0.7 m and varies slowly below it. The regional mean soil memories at the layer of 0.62 m and above in CLM, the layer of 0.7 m and above in Noah-MP, and the full layers in SSiB (considering it has only three soil layers) are separately

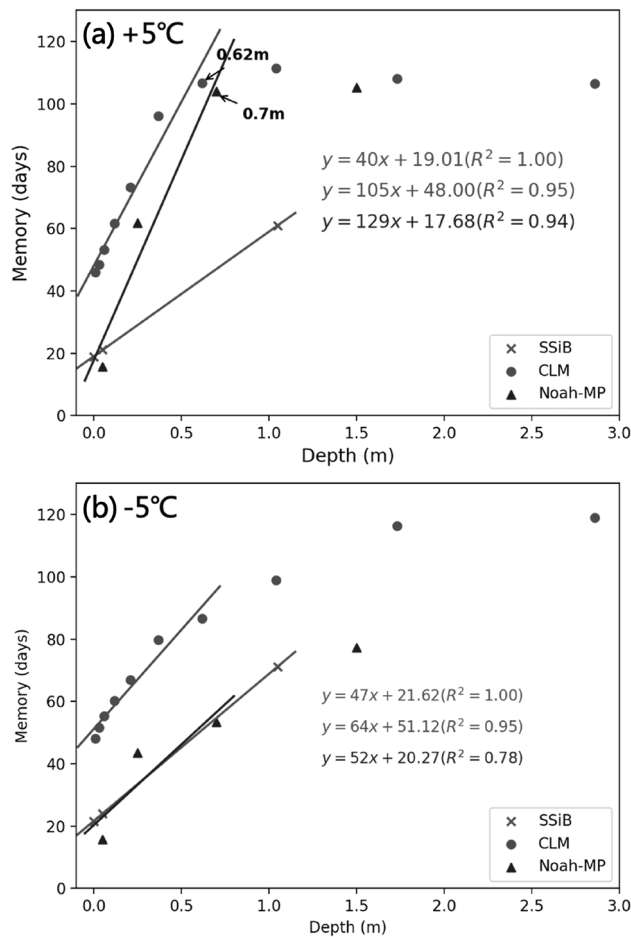
linearly fitted with soil depth. The variability of SSiB, CLM, and Noah-MP among their specified layers is 40, 105, and 129 days/m, respectively.

The data distribution in the boxplots (Fig. 5) shows that the soil memory of SSiB is more aggregated at each layer, meaning that its soil memory is more uniform over Tibetan Plateau. However, the soil memory of CLM and Noah-MP is more discrete, meaning that their soil memory is more heterogeneous over the plateau. These results are consistent with what the spatial distribution of soil memory indicates (Fig. 7 and S1). For instance, the 0.05 m soil memory of CLM has a high-value area (> 110 days) in the northern part of Tibetan Plateau and a large area of low value ( $\leq 10$  days) in the southeastern part (Fig. 7h). And the 0.5 m soil memory of Noah-MP presents an increasing pattern from northwest to southeast in the plateau (Fig. 7l).



**Fig. 5** Boxplots of T2m/surface/soil memories (units: days) over Tibetan Plateau in the +5 °C experiments with different land models, in which the digitals along the x-axis are the depths of the soil layers. In addition, the markers “x” indicate the means and the upper (lower)

whiskers extent to the last datum less (greater) than  $Q3 + 2 \times IQR$  ( $Q1 - 2 \times IQR$ ).  $Q3(Q1)$  is the third (first) quartile.  $IQR$  is the interquartile range ( $Q3 - Q1$ ). The outliers are not shown



**Fig. 6** Scatterplots of regional mean soil memory and original soil layers in the (a) +5 °C and (b) -5 °C experiment with different land models. The regional mean soil memories at the specified layers in each land model are linearly fitted with the soil depth (see lines). When doing the fitting, we used the layer of 0.62 m and above in CLM, the layer of 0.7 m and above in Noah-MP, and all the layers in SSiB

In terms of the magnitude of soil memory, the values of SSiB at the deeper layers ( $> \sim 0.05$  m) are generally much smaller than those of CLM and Noah-MP over Tibetan Plateau (Fig. 7 and S1). For instance, the regional mean soil memory at 0.5 m in SSiB is 39.1 days, while those of CLM and Noah-MP are respectively 101.6 and 85.2 days, which are more than twice of the value of SSiB (Table 3). Although the deeper-layer soil memory of SSiB is much smaller than CLM and Noah-MP, its T2m/surface memories are generally larger than them (Fig. 7a–f). In SSiB, the T2m/surface memories are greater than 10 days in almost the entire region, and even more than 30 days in some areas, with the regional means as large as  $\sim 20$  days. However, the T2m/surface memories of Noah-MP and surface memory of CLM are less than 10 days in most parts of the plateau.

Since the T2m memory is different among the land models, differences in May T2m between the control and +5 °C experiment are also distinct between them. Figure 8 (the left column) shows the values of SSiB and CLM are positive in almost the entire plateau, while the negative-value areas in Noah-MP accounts for  $\sim 60\%$  of the whole region. Differences in May T2m over most of Tibetan Plateau passed the significance test with the paired sample T-test at the 95% confidence level (see the slashed areas in Fig. 8).

### 3.2.2 The -5 °C experiments

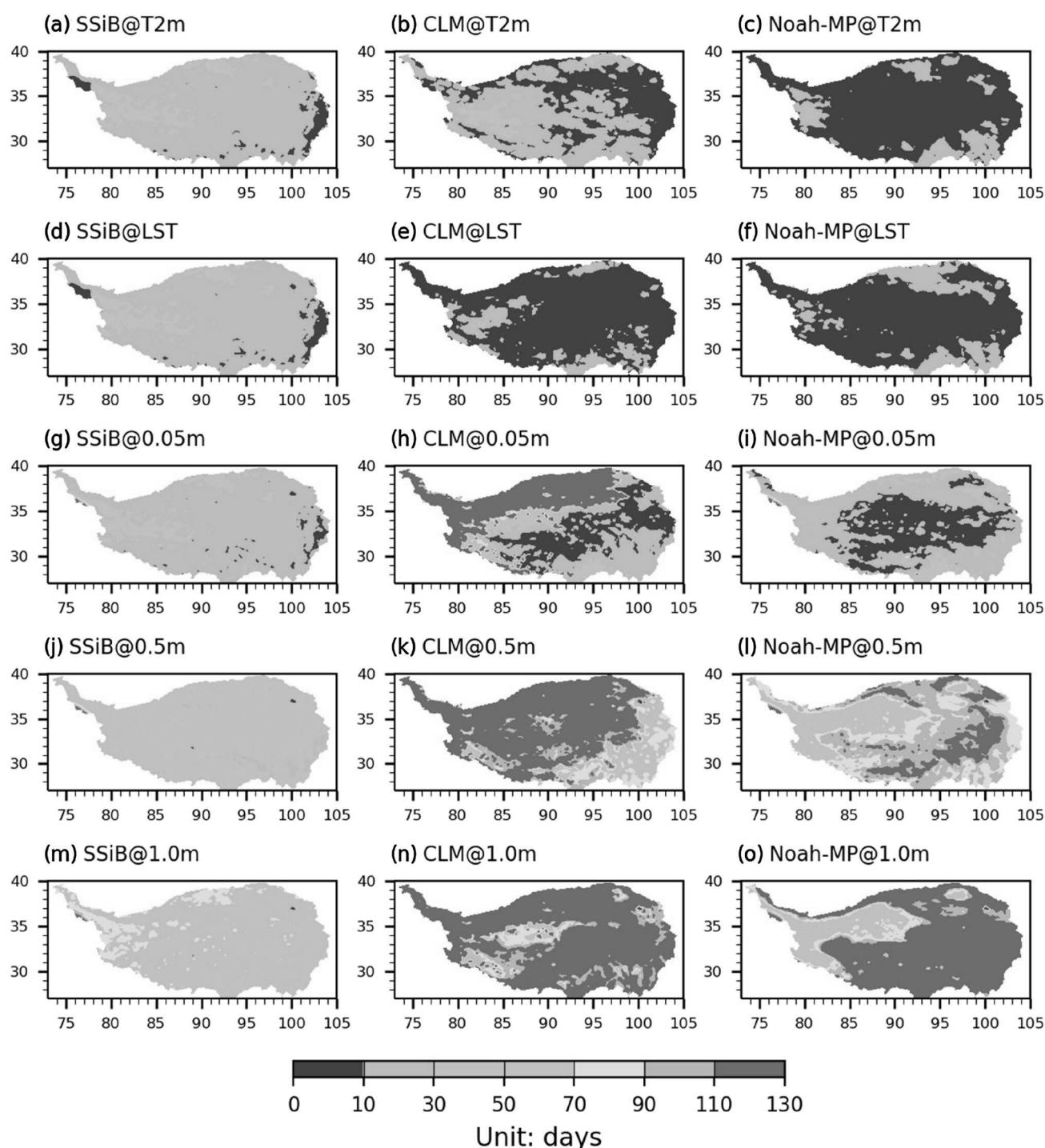
Compared with the results in the +5 °C experiments, there are some major differences in the -5 °C experiments. The T2m/surface memories and near-surface soil memory ( $\leq \sim 0.05$  m) of the three land models all increase slightly or remain (Fig. 5 vs Fig. 9, Fig. 7 vs Fig. 10, Table 3). In terms of the deeper-layer ( $> \sim 0.05$  m) soil memories, the values of SSiB increase, while those of CLM and Noah-MP largely decrease. For instance, the regional mean 0.5-m soil memory of Noah-MP drops from 85.2 to 48.9 days, with a decrease of 42.6% (Table 3). As a result, the change rate of soil memory with depth among the aforementioned specified layers in SSiB slightly increases from 40 to 47 days/m, while those of CLM and Noah-MP decrease dramatically. For instance, the change rate of CLM is reduced from 105 to 64 days/m, and that of Noah-MP drops from 129 to 52 days/m. Compared with the control experiment, the imposed -5 °C initial anomalies reduce the May T2m over almost the entire region in SSiB and CLM (Fig. 8 b, d). However, the May T2m of Noah-MP increases in more than half of the plateau (Fig. 8f).

## 4 Mechanisms

The T2m anomaly over Tibetan Plateau plays a significant role in the S2S prediction (Xue et al. 2021). The three land models in this study have quite different T2m memory as well as surface/soil memories (e.g., Fig. 7 vs Fig. 10). The possible causes for these differences are discussed in this section.

It's found that both changes in the surface heat fluxes (sensible and latent heat fluxes, referred as SH and LH) and variations in the hydrological processes over Tibetan Plateau can well explain why the T2m/surface/soil memories are various over Tibetan Plateau, distinct among the three land models, and different between the +5 °C and -5 °C experiment as detected in Sect. 3.

Figure 11a shows that adding +5 °C on the initial LST/SUBT causes a slight increase in SH and LH during the first  $\sim 20$  days of the simulation with SSiB, which favors the



**Fig. 7** Spatial distribution of T2m/surface/soil memories (unit: days) in the Tibetan Plateau in the +5 °C experiments with different land models. The soil memories are at the layers of 0.05, 0.5, and 1.0 m

preservation of the imposed positive T2m anomaly. However, LH in CLM and Noah-MP is triggered by the imposed initial anomalies to largely increase along with decreasing SH during the simulation, which means LH in these models are very sensitive to the surface temperature and is not

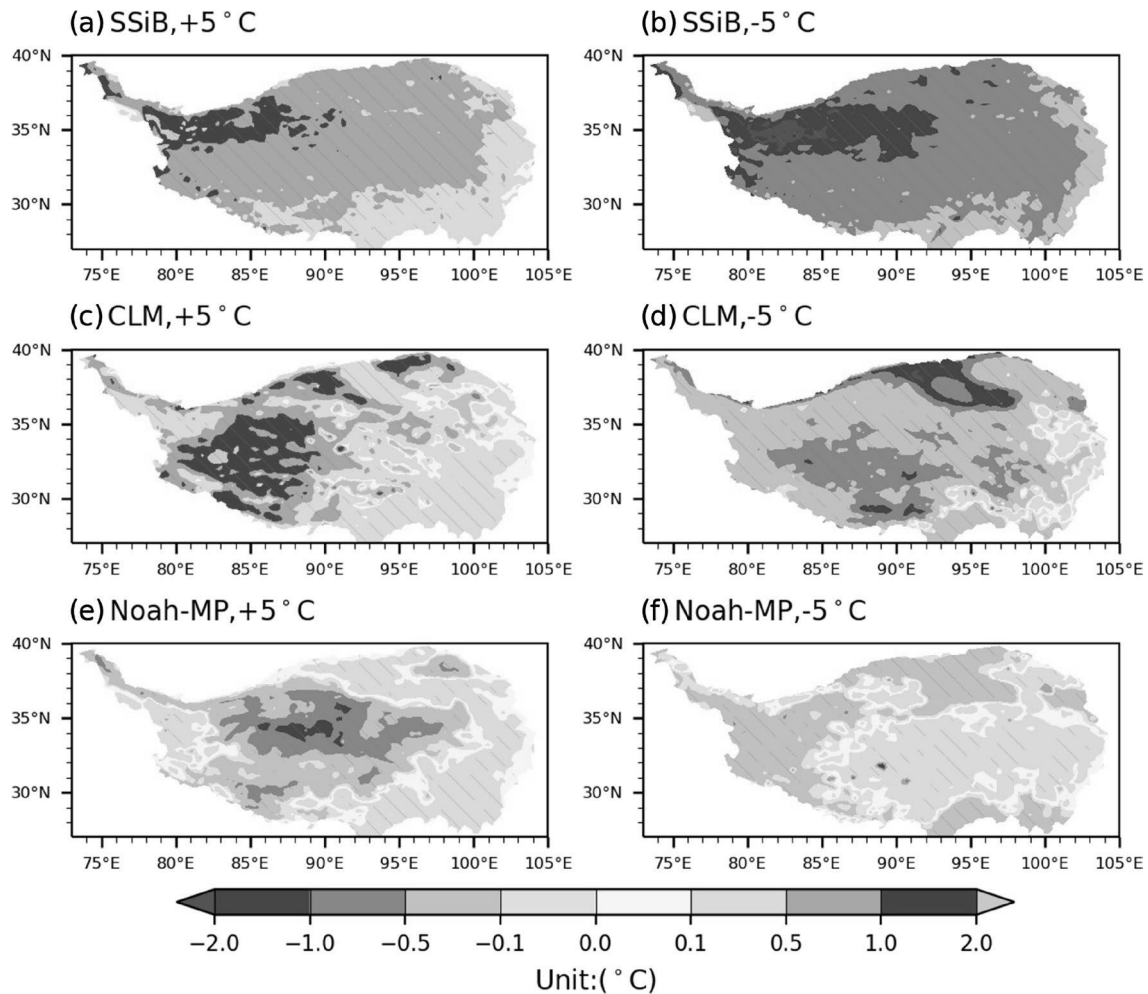
favorable for keeping the positive T2m anomaly. Time series of the differences in daily T2m and LST in CLM and Noah-MP (Fig. S3a) shows that increased LH causes LST decrease more rapid than T2m and thus time series of the differences in temperature gradient between daily LST and T2m (LST

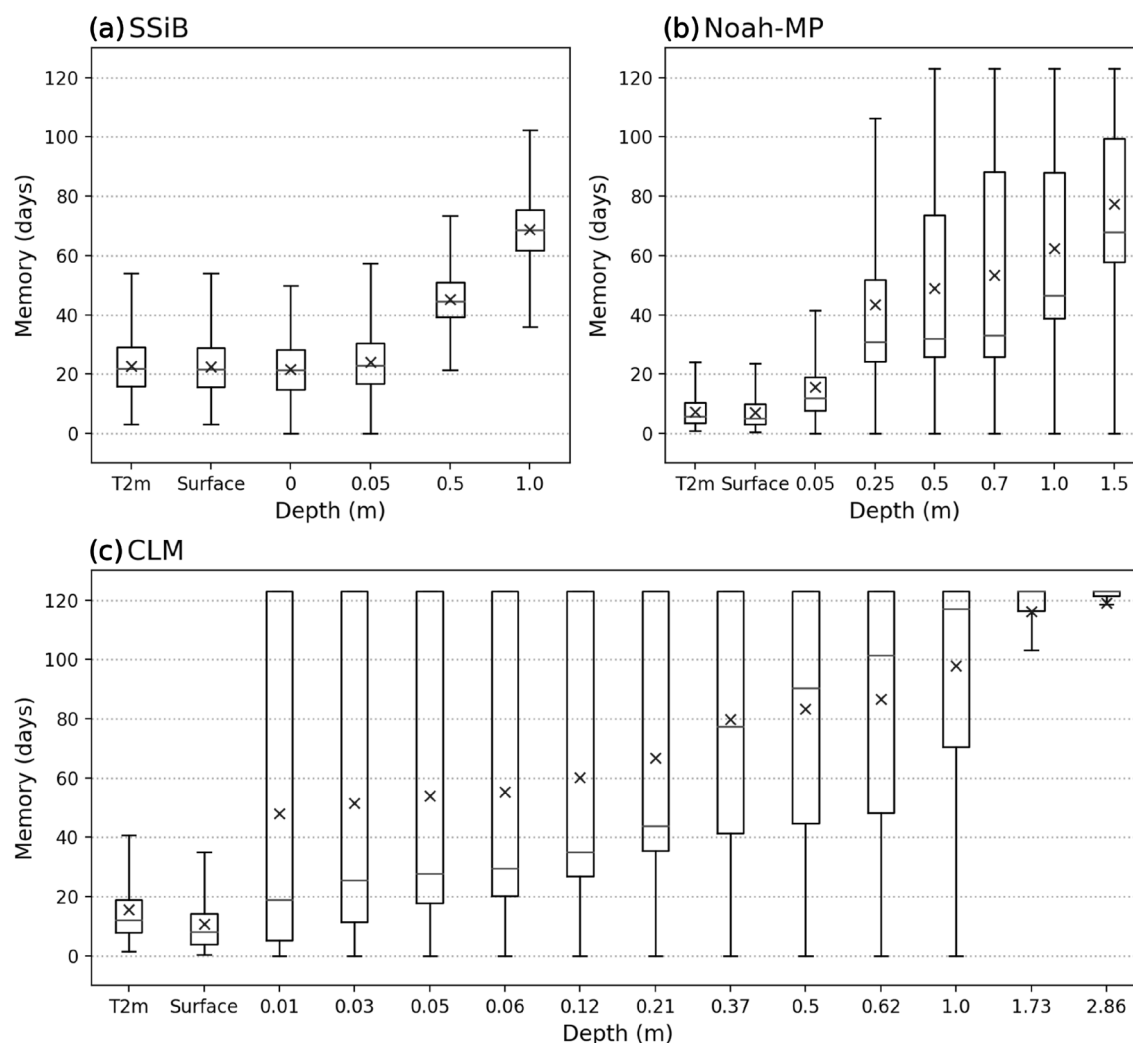


**Table 3** Statistics of T2m/surface/soil memories (unit: days) over Tibetan Plateau in the +5 °C and -5 °C experiment with different land models, in which “Range” refers to the interquartile range

Model	Variable	+5 °C			-5 °C		
		Mean	Median	Range	Mean	Median	Range
SSiB	T2m	19.9	19.2	14.3–24.8	22.6	21.8	15.8–29.0
	Surface	19.8	19.2	14.2–24.7	22.5	21.7	15.7–28.8
	0.05 m	21.1	20.2	15.5–25.8	24.0	22.8	16.8–30.5
	0.5 m	39.1	38.4	34.2–43.0	45.2	44.4	39.3–50.9
	1.0 m	59.0	58.2	53.5–63.7	68.8	68.6	61.8–75.4
CLM	T2m	13.0	10.8	7.2–15.8	15.7	12.0	7.8–18.8
	Surface	6.6	5.2	3.5–8.2	10.8	8.2	4.0–14.3
	0.05 m	51.6	19.9	9.2–123.0	54.0	27.8	17.8–123.0
	0.5 m	101.6	114.9	83.3–123.0	83.3	90.3	44.7–123.0
	1.0 m	111.0	122.5	110.2–123.0	97.8	117.2	70.6–123.0
Noah-MP	T2	6.1	4.8	3.2–8.0	7.3	5.7	3.5–10.3
	Surface	6.4	4.8	2.8–8.7	7.0	5.2	3.0–9.8
	0.05 m	15.8	12.0	8.2–20.3	15.8	12.0	7.7–19.0
	0.5 m	85.2	89.7	71.5–103.2	48.9	31.9	25.7–73.5
	1.0 m	104.5	118.8	92.2–123.0	62.3	46.5	38.8–88.0

The soil memories are at the layers of 0.05, 0.5, and 1.0 m

**Fig. 8** Spatial distribution of the differences (unit: °C) in May T2m between the control and  $\pm 5$  °C experiment with different land models. The slashed areas indicate that the differences passed paired sample *T*-test at the 95% confidence level



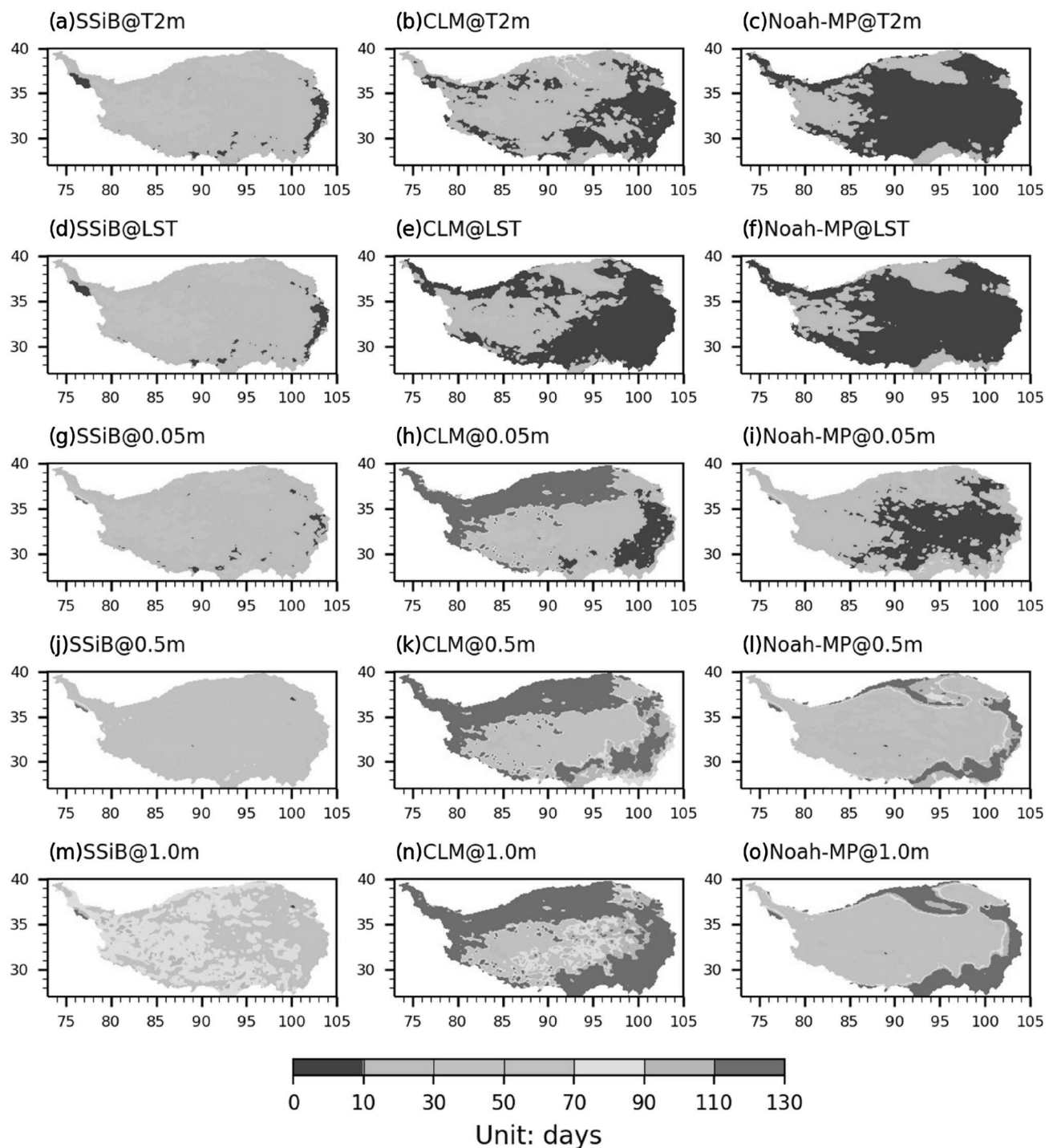
**Fig. 9** Similar to Fig. 5, but in the  $-5^{\circ}\text{C}$  experiments

– T2m) turn negative in the very beginning of the simulation (Fig. S3b). This explains why SH decreases in CLM and Noah-MP after adding  $+5^{\circ}\text{C}$  on the initial LST/SUBT.

The enhanced LH in CLM and Noah-MP is accompanied with stronger surface evaporation, which strengthens the convection in the atmosphere. For instance, the May equivalent potential temperature (EPT) and convective available potential energy (CAPE, equation S1) averaged over Tibetan Plateau consistently increase on the lower eta levels in the  $+5^{\circ}\text{C}$  experiment (solid lines in Fig. 11c, d). As a result, more precipitation falls on the ground (Fig. 12h, i), which leads to higher soil moisture in the near-surface layers, especially in the simulation with CLM (Fig. 12k, l). And wetter soil in turn exaggerates surface evaporation, which produces a feedback that continuously erases the soil thermal anomalies at the near-surface layers, as discussed in Xue et al. (2021), and conversely brings benefits in keeping the LST/SUBT anomalies at the deeper layers.

The opposite situations are found in the  $-5^{\circ}\text{C}$  experiment. The  $-5^{\circ}\text{C}$  initial anomalies causes a slight decrease in SH and LH during the first  $\sim 40$  days of the simulation with SSiB, which is in favor of maintaining the imposed negative T2m anomaly (Fig. 11b). However, LH in CLM and Noah-MP is triggered by the imposed initial anomalies to largely decrease along with increasing SH during the simulation. The increased SH is not favorable for keeping the negative T2m anomaly.

Meanwhile, the reduced LH in CLM and Noah-MP is accompanied with weaker surface evaporation, which weakens the convection in the atmosphere. For instance, the May EPT and CAPE averaged over Tibetan Plateau consistently decrease on the lower eta levels in the  $-5^{\circ}\text{C}$  experiment (dotted lines in Fig. 11c, d). As a result, less precipitation falls on the ground (Fig. 13h, i), which leads to lower soil moisture at the near-surface layers (Fig. 13k, l). And drier soil in turn weakens surface evaporation. The weakened

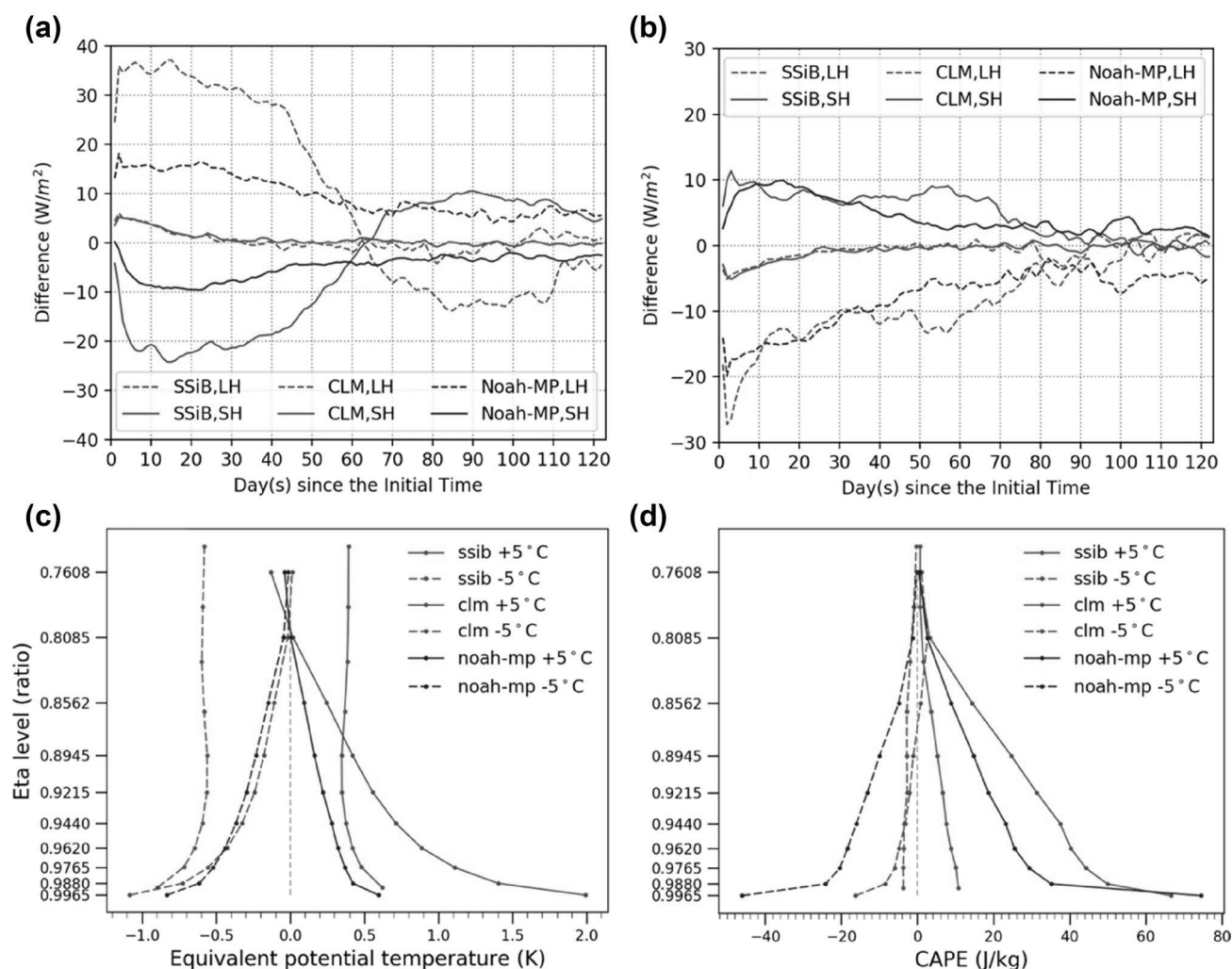


**Fig. 10** Similar to Fig. 7, but in the  $-5^{\circ}\text{C}$  experiments

hydrological process is good for maintaining the soil thermal anomalies at the near-surface layers and hastens the demise of the soil thermal anomalies at the deeper layers. The feedbacks caused by the imposed LST/SUBT initial anomalies between the soil heat fluxes, surface evaporation, convection in the atmosphere, precipitation, and soil moisture at the

near-surface layers in CLM and Noah-MP are summarized in Fig. 14.

Comparison of changes in the surface heat fluxes and the hydrological processes can well explain why the T2m/surface/soil memories are distinct among the land models (between the  $+5^{\circ}\text{C}$  and  $-5^{\circ}\text{C}$  experiment). Changes in



**Fig. 11** **a** Time series of the differences in daily sensible and latent heat (referred as SH and LH, unit: W/m<sup>2</sup>) averaged over Tibetan Plateau between the control and +5 °C experiment with different land models; **b** same as **a** but between the control and -5 °C experiments;

**c** differences in the vertical profile of the May equivalent potential temperature (EPT, unit: K) on the eta levels between the control and +5 °C experiment with different land models; **d** same as **c** but for the May convective available potential energy (CAPE, unit: J/kg)

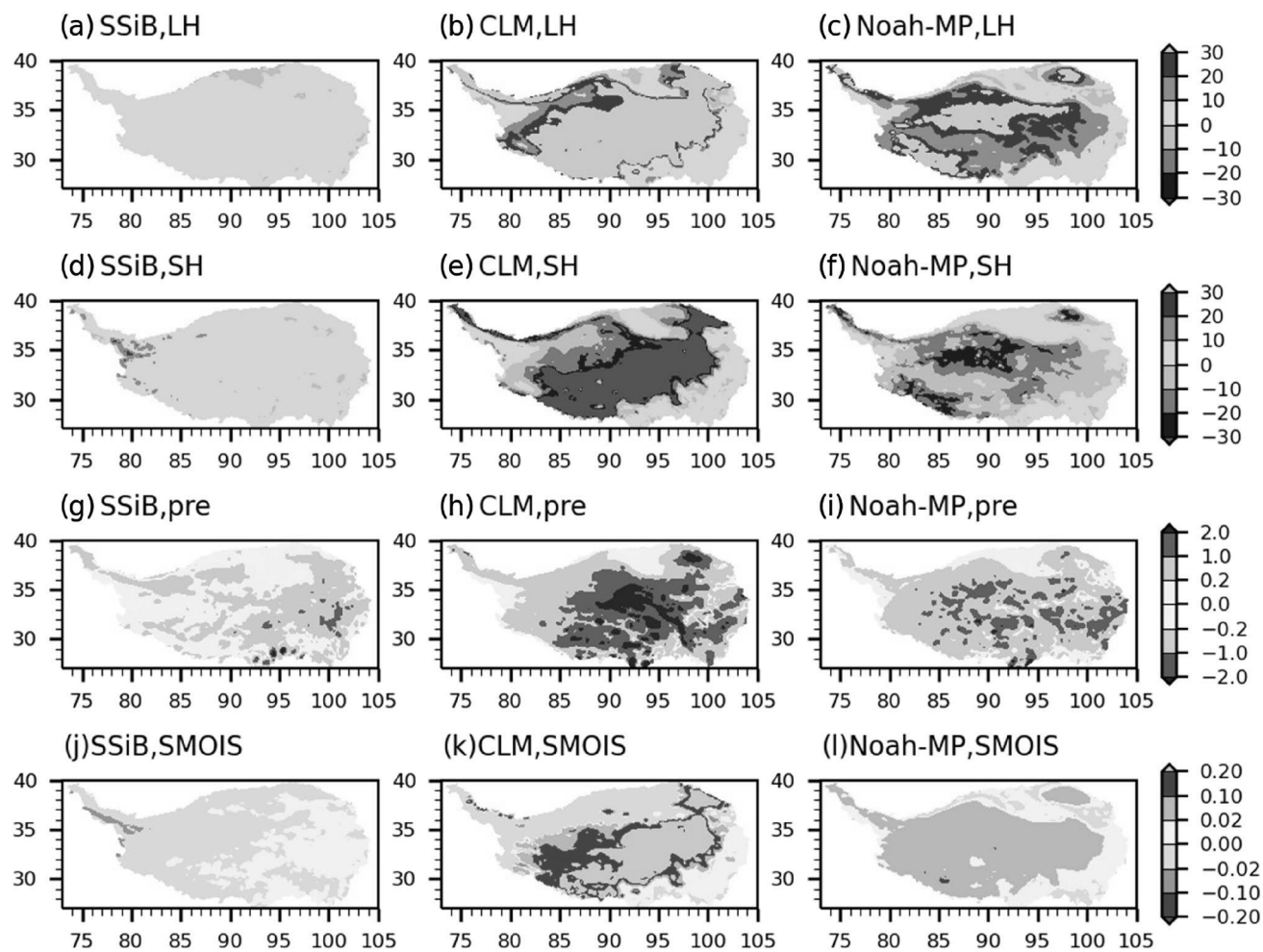
the surfaces heat fluxes, precipitation, and soil moisture are various over Tibetan Plateau, which results in the heterogeneity of the memories on the spatial distribution. For instance, the areas with increased (decreased) soil moisture at 0.05 m (Fig. 12k) have shorter (longer) soil memory (Fig. 7h) in the +5 °C experiment with CLM.

We calculated percentage of differences in May convective precipitation between the control and ±5 °C experiment to differences in May total precipitation (Fig. S4) and found that the value is generally above 90% in the middle and southeastern

part of the plateau. This indicates that the aforementioned feedback plays a major role in regulating the T2m/surface/soil memories in these areas.

## 5 Discussion and conclusion

This study applies three widely used land models (SSiB, CLM, and Noah-MP) coupled in the regional climate model WRF to quantitatively assess their skill in



**Fig. 12** Differences in May latent heat flux (LH, unit:  $\text{W/m}^2$ ), sensible heat flux (SH, unit:  $\text{W/m}^2$ ), precipitation (pre, unit:  $\text{mm/day}$ ), and soil moisture at 0.05 m (SMOIS, unit:  $\text{m}^3/\text{m}^3$ ) in the  $+5^\circ\text{C}$  experiment with different land models

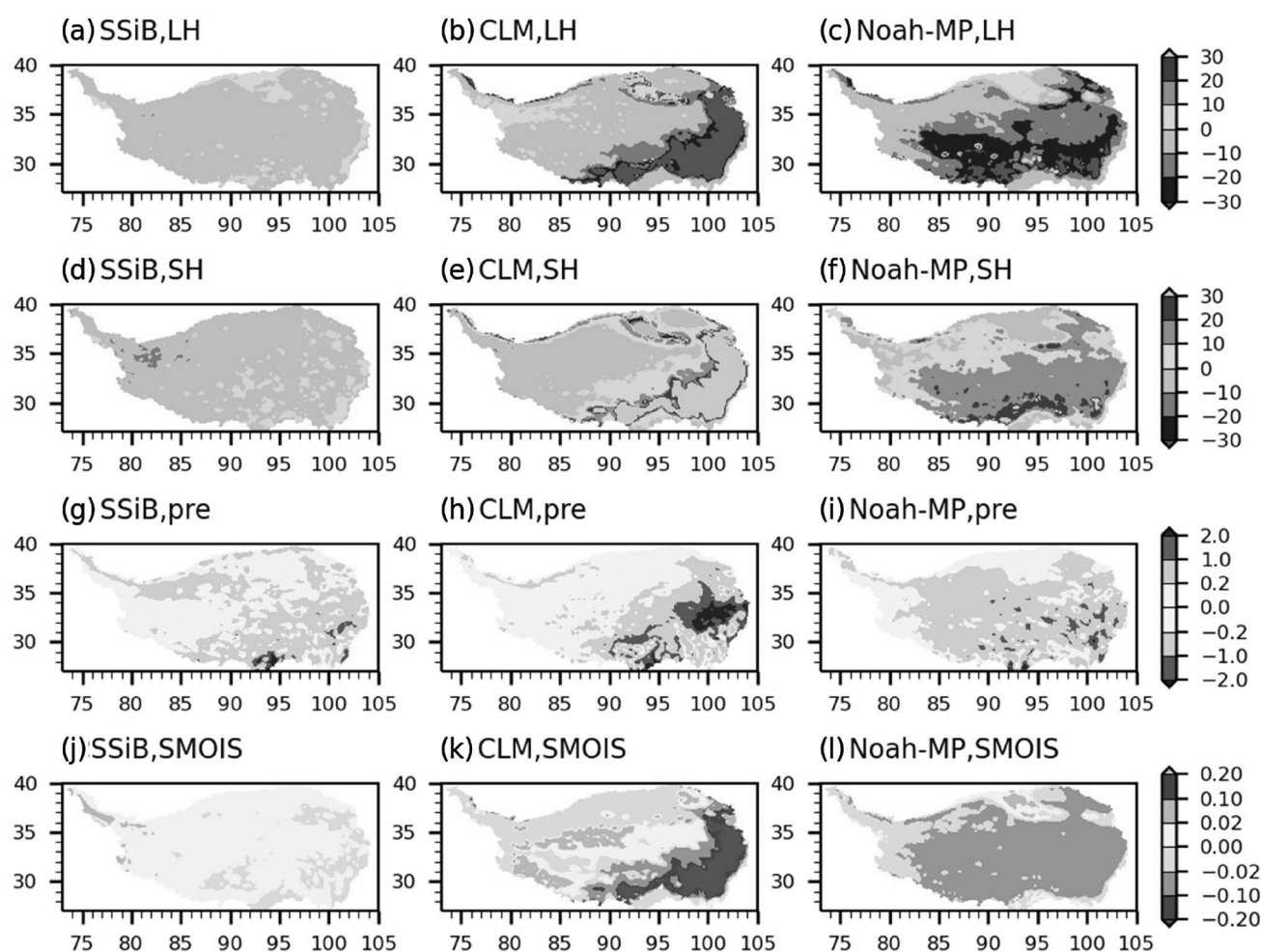
preserving the imposed  $\pm 5^\circ\text{C}$  anomalies on the initial LST/SUBT and generating the T2m anomaly over Tibetan Plateau during May–August of 6 years (1987, 1991, 1996, 1998, 2003, and 2007). The ensemble results in the three land models commonly indicate that the simulated soil memory generally increases with soil depth. And soil memory changes rapidly with depth above  $\sim 0.6\text{--}0.7\text{ m}$  and varies slowly below it. However, their change rates are different. For instance, in the  $+5^\circ\text{C}$  experiment, the variability of SSiB, CLM, and Noah-MP among their specified upper layers is 40, 105, and 129 days/m, respectively.

Moreover, the ensemble results show that the T2m/surface/soil memories are distinct between the land models. The soil memory of SSiB is highly uniform over the plateau, while that of CLM and Noah is more heterogeneous. In terms of the magnitude of the memories, the soil memory of SSiB at the deeper layers ( $> \sim 0.05\text{ m}$ ) are generally smaller than that of CLM and Noah-MP, while the T2m/surface memories and near-surface ( $\leq \sim 0.05\text{ m}$ ) soil memory

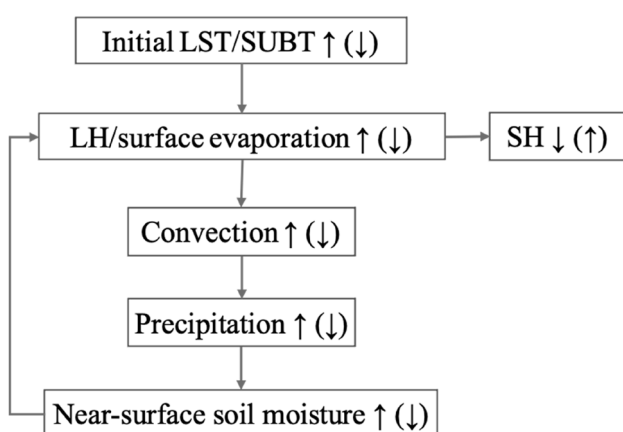
of SSiB are generally larger than them. Differences in May T2m between the control and  $\pm 5^\circ\text{C}$  experiment are also different between them. For instance, the imposed  $-5^\circ\text{C}$  initial anomalies reduce the May T2m over almost the entire plateau in SSiB and CLM, whereas the May T2m of Noah-MP increases in more than half of the region.

Compared with the  $+5^\circ\text{C}$  experiment, the T2m/surface memories and near-surface soil memory in the  $-5^\circ\text{C}$  experiment with each land model all increase slightly or remain. In terms of the deeper soil memory, the values of SSiB increases, while those of CLM and Noah-MP decreases, especially in the deep soil. As a result, the change rate of soil memory with depth among the aforementioned specified layers in SSiB slightly increases from 40 to 47 days/m, while those of CLM and Noah-MP decrease dramatically.

The heterogeneity of the memories over Tibetan Plateau, their distinctions among the land models, and their differences between the  $+5^\circ\text{C}$  and  $-5^\circ\text{C}$  experiment can be well explained by both changes in the surface heat fluxes



**Fig. 13** Similar to Fig. 12, but in the  $-5^{\circ}\text{C}$  experiment



**Fig. 14** Feedbacks caused by the imposed LST/SUBT initial anomalies between the surface heat fluxes (sensible and latent heat fluxes, referred as SH and LH), surface evaporation, convection in the atmosphere, precipitation, and soil moisture at the near-surface layers in CLM and Noah-MP, in which  $\uparrow$  ( $\downarrow$ ) means increase (decrease)

and variances in the hydrological processes over the plateau. The feedback caused by the imposed LST/SUBT initial anomalies between the soil heat fluxes, surface evaporation, convection in the atmosphere, precipitation, and soil moisture at the near-surface layers plays a major role in regulating the T2m/surface/soil memories, especially in the middle and southeastern part of the plateau. In addition, changes in snow conditions (such as snow melting) and subsequent monsoon circulation alternation can influence the air-land interaction over Tibetan Plateau and then regulate the T2m/surface/soil memories. Detailed analyses of changes in these physical processes are out of the scope in the current paper and will be investigated in the next stage.

In this study, the three land models have fairly long soil memories. For instance, the regional mean 1.0-m soil memories in these models are generally longer than 60 days. However, the T2m memory in them is much shorter than soil memory. For instance, the regional mean T2m memories in these models are generally below 20 days. This means that the soil thermal anomalies cannot continuously affect

the surface air temperature by the air-land interaction. CLM and Noah-MP have longer soil memory at the deeper layers ( $> \sim 0.05$  m) while SSiB has longer T2m/surface memories and near-surface soil memory ( $\leq \sim 0.05$  m). As a result, it is difficult to say which land model is optimal for the application of the LST/SUBT approach on the S2S prediction.

As a preliminary study in investigating the skill of land models in preserving the soil thermal anomalies, this work is to compare the memory of the LST/SUBT initial anomalies in different land models with their default soil parameters (such as soil textures and soil organic matters), which can give practical notes to the relevant numeric simulations, like those in the LS4P project. Considering the potential effect of different soil parameters in the land models to the T2m/surface/soil memories, comparison between the land models with same soil parameters will give a fairer assessment.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s00382-021-05937-z>.

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## Declarations

**Conflict of interest** No conflicts of interest/competing interests.

**Data availability** If necessary, the data and materials used in this study will be uploaded to a data center, like National Tibetan Plateau/Third Pole Environment Data Center (<http://data.tpdc.ac.cn/>).

**Code availability** If necessary, the codes of analyzing and plotting in this study will be upload to github.

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