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ORIGINAL PAPER

Spin-up behavior of soil moisture content over East Asia in a land surface model

Yoon-Jin Lim · Jinkyu Hong · Tae-Young Lee

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Abstract This study presents an investigation of the spin-up behavior of soil moisture content (SMC) and evapotranspiration (ET) in an offline Noah land surface model (LSM) for East Asia, focusing on its interplay with the Asian monsoon. The set of 5-year recursive runs is conducted to properly assess the spin-up behavior of land surface processes and consists of simulations initialized with (1) a spatially uniform soil moisture, (2) NCEP GDAS soil moisture data, and (3) ECMWF ERA-Interim soil moisture data. Each run starts either after or before the summer monsoon. Initial SMCs from GDAS and ERA-Interim data significantly deviate from the equilibrium state (spin-up state) with the given input forcing even though the same equilibrium is reached within 3-year spin-up time, indicating that spin-up of land surface process is necessary. SMC reaches the equilibrium much quickly when (1) the consistent LSMs have been used in the prediction and analysis systems and (2) the spin-up simulation starts before the onset of heavy rainfall events during summer monsoon. For an area with heavy monsoon rainfall, the total column SMC and ET spin up quickly. The spin-up time over dry land is about 2–3 years, but for monsoon rainfall area decreases dramatically to about 3 months if the spin-up run starts just before the onset of monsoon. Further scrutiny shows that the spin-up time is well correlated with evaporative fraction given by the ratio between the latent heat flux and the available energy at the land surface.

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Y.-J. Lim · J. Hong (✉) · T.-Y. Lee
Department of Atmospheric Sciences/Global Environment Laboratory, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, South Korea
e-mail: jhong@yonsei.ac.kr

1 Introduction

Land surface plays an important role in modulating atmospheric circulations through exchanges of momentum, energy, water, and carbon at the surface–atmosphere interface. In particular, soil moisture is a key factor in the exchange of water and energy, thus affecting weather and climate. Soil moisture also influences carbon–climate interactions by regulating ecosystem carbon processes (e.g., Falloon et al. 2011). Therefore, it is of fundamental importance to obtain accurate information about soil moisture content (SMC) for the better prediction of weather and climate events. Several improved forecasts of weather and seasonal climate variations have already been attributed partly to the improved initialization of SMC (e.g., Fennessy and Shukla 1999; Holt et al. 2006; Case et al. 2008; Koster and Suarez 2003; Koster et al. 2010).

The observed soil moisture fields are inadequate for the initialization of soil moisture because of their limited spatio-temporal resolution and discontinuity (Robock et al. 2000). Accordingly, initial soil moisture fields for numerical weather and climate predictions are generally provided by soil moisture datasets produced by land surface models (LSMs), which are directly or indirectly coupled to atmospheric models. For example, the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al. 1996), the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis (ERA-40) (Simmons and Gibson 2000), and the Japanese 25-year reanalysis (JRA-25) (Onogi et al. 2007) provide global soil moisture data that are produced by LSMs directly coupled to atmospheric models. The Global Land Data Assimilation System (GLDAS; Rodell et al. 2004) and the North American Land Data Assimilation System (NLDAS;

Mitchell et al. 2004) provide soil moisture data that are produced by offline LSMs.

However, soil moisture data from LSMs are highly model-dependent, because each LSM assumes its own unique land surface climatology and biophysical relationships between soil water and evapotranspiration (Koster and Milly 1997; Hong and Kim 2010). Even when LSMs are run assuming the same soil/vegetation conditions and identical atmospheric forcing, the simulated SMCs show significant discrepancies between LSMs. Thus, soil moisture initialization using data from a LSM that is different from the LSM used for a prediction model may result in some erroneous predictions of soil moisture and surface fluxes (Reichle et al. 2004; Dirmeyer et al. 2006). Indeed, this inconsistency in the LSMs for soil moisture initialization was found to result in a decrease in the skill score of seasonal precipitation forecasts over North America (Koster et al. 2009).

It is not always possible to initialize the atmospheric model using the same LSM. Furthermore, soil moisture fields can vary significantly with the LSM for given input forcing. Dirmeyer et al. (2006) proposed a simple scaling approach using the mean and standard deviation of soil moisture data obtained from various LSMs. In general, spin-up has been performed for several months, neglecting the first few months of simulation, without considering the LSM inconsistency issue (e.g., Schär et al. 1999; Kim and Hong 2007; Zhong et al. 2007; Laprise 2008). The spin-up procedure, which may be defined as an adjustment of the LSM to forcing fields, is important for achieving the realistic initialization of SMC and evapotranspiration (ET). Numerical modeling studies have shown that the spin-up time is related not only to the holding capacity and initial values of soil moisture, but also atmospheric forcing and surface conditions (e.g., Yang et al. 1995; Chen and Mitchell 1999; Cosgrove et al. 2003; Rodell et al. 2005; de Goncalves et al. 2006). These studies also indicate that the typical spin-up time is more than 1 year, varying from approximately 1 year to several years.

Despite such important aspects of the LSM spin-up procedure; there have been only a few studies on the LSM initialization and spin-up behavior of SMC for the East Asian region (e.g., Kim et al. 1998; Kanae et al. 2006; Lim et al. 2012). Importantly, they did not quantify the spin-up timescales with different initial conditions and their relationship with the East Asian monsoon. Heavy rainfall during the monsoon period can be an important factor in the LSM spin-up process because of its role in removing soil moisture memory. It is, therefore, essential to analyze the detailed spin-up behaviors of soil moisture for a better understanding of the potential problems arising from the LSM inconsistency over East Asia.

In this study, we have investigated the spin-up behavior of soil moisture in the offline Noah LSM of the Korea Land Data Assimilation System (KLDAS; Lim et al. 2012), focusing on the spin-up of SMC and ET in East Asia affected by the seasonal march of summer monsoon and thus having wide range of annual rainfall. The impact of LSM inconsistency on the spin-up behavior is also studied. A brief review of the KLDAS and experimental setup is described in Sect. 2. In Sect. 3, the spin-up behaviors of the simulated soil moisture and ET over the East Asian region obtained from the different spin-up runs are investigated. Finally, Sect. 4 summarizes the paper with concluding remarks.

2 Methodology

2.1 Korea land data assimilation system (KLDAS)

The KLDAS is used to understand the characteristics of the spin-up behavior of an LSM in an area that is significantly affected by the East Asian summer monsoon. The KLDAS is a stand-alone Noah LSM (Chen and Dudhia 2001; Ek et al. 2003) with an input system using both land surface information from the Weather Research and Forecasting (WRF) Preprocessing System (WPS) and Moderate Resolution Imaging Spectroradiometer (MODIS) static and time-varying land information (e.g., land cover, green vegetation fraction, and leaf area index) (Lim et al. 2012). When compared with the other LDAS projects, the KLDAS focuses on the East Asian region by combining the land surface model with in situ rainfall observation, geostationary satellite radiation, global reanalysis data, and the MODIS land products. Table 1 summarizes the land surface information and hourly input forcing for the KLDAS. Lim et al. (2012) found that hourly input forcing from the KLDAS is in good agreement with the ground measurement over East Asia. The KLDAS domain includes the East Asian region (between 10°–50°N and 110°–155°E) with a grid spacing of 10 km (Fig. 1). The total soil depth was set to 2 m in the Noah LSM and was divided into four soil layers with depths of 0.1, 0.3, 0.6, and 1.0 m (listed from the surface downward into the soil). Here, hourly forcing from January 1, 2006 to December 31, 2006 is applied recursively to drive the KLDAS for a 5-year simulation because the equilibrium of <1 % changes in surface conditions is reached within 3 years. More information on the quantitative analysis of input forcing generated by the KLDAS can be found in Lim et al. (2012).

2.2 Experiment design

To analyze the potential problems associated with the LSM inconsistency, two 5-year simulations of the Noah LSM version 2.5.2 using the KLDAS were conducted from August 1, 2006, and simulations were initialized with the NCEP Global Data Assimilation System (GDAS) data with

Table 1 Data used in KLDAS

Data	Sources
Offline LSM	Noah LSM
Land surface information	
Soil type, terrain height, albedo	WRF Preprocessing System 30 s data
Land cover	MODIS land products
Green vegetation fraction	
Leaf area index	
Atmospheric forcings	
Precipitation	WMO/GTS 6-h accumulated precipitation AWS hourly rain gauge data
Downward solar radiation	Li et al. (1993) algorithm using GOES and MTSAT-1R satellite data and surface albedo
Downward longwave radiation	
10-m wind speed	6-hourly 0.5625° GDAPS analysis data from Korea Meteorological Administration
2-m temperature	
Relative humidity	
Surface pressure	

1° resolution (NCEP-AM) and ECMWF ERA-Interim data with 1.5° resolution (ECMWF-AM) (Table 2). Here, "AM" indicates that the simulation started after the heavy rainfall period during a monsoon season. It is noteworthy that the Global Forecast System (GFS) model of the NCEP GDAS uses the Noah LSM, as does KLDAS. On the other hand, the current land surface scheme of the ECMWF is the Tiled ECMWF Scheme for Surface Exchanges over Land (TESSEL) described in van den Hurk et al. (2000). Overall, the ERA-Interim data provides relatively low SMC as compared to the GDAS data over East Asia. In addition, to estimate delay of spin-up time induced by the inconsistent LSM, the uniform wet simulation is also conducted by setting the initial SMC as 90 % of the average soil porosity.

Two simulations, namely, NCEP_BM and ECMWF_BM, which are listed in Table 2, are conducted with different starting dates to examine the impact of the East Asian Monsoon on the LSM spin-up behavior. Here, the "BM" runs (i.e. initializations before the monsoon) start from June 1, 2006. As shown in Fig. 1a, a wide belt of significant monsoon rainfall extends from southern China to eastern Japan. Accumulated rainfall during the period of June 1–August 1, 2006 over the Korean peninsula (696 mm) is about 57 % of the annual precipitation over the peninsula (1,217 mm) (Fig. 1b). Therefore, these BM simulations are useful for examining the impact of monsoon rainfall on the spin-up processes of the Noah LSM. Another simulation is conducted by starting the spin-up 3-month earlier than the BM case (i.e., 2006 March) to examine impacts of the starting time and the monsoon dynamics on the spin-up timescale in this region (Table 2). In particular, for better understanding of the relationship between the spin-up period and the monsoon dynamics and the amount of rainfall during summer, we compare the KO and CC regions in Fig. 1. The KO region is significantly influenced by the East Asian monsoon and about 2/3 of the annual rainfall is concentrated during the summer monsoon season. On the contrary, the CC region is relatively drier and the rainfall events evenly distributes throughout the year as compared to the KO region (Fig. 1a).

2.3 Measure of spin-up time

To measure the spin-up time, the percent cutoff (PC) time has been used in this study. The PC time is a measure of how long it takes for yearly changes in monthly averaged model output to decrease to a certain threshold. The yearly

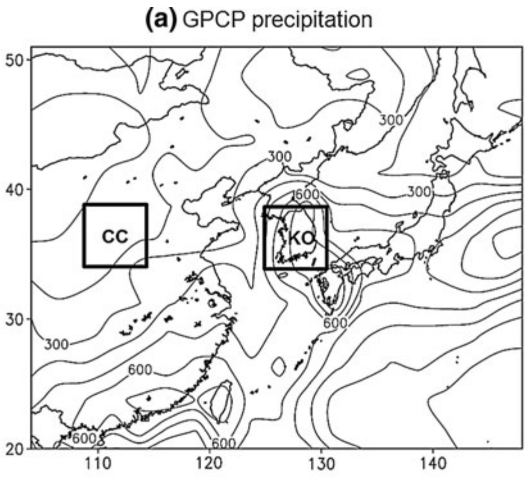
Table 2 Summary of experimental setup

Experiment name	Initial condition	Start time	Input forcings
NCEP_AM	NCEP GDAS	August 1, 2006	KLDAS (Lim et al. 2012) input forcings
NCEP_BM	NCEP GDAS	June 1, 2006	
ECMWF_AM	ECMWF ERA-Interim	August 1, 2006	
ECMWF_BM	ECMWF ERA-Interim	June 1, 2006	
UNIFORM_IC	Soil porosity × 0.9	August 1, 2006	
NCEP_March	NCEP GDAS	March 1, 2006	

change in percent (YCP) between consecutive years is given as

$$YCP = 100 \times \frac{M_1 - M_2}{M_2} \quad (1)$$

where M_1 and M_2 are the monthly average SMC for the previous and current year, respectively. In general, 1, 0.1, and 0.01 % have been suggested as thresholds for the model equilibrium depending on the purpose (e.g., Henderson-Sellers et al. 1993; Yang et al. 1995; Cosgrove et al. 2003; de Goncalves et al. 2006). More details of the PC time and the meaning of each threshold value are given in Cosgrove et al. (2003) and de Goncalves et al. (2006).



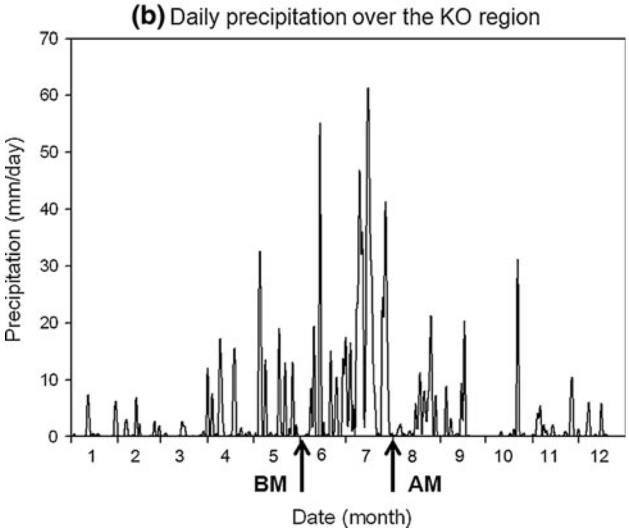


Fig. 1 **a** Accumulated precipitation amount (mm) from GPCP data with 1° resolution during the monsoon period (June–August) in 2006, and **b** time series of daily precipitation amount averaged over the KO region. *Arrows* in **b** indicate the starting times for two 5-year spin-up simulations

3 Results and discussion

3.1 Initial soil moisture content

Initial SMCs obtained from NCEP GDAS (NCEP_AM) and ECMWF ERA-Interim (ECMWF_AM) are compared by showing their difference in percentages, that is, 100 × (GDAS-ERA-Interim)/GDAS in Fig. 2. SMC from the GDAS is more than 10 % greater than that from the ERA-Interim data over the southern half of China, Taiwan, the Korean peninsula and all of the Japanese islands. Significant differences between the initial SMCs of the two analysis systems are found in the KO area (Fig. 2), for which the initial total column SMCs obtained from the GDAS and ERA-Interim data are approximately 613 and 441 kg m^{-2}. On the other hand, in case of the northern part of the continent, the SMC derived from the ERA-Interim data is more than 10 % greater than from the GDAS but the difference of total column soil moisture over that region is relatively smaller compared to the KO region.

Now, we compare the initial SMC with the spin-up fields. Figure 3 shows the percentage difference in the total column SMC between the initial (00 UTC August 1 in year 1, SMC1) and spin-up states (00 UTC August 1 in year 5, SMC5); this is calculated using the expression 100 × (SMC1 − SMC5)/SMC5. When considering the spin-up SMCs of NCEP_AM and ECMWF_AM are nearly same,

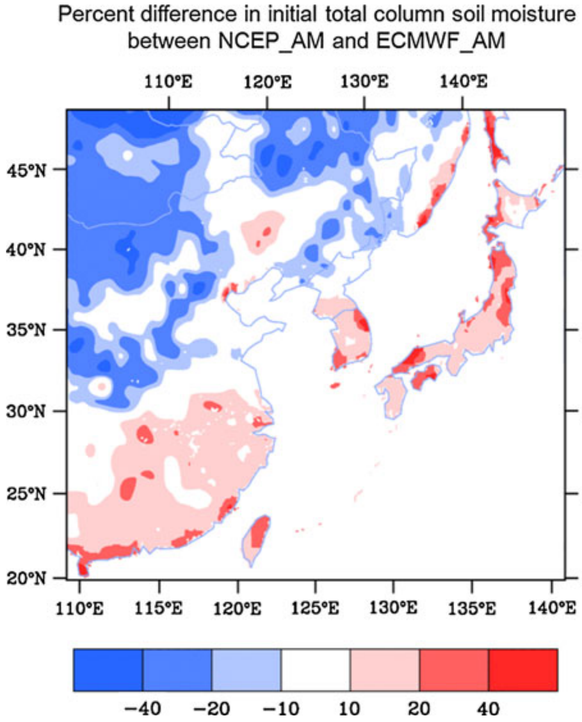


Fig. 2 Percentage difference between the initial SMC from NCEP GDAS and ECMWF-Interim data calculated using the expression 100 × (NCEP − ECMWF)/NCEP

we can interpret the difference shown in Fig. 3 as representing the character of the initial soil moisture fields from a particular analysis system, in comparison with the spin-up fields. For example, a negative area indicates that initial soil is relatively dry compared to the spin-up fields. The figure clearly shows the significant differences between the initial and spin-up soil moisture for the whole land area, suggesting the necessity of the LSM spin-up process.

The initial SMC from the GDAS is significantly larger than the spin-up fields over southern China, most of the Korean peninsula, and the Japanese islands. On the other hand, the opposite is roughly true over much of the abovementioned areas when the initial fields from the ERA-Interim data are used; that is, the initial soil fields are too wet (dry) over these areas for which the GDAS (ERA-Interim) data are used. Over the dry lands of Mongolia and northern China, the spatial patterns of positive and negative areas for both initial data sets are similar. However, an area of excessive soil moisture (compared to the spin-up fields) prevails in the initial soil fields from ERA-Interim, while it is somewhat balanced with the area of moisture deficit for the GDAS. Interestingly, the spatial patterns of percentage difference over southern China, Korea, and Japan in Fig. 3 show some correlation with the rainfall distributions of the two analysis systems (not shown here).

Mesoscale models are commonly initialized using the global model based soil moisture data that are very coarse, and then run a LSM that differs from a LSM producing the coarse initial analysis data. The present study indicates that the initial SMCs provided from the global models are not close to the equilibrium state for the given atmospheric forcing and LSM and thus emphasizing that the spin-up should be done preferably with the consistent LSMs as in the coupled run.

3.2 Spin-up behavior of soil moisture content in East Asia

Figure 4 shows the YCP values for the simulated SMC over the KO region. The decrease in YCP values with time indicates that the soil moisture fields approach the equilibrium state. The simulated SMC converges to the equilibrium state rapidly, despite the large difference between the total SMCs of the initial and spin-up states. The spin-up time required to reach an YCP level of 1 % is slightly less than 5 months when the KLDAS is configured with the same LSM (i.e., Noah LSM). Even when the model is initialized with soil moisture from a different LSM (i.e., ERA-Interim data), the spin-up time is only about 1 year. These spin-up times are generally much shorter than those reported in previous studies. For example, on the basis of one-site simulations using various LSMs, Yang et al. (1995) reported that most LSMs required several years to arrive at equilibrium. On the other hand, Cosgrove et al. (2003) reported a spin-up time of approximately 9 months to reach the 1 % threshold level in North America. However, it should be noted that the difference between the initial and final soil moisture states was less than 10 % in their study.

As mentioned in the previous paragraph, the spin-up time is longer when the initial soil data are derived from an

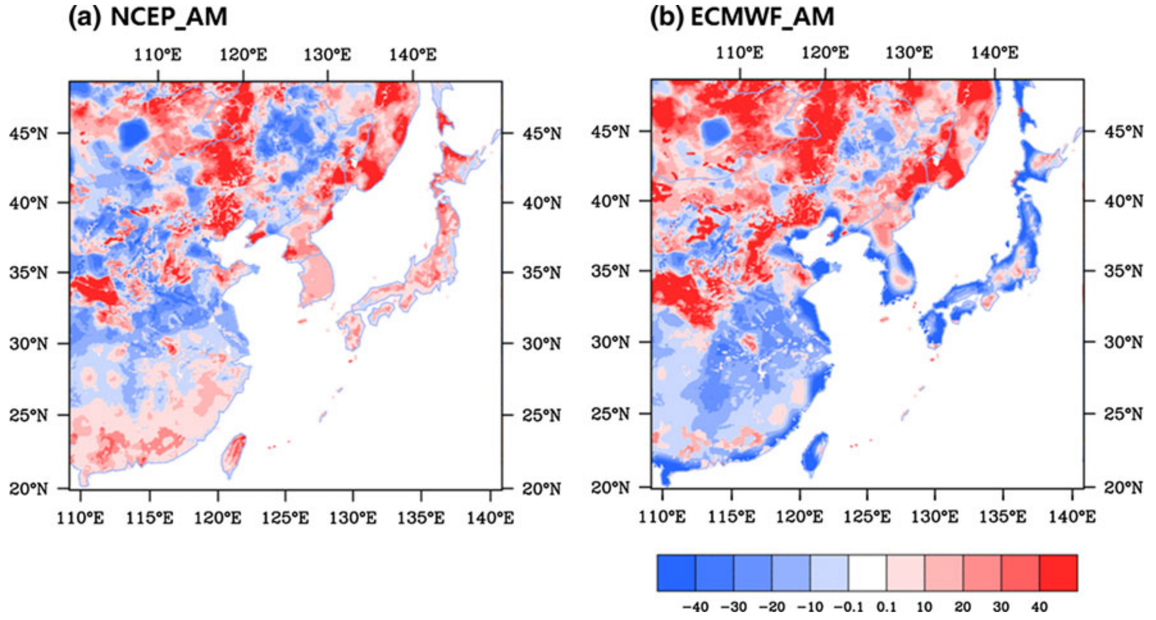


Fig. 3 Percentage difference in the total column SMC between the initial (the first day in year 1, SMC1) and spin-up states (first day in year 5, SMC5): 100 × (SMC1 − SMC5)/SMC5 in **a** NCEP-AM and **b** ECMWF-AM simulations. Positive (negative) area means that initial soil is relatively wet (dry) compared to that for spin-up fields

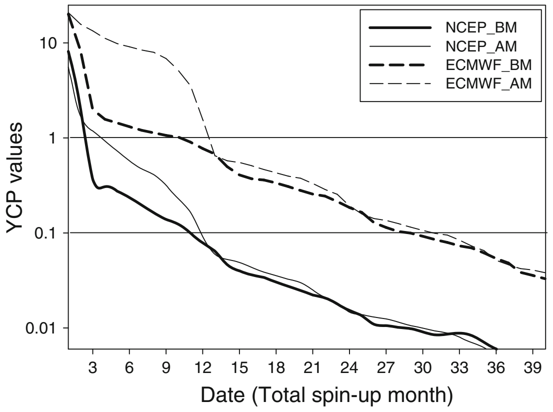
LSM that is different from that used for KLDAS (Fig. 4). That is, simulations performed with the initialization based on the GDAS data converge to the equilibrium state much faster than those performed with the ERA-Interim data. In fact, the GDAS simulations require approximately 8–10 and 16–18 months less than the ERA-Interim simulations to reach the 1 and 0.1 % YCP levels, respectively (Fig. 4a).

It is also noticeable that unrealistic uniform initial SMC reduces the spin-up time over the KO region, as compared to the ERA-Interim based initialization (i.e., the LSM inconsistent initialization) (Table 3). We speculate that the uniformly wet initial SMC is climatologically similar to soil conditions during summer over the KO region because of active monsoon precipitation; that is, wet soil condition of the Uniform_IC is similar to the equilibrium state over the KO region. Our finding indicates that the initialization with even uniform values can save the spin-up time, as compared to that with the spatially and vertically inconsistent soil moisture data, if climatology of the target region is properly represented in the uniform soil water contents.

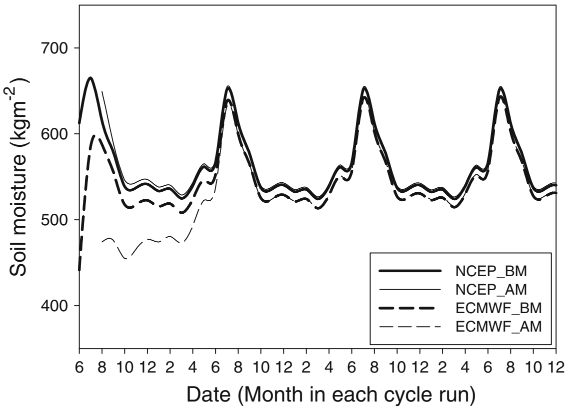
Figure 4 also reveals that monsoon rainfall affects the spin-up time significantly in the KO area. Monsoon rainfall has accelerated the spin-up. In the monsoon area, spin-up time can be dramatically reduced by initializing the KLDAS before the onset of the monsoon (BM cases in Fig. 4). The results of the simulation initialized 3-month earlier than NCEP_BM confirm that the monsoon period plays a significant role on reducing the spin-up time (Table 3). It is found that even though the NCEP_March simulation starts 3 months earlier than NCEP_BM, it is just spun up after the monsoon period with heavy precipitation.

Furthermore, the difference in the SMCs over the KO area between the GDAS and ERA-Interim based simulations decreases rapidly after the monsoon rainfall events, irrespective of when they are initialized. Note that the total column SMCs from the GDAS and ECMWF-Interim simulations become close to each other after spin-up (Fig. 4c). This indicates that through the spin-up process, different sets of initial SMCs effectively converge into an equilibrium state for the given LSM with the same forcing that drive the spin-up simulations.

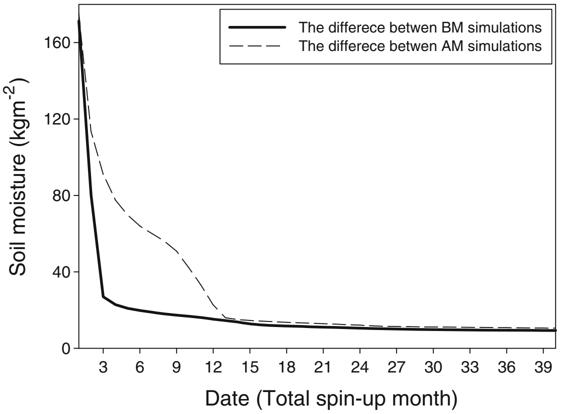
Spin-up behavior of SMC in the root zone and the deepest soil layer is similar to that for the total column SMC (Fig. 5). In particular, the soil moisture content in the deep layer reaches equilibrium at the same rate as the total column SMC, because the soil moisture in this layer accounts for most of the column SMC. The spin-up time required for the SMC in the root zone to converge to the spin-up state is approximately 3–5 months less than that required for the deep soil layer, possibly because of the rapid response of the soil to frequent precipitation events and its relatively shallow soil depth compared to the deep soil layer. This result is similar to that reported by Cosgrove et al. (2003) and de Goncalves et al. (2006). The spin-up behavior over the Central China (CC) region, where the amount of annual precipitation is small



(a) Time series of YCPs of the total column soil moisture content



(b) Time series of the total column soil moisture amount



(c) Time series of the differece of the total column soil moisture between GDAS and ERA-Interim based simulations

Fig. 4 Time series of **a** the YCP values of the averaged total column SMC, **b** total column soil moisture amount, and **c** difference in the total column soil moisture amount between the GDAS and ERA-Interim data simulations for the KO region

Table 3 Comparison of number of months required for monthly averaged total column soil moisture content to reach 1 % PC level in all simulations and the evapotranspiration deviation from the spin-up state at that time

Exp. name	KO		CC	
	Spin-up time	ET deviation (Wm^{-2})	Spin-up time	ET deviation (Wm^{-2})
NCEP_BM	3	1.7	27	1.8
NCEP_AM	5	1.8	28	1.6
ECMWF_BM	12	1.6	27	1.3
ECMWF_AM	13	1.6	33	1.4
Uniform_IC	5	1.8	37	1.5
NCEP_March	5	1.7	28	1.6

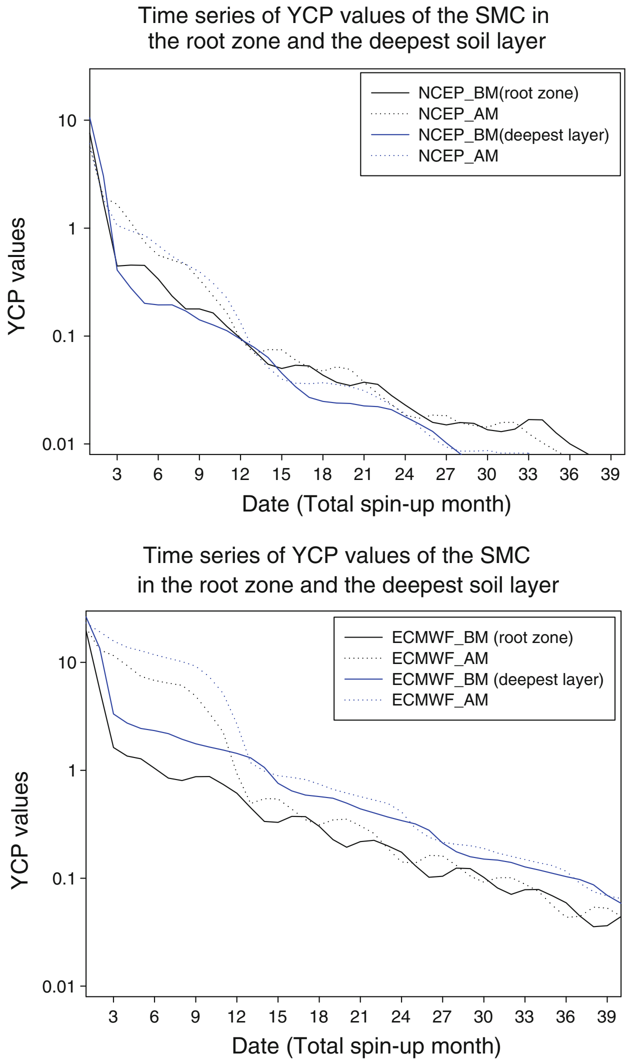


Fig. 5 Time series of the YCP values of SMC in the root zone and the deepest soil layer

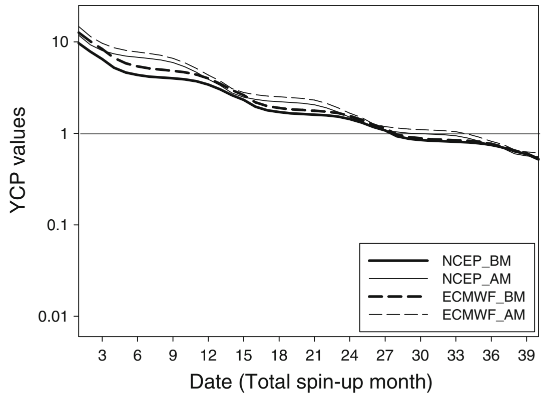
(<300 mm year^{-1}), has also been analyzed (Fig. 6). The difference in initial SMC between the two data sources is approximately 40 kg m^{-2}, which is only 30 % of the difference in the KO area. The spin-up rates in this region are much slow in general, as compared to the KO area. The spin-up time for the CC area is longer than 2 years for all simulations (Fig. 6a). The amplitude of the seasonal variation in the total column soil moisture is about half of that for the KO area (Fig. 6b). Unlike the KO region, the initial homogeneous SMCs given at the Uniform_IC simulation are relatively wetter than the climatology over the CC region and require longer spin-up time.

The spatial distribution of the spin-up time is shown for the whole domain in Fig. 7, in which spin-up time is given as the number of months required for the YCP of total column SMC to reach the 1 % level. Spin-up time is well correlated with the amount of annual rainfall (Fig. 7e) and the evaporative fraction (hereafter EF) (Fig. 7f), which is defined as the ratio of the latent heat flux to the sum of latent and sensible heat fluxes. Overall, the spin-up time of <5 months corresponds to rainfall of 1,000 mm year^{-1} and EF of >0.8. Spin-up takes more than 40 months in the dry land area over the northwestern part of the KLDAS domain. It is also noteworthy that spin-up time is reduced significantly if the spin-up starts before the summer monsoon (i.e., in the BM simulations).

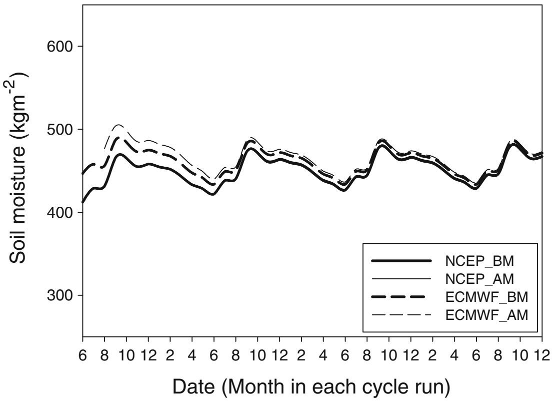
3.3 Spin-up behavior of evapotranspiration in East Asia

Evapotranspiration (ET) transports water vapor in the soil into the atmosphere and changes in soil water contents make impact on the atmospheric processes through ET. When different initial soil water content is provided into the atmospheric model, the atmospheric model starts to respond to the ET calculated from the initial SMC and therefore ET spin-up time can be surrogate of that of SMC especially in a coupled model. ET spin-up time and its relationship with the spin-up of soil moisture have been of interest for previous spin-up studies (e.g., Cosgrove et al. 2003; de Goncalves et al. 2006; Shrestha and Houser 2010). Notably, the previous studies reported disagreeing spin-up times between ET and SMC in the United States. For example, Shrestha and Houser (2010) showed that the SMC spin-up occurred more quickly than the ET. Cosgrove

(a) Time series of YCPs of the total column soil moisture content



(b) Time series of the total column soil moisture amount



(c) Time series of the differece of the total column soil moisture between GDAS and ERA-Interim based simulations

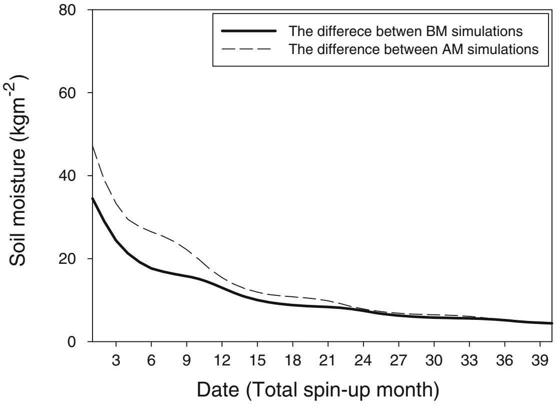


Fig. 6 Time series of **a** the YCP values of the averaged total column SMC, **b** total column soil moisture amount, and **c** difference in the total column soil moisture amount between the GDAS and ERA-Interim data simulations for the CC region

et al. (2003) reported that the relative spin-up timescales of ET to the SMC spin-up were different in five different regions.

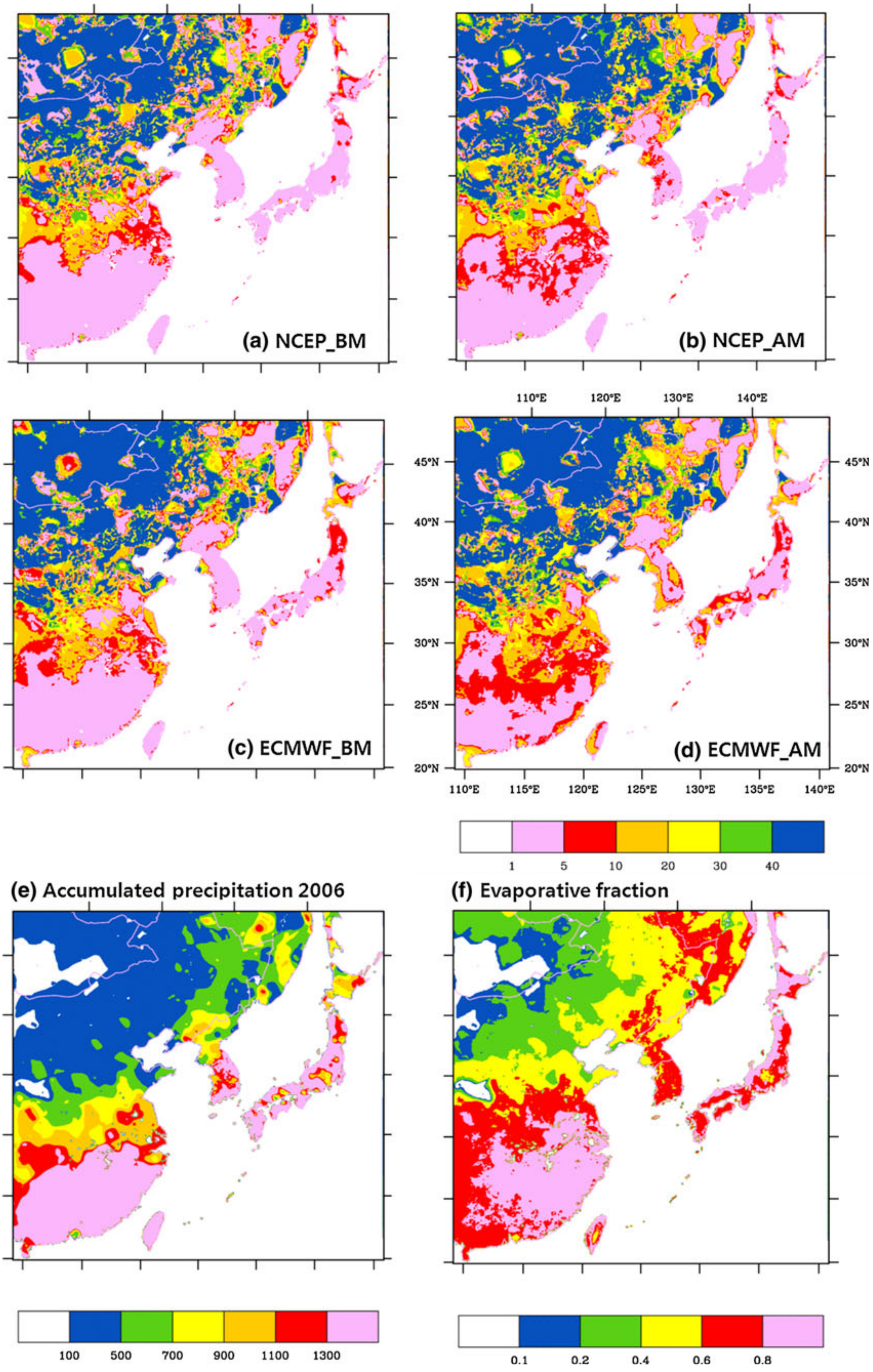
Fig. 7 Spatial distribution of YCP values showing the number of months required for the total column SMC to reach 1 % YCP level in **a** NCEP_BM, **b** NCEP_AM, **c** ECMWF_BM, and **d** ECMWF_AM simulations. **e** Accumulated precipitation for 2006, and **f** the evaporative fraction during the last spin-up cycle in NCEP_BM simulation ▶

Figure 8 compares the spin-up timescales of ET derived from the NCEP_BM and ECMWF_AM simulations over East Asia showing the rapidest and slowest spin-up timescales of soil moisture, respectively. The spin-up of ET shows the similarity to that of soil moisture in general. The ET spin-up time is much faster in the KO area, especially for summer, than that in the CC region. Further, the LSM inconsistency is also clearly observed in the ET spin-up time. As compared to the GDAS simulations, the ERA-Interim simulation shows relatively large ET deviation from the final state, slowly stabilizing with time. The slow stabilization for this simulation is due to both LSM inconsistency and the start time (after monsoon rainfall events).

When the SMC is in a spin-up state, the absolute magnitudes of the ET deviation from the final equilibrium state are only less than 2 Wm^{-2} (Table 3). Notably, we find that ET takes 1–2 months more quickly than SMC to reach the wide ranges of YCP level. Similar to Cosgrove et al. (2003) and Shrestha and Houser (2010), we also find the fluctuations in the YCP of ET, which are also found in the root zone soil water contents. In particular, the local minima of the YCP in Fig. 8 occur in summer and winter seasons when most of annual precipitation occur in East Asia. This indicates that in a coupled model, it is much better to spin up the LSM during or before the heavy precipitation events both in terms of evapotranspiration and soil water contents. Further research is required for better understanding of the impacts of this ET deviation from the equilibrium state on numerical weather prediction and regional climate modeling.

4 Summary and conclusion

In this study, we have investigated the spin-up behavior of soil moisture and evapotranspiration in the offline Noah LSM of the KLDAS, focusing on its quantification in monsoon Asia having wide range of annual precipitation. A 5-year recursive spin-up runs are carried out for three sets of initial soil moisture fields and two different starting times. The simulation set consists of Noah LSM initializations with a spatially uniform soil moisture, NCEP GDAS soil moisture data, and ECMWF ERA-Interim soil moisture data. Each run starts either after or before summer monsoon. In this study, hourly forcing from January 1, 2006 to December 31, 2006 was obtained from the KLDAS based on the in situ rainfall observation, geostationary satellite radiation, global reanalysis data, and the MODIS land products and then recursively used to drive the offline Noah LSM for 5 years. Thereafter, we examined the


(a) NCEP_BM
(b) NCEP_AM
110°E
120°E
130°E
140°E
45°N
40°N
35°N
30°N
25°N
20°N
110°E
115°E
120°E
125°E
130°E
135°E
140°E
(c) ECMWF_BM
(d) ECMWF_AM
1
5
10
20
30
40
(e) Accumulated precipitation 2006
(f) Evaporative fraction
100
500
700
900
1100
1300
0.1
0.2
0.4
0.6
0.8

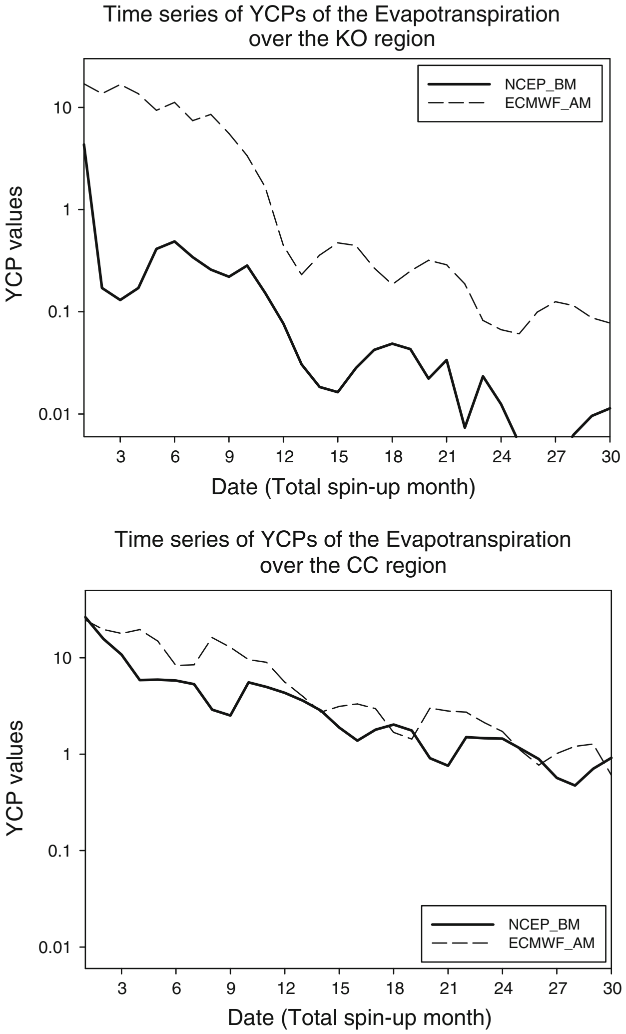


Fig. 8 Time series of the YCP values of the ET in NCEP_BM and ECMWF_AM simulations

behavior of soil moisture spin-up for different sets of initial soil moisture fields and different start times for the spin-up runs.

Initial SMCs from the GDAS are more than 10 % larger than those from the ERA-Interim data over the East Asian monsoon area (e.g., the southern half of China, the Korean peninsula, and the Japanese islands). Both sets of initial SMCs significantly deviate from the equilibrium state (spin-up state) for the Noah LSM and given input forcing, suggesting that spin-up process is necessary even if the LSMs for the prediction and analysis systems are identical. This study also indicates that final spun-up SMCs from the different spin-up runs are close to each other over the model domain; that is, the difference between the initial SMCs of the GDAS and ERA-Interim data does not significantly affect the final spin-up fields.

This study has shown that the spin-up time is reduced when the LSMs for the prediction and analysis systems are identical and when the spin-up simulation starts before monsoon season with heavy rainfall. Notably, the spin-up time is well correlated with the evaporative fraction given by the ratio between the latent heat flux and the available energy at the land surface. It is also found that for the monsoon region in East Asia, the initialization with even uniformly wet soil moisture data reduces the spin-up time, as compared to the ERA-Interim simulations. Consequently, if climatology of the target region is properly represented in the uniform soil water contents, homogenous soil moisture can be better for the LSM initialization than the data estimated from the analysis system using the inconsistent LSM. In particular, when considering the strong connectivity of the spin-up time with the evaporative fraction, the information on the values of uniform soil moisture can be inferred from the evaporative fraction data.

The land surface conditions converge to the equilibrium within a few early months, but such quick convergence to the spin-up state continues if the spin-up simulations start before the onset of heavy rainfall events in summer. For an area with strong monsoon rainfall, the total column SMC and ET spin up quickly, within approximately 1 year, as compared to previous studies over the other continental regions. Furthermore, spin-up time decreases dramatically to only <3 months if the spin-up run starts before the summer monsoon. In contrast to the spin-up for the monsoon rainfall area, spin-up for dry land surfaces takes more than 4 years, although the absolute amount of SMC is relatively small.

Our findings shed light on the spin-up timing and duration for the regional climate modeling. Most regional climate simulations are performed after spinning up the model for a few months and neglecting the first few months of simulation and our study supports that such short spin-up time is possible in East Asia. This study has shown the importance of soil moisture spin-up by showing that there can be significant differences between the initial and spin-up soil moisture fields, which are associated with LSM inconsistencies and insufficient soil moisture spin-up. The use of initial soil moisture fields, that are spun up properly, can improve regional climate prediction by reducing the uncertainties in the initial soil moisture fields. Yet, it remains the future research to understand the dependence of spin-up fields on LSMs and its interplay with the monsoon activity in a coupled model.

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