Evaluation of a multi-satellite soil moisture product and the Community Land Model 4.5 simulation in China

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Abstract

Twenty years of in situ soil moisture data from 306 stations located in China were used to perform an evaluation of two surface soil moisture datasets: (1) a microwave-based multi-satellite product (ESA CCI SM) and (2) soil moisture estimations from the Community Land Model 4.5 (CLM4.5), forced by observation-based atmospheric forcing data. Both soil moisture products generally showed a good agreement with in situ observations, with unbiased root mean square differences (ubRMSD) of 0.05 m^3 m^{-3}. The average Spearman rank correlation coefficient (R_{sp}) between the ESA CCI SM product and all in situ observations was 0.37. In contrast, the CLM4.5 model produced better temporal variation of surface soil moisture (R_{sp} = 0.42) than the ESA CCI SM product, but showed larger ubRMSD in southwestern China, which may have been related to inaccurate precipitation data. The ESA CCI SM product is more likely to be superior to the CLM4.5 model in semi-arid regions, mainly because of the accurate data retrievals and high observation density, but inferior over areas covered by dense vegetation. Furthermore, the ESA CCI SM product showed a stable to

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slightly better performance in China over time, except for a decline in performance during 2007–2010, when different data for the satellite product were blended. Results from this study can provide comprehensive insight into the performances of the two soil moisture datasets in China, which will facilitate improvements in merging algorithms or model simulations and for applications in soil moisture data assimilation.

Key words: soil moisture, remote sensing, CLM4.5, essential climate variable

1. Introduction

Soil moisture is a key variable in hydrological, climatological, biological and ecological processes. It is central to land–atmosphere interactions because of its control on the partitioning of water and energy fluxes at the Earth's surface (Dai et al., 2004). Soil moisture also affects the seasonal and inter-annual dynamics of vegetation, which is an essential component of the coupled hydrological and carbon cycles (Ciais et al., 2005). Many studies have been conducted to obtain estimates of soil moisture using remote sensing techniques (Njoku et al., 2003; Owe et al., 2008; Kerr et al., 2012), land surface modeling (Dirmeyer et al., 2006; Wang et al., 2011; Liu and Xie, 2013) or a combination of both through a land data assimilation system (e.g., Dharssi et al., 2011, de Rosnay et al., 2013).

Spaceborne microwave instruments can provide quantitative information about surface soil water content (Schmugge, 1983), particularly in the low-frequency microwave region from 1 to 10 GHz (Albergel et al., 2012). Several microwave-based soil moisture datasets have been generated using satellite data retrievals from active microwave sensors, e.g. the European Remote Sensing Satellites 1 and 2 Active Microwave Instrument Wind Scatterometer (AMI-WS; Scipal et al., 2002) and Advanced SCATterometer (ASCAT) onboard the Meteorological Operational satellite program (MetOp; Bartalis et al., 2007), and from passive microwave sensors, including the Scanning Multichannel Microwave Radiometer (SMMR; Owe et al., 2008), the Special Sensor Microwave Imager (SSM/I) of the

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Defense Meteorological Satellite Program (DMSP; Owe et al., 2008), the Tropical Rainfall Measuring Mission microwave imager (TMI; Jackson and Hsu, 2001; Gao et al., 2006; Owe et al., 2008), and more recently the Advanced Microwave Scanning Radiometer–Earth observing system (AMSR-E) onboard the Aqua satellite (Njoku et al., 2003; Owe et al., 2008). The AMSR-E radiometer was switched off in October 2011 because of rotation problems with its antenna; however, the AMSR2, launched in May 2012 onboard the Global Change Observation Mission 1–Water (GCOM–W1), was intended to extend its valuable heritage (Parinussa et al., 2015). Even though none of these sensors were specifically designed for measuring soil moisture, good correspondences have been found between the individual datasets and ground-based observations taken over a large variety of environmental conditions (Albergel et al., 2009, 2012; Draper et al., 2009; Gruhier et al., 2010; Brocca et al., 2011).

However, none of the individual microwave products cover the decadal timescales required to be considered for use in climate applications. Recently, a multi-satellite soil moisture dataset (ESA CCI SM) spanning over thirty years was constructed by merging two active and six passive microwave products (Liu et al., 2011, 2012). The combined product, which was initially developed under the European Space Agency (ESA) Water Cycle Multi-Mission Observation Strategy (WACMOS) project, is now being extended and improved within the Climate Change Initiative (CCI) (http://www.esa-soilmoisture-cci.org/; Wagner et al., 2012). A few studies have evaluated the ESA CCI SM product using in situ observations. Liu et al. (2011, 2012) indicated that the merged dataset had a similar accuracy to that of the best input product but with an increased temporal sampling density. Albergel et al. (2013a) found that the ESA CCI SM dataset agreed well with in situ measurements between 2007 and 2010 for 196 sites from five networks across the world, but that its performance over most networks remained poorer than that of the most recent reanalysis

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products. Dorigo et al. (2015) provided a more in-depth evaluation; they used 596 stations from 28 historical and active monitoring networks worldwide. Whilst the performance of the ESA CCI SM dataset appeared to be relatively stable over time, large discrepancies were observed among different networks. In addition, the ESA CCI SM can also capture long-term systematic changes in trends of ground-based observations (Dorigo et al., 2012; Albergel et al., 2013b), which suggests that it has a large potential for climate trend assessments (Loew et al., 2013).

China has the third largest land area and diverse climates and biomes. Previous studies have used only 34 sites for the period 1981–2000 across China and only 20 sites for the period 2008–2010 from the Maqu network in northwest China to investigate the performance of the ESA CCI SM product (Albergel et al., 2013a; Dorigo et al., 2015). Such sparse observations clearly affect the evaluation results, leading to large uncertainties. Recently, Chinese soil moisture observations for 306 sites from 1993 were updated by the China Meteorological Administration (CMA) National Meteorological Information Center (NMIC). These data have been extensively used to investigate the variations of soil moisture and evaluate the land surface modeling (Li et al, 2005; Wang and Zeng, 2011; Liu and Xie, 2013).

Land surface modeling is another strategy to produce large-scale surface and root zone soil moisture estimations. When forced by high quality atmospheric forcing data, this strategy has proved to be an effective tool to complement the commonly use of in situ measurements and for the evaluation of satellite retrievals at both regional and global scales (Albergel et al., 2010, 2012). The ESA CCI SM product has also demonstrated a potential for evaluating climate model performances (Loew et al, 2013; Szczypta et al., 2014). As one of the state-of-art land surface models, the Community Land Model version 4.5 (CLM4.5) from the National Center for Atmospheric Research (NCAR) was released in 2013 (Oleson et al.,

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2013). To our knowledge, few studies have focused on the performance of CLM4.5 soil moisture simulations in China. Lai et al. (2015) validated the temporal variation of soil moisture simulated from the CLM4.0, a previous version of CLM4.5, but used only 30 sites to cover China for the period 1981–1999; they also compared the spatial variation of soil moisture in China using the ESA CCI SM product. However, the performance of the ESA CCI SM product was not discussed in their work.

In this study, we conducted an in-depth evaluation of the ESA CCI SM product and CLM4.5 simulation in China using ground-based observations from 306 sites. We investigated their performances over various sub-regions under different climate conditions. This in-depth evaluation provided a better understanding of the quality of both soil moisture products and their potential problems than was hereafter available, and can be used to improve their accuracy. The soil moisture datasets used in this study and the methodology for their evaluation are described in Section 2. The results and discussion are then presented in Section 3 and Section 4, respectively. Finally, our conclusions are given in Section 5.

2. Material and methods

2.1 Community Land Model (CLM4.5)

The NCAR/CLM is a community-developed model for simulating land surface processes, such as water, energy, and carbon fluxes. The CLM4.5 version is the latest of the CLM family of models (Oleson et al., 2013). It contains several notable improvements over previous releases, including the decrease of biases associated with the modeled terrestrial carbon cycle and modifications of canopy and hydrology processes (Oleson et al. 2013). In CLM4.5, spatial land surface heterogeneity is represented as a nested subgrid hierarchy in which grid cells are composed of multiple land units, snow/soil columns, and plant functional types (PFTs). The model has one vegetation layer, fifteen layers for soil and up to five layers for snow, depending on snow depth. The soil depths for the uppermost five layers are 1.75,

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4.51, 9.06, 16.55, and 28.91 cm. For soil points, temperature calculations are performed over all layers, but hydrology calculations are performed over the top 10 layers only; the bottom five layers are classified as bedrock. A detailed description of the physical processes included within CLM4.5 can be found in Oleson et al. (2013). It should be noted that although CLM4.5 includes the option to be operated with a dynamic vegetation or prognostic carbon-nitrogen model, in our study, CLM4.5 was used with prescribed satellite-based phenology, taken from the Moderate Resolution Imaging Spectroradiometer (MODIS; Lawrence and Chase, 2007).

In this study, CLM4.5 was forced by a 34-yr (1979–2012) observation-based atmospheric forcing dataset from the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (hereafter ITP), with a spatial resolution of 0.1° × 0.1° at a three-hourly temporal resolution over China (15–55 °N, 70–140 °E). This dataset was constructed by merging the observations from 740 operational stations of the CMA with the corresponding meteorological forcing dataset from the Global Land Data Assimilation System (Rodell et al., 2004) to produce near-surface air temperature, pressure, wind speed and specific humidity fields. It combined three precipitation datasets, including ground-based observations and two satellite retrieval products (Chen et al., 2011), to determine the precipitation field. It also corrected the Global Energy and Water Cycle Experiment–Surface Radiation Budget (Pinker and Laszlo, 1992) with reference to radiation estimates (Yang et al., 2010) to ascertain the incident shortwave radiation fields. Chen et al. (2011) demonstrated that simulations driven by the ITP forcing data improve land surface temperature modeling for dry land in China. The soil moisture simulations of CLM3.5, an old version of CLM4.5, forced by four different atmospheric forcing datasets were compared against a common set of in situ observations and results showed that, over most regions of China, the soil moisture estimations forced by the

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ITP forcing dataset had closer correlations with ground-based observations than did the three other simulations (Liu and Xie, 2013).

2.2 ESA CCI SM data

In response to the Global Climate Observing System endorsement of soil moisture as an essential climate variable, the ESA-WACMOS and CCI projects have supported the generation of the ESA CCI SM product by merging multiple microwave-based soil moisture products (Wagner et al., 2012), including passive data derived from SMMR, SSM/I, TMI, and AMSR-E and active data from the ERS and ASCAT (Liu et al. 2011, 2012). The ESA CCI SM version 2.0 (v2.0), released by the Vienna University of Technology in July 2014, was used in this study. Compared to previous versions, the merging schemes and procedures for ESA CCI SM v2.0 has been improved. Furthermore, the dataset was extended to the year 2013 by including the WindSat and AMSR2 data (Parinussa et al., 2012, 2015). Initially, the ESA CCI SM data were separated into two homogenized products (one for active and one for passive data); and then merged into a single active-passive product according to their relative sensitivity to vegetation density (Liu et al, 2011, 2012; Wagner et al., 2012). The ESA CCI SM has a spatial resolution of 0.25° × 0.25° (unit: m^3 m^{-3}) and a daily time-step centered at 0:00 UTC, although the actual observation time corresponds to that of the input products at a specific time (Liu et al., 2012). Quality "flags" of the input products were transferred to ESA CCI SM to mask pixels affected by snow coverage, temperature below 0 °C, dense vegetation, and pixels where the retrieval of soil moisture data failed (Dorigo et al., 2015).

2.3 In situ measurements in China

This study made use of in situ soil moisture measurements from agricultural meteorological stations across mainland China, collected by the CMA-NMIC, to evaluate the ESA CCI SM and CLM4.5. The original data for 20 years (1993–2012) from 778 stations were obtained every 10 days (i.e., on the 8th, 18th and 28th day of every month) at soil

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depths of 0–10, 10–20, 20–50, 50–70 and 70–100 cm, respectively. No measurements were recorded in frozen soil. Soil water content was measured using the gravimetric technique and originally recorded as mass percentage. It was converted to volumetric soil moisture using field capacity and soil bulk density observations (Liu and Xie, 2013). This soil moisture observation dataset has been widely used to study temporal variations in soil moisture and evaluate land surface model simulations in China (Li et al., 2005; Wang and Zeng, 2011; Liu and Xie, 2013), and is constantly updated. However, not all datasets are suitable for the evaluation of remote sensing products and model simulations. In this study, we used a simple quality control procedure (Wang and Zeng, 2011; Liu and Xie, 2013) on the updated soil moisture observations in terms of observation frequency; specifically, the ratio of valid measurements during the period from March to October (1993–2012) was required to be greater than 50%. It is noted that if more than one in situ station remained in a single 0.25° grid box, only one of them was included. The correlation check method was adopted to remove the redundant sites (Dorigo et al., 2015); in this procedure, the correlation between the in situ measurements and ESA CCI SM product and that between the in situ measurements and CLM4.5 were first calculated, respectively, and their average value was compared for each site, after which the site with the highest average correlation was selected. Finally, the monthly soil water content values at depths of 0–10 cm at 306 stations were used in this study to evaluate the remotely sensed and simulated values. These stations were grouped into eight sub-regions on the basis of the spatial patterns of the centers of dryness and wetness throughout China, based on Zhu (2003) and Liu and Xie (2013), and are defined in Table 1. Figure 1 shows the eight sub-regions and the location of all 306 in situ measurement sites, 289 of which were located in the eight sub-regions in this study.

2.4 Evaluation strategy

For the CLM4.5 simulation, we first spun up 300 years by repeating 30-yr (1979–2009)

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ITP meteorological forcing data to achieve an equilibrium state. The 1979–2012 atmospheric forcing data were then used to force CLM4.5 and the simulated results were used in this study. To be consistent with the ESA CCI SM dataset, these simulations were all made at spatial resolution of 0.25° × 0.25° at 30-min time-steps. It should be noted that the data affected by snow cover and temperatures below 0 °C for both the in situ measurements and CLM4.5 predictions between March and October were masked using the quality flags of the ECV CCI SM product. Given the low temporal frequency of the in situ datasets, the validation of the ESA CCI SM and CLM4.5 was conducted at the monthly timescale to reduce the effect caused by the mismatch between actual observation and model time (Wang and Zeng, 2011; Liu and Xie, 2013). Only daily data of the ESA CCI SM product and CLM4.5 simulation on the days of each month when in situ observations were available were used to compute their monthly mean values.

The 'nearest neighbor' approach was retained to match the grid point location from the ESA CCI SM product or CLM4.5 simulation with that of the in situ measurements. Since soil layer thickness of CLM4.5 model did not match that of in situ observations (0−10 cm), the weighted average was computed based on top four soil layer thicknesses (1.75, 2.76, 4.55, 0.94 cm, respectively).

Previous studies (Loew et al., 2013; Dorigo et al., 2015) pointed out that the statistical metrics, e.g., the bias and the root mean square difference (RMSD), principally reflected the differences between the in-situ data and the GLDAS-Noah model dataset that was used as a reference for scaling, and thus were scientifically not meaningful. Besides, at the level of the individual stations little is known about the accuracy of the measurements themselves and the ability of the sites to represent absolute soil moisture levels over the coarse satellite footprint scale (Gruber et al., 2013). Therefore, the unbiased RMSD (ubRMSD) was used to express differences in soil moisture levels in this study, and can be calculated using Eq. (1):

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$$\mathrm{ubRMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(S_i - \overline{S}) - (O_i - \overline{O})\right]^2}, \qquad (1)$$

in which S represents soil moisture from either the ESA CCI SM dataset or CLM4.5 simulation, O is the in situ measurement and $\overline{S}$ and $\overline{O}$ are the corresponding mean values related to S and O. It is noted that, prior to computing the ubRSMD, both the ESA CCI SM dataset and CLM4.5 simulations were scaled into the dynamic range of the in situ data using a linear rescaling method based on the mean and standard deviation (Brocca et al., 2013):

$$S_{res} = \frac{S - \overline{S}}{\sigma_S} \times \sigma_O + \overline{O}, \qquad (2)$$

where S_{res} is the linearly rescaled soil moisture dataset, and σ_S and σ_O are the corresponding standard deviations related to S and O, respectively. In addition, the Spearman rank correlation (R_{sp}) was calculated to describe the temporal agreement between the in situ data and the ESA CCI SM dataset and CLM4.5 simulation (Dorigo et al., 2015).

Because the different products used to develop ESA CCI SM vary over space and time, the differences in the microwave observation channels and sampling densities are expected to influence the quality of the different periods for evaluating the new merged satellite product (Liu et al., 2012; Dorigo et al., 2015). The following describes the eight sub-periods used to construct the ESA CCI SM dataset (Albergel et al., 2013a; Dorigo et al., 2015):

- blend 1: January 1979–August 1987, based on SMMR observations only;
- blend 2: September 1987–June 1991, based on SSM/I only;
- blend 3: July 1991–December 1997, based on a combination of SSM/I and ERS AMI;
- blend 4: January 1998–June 2002, based on a combination of TMI and AMI between 40 °N and 40 °S, and a combination of SSM/I and ERS AMI elsewhere;
- blend 5: July 2002–December 2006, based on a combination of AMSR-E and ERS AMI;

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- blend 6: January 2007–September 2011, based on a combination of AMSR-E and ASCAT;
- blend 7: October 2011–June 2012, based on a combination of WindSat and ASCAT;
- blend 8: July 2012–December 2013, based on a combination of AMSR2 and ASCAT.

To illustrate the potential effects of these developmental stages on the quality of the ESA CCI SM dataset, the product evaluation was repeated for the last five time periods (during which in situ observations were available).

3. Results

3.1 Availability of the ESA CCI SM data in China

Previous studies (Loew et al., 2013; Dorigo et al., 2015) showed that the performance of the ESA CCI SM product may be strongly affected by data gaps and the period of observation. Therefore, we first analyzed the data availability of the ESA CCI SM product in China for the entire period (1979–2013) as well as for the eight individual time periods (described in Section 2.4). A clear increase of observation density can be observed over time (Fig. 2), which is mainly due to the growing number of satellites available for soil moisture data retrieval (Liu et al., 2012; Dorigo et al., 2015). The improved instrument design and sensor performance also contributes to this effect. Better sensors have led to a convergence of active and passive remote sensing products, especially over areas with intermediate vegetation cover (Liu et al., 2012), and an increase over time in the number of areas where both products are used in a synergistic way.

For example, for the second period (1 September 1987–30 June 1991), the ESA CCI SM product was generated using the SSM/I Ku-band (19.3 GHz) data alone, which was strongly attenuated by the vegetation canopy; thus, large areas were masked due to moderate to dense vegetation, such as northeast and southern China (Fig. 2b). The introduction of the ERS AMI C-band (5.3 GHz) scatterometer during the subsequent period (1 July 1991–31 December 1997) was able to partly fill these gaps (Fig. 2c), e.g. there was a clear increase in the number

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of observations over southern China. With the introduction of the high quality AMSR-E C-band (6.9 GHz) data in July 2002, a large increase of the observation density can be found over most areas of China, except the Tibetan Plateau (Fig. 2e). As a result of the unavailability of the AMSR-E data in October 2011, the observation density decreased over large parts of northwest China and Inner Mongolia, which are mainly arid or semiarid areas, despite the inclusion of the high quality WindSat data for this period (Fig. 2g). In addition, the introduction of the AMSR2 product clearly increases the fractions of valid observations over most areas of China, except central and southern China (Fig. 2h).

3.2 Evaluation using in situ data

Figure 3 presents the Spearman rank correlation coefficients (R_{sp}) of the ESA CCI SM product and CLM4.5 simulation against in situ measurements, in which the values from both techniques are ranked using the same intervals. The data gaps for the ESA CCI SM product (Fig. 2) lead to only 299 stations available; over 61% of these stations had correlation values between 0.2 and 0.6 (shown in green and purple, Fig. 3a), with a mean of 0.27 (Table 2). In contrast, the CLM4.5 model captured surface soil moisture temporal variability better (averaged R value is 0.35, Table 2) than the ESA CCI SM product; about 10% of the stations had R_{sp} values greater than 0.6 (shown as orange and blue, Fig. 3b), whereas only 5% stations for the ESA CCI SM achieved such correlations (Fig. 3a). When only the configurations associated to significant correlation values ($p \leq 0.05$) are considered (cycles), there were 212 and 253 stations available for the ESA CCI SM and CLM4.5, respectively. In the current study, the averaged R_{sp} value of the ESA CCI SM is 0.37, which is slightly higher than that (R_{sp} = 0.32) from 34 sites over China in Dorigo et al. (2015); the averagd R_{sp} is 0.42 for the CLM4.5 model.

As described in several studies (Liu et al., 2011, 2012; Dorigo et al., 2015), the mean and dynamic range of the ESA CCI SM time series represent those of the GLDAS-Noah

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surface soil moisture product. Therefore, we used a linear rescaling method (Eq. 2) to rescale both the ESA CCI SM dataset and CLM4.5 soil moisture predictions prior to computing their ubRMSDs (Brocca et al., 2013) against in situ measurements (Fig. 4). For the ESA CCI SM product, there were 214 stations (72% of total) with the ubRMSD values less than 0.06 m^3 m^{-3}. The CLM4.5 showed a slightly improved ubRMSD, of which about 29% of the stations had a value less than 0.04 m^3 m^{-3} (Fig. 4b), compared to 22% using the ESA CCI SM product (Fig. 4a). Table 2 shows that averaged ubRMSD values are 0.053 and 0.050 m^3 m^{-3} for the ESA CCI SM product and CLM4.5 simulation, respectively, which suggests that the CLM4.5 simulation is closer to in situ measurements in China than is the ESA CCI SM product. When only sites with a significant ($p < 0.05$) positive Spearman's correlation were considered (cycles in Figs. 3 and 4), the averaged ubRMSD values were 0.050 and 0.048 m^3 m^{-3} for the ESA CCI SM product and CLM4.5 simulation, respectively. It should be noted that because the ubRMSD is only an indication of the mismatch between in situ data and remote sensing or model simulated datasets, the errors in each dataset are also included. The triple collocation technique has proven to be an independent technique for estimating the random error component of soil moisture datasets and been applied to the direct comparison with the ubRMSD metric (Dorigo et al., 2010; Gruber et al., 2013; Dorigo et al., 2015). Therefore, future work is expected to use this method to reduce the effect of random errors in each dataset on the comparison.

3.3 Performances over eight sub-regions

Since soil moisture has a close relationship with the status of climate dryness and wetness, eight sub-regions were defined (Table 1 and Fig. 1) in this study based on Zhu (2003), which used a time series for dryness and wetness encompassing the last 530 years to analyze the spatial patterns of the centers of dryness and wetness throughout China by applying the rotated empirical orthogonal function method. To evaluate the performance of the satellite-based product and process-based model simulation over eight sub-regions, two evaluation strategies were adopted in our study: (1) we computed the statistical metrics for the stations individually (e.g., Figs. 3 and 4) and then averaged their values over each region (hereinafter referred to as "S1"); (2), we generated the time series of soil moisture by averaging available observations at all stations of each region, only considering those grid cells closest to the relevant observation stations for the ESA CCI SM product and CLM4.5 simulation, and then calculated their statistical metrics against in situ measurements (hereinafter referred to as "S2"). It should be noted that only sites with a significant ($p < 0.05$) positive Spearman's correlation (cycles in Figs. 3 and 4) for both ESA CCI SM product and CLM4.5 simulation were considered in the following analysis whatever the evaluation strategy. After screening using the criteria above, 200 stations remained available for the following evaluation, 189 of which were located in the eight sub-regions; the number of valid stations for each sub-region is shown in Table 2 (in the brackets). The statistical metrics of the ESA CCI SM product and CLM4.5 simulation against in situ measurements for both evaluation strategies are presented in Fig. 5.

Over most regions (except for China V), the ESA CCI SM product, of which average ubRMSD values ranged between 0.044 and 0.059 $m^3\ m^{-3}$, had slightly higher ubRMSD values than CLM4.5 simulations (0.042–0.056 $m^3\ m^{-3}$) for the first evaluation strategy (Fig. 5a), which is consistent with the results from Fig. 4 and Table 2. Figure 5b shows that the average Spearman correlation coefficients of the ESA CCI SM product ranged between 0.27 and 0.47, while higher correlations in situ measurements were achieved by CLM4.5 simulations (0.34–0.54), except in China V. Good performance over China V, which is a semi-arid region, for the ESA CCI SM product was also found by Albergel et al. (2013b) and Dorigo et al., (2015) using in situ observations from the Maqu network, which is located over the southern part of this sub-region. Our finding suggests that the ESA CCI SM product has a

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已删除: underestimates soil moisture (negative values) except for southwest China (China VII and VIII, Fig. 5a). Conversely,

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good potential for application in areas where models cannot realistically represent soil moisture (Albergel et al., 2013b).

Compared to S1, the other strategy (S2) showed large variations in ubRMSD (Fig. 5a) and R_{sp} (Fig. 5b) between different sub-regions. However, the two strategies produced similar results although CLM4.5 simulations showed a slightly higher R_{sp} and lower ubRMSD than the ESA CCI SM product. In addition, compared with performance in other regions, both remotely sensed and modeled soil moisture datasets showed larger ubRMSD values over southwest China (China VII and VIII), which is mainly covered with moderate to dense vegetation, including mixed evergreen coniferous and broadleaf deciduous forests, and broadleaf deciduous forests. This result is mainly due to strong attenuation by the vegetation canopy of the microwave retrievals for the ESA CCI SM product (Liu et al., 2012; Dorigo et al., 2015). For the CLM4.5 simulation, the precipitation data in the ITP atmospheric forcing data were generated by merging ground-based observations and two satellite retrieval products, because few in situ precipitation measurements were available over these areas (Chen et al., 2011).

Figure 6 compares the annual soil moisture cycle (March−October) of the ESA CCI SM product and CLM4.5 simulation against in situ measurements, averaged over the eight sub-regions using the S2 evaluation strategy (without the linear scaling). Both the ESA CCI SM product and CLM4.5 simulation generally captured the annual cycle well in most sub-regions. However, soil moisture simulated by the CLM4.5 model was usually greater than the observations, showing systematic overestimation in all sub-regions except for China VI and VIII; this is consistent with the research of Liu and Xie (2013), which was based on simulations with the CLM3.5 model using the same atmospheric forcing data as we used. The comparable findings suggest that land surface model simulation may reproduce temporal variations well, but fail to simulate the mean soil moisture (Entin et al., 2000; Gao and

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Dirmeyer, 2006; Liu and Xie, 2013). In contrast, the ESA CCI SM product was closer to matching in situ measurements than the CLM4.5 model over some areas (e.g., China V in this study, a semi-arid region), although it represents the dynamic range of the GLDAS-Noah surface soil moisture product (Liu et al., 2012; Dorigo et al., 2015).

3.4 Comparison of the anomaly time series

The results presented above are based on comparisons of the multi-year observation dataset and the ESA CCI SM or CLM4.5 datasets on a monthly timescale, which may be somewhat affected by the seasonal cycle of soil moisture. The time series of the soil moisture anomaly from the three datasets (ESA CCI SM, CLM4.5, and in situ observations) for the eight sub-regions using the S2 strategy (Section 3.3), computed by removing the multi-year annual cycle (only March−October available), are presented in Fig. 7. In general, both the ESA CCI SM product and the CLM4.5 simulation captured the temporal evolution of the observed soil moisture anomalies reasonably well for most of the regions, except a slight overestimation in the amplitude of fluctuations over China VII and VIII by the ESA CCI SM product, which was consistent with the results shown in Fig. 5.

As a further quantitative illustration of the effects of seasonal cycle on the evaluation results, Fig. 8 shows the Spearman correlation coefficients (R'_{sp}) for the anomaly data of both the ESA CCI SM product and CLM4.5 simulation over the eight sub-regions. In general, R'_{sp} values (Fig. 8) were lower than R_{sp} (Fig. 5) for most sub-regions, especially over China VI and VIII. This differences suggested that the seasonal cycle in soil moisture has a large effect on the comparison of Spearman correlation values over the areas with pronounced wet and dry periods (Liu et al., 2012; Albergel et al., 2013a; Dorigo et al., 2015).

3.5 Evolution of the ESA CCI SM over time

The microwave observation channels and sampling densities were expected to affect the quality of the dataset for different periods because the different products that were used to

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generate the ESA CCI SM dataset vary over space and time (Liu et al., 2012; Albergel et al., 2013a). Figure 9 presents the averaged ubRMSDs and R_{sp} of the ESA CCI SM product for the last five individual time periods defined in Section 2.4. Due to limited time length and sparse samples for the last two blended periods (blend 7 and blend 8), they were combined into one period. Considering the sites that have significant R_{sp} values (p = 0.05) for all periods (denoted by red in Fig. 9), averaged correlations ranged from 0.42 to 0.62 while ubRMSD values ranged from 0.024 m^3 m^{-3} to 0.045 m^3 m^{-3}. A similar pattern was obtained when considering the sites for which the correlation was significant for each blended period with averaged R_{sp} values ranging from 0.56 to 0.93.

For the fourth period (January 1998–June 2002), a higher correlation was observed (Fig. 9b) compared to the previous period (January 1993–December 1997), which may be related to the introduction of the circular non-polar orbiting TMI data in 1998 (Doirgo et al., 2015). In July 2002, a high quality soil moisture dataset from C-band AMSR-E retrievals was introduced instead of the SSM/I and TMI, which increased the correlations of the ESA CCI SM dataset with in situ measurements and reduced its ubRMSD values for the fifth period (July 2002–December 2006). These observations were consistent with the results of the comparison between the ESA CCI SM and the ERA-Land, an update of the land surface component of the ERA-Interim reanalysis from the European Centre for Medium-Range Weather Forecasts (Albergel et al. 2013a), and that between the ESAI CCI SM product and in situ measurements from other soil moisture networks (Dorigo et al., 2015). Unexpectedly, there was a decrease in quality in the sixth period (January 2007–September 2011), with weaker correlations and higher ubRMSD (Albergel et al., 2013a, Dorigo et al., 2015). The cause of this degradation is still not entirely clear, but it may be related to the resampling and scaling strategy used to incorporate a new active input product from ASCAT (Dorigo et al., 2015). The best performance for all metrics was obtained for the last two periods (October

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2011–December 2012), which was expected, given the higher quality satellite instrumentation (AMSR2) and improved retrieval algorithms. However, the shorter length of time within the two periods may have had a slight effect on the statistical metrics and therefore more in situ measurements would be needed to confirm our results.

4. Discussion

During the past twenty years, huge efforts have been made to make more in situ soil moisture observations available in China. These measurements are important for the evaluation of both remotely sensed and modeled soil moisture. In this study, we evaluated the performances of the ESA CCI SM product and CLM4.5 simulation in China using 20 years of in situ observations from 306 sites. However, some limitations to the evaluation should be noted. The spatial representativity, temporal mismatch, instrumental errors, and installation depth of in situ observations may have had a negative effect on the evaluation results. Such limitations have been extensively reported in previous studies (Brocca et al., 2010; Crow et al., 2012). Therefore, future work is expected to reduce these uncertainties through the enhancement of ground-based measurements and the improvement of the evaluation strategy. In addition, soil moisture was measured using the gravimetric technique. This destructive sampling method may affect the evaluation results (Dorigo et al., 2015). According to the user guide of in situ soil moisture measurements from agricultural meteorological stations of CMA (in Chinese, http://cdc.nmic.cn), soil moisture observation technique can be summarized as follows: (1) the observation field of each station is divided to four parts and four soil samples will be collected each time; (2) their soil moisture contents in dry weight basis (the ratio of water mass to dried soil's weight) are determined by drying the soil, respectively; (3) the average value from the four samples are recorded as mass percentage for this station. It is noted that the horizontal distance between two successive samples at the same part of each station is no more than 2 meters, which leads to almost the same

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meteorological and soil conditions. Moreover, to reduce the effect of soil moisture heterogeneity, the station was usually chosen to be over flat surface. However, the original observations from the four samples at each station were not available; thus, we could not investigate the effect of destructive sampling on the comparison results in this study. Previous studies (Brocca et al., 2014a, b) showed that soil moisture had enormous variability even at local scales, in particular in absolute terms. These methods will be used in our future work to discuss the impacts of spatial variability and destructive sampling method.

Land surface models can capture the temporal dynamics of soil moisture well when forced by high quality atmospheric forcing data (Albergel et al., 2010, 2012) and are usually employed to upscale in situ surface soil moisture observations or complete the evaluation of satellite derived products (Albergel et al., 2013a). In this study, the CLM4.5 was forced by an atmospheric forcing dataset generated using many ground-based observations, and showed better correlation with in situ soil moisture observations than did the ESA CCI SM product. However, many precipitation measurements were located in the same 0.25° grid box as the in situ soil moisture observations; although the two types of data were obtained from different sources and were not collected at the same locations, it was necessary to investigate the effect of in situ precipitation measurements on the comparison results. The averaged statistical metrics over the sites with ("Rain") and without ("No Rain") in situ precipitation measurements are presented in Fig. 10. It is noted that only the sites (200 of 306) with a significant ($p < 0.05$) positive Spearman's correlation for both the ESA CCI SM product and CLM4.5 simulation were considered, as described in Section 3.2. Figure 10 shows that, for the CLM4.5 simulation, in situ precipitation measurements (101 of 200) led to a slightly higher correlation (R_{sp} = 0.46) with in situ soil moisture measurements than was obtained without the precipitation measurements (R_{sp} = 0.44, 99 of 200). This may be related to the issues of spatial resolution. The observations from 740 operational stations of the CMA were

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merged with other meteorological forcing datasets to generate the ITP forcing data with a spatial resolution of 0.1° × 0.1°, while the CLM4.5 was run at 0.25° × 0.25° resolution in this study. If the CLM4.5 had been run at 0.1° × 0.1° resolution, the effect of ground-based precipitation on the comparison results may have been clearer (not shown in this study).

The in situ observations used in this study are average soil moisture values of surface soil of 0−10 cm; to be consistent with the in situ observations, the weighted average of CLM4.5 at 0−10 cm was computed based on the uppermost four soil layer thicknesses (Section 2.4). However, the ESA CCI SM data represent the upper 0−2 cm of the soil (Liu et al., 2011, 2012; Dorigo et al., 2015). As in situ soil moisture observations of 0−2 cm are not available, it is difficult to investigate the effect of the mismatch between soil depths on the statistical results. Instead, we compared the in situ observations and ESA CCI SM data with average soil moisture values of CLM4.5 at different soil depths: first layer (“L1”, 0−1.75 cm), uppermost two layers (“L1−2”, 0−1.75 cm, 1.75−4.51 cm), uppermost three layers (“L1−2−3”, 0−1.75 cm, 1.75−4.51 cm, 4.51−9.06 cm), 0−2 cm, 0−5 cm, and 0−10 cm. Their statistical metrics, including ubRMSD and R_{sp}, are presented in Fig. 11. Results showed that the choice of soil depth for CLM4.5 had a significant effect on the statics. The average R_{sp} against in situ observations ranged between 0.417 and 0.425 at different soil depths while the ESA CCI SM had higher R_{sp} values and a larger range, which was between 0.507 and 0.546. CLM4.5 agreed better with in situ observations at 0−10 cm than those at other soil depths, confirming that it is better to evaluate the CLM4.5 using the weighted average values at 0−10 cm. In contrast, the best agreement between the CLM4.5 simulation and ESA CCI SM product was found at the first layer (0−1.75 cm). These findings suggest that the mismatch in soil depths between the ESA CCI SM and in situ observations may have had a large effect on the statistical metrics, which is one of the reasons for its higher ubRMSD and lower R_{sp}.

In addition, although the CLM4.5 model had better performance against in situ

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observations than the ESA CCI SM product over most regions in China, there were still many unrealistic representations in model parameterizations (soil water and temperature, for example) and large uncertainties in land surface datasets (such as soil texture and PFTs) for the CLM4.5 model, which affected its accuracy in soil moisture simulation. To improve soil moisture estimations, many studies have incorporated remotely sensed brightness temperatures (Jia et al., 2013) or soil moisture retrievals (Draper et al., 2012) into land surface models using various modern land data assimilation systems. Our study provides an in-depth evaluation of both the ESA CCI SM product and CLM4.5 model in China, including their performances over different sub-regions. This evaluation is expected to be useful for the assimilation of the ESA CCI SM product into land surface models, especially the CLM4.5, because the observation and model errors have been estimated approximately.

For the ESA CCI SM product, only soil moisture retrievals acquired by night time overpasses (occurring between 19:00 and 08:00 local time) were used (Liu et al., 2012) because all input products had varying local observation times (Dorigo et al., 2015). However, the original in situ soil moisture observations were available every 10 days (three times each month) and the time step of CLM4.5 was 30 min. To reduce the effect caused by the mismatch between actual observation and model time, we compared the three datasets at a coarser time scale using their monthly values, in a similar way as previous studies (Li et al., 2005; Wang and Zeng, 2011; Liu and Xie, 2013). However, it should be noted that the effect of the temporal mismatch among different soil moisture datasets was not considered in this study.

5. Conclusions

In this study, the performances of a microwave-based merged satellite product (ESA CCI SM) and the CLM4.5 simulation were investigated using 20 years of in situ observations from 306 stations in China. In general, both soil moisture products represent in situ

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observations well, with ubRMSD values of about 0.05 $m^3\ m^{-3}$. The ESA CCI SM product has slightly weaker Spearman correlations (R_{sp} = 0.37) than the CLM4.5 model, but the CLM4.5 simulation produces better temporal variation of surface soil moisture (R_{sp} = 0.42).

Both the satellite product and model simulation show large discrepancies over eight sub-regions in China. The CLM4.5 model shows larger ubRMSDs in southwestern China (China VII and VIII) than other regions, which may be related to the scarcity of in situ precipitation measurements available in these areas. The ESA CCI SM product is likely to be best-suited for applicaiton in semi-arid regions (such as China V), even better than the CLM4.5 model, mainly because of accurate data retrievals and high observation density; in contrast, the ESA CCI SM product is not well suited for areas covered by dense vegetation (such as China VII and VIII). In addition, the statistical scores of the ESA CCI SM product in China corroborate the findings of Albergel et al. (2013a) and Dorigo et al. (2015) of a stable to slightly improving performance over time in China, with the exception of a decrease during the 2007–2010 blending period, which may be related to the resampling and scaling strategy used to incorporate the ASCAT product into the ESA CC SM dataset.

In response to the sparse observation temporal frequency (three times each month), all analyses were performed on a monthly timescale. Future efforts are expected to make more in situ soil moisture observations available in China for the evaluation of either remote sensing retrievals or modeled simulation. Furthermore, data assimilation has been an effective tool to incorporate remotely sensed soil moisture into land surface models to improve soil moisture simulation (Draper et al., 2012). The in-depth evaluation of the ESA CCI SM product and CLM4.5 model in China provided by this study will facilitate soil moisture data assimilation, which is expected to provide further information regarding observation and model errors.

Acknowledgements

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Table 1. Locations of the eight sub-regions in China.

Identification	Region Name	Location	Number of Observational Stations
China I	northeast China	120–135 °E, 40–50 °N	61 (40)
China II	northern North China	110–120 °E, 40–45 °N	15 (5)
China III	southern North China	110–120 °E, 34–40 °N	57 (47)
China IV	central and lower Yangtze River Basin	110–122 °E, 30–34 °N	28 (18)
China V	eastern northwest China	95–110 °E, 34–42 °N	77 (53)
China VI	western northwest China	80–95 °E, 34–50 °N	20 (8)
China VII	northern southwest China	100–110 °E, 28–34 °N	22 (12)
China VIII	southern southwest China	100–110 °E, 20–28 °N	9 (6)

[a]The values in the brackets represent the number of sites having significant ($p < 0.05$) positive Spearman's correlations for both the ESA CCI SM product and CLM4.5 simulation.

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Table 2. Averaged performance metrics and standard deviations of the ESA CCI SM product and CLM4.5 model for all available in situ sites. (Stations: Number of stations; N: Averaged value of number of valid measurements per station; ubRMSD: unbiased root mean square difference; R_{sp}: Spearman correlation coefficient).

	ESA CCI SM	CLM4.5
Stations	299 (212)[a]	306 (253)
N	124 (127)	126 (128)
ubRMSD (m^3 m^{-3})	0.053±0.017 (0.050±0.014)	0.050±0.017 (0.048±0.015)
R_{sp}	0.27 ± 0.21 (0.37 ± 0.14)	0.35 ± 0.21 (0.42 ± 0.14)

[a]The values in the brackets represent the average values from the sites having significant ($p < 0.05$) positive Spearman correlations.

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Figures

Fig. 1 Locations of the 306 in situ soil moisture measurement sites (red dots) in China. Also shown (blue boxes) are the eight sub-regions defined in Table 1.

Fig. 2 Fraction of days with valid observations, expressed as the number of days with observations divided by the total number of days per period, split into six different merging periods: (a) 1 January 1979–31 August 1987, (b) 1 September 1987–30 June 1991, (c) 1 July 1991–31 December 1997, (d) 1 January 1998–30 June 2002, (e) 1 July 2002–31 December 2006, (f) 1 January 2007–30 September 2011, (g) 1 October 2011–30 June 2012, (h) 1 July 2012–31 December 2013; and (i) for the total period 1 January 1979–31 December 2013.

Fig. 3 Spearman rank correlation coefficients (R_{sp}) between the in situ measurements and (a) ESA CCI SM and (b) CLM4.5 from 1993 to 2012 at 306 sites in China. Open circles represent statistically significant Spearman correlation ($p < 0.05$) while closed circles are not significant.

Fig. 4 Unbiased root mean square differences (ubRMSDs) between the in situ measurements and (a) ESA CCI SM and (b) CLM4.5 from 1993 to 2012 at 306 sites in China.

Fig. 5 Statistical scores, including ubRMSD (5a and 5c) and R_{sp} (5b and 5d), for the ESA CCI SM product (red) and CLM4.5 model (blue) between 1993 and 2012 in the eight studied sub-regions of China using two evaluation strategies (S1 and S2). S1: average values of statistical metrics for the stations over each region. S2: statistical metrics with in situ observations for the soil moisture time series averaged at the stations of each region.

Fig. 6 Multi-year (1993–2012) mean monthly volumetric soil moisture (SM, m^3 m^{-3}) for the period between March and October as described by in situ observations, the ESA CCI SM product and CLM4.5 simulation in the eight studied sub-regions of China.

Fig. 7 Comparison of the anomaly time series of monthly soil moisture derived from the ESA CCI SM product, CLM4.5 simulation and in situ observations between 1993 and 2012 for

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已删除: **Table 3.** The root mean square differences of soil moisture anomalies for the ECV-SM and CLM4.5 against in situ measurements over eight sub-regions (Table 1). Unit is m^3 m^{-3}. ... [44]

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已删除: The biases (top, the EVC-SM or CLM4.5 minus in situ measurements) and root mean square differences (RMSDs, bottom) between the ECV-SM product or CLM4.5 simulation and ground-based measurements from 1993 to 2012 at 308 sites in China

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已删除: Statistical scores for the ECV-SM product and CLM4.5 simulation between 1993 and 2012 in the eight sub-regions of China defined in Table 1: (a) BIAS; (b) RMSD; (c) correlation coefficients (R)

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the eight studied sub-regions of China.

Fig. 8 Spearman correlations (R'_{sp}) between the anomalies (seasonal cycle removed) of the ESA CCI SM product (red) or CLM4.5 model (blue) and those of in situ observations between 1993 and 2012 in the eight studied sub-regions of China using two evaluation strategies (S1 and S2).

Fig. 9 Averaged ubRMSD and R_{sp} values of the ESA CCI SM product against in situ observations for five blended time periods. Red bars represent the sites with significant R_{sp} values ($p \leq 0.05$) for all periods (1993–2012) while blue bars consider sites with significant R_{sp} values ($p \leq 0.05$) for each blended period. Blend 3: July 1991–December 1997; Blend 4: January 1998–June 2002; Blend 5: July 2002–December 2006; Blend 6: January 2007–September 2011; and Blend 7–8: October 2011–December 2012.

Fig. 10 Evaluation of the ESA CCI SM product and CLM4.5 simulation against in situ observations over different types of soil moisture stations. "All" is calculated using all valid sites (200) with significant ($p < 0.05$) positive Spearman correlation coefficients for both the ESA CCI SM product and CLM4.5 simulation. "Rain" represents the sites (101) located in the same 0.25° grid box as the in situ precipitation observations; "No Rain" represents the remaining sites (99). Presented are the average values, the standard deviations (as indicated by the box), and the maximum and minimum values (whiskers).

Fig. 11 Average statistical metrics: (a) ubRMSD, and (b) Spearman correlation coefficients (R_{sp}) between the ESA CCI SM product (red) or in situ observations (OBS, blue) and CLM4.5 simulation at different soil depths. "L1", "L1−2", "L1−2−3", "2cm", "5cm", and "10cm" represent the first layer (0−1.75 cm), uppermost two layers (0−1.75, and 1.75−4.51 cm), and uppermost three layers (0−1.75, 1.75−4.51, and 4.51−9.06 cm), 0−2 cm, 0−5 cm, and 0−10 cm, respectively. The average values of CLM4.5 were computed by using each soil layer thickness as the weight; the CLM4.5 simulations were scaled to the dynamic range of

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the in situ observations or ESA CCI SM dataset using a linear rescaling method (Eq. 1) prior to computing the ubRMSD values.

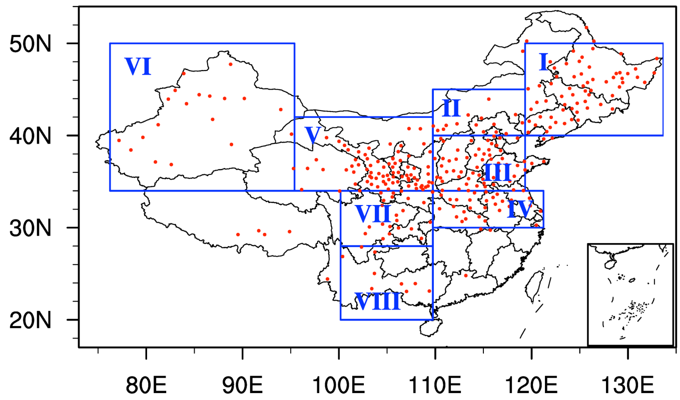

Fig. 1 Locations of the 306 in situ soil moisture measurement sites (red dots) in China. Also shown (blue boxes) are the eight sub-regions defined in Table 1.

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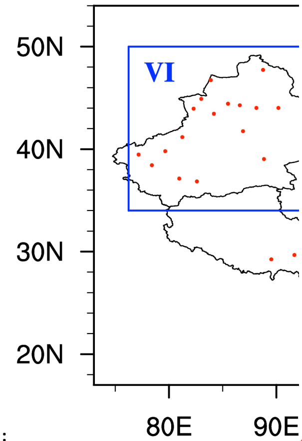

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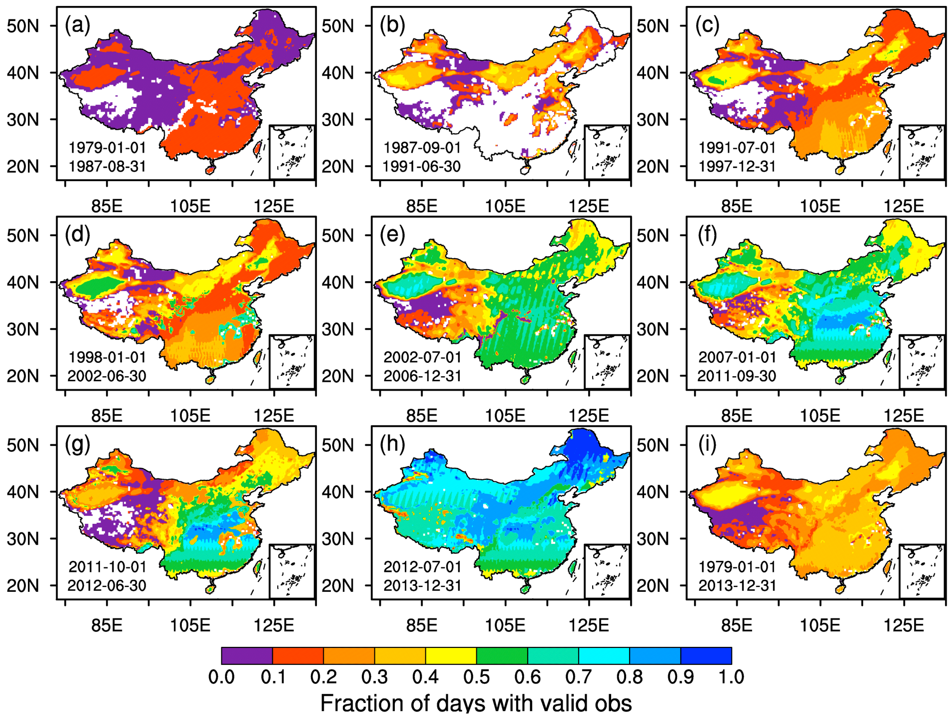

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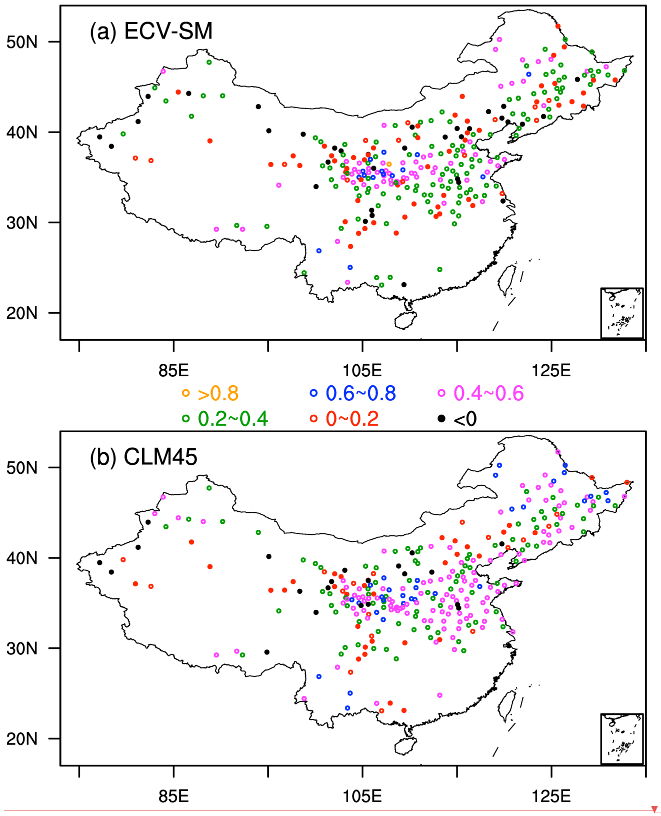

Fig. 3 Spearman rank correlation coefficients (R_{sp}) between the in situ measurements and (a) ESA CCI SM and (b) CLM4.5 from 1993 to 2012 at 306 sites in China. Open circles represent statistically significant Spearman correlation ($p \leq 0.05$) while closed circles are not significant.

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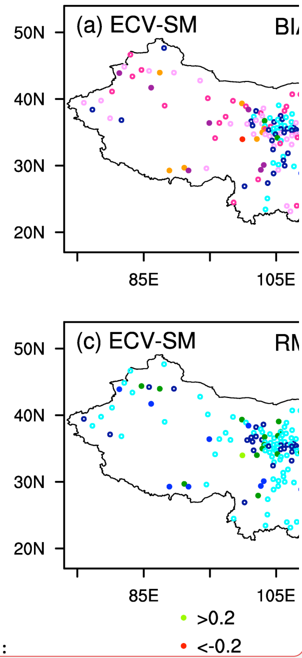

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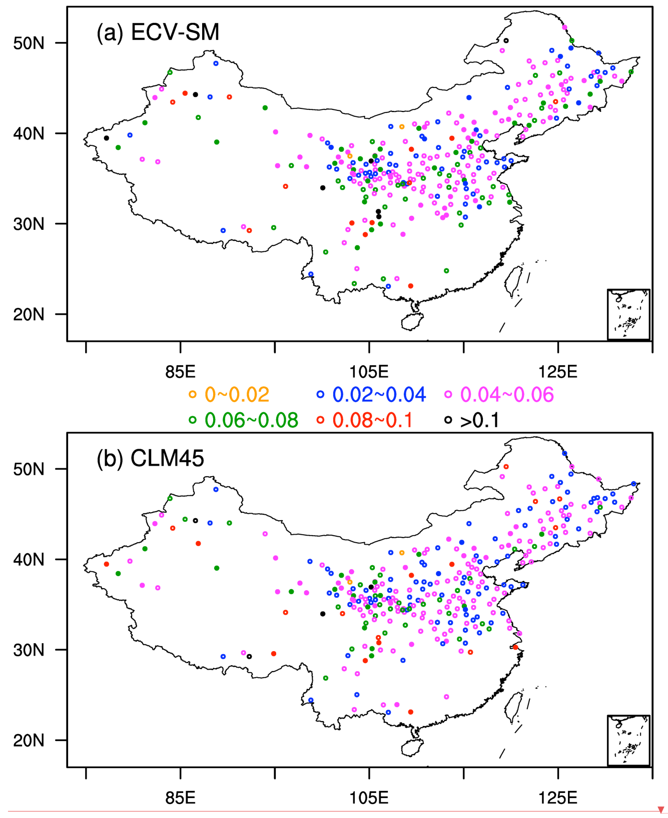

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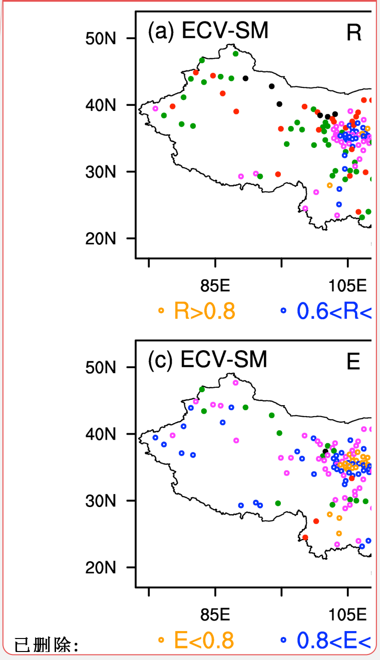

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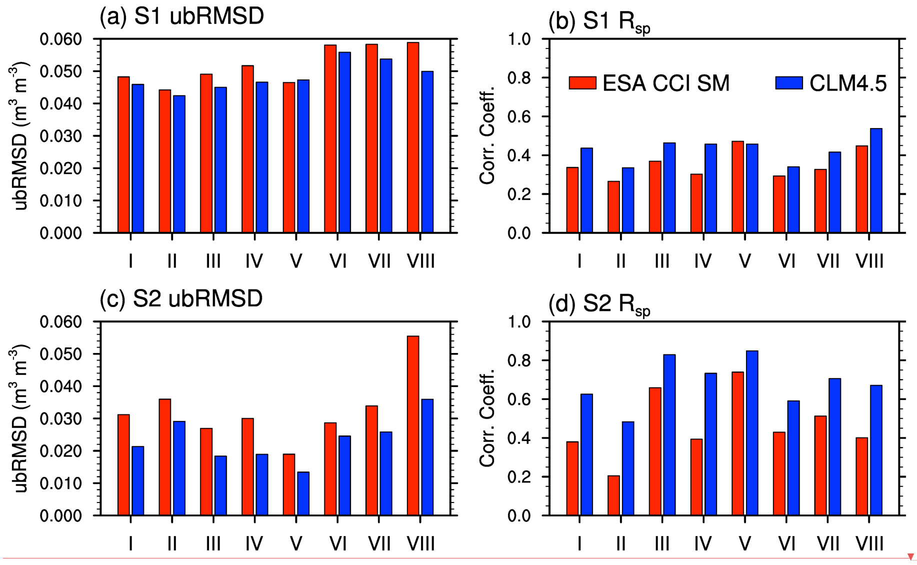

Fig. 5 Statistical scores, including ubRMSD (5a and 5c) and R_{sp} (5b and 5d), for the ESA CCI SM product (red) and CLM4.5 model (blue) between 1993 and 2012 in the eight studied sub-regions of China using two evaluation strategies (S1 and S2). S1: average values of statistical metrics for the stations over each region. S2: statistical metrics with in situ observations for the soil moisture time series averaged at the stations of each region.

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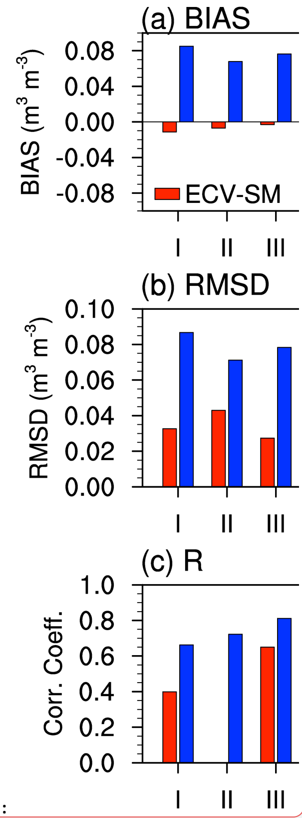

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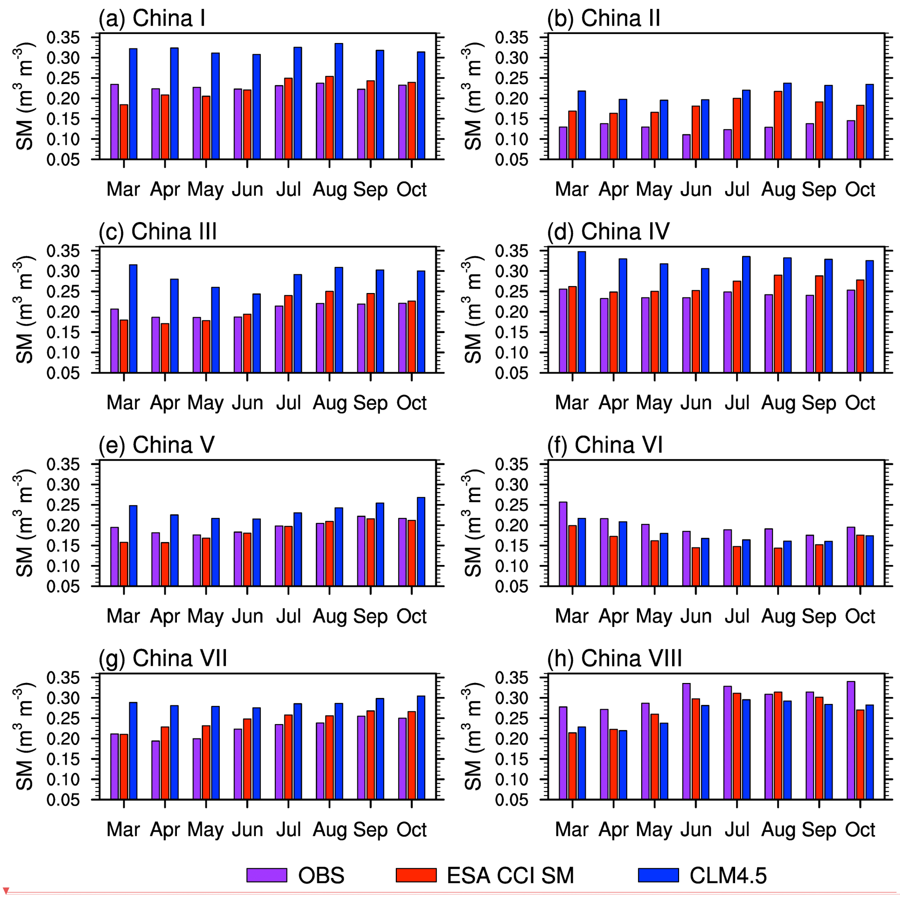

Fig. 6 Multi-year (1993–2012) mean monthly volumetric soil moisture (SM, m^3 m^{-3}) for the period between March and October as described by in situ observations, the ESA CCI SM product, and the CLM4.5 simulation in the eight studied sub-regions of China.

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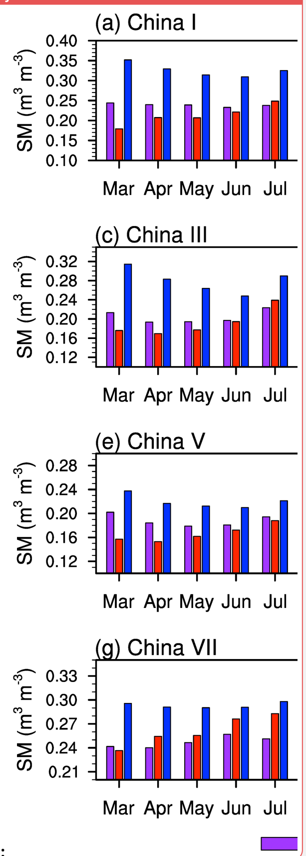

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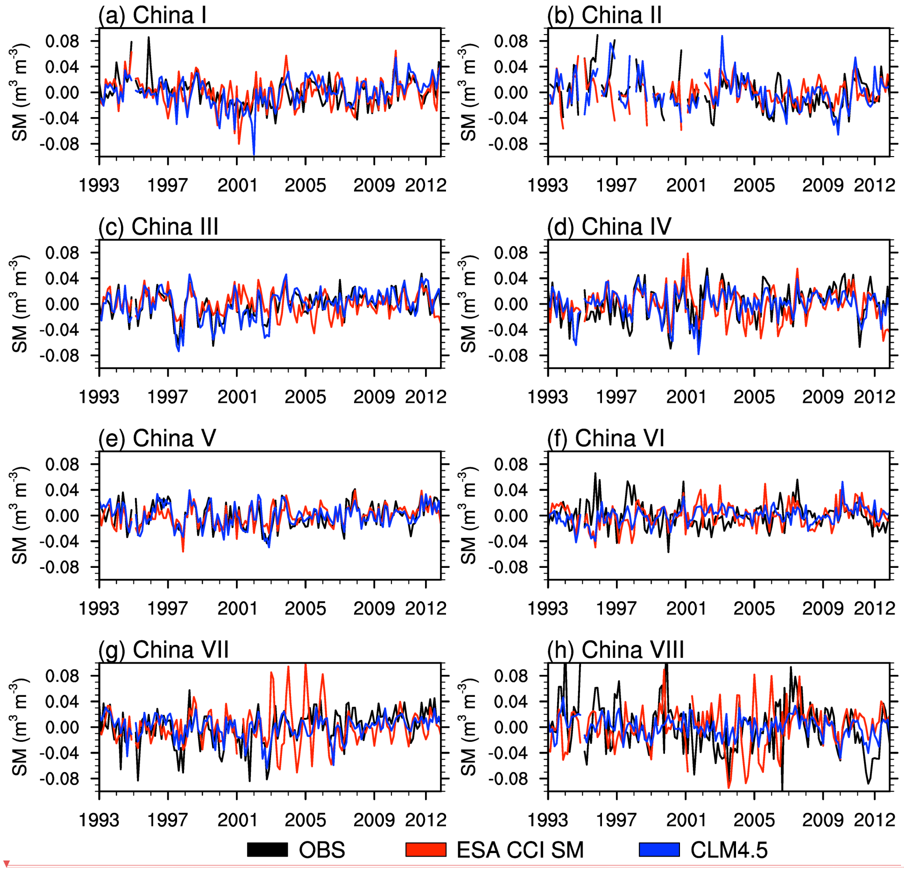

Fig. 7 Comparison of the anomaly time series of monthly soil moisture derived from the ESA CCI SM product, the CLM4.5 simulation, and in situ observations between 1993 and 2012 for the eight studied sub-regions of China.

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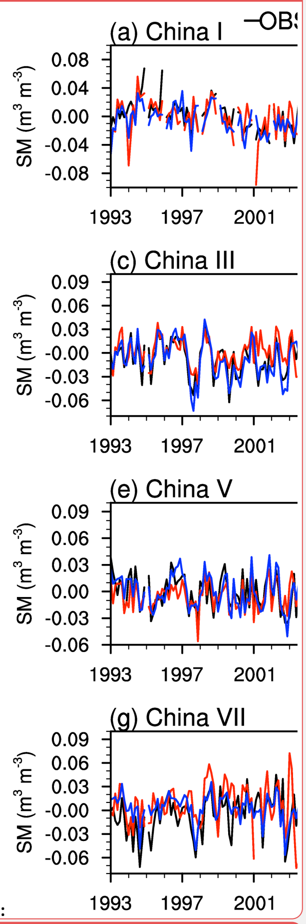

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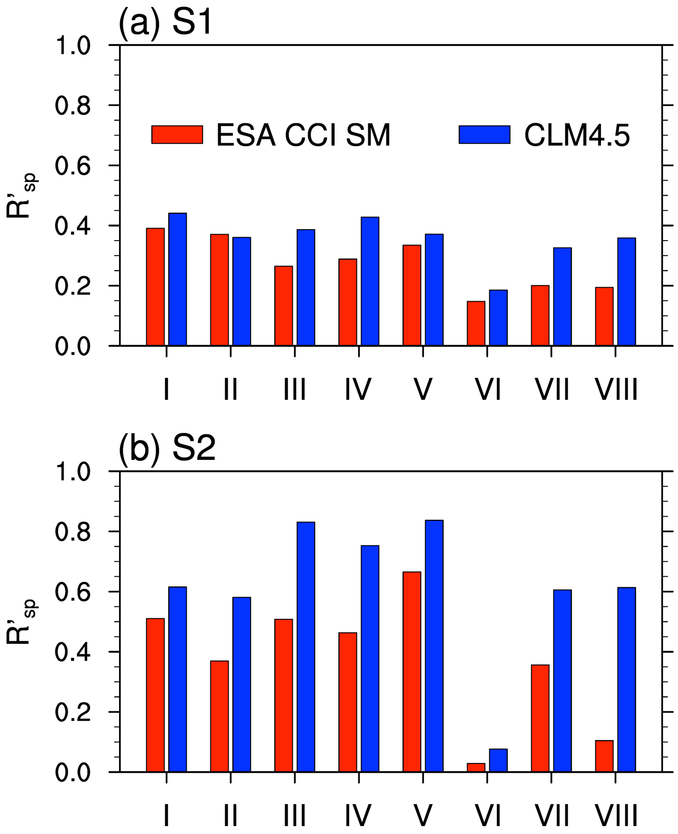

Fig. 8 Spearman correlations between the anomalies (seasonal cycle removed) of the ESA CCI SM product (red) or CLM4.5 model (blue) and those of in situ observations between 1993 and 2012 in the eight studied sub-regions of China using two evaluation strategies (S1 and S2) (R'_{sp}).

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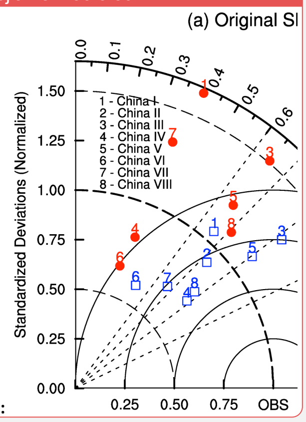

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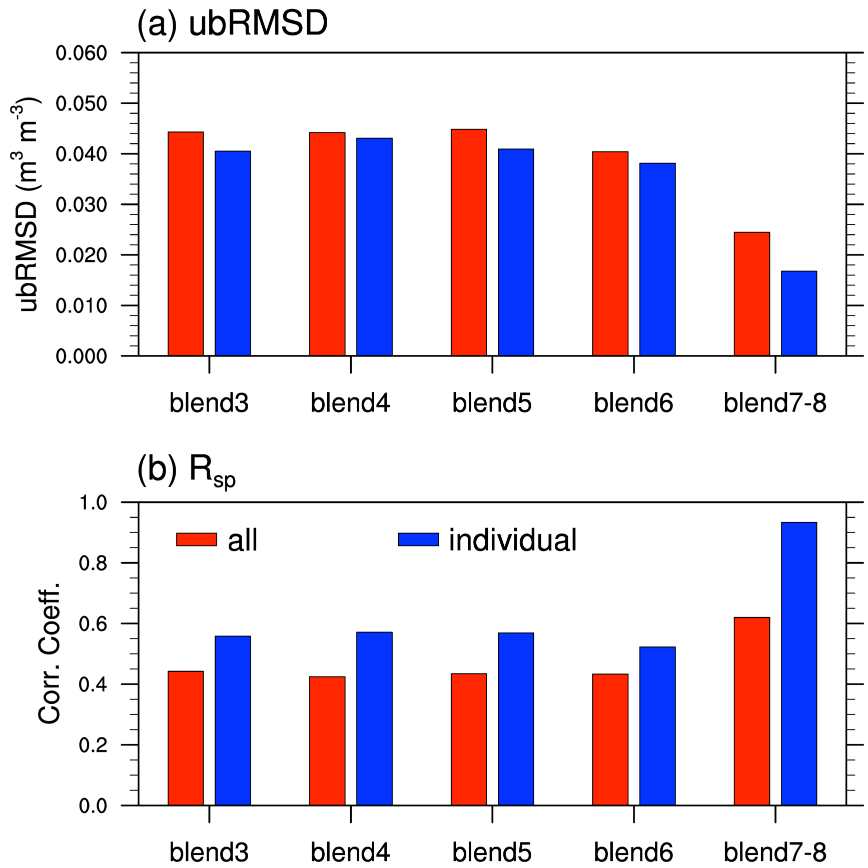

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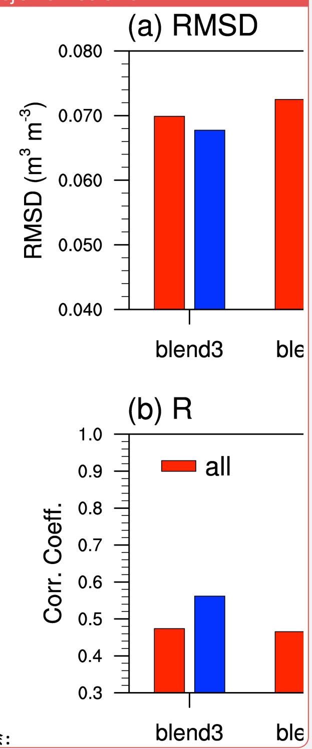

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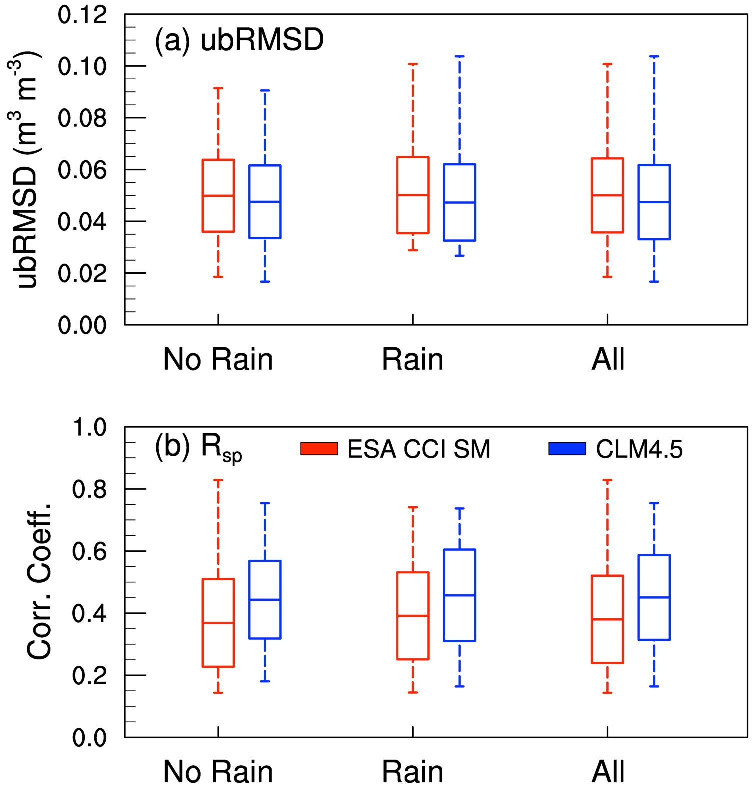

Fig. 10 Evaluation of the ESA CCI SM product and CLM4.5 simulation against in situ observations over different types of soil moisture stations. "All" is calculated using all valid sites (200) with significant ($p < 0.05$) positive Spearman correlation coefficients for both the ESA CCI SM product and CLM4.5 simulation. "Rain" represents the sites (101) located in the same 0.25° grid box as the in situ precipitation observations; "No Rain" represents the remaining sites (99). Presented are the average values, the standard deviations (as indicated by the box), and the maximum and minimum values (whiskers).

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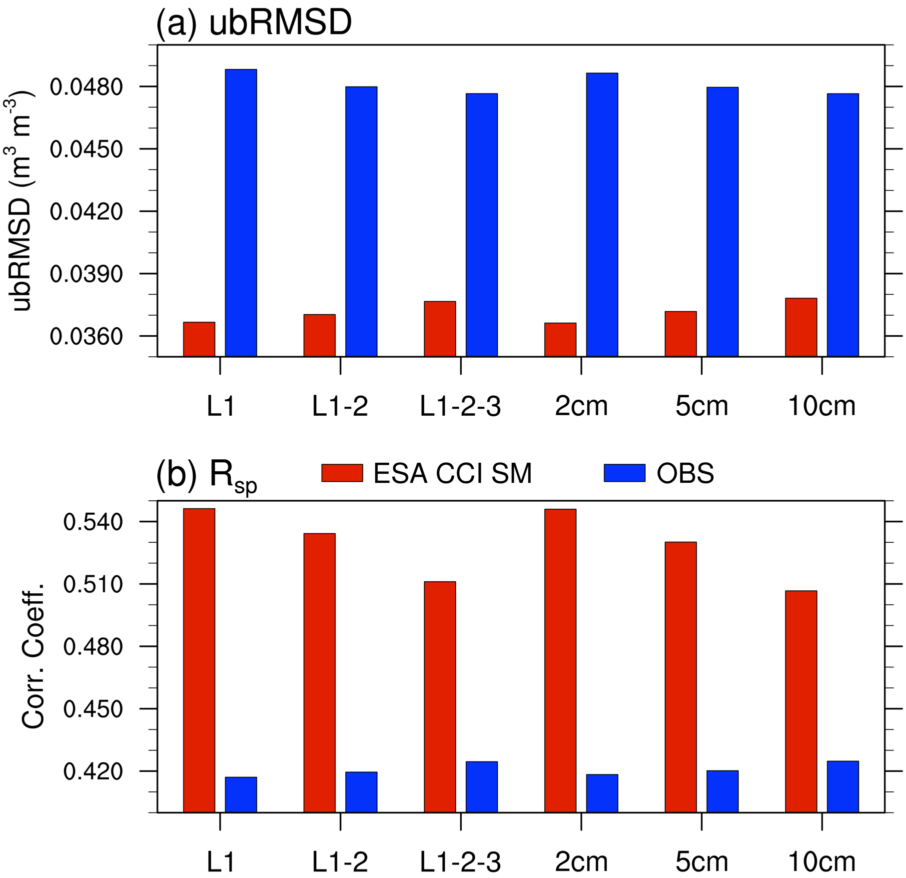

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