Extending the SMAP 9-km soil moisture product using a spatio-temporal fusion model

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ABSTRACT

SMAP satellite has provided us the first 9-km global soil moisture (SM) product, which is retrieved from the combined L-band radiometer and radar observations with a balance between accuracy and resolution. However, SMAP’s radar failed on July 7, 2015, making the continuous production of the 9-km SM impossible, which has considerably affected the application of SMAP in hydrological monitoring. This study was aimed at extending the SMAP 9-km SM by developing a non-local filter based spatio-temporal fusion model (STFM). With the auxiliary of the historical 9-km and 36-km products, the STFM was used to downscale the daily 36-km product to 9-km. Two-year 9-km product was estimated using STFM in the study. It shows that the estimated product has the detailed information retention of 9-km product and the comparable accuracy with 36-km product, which makes it feasible to improve the application potential of the current SMAP SM products.

1. Introduction

The Soil Moisture Active Passive (SMAP) satellite mission developed by the National Aeronautics and Space Administration (NASA) was launched on January 31, 2015. Its aim is to globally measure soil moisture every 2–3 days at a high spatial resolution using the L-band passive radiometer and active radar sensors (Chan et al., 2016; Entekhabi et al., 2010). The significant advantage of this system is the simultaneous acquisition of the L-band radiometer and radar observations, so that the high-accuracy radiometer and fine-resolution radar observations can be effectively combined to derive soil moisture (Das et al., 2011). Three different spatial resolution soil moisture products based on the Equal-Area Scalable Earth 2.0 (EASE2) grid have been released by the SMAP team: 36-km soil moisture (P36) is retrieved only from the SMAP passive radiometer observation; 3-km soil moisture is retrieved only from the SMAP active radar observation; and 9-km soil moisture (AP9) is retrieved from the combined SMAP active and passive observations. In particular, AP9 is the first global satellite soil moisture product with a balance between spatial resolution and accuracy. AP9 can greatly strengthen our understanding of the coupling processes of the terrestrial water, energy, and carbon cycles, improve the capability of flood prediction and drought monitoring, and enhance short-term weather and long-term climate forecasting (Entekhabi et al., 2014b). However, the SMAP radar failed on July 7, 2015, marking it impossible to continue the generation of AP9, which has seriously affected the application of SMAP in scientific research and hydrological monitoring.

To compensate for the missing AP9 data, the Backus-Gilbert (BG) interpolation method (Backus and Gilbert, 1970) was adopted by NASA to post the microwave polarization brightness temperature (TB) onto the 9-km EASE2 grid. The enhanced SMAP passive 9-km soil moisture product (EP9) was then retrieved by the interpolated TB using the V-polarized single-channel algorithm (SCA-V) (Jackson, 1993). Although EP9 enhances the spatial resolution of P36, the richness of the detailed spatial information is far less than that of AP9, especially in areas with strong spatial heterogeneity. Another solution to extending the fine-resolution soil moisture product was also developed by the SMAP team, where they substituted the SMAP radar L-band observation with the Sentinel-1 synthetic aperture radar (SAR) C-band observation. Thus, the SMAP passive and Sentinel-1 active observations were combined to generate a global soil moisture product with a fine spatial resolution (Das et al., 2016; Lievens et al., 2017; Rudiger et al., 2016; Das et al., 2018). Although the orbit parameters of Sentinel-1 are similar to those of SMAP, and the time difference of the overlapping regions is small, this approach is greatly limited by the narrow bandwidth and long temporal resolution (Das et al., 2016).

The conventional soil moisture downscaling methods can also be used to enhance the spatial resolution of P36 and to estimate the 9-km soil moisture. The key idea of these methods is to establish the
relationship between microwave soil moisture and other high spatial resolution surface parameters, such as land surface temperature (LST) or vegetation indices retrieved from optical/thermal infrared data (Peng et al., 2017; Wang et al., 2016; Sabaghy et al., 2018). In recent years, based on optical/thermal infrared data, a number of scholars have proposed a variety of soil moisture downscaling methods, which have been successfully applied to the Soil Moisture and Ocean Salinity (SMOS) mission, the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), and so on (Djamai et al., 2016; Jiang et al., 2017; Merlin et al., 2012; Piles et al., 2011; Piles et al., 2016; Sánchez-Ruiz et al., 2014; Song et al., 2014). In terms of SMAP soil moisture, Chen et al. (2017) used a downscaling method to improve the spatial resolution of P$_{36}$ to 250 m, which significantly enriched the detailed spatial information of P$_{36}$. However, it is very difficult for the conventional downscaling methods to capture the complex relationships between soil moisture and other surface parameters (Peng et al., 2017). Moreover, optical/thermal infrared data are severely affected by missing information caused by cloud contamination, which poses a great challenge to global 9-km soil moisture estimation.

It should be noted that most of the above methods need other ancillary satellite data (such as SAR data or optical/thermal infrared data). This is not beneficial for estimating soil moisture with a high spatial resolution because of the inherent problems of the ancillary data (e.g., long revisit periods or cloud contamination). Moreover, the historical AP$_9$ data are not taken into consideration by these methods. As a result of the strong spatio-temporal correlation of soil moisture (Zhang and Chen, 2016; Zeng et al., 2013), the historical AP$_9$ data may be very helpful to estimate the missing 9-km soil moisture. The spatio-temporal fusion model (STFM) can be utilized to fuse the complementary spatial and temporal information of multi-source remote sensing data and to simultaneously estimate remotely sensed data with high spatial and temporal resolutions (Gao et al., 2006; Zhu et al., 2016; Shen et al., 2015; Shen et al., 2016a, 2016b). The STFM has been widely used in the estimation of surface biophysical parameters, such as LST (Shen et al., 2016a, 2016b; Weng et al., 2014; Wu et al., 2015), the normalized difference vegetation index (NDVI) (Meng et al., 2013; Tewes et al., 2015), the leaf area index (Houborg et al., 2016; Zhang et al., 2014), biomass (Dong et al., 2016), and evapotranspiration (Cammalleri et al., 2014; Semmens et al., 2016). Therefore, the STFM provides a new possibility for extending SMAP high-resolution soil moisture, i.e., the use of the STFM for 9-km soil moisture estimation.

In this study, the STFM method is presented to extend the AP$_9$ product. With the auxiliary of paired baseline data composed of the historical AP$_9$ and P$_{36}$ data, 9-km soil moisture (STF$_9$) is estimated based on the corresponding daily P$_{36}$. One notable advantage of this kind of downscaling method is that it has no need for other ancillary satellite data, which increases the feasibility of continuous production and reduces the possible uncertainty. A two-year period of STF$_9$ products was estimated from April 2015 to April 2017, and these products were validated using the available three months of the original SMAP 9-km product and in-situ data from the International Soil Moisture Network (ISMN) (Dorigo et al., 2011; Dorigo et al., 2013).

### 2. Data

#### 2.1. Satellite microwave soil moisture

This study deals with the SMAP soil moisture products of P$_{36}$, AP$_9$, and EP$_9$, which have been released by NASA as volume water content ($m^3/m^2$). The accuracy of P$_{36}$ is high in areas where the vegetation water content is < 5 kg/m$^2$, because TB is only slightly affected by the vegetation and the retrieval error is small (Chan et al., 2016). AP$_9$ is retrieved from the combined SMAP active and passive observations and makes better use of the advantages of the SMAP L-band in soil moisture monitoring (Ciolfi et al., 2017; Entekhabi et al., 2014b). Moreover, the detailed spatial information of AP$_9$ is clearly better than that of P$_{36}$, which makes it more practical, for applications such as regional-scale agricultural yield estimation, drought monitoring, and soil moisture assimilation. Unfortunately, the SMAP radar failed on July 7, 2015, and NASA was forced to stop production of AP$_9$. The alternative product, EP$_9$, released by the NASA SMAP team, is retrieved from the BG-interpolated EASE2 9-km TB using SCA-V. It has been reported that the accuracy of EP$_9$ is close to that of P$_{36}$ and is better than that of AP$_9$ (Chan et al., 2017), but the detailed spatial information is clearly weaker than that of AP$_9$.

In this study, the 9-km soil moisture estimated by the conventional downscaling method (CD$_9$) (Piles et al., 2011) was used as a comparative dataset for validating the effectiveness of STF$_9$. The auxiliary data used to estimate CD$_9$ were the Moderate Resolution Imaging Spectroradiometer (MODIS) LST and NDVI (version 6, global 0.05° MOD11C1 and MOD13C1) and the SMAP 36-km V-polarized TB. The satellite soil moisture products used in this study are summarized in Table 1.

To date, NASA has released SMAP soil moisture products in both ascending and descending nodes, which can be downloaded freely through the National Snow and Ice Data Center (NSIDC). The near-surface temperature homogenization in the morning is better than that in the afternoon, and is thus more conducive to soil moisture retrieval. As a result, the SMAP soil moisture in descending node (06:00 a.m.) is more accurate than that in ascending node (18:00 p.m.) (Burgin et al., 2017). Therefore, only the SMAP soil moisture in descending node was used for the STF$_9$ estimation. The two study years (Table 1) can be divided into two parts by the failure date of the SMAP radar: the working SMAP radar period T1 (April 13–July 7, 2015) and the SMAP radar failure period T2 (July 8, 2015–April 12, 2017). AP$_9$ only exists in T1 period. The division is made for the following reasons: 1) it allows convenient comparison of the detailed spatial information and accuracy difference between STF$_9$ and AP$_9$ (T1 period); and 2) it allows us to verify the feasibility of the STFM for long time series STF$_9$ estimation (T2 period).

#### 2.2. In-situ soil moisture

In addition to the evaluation of STF$_9$ against AP$_{36}$ in the T1 period (before the failure of the SMAP radar), in-situ soil moisture data from the ISMN were also used for accuracy assessment of the T1 and T2 periods. The ISMN is hosted by the Technical University of Vienna and is intended to serve as a centralized data hosting facility where different

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Table 1

<table>
<thead>
<tr>
<th>Product</th>
<th>EASE2 grid</th>
<th>Period</th>
<th>Data level</th>
<th>Method</th>
<th>Auxiliary data$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P$_{36}$</td>
<td>36 km</td>
<td>April 13, 2015–April 12, 2017</td>
<td>L3, Version 4</td>
<td>SCA-V</td>
<td>/</td>
</tr>
<tr>
<td>CD$_9$</td>
<td>9 km</td>
<td>April 13, 2015–April 12, 2017</td>
<td>/</td>
<td>Piles et al., 2011</td>
<td>P$_{36}$, TB, and MODIS</td>
</tr>
<tr>
<td>STF$_9$</td>
<td>9 km</td>
<td>April 13, 2015–April 12, 2017</td>
<td>/</td>
<td>STFM</td>
<td>P$_{36}$ and AP$_9$</td>
</tr>
</tbody>
</table>

$^a$ The data for SCA-V are not listed. Please refer to the SMAP soil moisture product algorithm documentation.
in-situ soil moisture networks across the globe are collected. The in-situ soil moisture values were transformed into volumetric units (m$^3$/m$^3$) and checked for outliers and implausible values. The in-situ data from the ISMN have been widely used to validate satellite-derived soil moisture and model-simulated or assimilated soil moisture products across the world (Chan et al., 2016; Dorigo et al., 2015; Fascetti et al., 2016; Wu et al., 2016; Zeng et al., 2016). Please refer to Dorigo et al. (2011) and Dorigo et al. (2013) for a detailed description of the ISMN.

In this study, in-situ data from April 13, 2015, to April 12, 2017, were downloaded from the ISMN. The microwave emission measured by the radiometer mostly emanates from the top ~5 cm in the L-band. Only the surface in-situ data (no > 5 cm) from 06:00 a.m. (local time) were utilized to evaluate the satellite-based soil moisture. To allow a better evaluation, the daily P$_{36}$, E$_{P9}$, and in-situ soil moisture should exist at the same time. Furthermore, we set two filtering conditions for the in-situ site selection: 1) the temporal length should be larger than 20 in the T1 period (before the radar failure, April 13, 2015 to July 7, 2015); and 2) the temporal length should be larger than 80 in the T2 period (after the radar failure, July 8, 2015 to April 12, 2017). After screening and merging (where there was more than one in-situ site in the corresponding 9-km pixel), 649 in-situ sites out of 1418 were used to evaluate the gridded soil moisture. A brief introduction to the ISMN soil moisture monitoring networks and the spatial distribution of all the available in-situ sites are provided in Table 2 and Fig. 1, respectively.

### 3. Method

The purpose of this study was to extend AP$_9$ using STFM in the case of the SMAP radar failure. As shown in Fig. 2, with the auxiliary of paired baseline data (composed of AP$_9$ and the corresponding P$_{36}$ in the T1 period), the daily P$_{36}$ was input into the model and then the daily AP$_9$ was estimated at the corresponding date.

#### 3.1. Composition of the baseline data

As shown in Fig. 2, the ideal baseline data with different spatial resolutions would be P$_{36}$ and AP$_9$ with a global coverage, so as to estimate STF$_9$, with the maximum spatial coverage. Considering the short-term stability of soil moisture and the exact 8-day revisit period of SMAP, it should be considered that the 8-day composite can cover the globe. However, there is a difference in spatial coverage for the different 8-day composites in the T1 period. Because surface soil temperature can be < 0 °C or the surface may be covered by snow and ice, there is a lot of uncertainty for soil moisture retrieval (Maitzler, 1994), and SMAP does not carry out soil moisture generation (Entekhabi et al., 2014b). With the failure of the SMAP radar, the available AP$_9$ for composing fine-resolution soil moisture as baseline data covers less than three months (April 13–July 7, 2015). From April to July, the surface soil temperature is on the rise in most areas of the world, and the spatial coverage and the accuracy of SMAP soil moisture are gradually increasing. Experiments have shown that the composite data of the last eight days of the working SMAP radar sensor (June 30–July 7, 2015, T1 period) have the largest spatial coverage of all the continuous 8-day composite data. However, there are some missing data areas for the last 8-day composites, especially for the composed AP$_9$. To reduce the missing data, the remaining P$_{36}$ and AP$_9$ in the T1 period were used to fill the gaps in the last 8-day composites, respectively. Finally, paired baseline data (Fig. 3) were obtained with the largest spatial coverage.

#### 3.2. The STFM for soil moisture estimation

The STFM has been employed in many different methods and has been widely used for estimating surface parameters with a fine spatial resolution. Inspired by the non-local filter based STFM originally proposed for surface reflectance (Cheng et al., 2017), we present a 9-km soil moisture estimation method by considering the strong spatio-temporal correlation information of soil moisture. In this method, it is assumed that the soil moisture at different spatial resolutions has the same temporal variation. The temporal variation of AP$_9$ from $t_0$ day to $t_p$ day can be estimated linearly as follows:

$$STF_p(x, y, t_p) = a(x, y, \Delta t) \cdot AP_9(x, y, t_0) + b(x, y, \Delta t)$$

(1)

where $STF_p(x, y, t_p)$ indicates STF$_9$ at $t_p$, and $AP_9$ indicates the composed AP$_9$ in the baseline data (Fig. 3b). $\Delta t = t_p - t_0$ indicates the date of the composed baseline data, $t_0$ indicates the date to be estimated, and $a(x, y, \Delta t)$ and $b(x, y, \Delta t)$ are the linear regression coefficients of pixel $(x, y)$ from $t_0$ to $t_p$.

Soil moisture has correlation in the temporal variation information; moreover, it also has strong correlation in the spatial neighborhood information. To make the estimation more accurate, the neighborhood (such as a 5 × 5 window size) similar pixel information is introduced into the estimation process. The so-called similar pixels indicate that the pixels differ from the target pixel (pixel to be estimated) by less than a certain threshold. Please refer to Cheng et al. (2017) for more details about similar pixels. Considering the neighborhood similar pixels, the 9-km soil moisture estimation model is as follows:

$$\begin{align*}
STF_p(x, y, t_p) &= \sum_{i=1}^{n} W(x_i, y_i, t_0) \times [a(x_i, y_i, \Delta t) \cdot AP_9(x_i, y_i, t_0) + b(x_i, y_i, \Delta t)]
\end{align*}$$

(2)

where $n$, $(x_i, y_i)$, and $W(x_i, y_i, t_0)$ indicate the numbers of similar pixels, the locations, and the weights of similar pixels at $t_0$, respectively.

However, STF$_9$ is to be estimated, and it is impossible to select soil moisture similar pixels at a 9-km resolution. To solve this problem, the STFM assumes that the 36-km and 9-km soil moisture products have the same temporal differences. Therefore, the similar pixels of the corresponding position in P$_{36}$ (resampled to 9 km) are used to estimate the regression coefficients and weights. The least-squares regression method is employed to estimate the regression coefficients $a$ and $b$ according to the temporal variation of the neighborhood similar pixels. For the similar pixel weights, taking into account the spatial correlation between similar pixels, the idea of non-local filtering (Buades et al., 2005) is employed for the calculation, as follows:

$$W(x, y, t_0) = \exp\left(-\frac{G * ||P_{36}(B(x_i, y_i, t_0)) - P_{36}(B(x, y, t_0))||^2}{h^2}\right)$$

(3)

where $G$ indicates the Gaussian kernel, $h$ indicates the filtering parameter, $\dagger$ indicates the 36-km soil moisture resampled to 9 km using the nearest sampling method, $P_{36}$ indicates the composed P$_{36}$ in the baseline data (Fig. 3a), and $B(x_i, y_i, t_0)$ indicates the non-local block $B$ of the composed P$_{36}$.
centered at \((x_i, y_i)\).

The STFM assumes the same temporal variation for the 36-km and 9-km soil moisture, so the regression coefficients and weights of the temporal variation are calculated at the 36-km scale and then applied for estimating the 9-km soil moisture using the composed AP9 in the baseline data (Fig. 3b). There are four processes for estimating daily STF9 using the STFM: 1) the similar pixels of 9-km resolution at location \((x, y)\) are selected according to the soil moisture at the 36-km resolution; 2) the regression coefficients and the weights of the similar pixels are calculated by the least-squares algorithm and formula (3), respectively; 3) the 9-km soil moisture is estimated by formula (2) at location \((x, y)\) of \(t_p\); and 4) repeat 1–3 until all the 9-km soil moisture values are estimated at \(t_p\).

4. Results

4.1. Estimated 9-km soil moisture

With the auxiliary of the baseline data (Fig. 3), the missing AP9 could be extended by the STFM using the corresponding daily P36 (Fig. 2). It was found that the suitable spatial moving window size for the STFM was 5 × 5 for the 9-km soil moisture estimation. A two-year period of 9-km soil moisture was estimated from April 13, 2015, to April 12, 2017. The estimated soil moisture has been publicly released on http://rs-pop.whu.edu.cn/. The global spatial coverage of the baseline data (Fig. 3) ensures the close spatial coverage for the daily P36 and STF9. Moreover, the SMAP passive observation coverage is clearly larger than its active observation coverage (Entekhabi et al., 2014a), so the AP9 retrieved from the combined passive and active observations has the same spatial coverage as the SMAP active observation. Therefore, the spatial coverage of the daily STF9 is close to that of the corresponding daily P36 and should be larger than the daily AP9.

Fig. 4 shows the spatial distribution of STF9 in the different seasons of 2016. The spatial distribution of STF9 is similar to that of P36 (Fig. 4); however, the intensity differs greatly in the dense vegetation coverage areas (e.g. the Amazon basin and the Congo basin). This is mainly due to the different spatial distribution between P36 and AP9 (Fig. 3), which is caused by the different surface responses of the SMAP radiometer and the radar observations and the disaggregation method of the SMAP passive TB. Without consideration of the intensity, it can be seen that STF9 captures the seasonal variation of soil moisture well, and its spatial distribution is consistent with that of P36. This demonstrates the reliability of the STFM for 9-km soil moisture estimation. STF9 obtains more detailed spatial information than P36, which will be beneficial to the practical applications and makes up for the adverse effects brought about by the SMAP radar failure. Notably, there are some missing areas in STF9 that are inherited from the composed AP9 (Fig. 3b). The missing areas of STF9 could be filled by an interpolation method, which will be

Fig. 1. The 649 in-situ soil moisture sites out of 1418 from the ISMN.

Fig. 2. Flowchart of daily 9-km soil moisture (STF9) estimation using STFM.
Fig. 3. The baseline data pair composition in the T1 period: (a) $P_{36}$ and (b) $AP_0$.

Fig. 4. The spatial distribution of the soil moisture in the different seasons of 2016.
addressed in our future study.

4.2. Evaluations

4.2.1. Evaluation before the SMAP radar failure

The 9-km soil moisture estimated by the STFM should have a similar spatial distribution, similar detailed information, and comparable accuracy to AP9. To compare the difference between AP9 and STF9 quantitatively, the last 8-day composed P36 and AP9 in the T1 period were used as baseline data, instead of the baseline data shown in Fig. 3, to estimate STF9. In addition, EP9 and CD9 were used as comparative datasets to further verify the effectiveness of STF9.

As the last 8-day composed AP9 and P36 in the T1 period were used as baseline data in the STFM, the remaining 76-day AP9 data were used as reference to evaluate the difference with STF9. Fig. 5 shows the spatial distribution of the remaining 76-day composed results of the five soil moisture products (P36, AP9, EP9, CD9, and STF9) at a global coverage. There is a slight difference between P36 and AP9 (Fig. 5a and b), which is mainly due to the different surface responses of the SMAP radiometer and radar observations and the disaggregation method of SMAP passive TB. In the baseline algorithm of AP9 retrieval, the TB disaggregation ensures that the TB from the active-passive algorithm is consistent with the radiometer TB, so P36 and AP9 have strong spatial consistency (Entekhabi et al., 2014a, 2014b). Compared with AP9, the spatial distribution of EP9 is closer to that of P36 because they both use the same microwave polarization TB for soil moisture retrieval (Fig. 5c). CD9 cannot accurately capture the spatial distribution of P36 and AP9 (Fig. 5d), so there is a big difference. Because the downscaling model cannot accurately simulate the relationship between soil moisture and MODIS data (Peng et al., 2017), it introduces errors while improving the coarse spatial resolution. Moreover, the cloud contamination of MODIS data results in a large amount of missing data for the daily CD9 (not shown in this paper). Compared to P36, the spatial distribution of STF9 is much closer to that of AP9, which meets the expectation of the STFM (Fig. 5e). In general, the spatial distribution of STF9 is closer to that of AP9 than EP9 and CD9. It is worth noting that the spatial coverage of STF9 is limited by the 8-day composed AP9 in the baseline data (Fig. 3b), resulting in less spatial coverage than the 76-day composed AP9.

Fig. 6 shows the detailed spatial information of the five soil moisture products under different vegetation cover conditions (Fig. 5a, red box areas). The left side of the blue dotted line (Fig. 6) is the SMAP soil moisture, and the right side is the three kinds of 9-km soil moisture. Clearly, the spatial resolution of P36 can be improved by all three kinds of 9-km soil moisture. Although the detailed spatial information of EP9 is somewhat better than that of P36, the richness is far less than that of AP9. The 9-km TB for EP9 retrieval is BG-interpolated by the SMAP original passive TB, so the improvement of detailed spatial information is limited. The detailed spatial information of CD9 is better than that of P36 and weaker than that of AP9. Because the coarse-resolution TB is added into the downscaling model, the promotion of detailed spatial information is limited. The detailed spatial information of STF9 is very close to that of AP9 and is clearly better than that of P36, as the estimation of STF9 takes full account of the temporal and spatial correlation of soil moisture. In general, compared with EP9 and CD9, STF9 demonstrates more detailed spatial information, it shows spatial features more clearly than the others, and it is much closer to AP9.

The above analysis does not determine the quantitative difference...
between the 9-km soil moisture estimates and AP₉. Therefore, the evaluation indices of the correlation ($R$), bias (i.e. STF₉ − AP₉), root mean square error ($RMSE$), and unbiased RMSE ($ubRMSE$) were used to evaluate the temporal variation of the three kinds of 9-km soil moisture at the pixel scale, taking the remaining 76-day AP₉ as reference. The global means of the four indices are summarized in Table 3, and the spatial distribution of bias is taken as an example to show the difference between the 9-km soil moisture estimates and AP₉ (Fig. 7).

It can be seen from Table 3 that the evaluation results of the three kinds of 9-km soil moisture against AP₉ are significantly different: the evaluation result of STF₉ is the best, followed by EP₉, and CD₉ is the

Table 3

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<thead>
<tr>
<th></th>
<th>$R$</th>
<th>bias</th>
<th>RMSE</th>
<th>ubRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP₉</td>
<td>0.637</td>
<td>0.003</td>
<td>0.069</td>
<td>0.040</td>
</tr>
<tr>
<td>CD₉</td>
<td>0.422</td>
<td>0.031</td>
<td>0.094</td>
<td>0.049</td>
</tr>
<tr>
<td>STF₉</td>
<td>0.679</td>
<td>−0.001</td>
<td>0.048</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Fig. 6. Detailed spatial information of the five soil moisture products (Fig. 5a, red box areas). The legend is the same as Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. The bias spatial distribution of the three kinds of 9-km soil moisture against AP₉.
worst. The global mean correlation coefficient of STF9 is 0.679, which is higher than the 0.637 of EP9 and much higher than the 0.422 of CD9. This shows that STF9 can better maintain the temporal variation of AP9. Moreover, STF9 has the lowest bias, RMSE, and ubRMSE (indicated by the bold font in Table 3), indicating that its absolute difference with AP9 is the smallest among the three kinds of 9-km soil moisture. Notably, the bias of STF9 is negative (−0.001 m³/m³), indicating the underestimation of AP9, while the two other methods overestimate AP9. In brief, STF9 keeps the temporal variation of AP9 with the lowest error, confirming the advantage of the STFM for 9-km soil moisture estimation.

From the spatial distribution of the bias (Fig. 7), it can be seen that the spatial variability of CD9 is the strongest, followed by EP9, and STF9 is the weakest. The stronger the spatial variability, the greater the difference between the 9-km soil moisture estimate and AP9, and the greater the difference caused by the estimation model in different regions. EP9 is retrieved by the BG-interpolated TB and its spatial distribution is consistent with that of P36 (Fig. 5). The difference between P36 and AP9 mainly causes the spatial variability of the EP9 bias (Fig. 7a). The error of CD9 is high in dense vegetation coverage and high-latitude areas, which demonstrates the strong spatial variability of the CD9 bias (Fig. 7b). There are two reasons for this: 1) the accuracy of the soil moisture retrieval is decreased and the NDVI is prone to being supersaturated in the dense vegetation coverage areas, so the downscaling model has less capability in these areas (Piles et al., 2016); and 2) the downscaling model and the SCA-V retrieval model show greater errors during frozen periods (Maitzler, 1994; Sánchez-Ruiz et al., 2014). The spatial variability of the STF9 bias is the weakest (Fig. 7c) and the bias values are very low in most parts of the world. A possible reason for this is that STF9 takes full account of the spatial and temporal correlation of the soil moisture, resulting in the estimation being closer to AP9. Generally speaking, STF9 is much closer to AP9 than EP9 and CD9 in both temporal variation and numerical value (Table 3 and Fig. 7). The accuracy of the three kinds of 9-km soil moisture with regard to AP9 is STF9 > EP9 > CD9. Therefore, STFM is more suitable for extending 9-km soil moisture than the other two methods.

### 4.2.2. Evaluation against the SMAP-Sentinel Soil Moisture product and EP9

The SMAP-Sentinel Soil Moisture (SSSM) product is another possible solution for recovering the missing SAR data. The SSSM product (version 2) has been released by NASA with two kinds of spatial resolution: 3 km and 1 km. The officially released products began in March 31, 2015; however, the amount of data released was very small at the beginning. It was not until the end of 2016 that mass data release really started. The temporal resolution between SSSM and STF9 has a great difference. The period of STF9 covers two years from April 13, 2015 to April 12, 2017, and the period of mass SSSM is from the end of 2016 to date. The time coincidence between the two products is relatively small, so it is difficult to make an effective temporal variation comparison.

The SSSM global product has not yet been released. Fig. 8 shows the global composite of daily 3-km SSSM and the daily STF9 on April 12, 2017. It can be seen that the spatial distributions of the two soil moisture products are very similar, but the spatial coverage of daily SSSM is far less than that of STF9. However, the higher spatial resolution of SSSM and the longer temporal resolution make it unsuitable for weather prediction and hydrological monitoring.

At 9km scale, the EP9 and SSSM have been demonstrated the similar accuracy against the SMAP core cal/val sites. Therefore, the two years temporal variation of STF9 is further compared with EP9 and SSSM which is resized to 9 km scale and is merged globally. As the mass absence of SSSM in global (Fig. 8), the length of temporal variation for STF9 and SSSM longer than 20 is used for evaluation. As for STF9 and EP9, the length of temporal variation is longer than 100. Table 4 shows the evaluations results of STF9 against EP9 and 9 km SSSM. It demonstrates that STF9 has the similar temporal trend with EP9 and SSSM as the high R globally. The small bias and ubRMSE indicate that STF9 is close to the EP9 and 9 km SSSM in global scale. The less length of temporal variation results in the more uncertainty of evaluation. Therefore, the evaluation result for EP9 is better than that of SSSM.

The ubRMSE is computed between STF9 and the two other SM products at the global extent for each and every valid grid cells at 9 km (Fig. 9). Notably, the length of temporal variation is no < 100 and 20 for EP9 and SSSM, respectively. Except the dense vegetation covered area, the large amount of ubRMSE between STF9 and EP9 is < 0.02 m³/m³. It indicates the similar accuracy of EP9 and STF9 and can be considered that STF9 get the good accuracy with detailed spatial information. The difference between STF9 and SSSM is larger and the absolute difference is larger than 0.02 m³/m³ in the mass areas. It may be considered that the accuracy slightly differs between STF9 and SSSM. The good accuracy of SSSM evaluated by the SMAP core cal/val sites, however, the small amount of in-situ data makes the accuracy doubtfully. Furthermore, the other aspect makes the accuracy doubtfully is that the less amount of SSSM data. Nevertheless, it can be considered that the STF9 can get the good accuracy shown in Table 4 and Fig. 9 in global scale.

### 4.2.3. Evaluation against ISMN in-situ soil moisture

The 9-km soil moisture estimated by the STFM can capture the detailed spatial information and temporal variation of AP9 very well; however, the accuracy difference against in-situ data is still unknown. To explore the difference, the two-year period of STF9 was estimated by the STFM using the baseline data shown in Fig. 3. The results were then evaluated against ISMN in-situ soil moisture data (Table 2 and Fig. 1). In this way, we could assess the ability of STF9 for subsequent 9-km soil moisture estimation after the SMAP radar failure. In order to decrease the diversity of more than one in-situ site in the same 9-km soil

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**Table 4**

Temporal evaluation result of STF9 against EP9 and 9 km SSSM (Global mean, unit: m³/m³).

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>RMSE</th>
<th>bias</th>
<th>ubRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP9</td>
<td>0.901</td>
<td>0.052</td>
<td>0.001</td>
<td>0.013</td>
</tr>
<tr>
<td>9 km SSSM</td>
<td>0.700</td>
<td>0.101</td>
<td>0.003</td>
<td>0.059</td>
</tr>
</tbody>
</table>

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**Fig. 8.** The spatial distribution of STF9 and 3-km SSSM on April 12, 2017.
moisture pixel, the arithmetic average of multiple sites of in-situ data was used in the evaluation. The temporal variation validates the accuracy of STF9, because the in-situ and 9-km soil moisture show some mismatch in spatial resolution and probing depth (Dorigo et al., 2015). The sparse in-situ soil moisture (the ISMN sites used in this study) cannot fully represent the pixel values. Meanwhile, the temporal variation of soil moisture is less affected by the mismatch (Owe et al., 2008). The basic principle of the evaluation is to compare the temporal variation between the in-situ data and the corresponding pixel soil moisture directly, quantified in terms of Rs, bias (9-km pixel minus in-situ), RMSE, and ubRMSE.

Table 5 shows the average accuracies of the five soil moisture products against ISMN in-situ data during the T1 and T2 periods. In fact, it can be seen that the accuracy of AP9 is less than that of P36 (Colliander et al., 2017; Pan et al., 2016), which is validated in the T1 period (Table 5). The accuracy of EP9 is close to that of P36, because P36 is retrieved by the BG-interpolated 9-kmV-polarized TB and inherits the accuracy of P36. The accuracy of CD9 is significantly lower than that of P36, is comparable with that of AP9, and is slightly better than that of AP9 in some indices such as RMSE and ubRMSE. However, CD9 is not estimated in the cloud-contaminated area of the MODIS data, resulting in fewer pixels than AP9. The accuracy of STF9 is comparable with that of P36 and better than that of AP9. Among the three kinds of 9-km soil moisture, STF9 has the highest Rs and ubRMSE values (as indicated by the bold font in Table 5), which shows that the STFM can accurately estimate the temporal variation of in-situ soil moisture. Although the RMSE and bias of STF9 do not show an advantage, this will not affect the accurate application in climate research or weather prediction studies (De Jeu et al., 2014; Dorigo et al., 2012; Liu et al., 2012). The applications do not directly use the absolute value of soil moisture, but instead convert the soil moisture to the range relative variations in soil moisture, their evaluation using the TC method.

4.2.4. Evaluation based on the triple collocation method

The accuracy evaluation against ISMN in-situ soil moisture shows that STF9 can be considered for the extension of the SMAP 9-km soil moisture product. However, too much uncertainty is brought into the accuracy evaluation, as a result of the big difference between in-situ soil moisture and SMAP pixels in spatial scale. To eliminate the uncertainty, the triple collocation (TC) method was used for the further evaluation of the estimated 9-km soil moisture. The TC method was developed by Stoffelen (1998) to estimate the unknown RMSE of three or more linearly-related measurements over the same geophysical variable with mutually independent errors. It also allows the possibility of obtaining the correlation coefficients between the satellite retrievals and the true (but unknown) footprint value (Draper et al., 2013). Therefore, the R and RMSE were selected as the dominated metrics for the soil moisture evaluation using the TC method.

To estimate the accuracy with the TC method, three kinds of soil moisture products from independent sources are required. Although many kinds of SMAP soil moisture products were used in the study, they are all related to each other. Thus, to use the TC method, the model-
based surface soil moisture was introduced. This was extracted from the NOAH land surface model (version 2.8), which has been well-evaluated (Ek et al., 2003) and applied in TC application (Hain et al., 2011). Thus, a triplet pattern of in-situ, NOAH, and microwave data was built for the TC evaluation. Two kinds of triplets were constructed—in-situ-NOAH-STF9 and in-situ-NOAH-P36—as to compare the temporal accuracy difference between P36 and STF9 from April 13, 2015 to April 12, 2017. Table 6 shows the average TC evaluations of the two kinds of triplets. The R and RMSE of the in-situ and NOAH data are comparable between the two triplets, which confirm the reliability of TC method for soil moisture evaluation without the ground truth values. The Rand RMSE of the in-situ data are very low, as a result of the big difference between the point scale and the satellite footprint scale. Both the R of STF9 (0.829) and the R of P36 (0.826) are the highest in the each triplet and are very close to 0.83. This confirms the robustness of SMAP for soil moisture retrieval and the comparable accuracy between STF9 and P36.

As a result of the obvious seasonal variations of soil moisture, the R of the temporal variation cannot be used to evaluate precipitation well. This is not conducive to the study of weather and climate change. For this purpose, we further evaluated the variation of the temporal anomaly soil moisture under the framework of the TC method. The method described in Albergel et al. (2009) is used to extract the temporal anomaly soil moisture, and the moving window of the temporal variation was 31 days, 15 days before and after. We stipulated that the temporal anomaly soil moisture was extracted when there were three valid data records in each of the 15 days before and after, and seven valid data records, in total, in the 31-day moving window. According to the pattern of Table 6, Table 7 shows the average TC evaluations of the anomaly soil moisture. The anomaly R (Table 7) is less than the R shown in Table 6. This phenomenon has been validated in previous works (Zeng et al., 2016; Liu et al., 2012). The anomaly R and RMSE of STF9 are slightly better than those of P36, which suggests that STF9 is more suitable for the study of weather and climate change. The results confirm that STF9 has a better accuracy and can better capture the soil moisture. Generally speaking, it can be considered that this further confirms the advantage of STFM for 9-km soil moisture estimation.

5. Discussion

In terms of 9-km soil moisture estimation, the performance of the STFM is clearly better than that of the BG interpolation retrieval method adopted by NASA and the conventional soil moisture downscaling method. This is because STF9 integrates the respective advantages of the SMAP soil moisture products: the accuracy of P36 (Tables 5, 6, and 7) and the spatial resolution of AP9 (Figs. 5 and 6). The STFM takes full advantage of the temporal and spatial correlation of soil moisture, and only P36 and AP9 are used for estimating the 9-km soil moisture. The method does not require a soil moisture retrieval process or other ancillary satellite data (such as SAR or optical/thermal infrared data), so the error in the 9-km soil moisture estimation process can be decreased. Moreover, there is no time gap between P36 and AP9 as the SMAP passive and active sensors work together on the same satellite.

Table 6
TC evaluations of the two kinds of triplets.

<table>
<thead>
<tr>
<th>Triplet</th>
<th>In-situ-NOAH-STF9</th>
<th>In-situ-NOAH-P36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>RMSE(m^3/m^3)</td>
</tr>
<tr>
<td>In-situ NOAH STF9</td>
<td>0.438</td>
<td>0.107</td>
</tr>
<tr>
<td>In-situ NOAH P36</td>
<td>0.808</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Table 7
TC evaluations based on anomaly Rand RMSE for the two kinds of triplets.

<table>
<thead>
<tr>
<th>TC</th>
<th>In-situ-NOAH-STF9</th>
<th>In-situ-NOAH-P36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>RMSE(m^3/m^3)</td>
</tr>
<tr>
<td>In-situ NOAH STF9</td>
<td>0.312</td>
<td>2.054</td>
</tr>
<tr>
<td>In-situ NOAH P36</td>
<td>0.703</td>
<td>0.626</td>
</tr>
</tbody>
</table>


Fig. 10. The average R and ubRMSE of the three kinds of 9-km soil moisture estimations for each International Geosphere-Biosphere Program (IGBP) land cover in the T2 period.
Table 5 does not achieve the expected accuracy of SMAP (< 0.04 m$^3$/m$^3$) (Chan et al., 2016) in this study. This is mainly due to the sparse clearings; the 9-km soil moisture retrievals increases in winter, which may be the main factor that leads to the obvious difference between STF9 and P36. Therefore, it is suggested that the seasonal factors may have a greater effect than the distance from the date of the SMAP radar failure in 9-km soil moisture estimation using the STFM in the case of small-land-cover changes.

P36 underestimates the in-situ soil moisture (negative bias in Table 5), which was confirmed in previous studies (Chan et al., 2016; Kim et al., 2017; Zeng et al., 2016); however, the $ubRMSE$ of P36 in Table 5 does not achieve the expected accuracy of SMAP (< 0.04 m$^3$/m$^3$) (Chan et al., 2016) in this study. This is mainly due to the sparse evaluation sites used in the study leading to the larger $ubRMSE$ (Dorigo et al., 2015). Only one in-situ site is used in most cases to evaluate the temporal variation of the corresponding 9-km pixel soil moisture. As a result, the large spatial resolution difference between the two kinds of data increases the evaluation error. Furthermore, abnormal value information in the SMAP soil moisture products (Burgin et al., 2017) may be another reason that causes the $ubRMSE$ to be on the high side. Although there are some uncertainties in the evaluation against the sparse ISMN in-situ sites, STF9 keeps the temporal variation of P36 very well (Fig. 11). This is the reason why STF9 inherits the temporal accuracy of P36 (Table 5). Moreover, the temporal $R$ and $ubRMSE$ values of STF9 are slightly better than those of P36 (Table 5), which is determined by the STFM itself. The evaluations using the TC method also confirm that the temporal variation of STF9 is slightly better that of P36 (Tables 6 and 7). Essentially, the STFM is a kind of filtering algorithm and has a certain smoothing effect (Cheng et al., 2017). For STF9 estimation, the smoothing of outliers can help to decrease the errors and improve the temporal correlation with in-situ soil moisture. The accuracy of STF9 is clearly better than that of AP9 (Table 5), suggesting that the 9-km soil moisture estimated by the STFM will have a wider range of applications. However, only a two-year period of STF9 was estimated in this study, and the subsequent estimation results still need further testing and validation.

### 6. Conclusions

The failure of the SMAP radar has resulted in the unavailability of 9-km soil moisture products. In this study, we adopted the STFM to extend the SMAP 9-km products. The two-year STF9 products have been publicly released on http://rs-pop.whu.edu.cn/. Compared with other substitute products, i.e., AP9 and CD9, the STFM-based STF9 product has an obvious advantage in spatial distribution and detailed information, and is much closer to the original AP9. The R values between AP9 and EP9, EP9 and CD9, and STF9 are 0.422, 0.637, and 0.679, respectively. In addition, the evaluation against ISMN in-situ soil moisture shows that STF9 obtains the best $R$ and $ubRMSE$ values ($R = 0.667$ and $ubRMSE = 0.048$ m$^3$/m$^3$ in the T1 period; $R = 0.598$ and $ubRMSE = 0.060$ m$^3$/m$^3$ in the T2 period), performing better than AP9 and CD9 and slightly better than P36 and EP9. Furthermore, the evaluations using TC method show that the accuracy of STF9 is comparable with that of P36. Overall, STF9 integrates the respective advantages of both SMAP soil moisture products: the high accuracy of P36 and the spatial resolution of AP9. The validation of the two-year products confirmed that the presented method is an effective way to extend the 9-km soil moisture in the case of the SMAP radar failure. However, whether it could be used for the subsequent multi-year data still needs further validation.

### Acknowledgment

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### References
