VERSION 8 OF THE NASA SMAP LEVEL 4 SOIL MOISTURE PRODUCT

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***Abstract*—The NASA Soil Moisture Active Passive (SMAP) mission Level 4 Soil Moisture (L4_SM) product provides global, 3-hourly, 9-km resolution soil moisture estimates with a mean latency of ~2.5 days from the time of observation. The L4_SM estimates are derived through the assimilation of the brightness temperature (Tb) observations from the SMAP radiometer into the NASA Catchment land surface model. The L4_SM assimilation system is based on a spatially distributed ensemble Kalman filter and produces optimal soil moisture estimates by considering the uncertainties in the land model estimates and the Tb observations. Version 8 of the L4_SM product, first released in April 2025, features updated precipitation data used to drive the Catchment model and an improved version of the microwave radiative transfer model that links the simulated soil moisture and temperature estimates to the observed Tb. Validation against in situ measurements from SMAP core validation sites indicates that the L4_SM Version 8 surface (root-zone) soil moisture estimates have an unbiased RMSE of 0.039 (0.026) m^3 m^{-3}, thereby meeting the SMAP mission accuracy requirement. The typical magnitude of the Tb observation-minus-forecast differences in the L4_SM Version 8 product is 4.8 K, which represents an improvement of 0.2 K over the same metric for the Version 7 estimates.**

Keywords—Soil moisture, precipitation, data assimilation, SMAP, IMERG.

I. INTRODUCTION

The NASA Soil Moisture Active Passive (SMAP) mission [1] was launched in 2015 and has since been providing global observations of L-band (1.4 GHz) brightness temperature (Tb) at a resolution of ~40 km and with a local repeat interval of 2-3 days. By assimilating the SMAP Tb observations into the NASA Catchment land surface model [2], the SMAP Level 4 Soil Moisture (L4_SM) algorithm generates global, 3-hourly, 9-km resolution estimates of soil moisture and related land surface states and fluxes with a mean latency of ~2.5 days [3,4]. The L4_SM algorithm is based on a spatially distributed ensemble Kalman filter that considers the respective uncertainties of the land model estimates and the SMAP Tb observations and thereby produces optimal estimates of "surface" (0-5 cm) and "root-zone" (0-100 cm) soil moisture. The L4_SM estimates are thus informed by and fully consistent with the SMAP observations.

Over the 10+ year history of SMAP observations to date, the L4_SM product was updated approximately annually, each time with a full reprocessing of the entire SMAP record. A key component of the L4_SM algorithm are precipitation observations, which are used to drive the Catchment land surface model (except in the high latitudes, where precipitation from a weather analysis is used). Beginning with Version 6 of the L4_SM algorithm, the primary precipitation inputs for L4_SM are from the suite of NASA Integrated Multi-satellitE Retrievals for the Global Precipitation Measurement (GPM) mission (IMERG) products [5]. The IMERG precipitation, which is based on a merger of satellite and gauge observations, is now used in L4_SM outside of North America, where it replaces the gauge-only precipitation product that was used globally in earlier L4_SM versions and that is now used only in North America [6]. The change to the IMERG precipitation inputs was shown to substantially improve the quality of the L4_SM soil moisture and Tb estimates [6]. For example, the global average of the time series standard deviation of the observation-minus-forecast (O-F) Tb residuals was reduced from 5.5 K in L4_SM Version 5 to 5.1 K in Version 6. The improvements were particularly pronounced in the Southern Hemisphere, where rain gauge coverage is typically poor.

The most recent version of the L4_SM product is Version 8, which was first released in April 2025. Version 8 of L4_SM features a version update of the IMERG precipitation inputs. Moreover, the new L4_SM version features an updated L-band radiative transfer model, which acts as the observation operator in the assimilation system by relating the simulated soil moistures and soil temperatures to the L-band Tb observations. Additionally, Version 8 of L4_SM features climatological parameters that are based on longer records compared to the preceding version and a couple of minor bug fixes. The

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objective of the present paper is to document these updates and provide key validation results for the L4_SM Version 8 product.

II. Data and Methods

This section discusses the L4_SM data examined here (section II.A), the key changes in Version 8 of the L4_SM algorithm (sections II.B), and the validation approach (section II.C). For reference, a complete description of the validation data and methods are provided in [11].

A. L4_SM data

This paper uses soil moisture data from the Version 7 and 8 L4_SM "geophysical" (gph) products [7,8] and Tb forecasts and observations from the corresponding "analysis update" (aup) products [9,10]. Like all previous L4_SM versions, L4_SM Version 8 includes a full reprocessing of the entire SMAP period from 31 March 2015.

B. Changes in L4_SM Version 8

1) Precipitation inputs

In November 2023, the orbit of the GPM core satellite was raised, which resulted in considerable regional bias in the operational V06 IMERG-Late precipitation that was used in the L4_SM Version 7 algorithm at that time. This orbit change happened during the multi-stage version update of the GPM and IMERG products from V06 to V07 that was undertaken during 2023 and 2024. As a consequence, the L4_SM Version 7 algorithm dropped the use of IMERG data beginning in November 2023. After the IMERG version update was complete, the new L4_SM Version 8 product was finalized and released in April 2025, thereby restoring the use of IMERG inputs in the L4_SM algorithm.

The IMERG suite of products includes IMERG-Final and IMERG-Late. The former is more accurate because it is constrained by monthly gauge observations in addition to satellite data, but it has a latency of several months. The IMERG-Late product is less accurate because it is constrained only by satellite observations; it is available with a latency of less than one day.

Since the IMERG-Final V06 product ended in September 2021 (in preparation for the IMERG version update), L4_SM Version 7 used the less accurate IMERG-Late product from October 2021 through October 2023, and – as mentioned above – no IMERG inputs thereafter. In contrast, L4_SM Version 8 used the higher-accuracy IMERG-Final V07 product until processing switched to IMERG-Late V07 inputs on data-day 1 October 2024 for latency reasons. For the quality of the L4_SM estimates, the IMERG version update is therefore particularly important beginning in October 2021.

Furthermore, development of the L4_SM Version 8 product revealed a bug in the IMERG-Final V07 half-hourly product. When IMERG-Final data are used in L4_SM, daily precipitation rates are first calculated from the half-hourly IMERG product [6]. Unfortunately, owing to a science change in the IMERG-Final V07 algorithm, the precipitation rates in the half-hourly IMERG-Final V07 product are sometimes inconsistent with those of the *monthly* IMERG-Final V07 product, which is directly constrained with gauge observations and thus serves as the reference. The inconsistency occurs primarily (but not exclusively) during periods of snowfall. We therefore implemented an additional correction step in the L4_SM Version 8 algorithm that ensures consistency of the precipitation rates applied in L4_SM with those in the (reference) monthly IMERG files.

Additionally, Version 8 of the L4_SM algorithm fixes a bug in the gauge-only precipitation corrections (now used only in North America). This bug fix eliminates occasionally excessive precipitation rates along certain longitudes that are present in earlier L4_SM versions.

Finally, Version 8 of L4_SM minorly revised the southern boundary of the North America domain for use of the gauge-only precipitation. In Version 8, this boundary is at 13°N latitude; it was at 20°N latitude in Versions 6 and 7.

2) Radiative transfer modeling

The L4_SM algorithm includes a microwave radiative transfer model that estimates L-band Tb from the simulated soil moistures and soil temperatures [12,13]. The difference of the SMAP-observed L-band Tb and the simulated Tb is then used to calculate the SMAP-based corrections of the simulated soil moistures and soil temperatures in the ensemble Kalman filter analysis step.

Through Version 7 of L4_SM, the radiative transfer model used the soil dielectric mixing parameterization of Wang and Schmugge [14]. For consistency with the configuration of the SMAP Level 2/3 passive soil moisture algorithm (SPL2SMP_E), the Wang and Schmugge parameterization was replaced with that of Mironov et al. [15] in the Version 8 algorithm. Furthermore, we updated the values of the polarization mixing parameters for rough surface reflectivity to match those of the SPL2SMP_E algorithm. (In earlier versions of L4_SM, this polarization mixing was turned off.)

Finally, in the L4_SM Version 8 algorithm we updated the L-band scattering albedo, soil roughness, and vegetation opacity climatology with estimates obtained from Version 6 ("R19") of SPL2SMP_E [16], replacing the older parameters based on SPL2SMP_E Version 5.

3) Miscellaneous land model and analysis updates

In Version 8 of L4_SM, the snow albedo in the Catchment land surface model is based on a climatology obtained from satellite observations collected by the Moderate Resolution Imaging Spectroradiometer [17]. The satellite-based parameter values replace the corresponding lookup table parameterization used in earlier L4_SM versions.

Version 8 of L4_SM also corrects the soil parameters for a small (~10,000 km^2) region in Argentina near 38°S latitude and 60°W longitude. This region was erroneously classified as peat in earlier L4_SM versions owing to an error in the ancillary soil data.

Version 8 of L4_SM also benefits from an improved long-term Catchment model spin-up that avoids excessive multi-year snow accumulation in a few locations.

Finally, the Tb scaling parameters in L4_SM Version 8 are based on 9 years of data (April 2015-March 2024). Moreover, retrospective processing exclusively used observations from Version 6 ("R19") of the SMAP Level 1 Tb product [18].

C. Validation

We use in situ measurements from SMAP core validation sites [19] to determine the unbiased RMSE (ubRMSE; [20]) in the L4_SM soil moisture estimates. These sites contain locally dense networks of point-scale soil moisture sensors that can provide soil moisture measurements at the 9-km scale of the L4_SM product.

We further use surface soil moisture retrievals from the Advanced Scatterometer (ASCAT; [21]) to compute the difference in the anomaly time series correlation coefficient (R) between the L4_SM product versions following the approach of Reichle et al. (their section 3d) [22]. This metric determines which L4_SM product version provides better estimates of soil moisture anomalies from the long-term mean seasonal cycle.

Finally, we examine the O-F Tb residuals, which are calculated by differencing each (scaled) SMAP Tb observation and the corresponding L4_SM estimate ("forecast") just prior to the assimilation of the Tb observation [4]. It is important to stress that the SMAP Tb observations used to calculate these residuals have not been used to make the corresponding Tb forecast; consequently, even though the L4_SM product generally depends on the SMAP Tb observations, the O-F Tb residuals nevertheless support an independent validation of L4_SM.

III. Results and Discussion

Validation of the L4_SM Version 8 product against SMAP core site in situ measurements indicates an ubRMSE of 0.039 m^3 m^{-3} for surface soil moisture and 0.026 m^3 m^{-3} for root-zone soil moisture (Fig. 1). The surface soil moisture ubRMSE of the L4_SM Version 8 product is slightly improved over that of the Version 7 product. Additional tests (not shown) suggest that this improvement is primarily owing to the changes in the L-band radiative transfer model. Other metrics of the Version 8 product, including the mean difference, R, and anomaly R vs. in situ measurements, are unchanged from those of the Version 7 product (not shown; [11]).

Fig. 2 shows the difference in the surface soil moisture anomaly R (versus ASCAT observations) between the L4_SM Version 8 and Version 7 products for October 2021 through September 2024. During this period, the L4_SM Version 8 algorithm used the best-quality IMERG-Final V07 inputs, whereas the L4_SM Version 7 algorithm used IMERG-Late V06 during October 2021 through October 2023 (because IMERG-Final V06 ended in September 2021) and no precipitation observations outside of North America thereafter (section II.B). The figure shows that Version 8 has better surface soil moisture anomaly skill across much of the global land area, although minor degradation is seen in some regions; on balance, the L4_SM Version 8 surface soil moisture anomalies are superior to those of L4_SM Version 7. In the global average, the anomaly R of the Version 8 surface soil

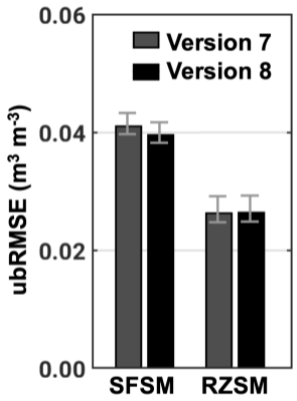


Fig. 1. Unbiased RMSE (m^3 m^{-3}) for L4_SM Version 7 and Version 8 surface soil moisture (SFSM) and root-zone soil moisture (RZSM). The ubRMSE is computed vs. in situ measurements for the 9-km reference pixels at the SMAP core validation sites (N=18 for SFSM, N=7 for RZSM), then averaged across sites. Error bars indicate 95% confidence intervals. Metrics computed for April 2015 to March 2021.

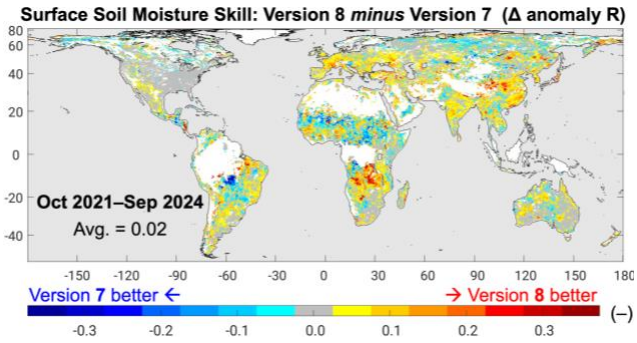


Fig. 2. Surface soil moisture anomaly R for L4_SM Version 8 minus same for L4_SM Version 7 (dimensionless), computed for October 2021–September 2024 using ASCAT soil moisture retrievals. Red (blue) colors indicate that Version 8 (Version 7) is better. White shading indicates no-data values.

moisture exceeds that of Version 7 by ~0.02, reflecting the higher-quality precipitation inputs in Version 8 during this period.

The improvements in the L4_SM Version 8 product are also reflected in the O-F Tb residuals. During April 2015 to September 2021, when both versions use IMERG-Final precipitation inputs, the typical magnitude of the O-F Tb residuals in the Version 8 product is 4.8 K in the global average, which is smaller by 0.2 K than the same metric in the Version 7 product (Fig. 3, 4a). The O-F Tb residuals are most improved in predominantly dry regions, including the western United States, southern South America, south-central Eurasia, India, eastern Africa, and Australia. There are minor degradations across portions of South America, the Sahara, and the Sahel.

During October 2021 to September 2023, the typical magnitude of the O-F Tb residuals of the Version 8 product is smaller by 0.4 K than the same in the Version 7 product (Fig. 3, 4b). The larger improvement during this period reflects the difference in the precipitation inputs, which are from IMERG-Final (V07) in the L4_SM Version 8 algorithm and from IMERG-Late (V06) in the L4_SM Version 7 algorithm.

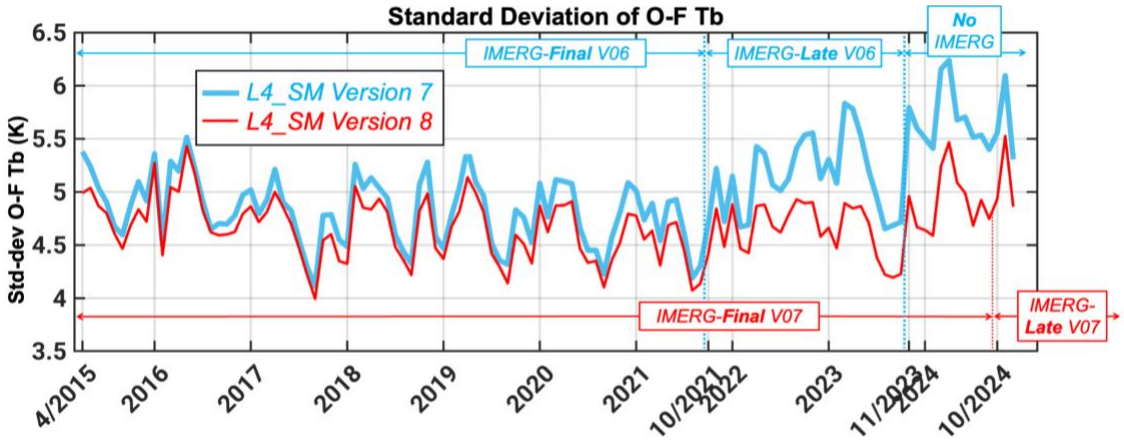


Fig. 3. Monthly, global standard deviation of O-F Tb residuals (K) from L4_SM Version 7 (thick blue line) and Version 8 (thin red line). For each L4_SM version, text boxes and arrows indicate changes in the sub-product and version of the IMERG precipitation inputs.

Lastly, during November 2023-September 2024, the typical magnitude of the O-F Tb residuals of the Version 8 product is smaller by 0.6 K than the same in the Version 7 product (Fig. 3, 4c). During this period, the L4_SM Version 8 algorithm uses IMERG-Final whereas the L4_SM Version 7 algorithm does not use any precipitation observations outside of North America.

Finally, Fig. 5 shows the global average of the typical magnitude of the O-F Tb residuals for L4_SM Versions 5 through 8. In the Version 5 product, first released in 2020, the O-F Tb residuals had a typical magnitude of 5.5 K. This metric continually improved by a total of >10% across successive version updates to a value of 4.8 K for the Version 8 product.

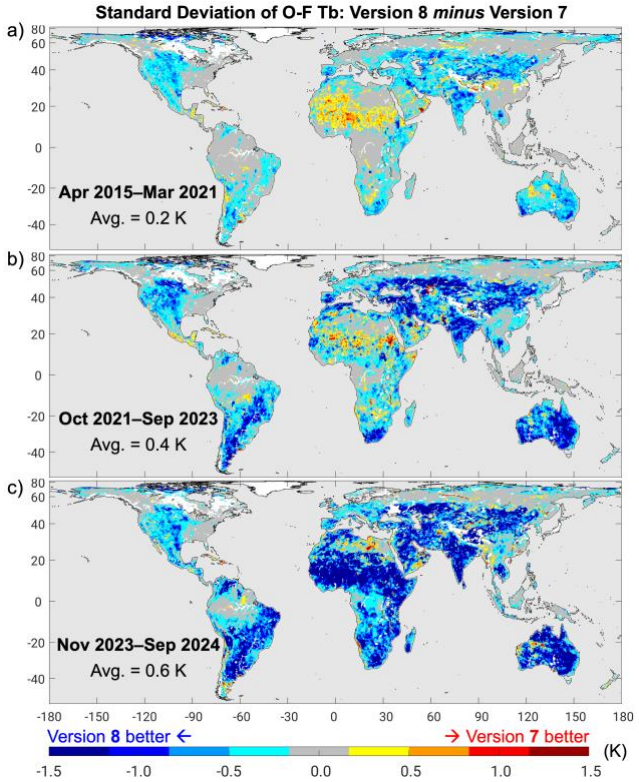


Fig. 4. Difference in time series standard deviation of O-F Tb residuals (K) from L4_SM Version 8 and Version 7 for (a) April 2015–March 2021, (b) October 2021–September 2023, and (c) November 2023–September 2024. Blue colors indicate improved Tb simulation skill in L4_SM Version 8 compared to Version 7. White shading indicates no-data values.

IV. Conclusion

In this paper, we documented the key improvements in the L4_SM Version 8 product, including the update of the input precipitation observations from IMERG and the change in the L-band radiative transfer model. The latter resulted in a lower surface soil moisture ubRMSE of 0.039 m^3 m^{-3}, relative to the same metric of the L4_SM Version 7 product.

The update in the precipitation inputs were necessitated by the changes in the IMERG version and the GPM orbit. The L4_SM Version 8 product now uses the better-quality IMERG-Final inputs through September 2024. Thereafter IMERG-Late inputs are used. In contrast, during its final 16 months of production (ending in April 2025), the L4_SM Version 7 algorithm did not use any precipitation observations outside of North America, and it relied on IMERG-Late inputs from October 2021 through October 2023. The improvements in the precipitation inputs are reflected in the better anomaly time series correlation of surface soil moisture from the Version 8 product (relative to that of Version 7). They are also reflected in the lower typical magnitude of the O-F Tb residuals (relative to that of the Version 7 product) throughout the entire SMAP period, and especially since October 2021.

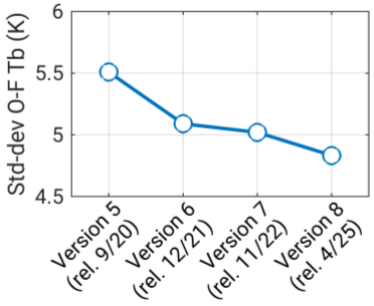


Fig. 5. Global average of time series standard deviation of O-F Tb residuals (K) for L4_SM Versions 5 through 8. Metric computed for April 2015 to March 2021. For each version, the month and year of the initial release is indicated in the abscissa label.

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