

Response letter

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We thank the reviewers for their time and constructive feedback. Below we address each comment point by point.

Reviewer 1

Point 1.1 – Overall, the authors did a good job of improving their paper.

Response – Thank you!

Point 1.2 – However, they could have been more cautious when making the suggestion that “SWI is computed using an exponential filter of SSM. This mimics water infiltration into deeper soil layers”. This is not satisfactory. The authors responded “We are aware that the exponential filter is mathematically simple but we respectfully disagree that it is purely statistical method. It was derived by solving a first-order differential equation that connects the soil surface layer and second layer below, yielding a spectral behavior as produced by models such as the Geophysical Fluid Dynamics Laboratory (GFDL) model as e.g. described in Delworth and Manabe (1988). Please see the paper by Ceballos et al. (2005) published in Hydrological Processes (<https://doi.org/10.1002/hyp.5585>).” Unfortunately, this Ceballos et al. paper is not open access and I cannot access it. I tried to expand the exponential filter equation myself and could not find any real connection to the diffusion equation. Therefore, if the authors wish to maintain their statement, they must provide the full mathematical demonstration in the paper itself.

Response – A complete mathematical derivation of the SWI is outside the scope of this article. The SWI was introduced for two purposes: to provide a smoothed visualization of the SSM and to represent SM at a deeper soil layer. Since the latter is strictly not required for this showcase, we instead use a simple moving average. Still, a more detailed derivation of the SWI is provided below.

Exponential filter

The exponential filter, used to derive the Soil Water Index (SWI) from surface soil moisture observations, comes from a simple two-layer water balance. The derivation follows Wagner et al. (1999, doi:10.1016/S0034-4257(99)00036-X) and the framework discussed by Ceballos et al. (2005, doi:10.1002/hyp.5585)

Consider a two-layer soil model comprising a thin surface layer with soil moisture $m_s(t)$ (as measured by the satellite) and a deeper reservoir layer with water content $m(t)$. Assuming the vertical water movement is proportional to the difference in soil moisture content, a simplified water balance equation can be used to quantify the hydrological coupling between the two layers.

$$L \frac{dm(t)}{dt} = C[m_s(t) - m(t)]$$

where t is time, L is the effective depth of the reservoir layer (units: length) and C is a hydraulic transfer coefficient representing the exchange capacity between layers (units: length · times⁻¹). Defining the characteristic time length $T = L/C$ the equation simplifies to

$$T \frac{dm(t)}{dt} = m_s(t) - m(t)$$

Here, T (units: time) represents the system's memory or relaxation timescale. Rearranging into standard linear ordinary differential equation form gives:

$$\frac{dm(t)}{dt} + \frac{1}{T} \cdot m(t) = \frac{1}{T} \cdot m_s(t)$$

Applying the factor $e^{t/T}$ and integrating from $-\infty$ to t the solution becomes:

$$m(t) = \frac{1}{T} \int_{-\infty}^t m_s(t') \cdot e^{-(t-t')/T} dt'$$

So the reservoir moisture is a convolution of the surface signal with an exponentially decaying kernel (i.e. an exponential filter). Past surface observations contribute with weights that decay as $e^{-\Delta t/T}$.

Connection to the diffusion equation

The two-layer ordinary differential equation above is an approximation of a more fundamental description: vertical water movement in soil is, to first order, a diffusive process governed by

$$\frac{\partial \theta(z, t)}{\partial t} = D \frac{\partial^2 \theta}{\partial z^2}$$

where $\theta(z, t)$ is the soil moisture at depth z and D is an effective hydraulic diffusivity. Integrating this equation vertically over the reservoir layer of thickness L , applying a no-flux bottom boundary, and approximating the surface gradient by a finite difference $(m - m_s)/L$, yields

$$L \frac{dm}{dt} = \frac{D}{L} [m_s(t) - m(t)]$$

which is exactly the two-layer balance with $C = D/L$ and therefore $T = L/C = L^2/D$. The relation $T \sim L^2/D$ is the characteristic diffusive timescale, i.e. the time required to homogenize moisture over a depth L by diffusion. In this sense, the exponential filter is the slowest eigenmode of the diffusion equation: higher modes decay rapidly, leaving a single dominant timescale T that controls the reservoir's memory of surface forcing.

Reviewer 2

Point 2.1 – The authors have adequately addressed my previous concerns, and the manuscript has been substantially improved. Before recommending acceptance, I would still like to provide a few minor suggestions for further clarification and readability.

Response – Thank you!

Point 2.2 – In my previous review, I mentioned that some parts of the methodology section appear somewhat overly detailed. More specifically, my concern mainly relates to the readability and structure of Section 3.3. The large number of relatively short subsections (e.g., Sections 3.3.1–3.3.8) makes it somewhat difficult for readers to follow the overall processing workflow and clearly identify the key algorithmic innovations. In particular, some technical descriptions and intermediate processing details could poten-

tially be condensed, merged, or moved to supplementary material, while keeping the core methodological concepts in the main text. Overall, the intention of this comment is not to reduce the technical rigor of the manuscript, but rather to improve readability and help readers more easily recognize the primary methodological contributions of the new ASCAT SSM dataset.

Response – We have moved section 3.3.1-3.3.4, 3.3.6 and 3.3.8 into the appendix, focusing only on those steps with updates in the main methodology section.

Point 2.3 – Regarding Section 4.3, the authors have added a valuable comparison between the discontinued ASCAT SSM NRT 12.5 km dataset and the new ASCAT SSM NRT 12.5 km dataset. As shown in Figure 16, the new dataset demonstrates a clear improvement in performance compared to the previous version. It would be helpful if the authors could further explain which specific algorithmic updates are considered the main contributors to this improvement. In addition, for the networks showing relatively poor performance, a more network-specific discussion of the possible reasons would further strengthen the validation analysis. The manuscript provides a discussion of the reduced performance over the VDS network; however, it still remains somewhat unclear whether the issue mainly arises from the updated vegetation correction itself or from the lack of masking during periods when backscatter dynamics are no longer dominated by soil moisture variations.

Response – In the revised version we have mentioned the main algorithmic updates improving the latest ASCAT SSM dataset, discussed in-situ network with an overall poor performance and further clarified the reduced performance over the VDS network. After carefully reviewing in-situ networks with lower performance, we decided to remove the HOAL network entirely. Several sensors were only temporarily installed, while others may have suffered from calibration issues.

Point 2.4 – Furthermore, in the BNZ-LTER network, Figure 16 indicates that three sensors are available, whereas only one point is shown for the new product. Could the authors clarify the reason for this discrepancy?

Response – The correlation coefficients for the three sensors are 0.514, 0.516, 0.509 (H SAF ASCAT SSM 12.5 km) and 0.214, 0.189, 0.015 (discontinued ASCAT SSM NRT 12.5 km). Unfortunately, the boxplot for such a low number of sensors with very similar values appears as a single point.

Point 2.5 – Finally, there appears to be an extra letter “k” next to “Pearson correlation” in Figure 15, which should be removed.

Response – Fixed.