Revision of manuscript **egusphere-2025-2606**

*"From grid to ground: How well do gridded products represent soil moisture dynamics in natural ecosystems during precipitation events?"*

# Responses to Reviewer 02

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We would first like to express our sincere gratitude to the handling editor, Dr. Roberto Greco, and to the two anonymous reviewers for their valuable comments and suggestions, which have helped us to substantially improve the quality and clarity of our manuscript.

The main revisions introduced in the manuscript are as follows:

- **Methodological clarification of the RZSM definition (0-100 cm)**: We clarified the harmonisation strategy adopted to account for differing vertical discretisations across products, discussed the implications of this approach across soil horizons, and identified sub-layer evaluation as a priority for future work.
- **Improved description of TEROS sensors as ground truth**: Additional details were provided on TEROS sensor technology, including the measurement principle, temporal resolution, and main sources of uncertainty. The use of factory calibration (±3–4% in non-saline mineral soils) was explicitly justified based on site-specific constraints such as remoteness, complex topography, and limited accessibility.
- **Clarification of performance classes (E, G, S, B)**: Performance thresholds and their reference sources were explicitly defined in the methodology. Traceability was further strengthened by adding a reference column to the corresponding table.
- **Precipitation evaluation and contextualization**: A direct comparison of ERA5 and ERA5-Land precipitation time series against in situ rain gauge observations was added as Supplementary Material S3, together with standard performance metrics (correlation, ubRMSE, KGE, and PBIAS), to contextualize atmospheric forcing uncertainty when interpreting soil moisture event responses.
- **Reorganization and streamlining of the Conclusions section**: The Conclusions were restructured to reduce text density, improve readability, and more clearly highlight the study's main findings and take-home messages.
- **Explicit recognition of temporal limitations**: The manuscript now clearly acknowledges that the 2022–2023 study period limits the assessment of interannual variability, while justifying the focus on event-scale dynamics and short-term hydrological responses.
- **Strengthening of implications and applications**: The discussion was expanded to better emphasise the practical relevance of the study, including the selection of soil moisture products for hydrological model calibration and forcing, drought and water-stress monitoring, and ecohydrological applications. Particular emphasis was placed on the differentiated suitability of products across contrasting hydroclimatic regimes (arid versus humid).
- **Reduction of acronyms and editorial improvements**: The Abstract was streamlined, terminology and naming conventions were corrected (e.g., TERENO), and minor editorial, formatting, and terminology revisions were implemented to improve clarity without increasing manuscript length.

In the following sections, we provide a point-by-point response to all comments raised by Reviewer 02 regarding our article entitled "*From grid to ground: How well do gridded products represent soil moisture dynamics in natural ecosystems during precipitation events?*". We hope that our detailed explanations will satisfactorily address all concerns.

# REVIEWER 2

**R2-C0:** The manuscript addresses an interesting and relevant topic, namely the comparison and reliability of different datasets, including Earth Observation and reanalysis products, in reproducing observed patterns of soil moisture. The paper is highly technical and, in some sections, the succession of data and results makes the reading somewhat heavy, at the expense of a deeper discussion on the reasons behind the observed trends. To avoid the impression that the manuscript reads as a technical report, some of the results could be moved to the Appendix.

We sincerely thank Reviewer 2 for the careful and constructive evaluation of our manuscript. Below, we provide detailed, point-by-point responses to all comments, which have helped us to improve the clarity, depth, and overall readability of the paper.

**R2-C1:** One major point that is not addressed is that the capacitive probes used as reference sensors often require calibration themselves. What is referred to as ground truth therefore also deserves further investigation

Thank you for this important comment. We fully agree that capacitive soil moisture sensors require calibration and that this introduces an inherent source of uncertainty when in situ observations are used as reference measurements. Accordingly, the sensor-based observations in this study should be interpreted as best-available field references rather than error-free ground truth.

The TEROS-10 and TEROS-12 sensors used in our monitoring network operate using the manufacturer's factory calibration for mineral soils, which provides a typical accuracy of ±3–4% volumetric water content for non-saline mineral textures (METER Group, 2023a). All Kimün-Ko sites are characterised by mineral soils with low electrical conductivity, making the factory calibration appropriate for the prevailing soil conditions. These sensors estimate soil dielectric permittivity using a high-frequency (70 MHz) capacitance/frequency-domain technique, which reduces sensitivity to salinity and temperature effects and is widely used in long-term environmental monitoring (METER Group, 2023a,b).

While soil-specific calibration can reduce absolute bias, currently available methods require disturbed or repacked soil samples (METER Group, 2023b). Such approaches are incompatible with the objectives of this monitoring network, which is intentionally installed in undisturbed natural soil profiles where soil structure, macroporosity, and aggregation strongly influence hydrological behaviour. Extracting intact monoliths of sufficient size to preserve pore connectivity is technically challenging and operationally unfeasible at several remote sites, and calibrations based on disturbed samples would likely be unrepresentative of in situ conditions.

For these reasons, we rely on factory calibration, acknowledging that it introduces modest absolute uncertainty while preserving the temporal dynamics, response timing, and event-scale variability that are central to our analysis. Numerous studies have shown that factory-calibrated capacitive sensors provide robust temporal soil moisture dynamics even when small systematic offsets may be present. To enhance transparency, we now report sensor-derived saturation levels in the Supplementary Material S1, providing additional context on the hydraulic behaviour of each soil profile. Future work could explore in situ or monolith-preserving calibration strategies should technically and logistically feasible methods become available.

The revised text reads for subsection 2.3 (In situ SM observations) reads as follows:

*TEROS-10 and TEROS-12 sensors operate under the manufacturer's factory calibration for mineral soils, which provides a typical accuracy of ±3–4% volumetric water content for non-saline mineral textures (METER Group, 2023a). The sensors estimate soil dielectric permittivity using a high-frequency (70 MHz) capacitance/frequency-domain technique, which minimises sensitivity to salinity and temperature variations (METER Group, 2023a,b). This configuration is well suited for long-term monitoring in the low-salinity mineral soils characterising the Kimün-Ko sites.*

*An additional source of uncertainty might arise from the use of capacitive sensors as reference measurements. Although soil-specific calibration can reduce absolute bias, available procedures rely on disturbed or repacked samples (METER Group, 2023b) and cannot preserve the natural soil structure, macroporosity, and aggregation that govern* *hydrological responses in undisturbed forest and shrubland soils. Given the remoteness and limited accessibility of several sites, extracting large intact monoliths was not operationally feasible. Consequently, factory calibration was adopted, introducing modest absolute uncertainty while retaining reliable temporal soil moisture dynamics.*

**R2-C2:** although a large amount of information is reported, one of the most relevant aspects of the comparison remains underexplored, namely the type of soil and its hydraulic properties as represented in the models used for the analysis. This factor could be important in explaining differences across datasets. For this reason, some of the results might also be interpreted in terms of saturation degree rather than volumetric water content.

We agree that soil type and hydraulic properties play an important role in shaping soil moisture dynamics and can influence the behaviour of gridded soil moisture products. In the gridded datasets analysed here, soil hydraulic properties are prescribed using global soil databases that are largely derived from the FAO/UNESCO soil map, or its subsequent harmonised products, which provide a common baseline for soil texture, bulk density, and pedotransfer-based hydraulic parameters. As a result, the large-scale spatial patterns of soil properties are broadly consistent across ERA5, ERA5-Land, and GLDAS-Noah, and substantial differences attributable solely to soil input data are not expected.

Nevertheless, we acknowledge that differences in how these soil properties are implemented within each modelling framework can contribute to inter-product discrepancies. In particular, variations in soil layer discretisation, hydraulic parameterisation schemes, and land surface model formulations can lead to different representations of soil water storage, drainage, and near-surface moisture dynamics, even when similar underlying soil information is used (Niu et al., 2011; Lawrence et al., 2019). These structural and parametric differences are therefore more likely to explain the observed divergences among products than the use of distinct soil datasets per se.

We also agree that expressing results in terms of degree of saturation could provide complementary insights, especially when comparing sites with contrasting soil textures or hydraulic conductivities. Normalising volumetric water content by site-specific porosity can help disentangle climatic controls from soil physical constraints and facilitate cross-site interpretation. This approach is of clear interest and is being considered for future analyses. In the present study, however, we focused on volumetric soil moisture because it is the native variable provided by all gridded products and remains the standard metric for operational evaluation and intercomparison of soil moisture datasets (Rahmati et al., 2024). This choice allowed us to establish a consistent baseline comparison, which, to our knowledge, has not previously been reported for undisturbed natural ecosystems in southern South America.

**R2-C3:** Another important aspect concerns the precipitation input to the models, which strongly influences soil response. It would be useful to show how precipitation varies across models compared to the observational values used.

We thank for this important comment, which agree with comment R1-C8 (from reviewer 01).

We would like to emphasise that the primary objective of this study is to evaluate surface and root-zone soil moisture datasets (SSM and RZSM, respectively) as integrated, operational products, rather than to isolate or independently validate their individual forcing components. In ERA5, ERA5-Land, and GLDAS-Noah, soil moisture is generated as the outcome of coupled atmospheric forcing, land–surface parameterisations, and, in some cases, data assimilation, and these products are commonly used in hydrological, ecological, and climate applications in this final form.

Nevertheless, we fully agree that precipitation is the dominant driver of soil moisture dynamics and that explicitly examining precipitation inputs provides important context for interpreting soil moisture behaviour. In response to the reviewer's suggestion, we have therefore extended the analysis to include an explicit comparison between gridded precipitation from ERA5 and ERA5-Land and in situ rainfall observations at each study site. These comparisons are now presented in the Supplementary Material S3 as precipitation time series, allowing a direct assessment of differences in precipitation timing and magnitude across models relative to local observations.

This additional analysis strengthens the interpretation of soil moisture responses to rainfall events and increases confidence in the event-scale results, while maintaining the study's focus on soil moisture as an integrated model output. The manuscript has been revised accordingly, and the subsection 4.4 (Challenges of temporal and spatial comparisons) now explicitly refers to the precipitation comparison, as detailed below:

*[....] Beyond these spatial controls, differences in the atmospheric forcing used by each modelling system also contribute to uncertainty in the comparison. Although precipitation strongly controls soil moisture dynamics, our analysis evaluates the products as integrated outputs generated by their respective modelling frameworks. ERA5, ERA5-Land, and GLDAS-Noah each combine precipitation, evapotranspiration, and land–surface processes in different ways (Hersbach et al., 2020; Muñoz-Sabater et al., 2021; Rodell et al., 2004; Reichle et al., 2017). On the other hand, in SMAP-L4 precipitation is not directly observed but is incorporated as a bias-corrected meteorological forcing to the land surface model, derived from combined gauge and satellite products, while soil moisture states are subsequently refined through the assimilation of SMAP brightness temperature.*

*To provide additional context for the interpretation of soil moisture responses, we compare gridded precipitation from ERA5 and ERA5-Land with in situ rainfall observations at each site (Supplementary Material S3; Zambrano-Bigiarini et al., 2025). In addition to time series comparisons, basic statistical metrics (correlation, ubRMSE, KGE, and PBIAS) are reported to characterise the agreement between reanalysis precipitation and local observations.*

*Overall, the results indicate a moderate temporal correspondence between reanalysis precipitation and observed rainfall events, while also revealing substantial biases in precipitation magnitude at several sites, particularly in arid and topographically complex environments. These results are not intended as a standalone validation of precipitation products, but rather to contextualise the uncertainty associated with atmospheric forcing when interpreting soil moisture dynamics at the event scale. Evaluating soil moisture in this final, integrated form reflects how these products are commonly used in hydrological and climate studies and provides a practical basis for comparing their behaviour across contrasting hydroclimatic regions.*

**R2-C4:** In the abstract, the number of acronyms should be reduced, and the correct name of the dataset is TERENO rather than TERRENO. For each dataset considered, it would also be useful to report the temporal and spatial coverage

Thank you for this helpful comment. We have corrected the name of the reference network from TERRENO to TERENO in the Introduction. To further improve clarity and readability, we revised the Abstract to reduce the number of acronyms and ensured that each dataset is written in full at its first occurrence. In addition, we now explicitly report the temporal and spatial coverage of all gridded soil moisture products in Table 1 (subsection 2.2, Gridded SM datasets), providing a clearer and more transparent overview of the data used in the study.

The manuscript has been revised accordingly, and the revised text in the Introduction now reads as follows:

*[...] Noteworthy networks; such as TERENO (Zacharias et al., 2011), OzNet (Smith et al., 2012), COSMOS-UK (Evans et al., 2016), and the International Soil Moisture Network (ISMN; Dorigo et al., 2021); provide valuable long-term datasets. [...]*

**R2-C5:** The choice of the models needs to be better justified, in particular why ERA5 and ERA5-Land are used when they are largely overlapping, and why the two specific EO products were selected over other available alternatives

Thank you for this valuable comment. Although the Datasets section describes each product in detail, we agree that the rationale for the dataset selection requires stronger justification to ensure the study's transparency.

We have revised the manuscript to clarify that these four products were selected not randomly, but to form a specific comparative framework representing the current state-of-the-art in global soil moisture estimation:

1. **ERA5 vs. ERA5-Land**: these products share the same atmospheric forcing but differ in spatial resolution and land-surface treatment, both of which are critical for soil moisture estimation. ERA5 is a fully coupled reanalysis that assimilates satellite soil moisture (ASCAT), whereas ERA5-Land is an offline land-surface rerun at higher spatial resolution without direct soil moisture assimilation. Their joint evaluation enables a clear assessment of the relative benefits of satellite data assimilation versus high-resolution land-surface forcing, and how these choices affect soil moisture performance across contrasting hydroclimatic regimes.

2. **SMAP-L4 (SPL4SMAU)**: We selected SPL4SMAU over other satellite-based products (e.g., ESA CCI or AMSR2) because it uniquely combines the high penetration capability of L-band radiometry with a water balance model to provide root-zone estimates, representing the most advanced satellite-assimilation product currently available.

3. **GLDAS-Noah**: is a model-driven land-surface system forced by multiple meteorological inputs and commonly used in hydrological studies. It was selected as the standard "open-loop" benchmark widely used in the hydrological community, providing a baseline for comparison against the reanalysis and assimilation-based products.

We have updated the subsection 2.2 (Gridded SM datasets) to explicitly state these justifications, as follows:

*"We evaluated four gridded soil moisture datasets selected to represent distinct modelling frameworks and assimilation strategies. Our selection includes ERA5 and ERA5-Land reanalysis products, which share atmospheric forcing but differ in resolution (31 km in ERA5, 9 km in ERA5-Land) and assimilation (active in ERA5, absent in ERA5-Land); this pairing allows us to isolate the specific impacts of spatial downscaling and satellite data assimilation. Furthermore, we selected GLDAS-Noah and SPL4SMAU to complement the reanalysis products by using two additional and widely used global frameworks. In particular, SPL4SMAU (SMAP Level 4) represents the state-of-the-art in L-band satellite data assimilation for root-zone estimates, while GLDAS-Noah serve as the standard open-loop model benchmark. This selection encompasses the full spectrum of available global products: reanalysis, high-resolution land replay, satellite-driven assimilation, and model-only simulations. These four products are briefly described below."*

**R2-C6:** Some background on the TEROS sensor technology and the associated measurement uncertainties should be included.

Thank you for this helpful comment. We agree that providing technical context and explicitly stating the limitations of the sensors improves the interpretation of the results. Therefore, building on our reply to R2-C1, we have expanded the Datasets section to include a technical overview of the TEROS capacitance technology. Specifically, we now detail the 70 MHz operating frequency and its role in minimizing texture and salinity effects.

Furthermore, in our reply to R2-C1 we have added a discussion on measurement uncertainties, explicitly addressing the trade-offs of using factory calibrations versus soil-specific calibrations and the potential influence of installation artifacts (e.g., air gaps).

**R2-C7:** Clarification is also needed on how the classes E, G, S, and B are defined

Thank you for this comment. We have clarified the definition of the performance classes (E: Excellent, G: Good, S: Satisfactory, B: Bad) in the subsection 3.2.1 (Statistical metrics of performance) we have added a new column to Table 4, specifying the corresponding references and threshold ranges used to classify the metrics (KGE', ubRMSE, PBIAS, and $\rho$). This addition improves transparency in how the quality categories were assigned and allows for reproducibility across studies.

The new Table 4 is the following:

Table 4: Performance metrics, including formulas, ranges of variation, ideal values, and interpretation criteria.

| Metric | Formula | Range | Ideal value | Interpretation criteria | Reference |
|---|---|---|---|---|---|
| *ubRMSE* | $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(GP_i - IS_i - \text{Bias})^2}$ | $[0, +\infty[$ | 0 | E < 0.04 ; G > 0.04 ; S > 0.08 ; B > 0.12 | Entekhabi et al. (2014) |
| *PBIAS* | $\frac{1}{N}\sum_{i=1}^{N}(GP_i - IS_i)$ | $]-\infty, +\infty[$ | 0 | E < \|10%\| ; G < \|20%\| ; S < \|30%\| ; B ≥ \|30%\| | Yapo et al. (1996) |
| $\rho$ | $1 - \frac{6\sum_{i=1}^{N} d_i^2}{N(N^2-1)}$ | $[-1, 1]$ | 1 | E ≥ 0.75 ; G ≥ 0.65 ; S ≥ 0.50 ; B < 0.50 | Beck et al. (2021) |
| *KGE* | $1 - \sqrt{(r-1)^2 + \left(\frac{\text{CV}_{GP}}{\text{CV}_{IS}} - 1\right)^2 + \left(\frac{\overline{IS}}{\overline{GP}} - 1\right)^2}$ | $]-\infty, 1]$ | 1 | E ≥ 0.70 ; G ≥ 0.30 ; S ≥ -0.40 ; B < -0.40 | Kling et al. (2012) |

GP: gridded product; IS: in situ observation; CV: coefficient of variation; E: Excellent; G: Good; S: Satisfactory; B: Bad

**R2-C8:** The mismatch between SSM and RZSM may also be related to the different timescales of the processes involved.

Thank you for this insightful comment. We fully agree that mismatches between surface soil moisture (SSM) and root-zone soil moisture (RZSM) are closely linked to the different characteristic temporal scales governing the underlying processes in each soil layer. SSM is dominated by fast processes, responding almost immediately to precipitation inputs and atmospheric demand, whereas RZSM reflects slower dynamics controlled by infiltration, percolation, root uptake, and soil water storage. These contrasting response times are clearly expressed in our event-based analysis, where RZSM exhibits systematically delayed and attenuated responses relative to SSM.

We now explicitly state that the soil profile acts as a low-pass filter, where high-frequency atmospheric forcing (precipitation) seen in the SSM is attenuated and phase-shifted as it percolates to the root zone. This explains why the RZSM signal appears smoother and decoupled from the immediate variability of the SSM.

The updated text in subsection 4.2.2 (Root zone soil moisture) now reads as follows:

*[...] The mismatch between SSM and RZSM primarily reflects their contrasting characteristic timescales. SSM responds rapidly to precipitation and atmospheric demand, whereas RZSM evolves more slowly as infiltration, percolation, root uptake, and soil water storage integrate surface inputs over time. As a result, the vadose zone acts as a low-pass filter, attenuating and phase-shifting high-frequency surface signals as wetting fronts propagate downward. This leads to systematically delayed and dampened RZSM responses relative to the more dynamic SSM, as observed in the event-based analysis (Faúndez Urbina et al., 2023).*

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