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 01

Daniel A. Núñez-Ibarra, Mauricio Zambrano-Bigiarini and Mauricio Galleguillos

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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 01 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 1

R1-C0: The manuscript tackles an important and timely topic: evaluating state-of-the-art gridded soil moisture (SM) products in natural ecosystems of central and southern Chile. The study is original, methodologically robust, and provides valuable insights into the performance of SM datasets in under-monitored areas of the Southern Hemisphere. The combination of standard statistical performance metrics with event-based soil moisture signatures (rising time and amplitude) is a notable strength and introduces novelty. Overall, the manuscript is well-prepared and deserves publication after significant revisions. Below, I offer detailed comments that could help enhance the clarity, impact, and wider relevance of the research.:

We appreciate the constructive and comprehensive evaluation that Reviewer 1 made of our manuscript. The comments and suggestions were highly valuable and have helped us improve the clarity, structure, and interpretative depth of the paper. Below, we provide detailed point-by-point responses to each comment.

R1-C1: Conclusions (clarity and structure). The conclusions are dense and could be reorganized into a concise list of take-home messages. This would enhance readability and emphasise the main findings for a broader audience.

We thank the reviewer for this constructive suggestion. We agree that clear and concise conclusions are essential for emphasising the key messages of the study. Although we consider the narrative format appropriate for highlighting the main findings and their implications, we carefully revised the Conclusions section to reduce textual density, improve readability, and ensure that the central take-home messages are more clearly articulated. These adjustments preserve the structure of the section while providing a more accessible summary for a broader audience.

- **ERA5 and ERA5-Land provide the most robust performance across ecosystems**. They reproduce both surface and root-zone soil moisture dynamics with the highest skill, particularly in humid southern sites, and offer strong temporal consistency for ecohydrological applications.
- **Root-zone soil moisture is generally easier to reproduce than surface soil moisture**. All products perform better for deeper layers due to their more buffered dynamics. ERA5 and ERA5-Land remain the most reliable datasets for studies requiring accurate representation of root-zone variability.
- **Arid ecosystems continue to pose significant challenges for all datasets**. At northern sites, all products overestimate the amplitude and rising time of the first soil-moisture response of the hydrological year, highlighting persistent limitations under dry antecedent conditions and low soil water storage.
- **Performance improves substantially during wetter periods**. Intense precipitation events markedly reduce amplitude and timing errors in both arid and humid regions, indicating that gridded products capture soil moisture dynamics more effectively when hydrological signals are stronger.
- **Deseasonalised correlations provide clearer insights into short-term dynamics**. The Spearman rank correlation computed on deseasonalised time series is particularly informative in arid climates, where strong seasonality can mask short-term variability. Seasonality-adjusted metrics should therefore be incorporated more routinely in product evaluation.
- **Soil-moisture signatures reveal diagnostic information overlooked by standard statistics**. Event-based signatures such as amplitude and rising time expose systematic discrepancies not visible in traditional statistical metrics, demonstrating the value of integrating process-based diagnostics in future assessments of gridded soil moisture products.

R1-C2: Implications and applications. Expand the discussion on the practical relevance of the results. For example: How can the findings support water management or drought monitoring? What are the implications for regional climate modeling in semi-arid Chile?

Thank you for this constructive comment. We have expanded the discussion to more clearly emphasize the practical implications of our findings for water resources management, drought monitoring, and regional climate modelling. Specifically, we added a new paragraph describing how differences in spatial and temporal performance among products can inform their selection for both operational and research applications across contrasting hydroclimatic regions. This paragraph has been incorporated in a new section named "*Practical implications*", located at the end of the "*Results and discussion section*".

[...] Identifying products that exhibit superior performance under specific hydroclimatic regimes can guide the choice of data sources for operational applications in poorly monitored regions. Such applications include the calibration and forcing of hydrological models (Rajib et al., 2016; Probst and Mauser, 2022; Silwimba et al., 2025; Zeng et al., 2021b), digital soil mapping (Aljanabi and Dedeoğlu, 2025; Luo et al., 2025), improving the spatio-temporal analysis of drought propagation (Lin et al., 2023), evaluating surface water stress monitoring in semi-arid environments (Ceppi et al., 2025), and deepening dendrochronological analyses that depend on soil moisture availability or antecedent water balance as key controls on tree growth in Chilean forests (Álvarez et al., 2024).

R1-C3: Limitations and future work: The relatively short observational period (2022–2023) limits the assessment of interannual variability. This should be explicitly acknowledged, with suggestions on how longer records (or complementary datasets) could improve robustness.

We thank the reviewer for this important comment. We fully acknowledge that the relatively short observational period (2022–2023) limits the assessment of interannual variability. This limitation has now been explicitly stated and discussed in the revised manuscript. At the same time, we emphasise that analyses based on one or two hydrological years of high-frequency observations can effectively identify dominant error sources and sensitivities in soil moisture products. We have revised section 4.4 (Challenges in temporal and spatial comparisons) accordingly and the new text read as follows:

The temporal coverage of this study (2022–2023) limits the assessment of inter-annual variability. Nevertheless, high-frequency analyses spanning one or two hydrological years have been shown to be effective in identifying dominant error sources and sensitivities in gridded soil moisture products, particularly in regions characterized by strong seasonal contrasts (Albergel et al., 2012; Brocca et al., 2010; Beck et al., 2021). In semi-arid and temperate ecosystems, soil water content typically undergoes pronounced intra-annual transitions, from near-saturated conditions during winter to minimal plant-available water at the end of the dry season, driven by precipitation pulses, atmospheric evaporative demand, and vegetation water use (Dai et al., 2022; Sun et al., 2015; Räsänen et al., 2020). Capturing these transitions is critical for evaluating the capacity of soil moisture products to reproduce key hydrological processes.

The spatial diversity of the monitoring sites across contrasting hydroclimatic regimes partially compensates for the limited temporal extent by enabling a process-oriented evaluation across a broad range of hydrological responses. Nonetheless, extending the in situ observational record and integrating complementary gridded datasets would enhance the robustness of the present analysis.

In addition, we have added a new section entitled "*Future research*" before the "*Conclusions*" section, with a forward-looking perspective on how longer records and future research could further strengthen our analyses. The new text reads as follows:

Building on our findings, future research should aim to strengthen the spatial and temporal representativeness of soil moisture assessments in natural ecosystems. Although the spatial diversity of the monitoring sites across contrasting hydroclimatic regimes partially compensates for the limited temporal coverage by enabling a process-oriented evaluation of a wide range of hydrological responses, extending the in situ observational record remains a priority to improve robustness. This effort would benefit from the integration of complementary gridded datasets. For example, combining three independent soil moisture products within a triple-collocation framework would allow the estimation of error characteristics (e.g., variance and bias) even in the absence of absolute ground truth (e.g. Gruber et al., 2016). High-resolution active microwave observations, such as those from Sentinel-1, offer a promising pathway to bridge the scale gap between point-scale measurements and coarse-resolution gridded products (e.g. Bauer-Marschallinger et al., 2018; Madelon et al., 2023). In parallel, incorporating vegetation information, *such as leaf area index and related indices from MODIS or Copernicus, would support a more explicit evaluation of vegetation–soil moisture coupling (e.g. Chen et al., 2015), while high-resolution soil property maps could help quantify the influence of soil texture and water-holding capacity on discrepancies between in situ and gridded estimates (e.g. Coopersmith et al., 2014). Additional hydrological variables may further serve as soft data for process-level validation, including streamflow records to assess integrated soil moisture–streamflow responses and drought indices to evaluate the consistency of soil moisture anomalies at seasonal scales (e.g. Popat and Döll, 2021; Afshar et al., 2022). Finally, expanding the Kimün-Ko monitoring network to encompass a broader range of ecohydrological settings and conducting systematic cross-comparisons with global databases such as the International Soil Moisture Network (ISMN) would enhance interregional consistency and contribute to the development of harmonized soil moisture validation frameworks, particularly in under-represented regions of the Southern Hemisphere.*

R1-C4: The definition of RZSM (0–100 cm) is harmonized across products but may obscure differences in vertical soil processes. A brief sensitivity discussion would strengthen the analysis

We thank the reviewer for this comment. We agree that harmonising root-zone soil moisture to a 0–100 cm layer may smooth vertical gradients and partially obscure depth-dependent soil processes. Nevertheless, this approach was required to ensure comparability among datasets characterised by heterogeneous vertical discretisations and parameterisations. We have clarified this methodological choice in section 3.1.3 (Root zone soil moisture) and explicitly acknowledged its implications. The revised text reads as follows:

[...] Therefore, in this work, root-zone soil moisture was harmonised to the 0–100 cm layer across all datasets to ensure consistency and enable a fair comparison among products with differing vertical resolutions and modelling schemes. This integration depth represents the active root zone for most natural ecosystems in Chile and is commonly adopted in global validation studies (Guo et al., 2023; Liu et al., 2024; Zheng et al., 2024).

R1-C5: Consider proposing specific future research avenues (e.g., integration with Sentinel-1 or other high-resolution sensors, extension of the monitoring network, cross-comparisons with ISMN data).

We appreciate this constructive comment. We have added a new section entitled "*Future research*" before the "*Conclusions*" section, as described in our reply to R1-C3.

R1-C6: International connection: The study would gain broader relevance if results were briefly compared with findings from other arid/humid regions (e.g., Africa, Asia). This would highlight the global implications of the Chilean case study.

We thank the reviewer for this valuable comment and for encouraging a stronger international contextualization of our results. In response, we have expanded and updated the bibliography to include recent evaluations of gridded and satellite-based soil moisture products conducted in Africa and Asia. We have also added a dedicated paragraph to subsection 4.2.3 (Summary of regional performance) that explicitly compares our findings with global patterns reported in the literature. This comparison situates the Chilean case study within a broader international context and demonstrates its consistency with observations from other arid and humid regions worldwide. The added text reads as follows:

The regional contrasts identified in this study are consistent with patterns reported across a range of hydroclimatic settings worldwide. Large-scale evaluations in China have shown that soil moisture products tend to exhibit reduced performance in steep or topographically heterogeneous regions, where coarse-resolution models struggle to represent local water retention and drainage processes (Wu et al., 2021; Zhang et al., 2021; Zheng et al., 2022). Extensive validations at more than one thousand ground stations across China further indicate that performance varies strongly with vegetation density and soil texture, particularly for root-zone soil moisture (Tian and Zhang, 2023; Nadeem et al., 2022). Similar behaviour has been reported in Central Asia, where ERA5 showed the highest temporal correlation with in situ observations (mean $r = 0.59$*), while GLDAS exhibited lower overall uncertainty but systematically underestimated soil moisture under arid conditions (Yu et al., 2023). In the Upper Blue Nile Basin, satellite-based products such as SMAP and SMOS were found to better capture temporal soil moisture dynamics than reanalysis datasets, underscoring the importance of dense monitoring networks in African basins (Alaminie* *et al., 2024). Over the Tibetan Plateau, SMAP outperformed other satellite products, with performance primarily constrained by elevation, vegetation biomass, and surface roughness (Zeng et al., 2021a). Collectively, these international studies reinforce the conclusion that no single soil moisture product performs consistently best across all environments; rather, performance is strongly modulated by vegetation characteristics, soil texture, topography, and climatic regime. In this context, the pronounced hydroclimatic gradient of Chile provides a valuable natural laboratory for identifying the strengths and limitations of different soil moisture products under contrasting arid and humid conditions in the Southern Hemisphere.*

R1-C7: Verification of assumptions: You averaged all data to 3-hour resolution. Could this temporal aggregation mask short-term dynamics, particularly in ERA5/ERA5-Land, which have hourly outputs? Please justify

We thank the reviewer for this pertinent observation. We acknowledge that temporal aggregation can, in principle, affect the representation of short-term variability, particularly for datasets available at hourly resolution. However, the choice of a 3-hour temporal resolution was motivated by the need to harmonise the temporal sampling across all datasets and to ensure a fair and internally consistent comparison. Specifically, both SMAP-L4 and GLDAS-Noah are provided at 3-hour intervals, making aggregation necessary to avoid unequal temporal comparison among all products.

In addition, aggregating to 3-hourly time steps reduces the influence of sub-hourly noise and timing mismatches between precipitation forcing and soil moisture response, which are common when combining in situ observations with gridded products. Importantly, this resolution remains sufficiently fine to capture the soil moisture dynamics associated with precipitation events and short-term hydrological responses that are central to our analysis. This methodological choice is consistent with practices adopted in previous large-scale soil moisture intercomparison and validation studies (Beck et al., 2021). The revised text for subsection 3.1.1 (Common temporal resolution) now reads as follows:

All gridded SM datasets were downloaded at their highest temporal resolution, and time series were extracted at the grid cell corresponding to each in situ monitoring site. To ensure temporal consistency across datasets, hourly outputs from ERA5, ERA5-Land, and in situ measurements were aggregated to 3-hour intervals starting at 00:00:00 UTC. This harmonisation avoids unequal temporal comparison among products and minimises phase mismatches between precipitation forcing and soil moisture response, while preserving the temporal variability relevant for event-scale analyses. Similar aggregation strategies have been adopted in previous global soil moisture validation studies to ensure methodological consistency across datasets (Beck et al., 2021).

R1-C8 Moreover, precipitation drives soil moisture. A more explicit evaluation of precipitation inputs in ERA5/ERA5-Land (and their consistency with local rain gauges) would strengthen confidence in the results.

We thank the reviewer for this relevant comment and fully agree that precipitation is the primary driver of soil moisture dynamics. However, we would like to emphasise that the original objective of this study was to evaluate soil moisture products as integrated outputs of operational reanalysis and land-surface modelling systems, rather than to independently assess the accuracy of individual forcing components.

In ERA5, ERA5-Land, and GLDAS-NOAH, soil moisture emerges from the coupled interaction of precipitation, evapotranspiration, land-surface parameterisations, and data assimilation processes within a unified modelling framework (Hersbach et al., 2020; Muñoz-Sabater et al., 2021; Rodell et al., 2004; Reichle et al., 2017). In most hydrological and climate applications, these products are used in this final, integrated form, without explicit decomposition of their underlying forcings.

Nevertheless, in direct response to the reviewer's suggestion, we have expanded the analysis to include an explicit comparison between gridded precipitation from ERA5 and ERA5-Land and in situ rain gauge observations at each study site. These precipitation time series and their associated performance metrics are now provided in the Supplementary Material S3, offering a direct assessment of the temporal consistency between reanalysis precipitation and local rainfall measurements. This additional analysis strengthens the interpretation of soil moisture responses to precipitation events and increases confidence in the event-scale comparisons presented in the manuscript.

The revised text for subsection 4.4 (Challenges of temporal and spatial comparisons) now reads as follows:

[...] 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.

R1-C9 Minor Suggestions

Writing style: Sometimes the text is dense and filled with acronyms. Making the prose simpler and cutting down on jargon where possible would make it easier to understand, especially for readers who are less familiar with SM modelling.

Figures: Some figures are very detailed and hard to interpret. Think about adding schematic diagrams or visual summaries that compare key differences (e.g., "north arid vs south humid") to make the main points clearer.

Terminology: Make sure the terms are used consistently (e.g., SSM vs "surface SM") and check that all acronyms are explained when first introduced.

Formatting: While tables that summarise site details and datasets are useful, they could be made clearer by streamlining their layout. At times, the text is dense and acronym-heavy. Simplifying the prose and reducing jargon where possible would improve accessibility, especially for readers less familiar with SM modelling.

We thank the reviewer for this minor suggestions, which were analysed and introduced in the manuscript as described below:

1. **Writing style and usage of acronyms**: We reduced the usage of acronyms and tried to cut down on jargon. If we missed something, we will appreciate specific further suggestions.

2. **Terminology**: We revised the consistency in the usage of terms (e.g., SSM vs "surface SM") and checked that all acronyms are explained when first introduced. If we missed something, we will appreciate specific further suggestions.

3. **Formatting**: We reduced the usage of acronyms and tried to cut down on jargon. If we missed something, we will appreciate specific further suggestions.

4. **Figures**: We created a new schematic Figure 14 (see figure below), which summarises all our conclusions to make the main points clearer, highlighting key differences between northern arid sites vs southern humid ones. Does the reviewer agree that this figure could be used in the Conclusions sections to provide a graphical summary of our main findings?. If not, what specific comments might help us to improve this figure?

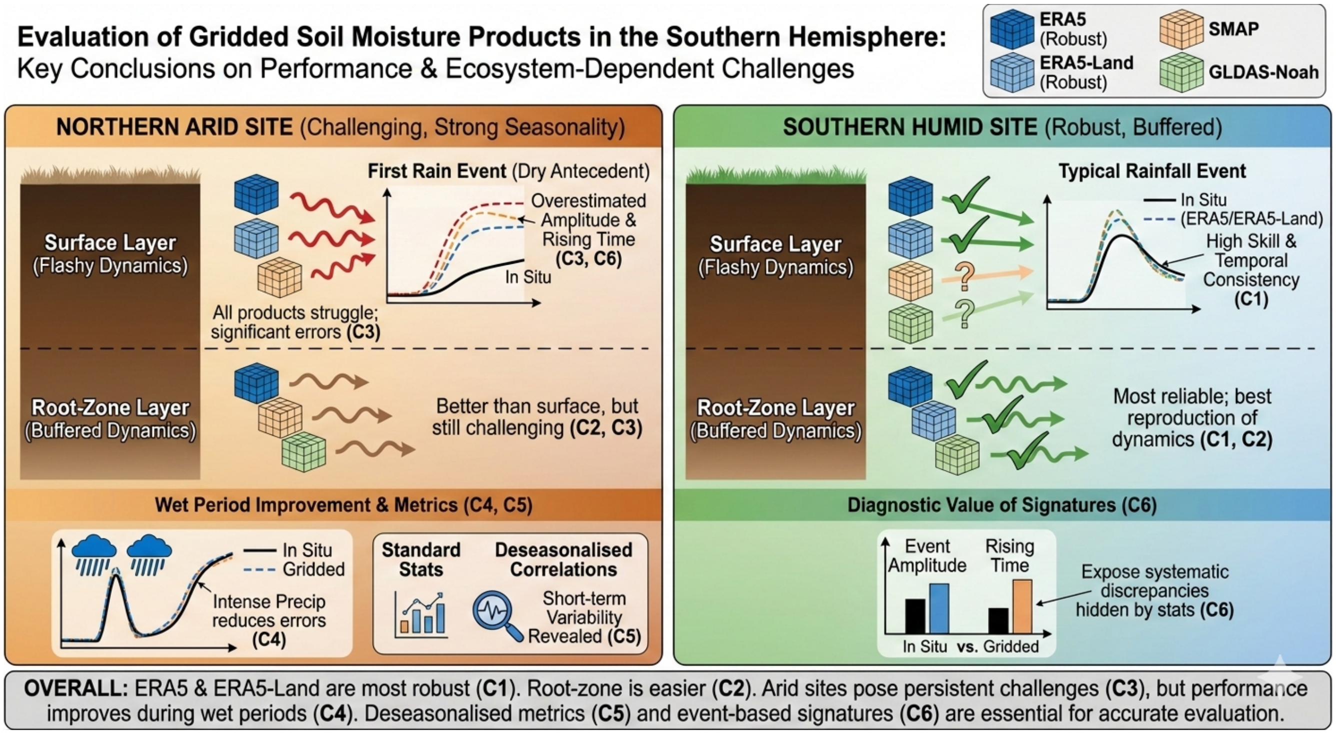

Figure 14: Schematic summary of the main conclusions of this article.

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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

Daniel A. Núñez-Ibarra, Mauricio Zambrano-Bigiarini and Mauricio Galleguillos

December 25, 2025

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 ρ). 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)
ρ	$1 - \frac{6\sum_{i=1}^{N} d_i^2}{N(N^2-1)}$	$[-1, 1]$	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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