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

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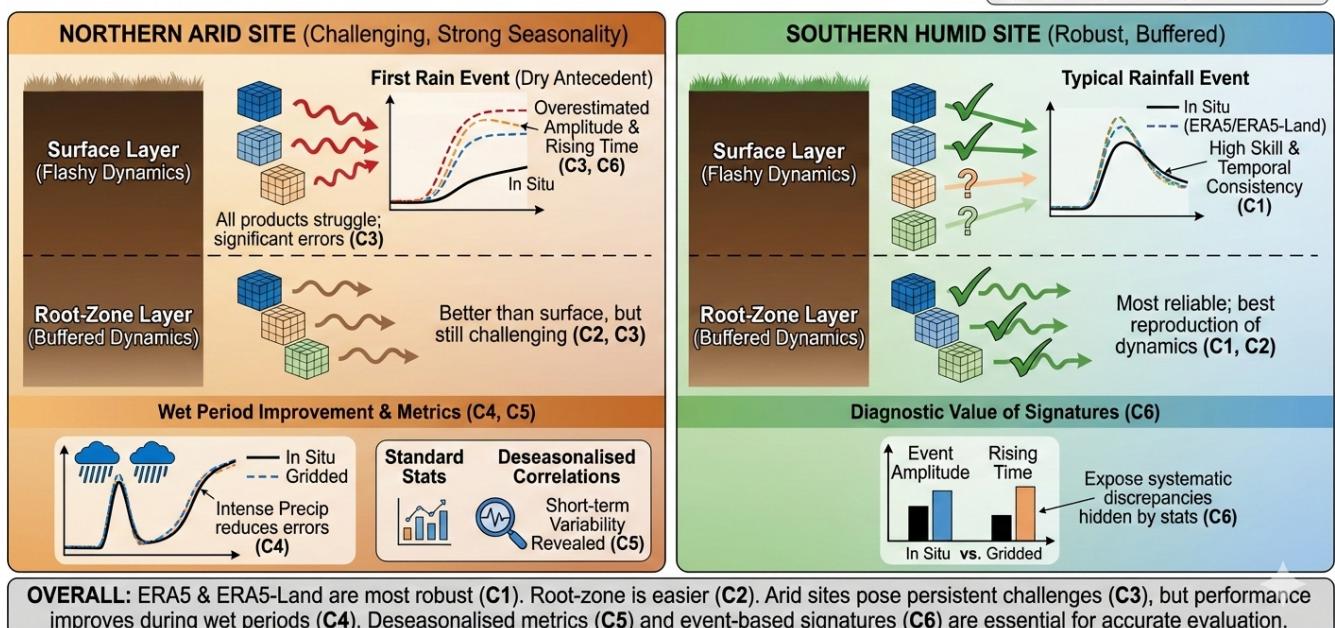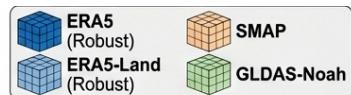
Figure 14: Schematic summary of the main conclusions of this article.

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