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Title: A Study of the Dependence between Soil Moisture and Precipitation in different Ecoregions of the Northern Hemisphere

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We highly appreciate the editor and anonymous reviewers for the very helpful and insightful comments that lead to the significant improvement this manuscript. We have checked our work carefully according to these comments and made the requested changes. In the revised version, we emphasized the new insights, improved the clarity and added more physical interpretation about the results. Figure S2 was reproduced and all figures were provided with high qualities.

Below we indicate the comments and use blue font for our responses. The corresponding revised texts are also used blue font in the revised version of our manuscript.

Anonymous Referee #1

The authors have made notable efforts to revise the manuscript. Most of my concerns have been addressed, and the overall clarity of the paper have improved. However, a few issues still require attention before the manuscript can be considered for publication:

1. While the authors state that lags range from 0 to 12 months, Figure S2 shows negative lags. The inconsistency needs to be addressed.

Response: Thank you for your comment. The positive values in the initial version of Figure S2 indicate that soil moisture lags behind precipitation, while negative values indicate that precipitation lags behind soil moisture. To ensure consistency with the manuscript, the negative lags were converted to positive ones by adding 12 months, which represent soil moisture lags behind precipitation in the following year. Then, Figure S2 was reproduced with lags ranging from 0 to 12 months.

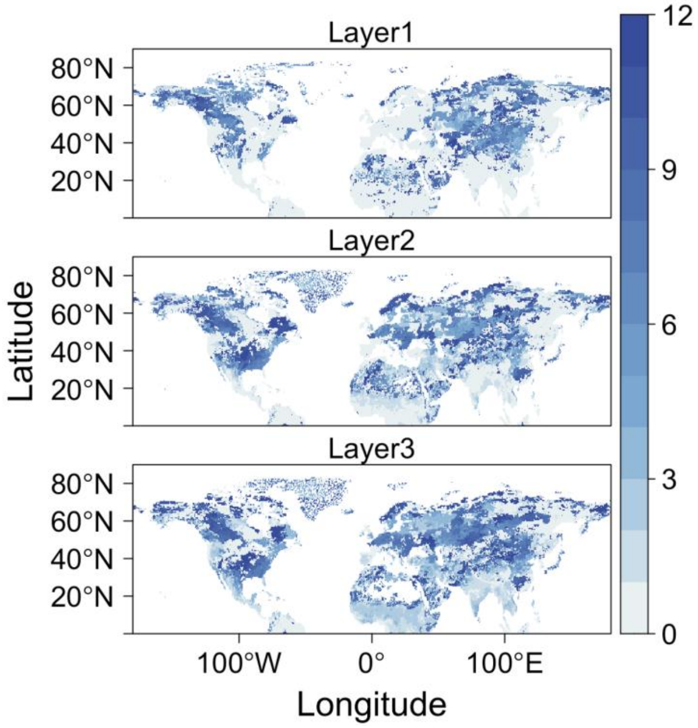

Fig. S2 The estimated number of lagged month for each grid in the Kendall's tau correlation.

2. The quality of the figures remains suboptimal, especially Fig. 7 and 8.

Response: Thank you for your comment. In the revised manuscript, we have provided all figures with high qualities.

Anonymous Referee #3

Please note that I wrote my review before reading the comments from the first stage of the review process. Nevertheless, I share many of the same concerns previously raised, most importantly, the novelty of the paper is not clearly stated. While the research topic is certainly interesting and the relationships among the analyzed variables remain an open area of investigation, the manuscript fails to clearly explain how it contributes new insights or identifies novel relationships.

Response: Thank you for your thorough review and valuable comments. This study focused on the coupled precipitation–soil moisture system and the nonlinear dependence between precipitation and soil moisture was investigated, different from the traditional linear methods. The underlying drivers in the dependencies between soil moisture and precipitation across different regions were revealed. The results provide new insights into the spatial variability of precipitation–soil moisture dependencies and can contribute to a better understanding of how climatic and vegetation factors jointly shape soil water dynamics.

Following your comments, we have rephrased the related texts more clearly, corrected some writing issues and provided all figures with high qualities.

Specific Comments:

• Line 75: “Most current analyses of the relationship between soil moisture and precipitation assume a linear relationship.” This is an important statement. Could you please provide supporting references to substantiate this claim?

Response: Thanks, we have added several references to support the statement.

“Most current analyses of the relationship between soil moisture and precipitation assume a linear relationship (Sehler et al., 2019; Yang et al., 2018).”

Sehler, R., J. Li, J.T. Reager, and H. Ye. 2019. Investigating Relationship Between Soil Moisture and Precipitation Globally Using Remote Sensing Observations. Journal of Contemporary Water Research & Education. 168:106-118.

Yang, L., G. Sun, L. Zhi, and J. Zhao. 2018. Negative soil moisture-precipitation feedback in dry and wet regions. Scientific Reports. 8:4026.

• Data Sources:

You use soil moisture data from ERA5, which also provides precipitation and near surface air temperature data. Why did you not use ERA5 for all variables, where available, to ensure consistency?

Response: Thank you for your valuable comment. In this study, we tried to use different datasets based on their observational foundations. Specifically, the CRU TS, ESA CCI, and GPCP datasets are all based on ground-based and/or satellite observations, whereas ERA5-Land is a model-derived reanalysis product. Although ERA5 does offer a wide range of meteorological variables, it can introduce model uncertainties. Therefore, the datasets used in this study have independent source, which can avoid the potential false relationships between soil moisture and precipitation that may be caused by the same model architecture and input parameters. We have added these explanations in the *Data Reliability* section of the revised version. (Lines 608-615)

• Line 207:

"In this study, the ecoregion boundaries rather than Köppen climate zones were used to investigate the spatial patterns of precipitation–soil moisture feedbacks." If you are not using Köppen climate zones, why are you mentioning them here? Please clarify the purpose of this comparison.

Response: Thank you for your comment. The Köppen climate zone was specifically mentioned to address the reviewer's comment regarding the regional division. To avoid confusion, we have revised the texts as follows.

"Although the Köppen climate classification provides a standardized framework based on temperature and precipitation, it may perform not well in accounting for critical biophysical factors, particularly for vegetation. Alternatively, the ecoregion divisions integrate both climatic and ecological factors, offering a more comprehensive understanding of the spatial heterogeneity in vegetation types and hydrological processes (Gerken et al., 2019; Olson et al., 2001). This makes it particularly advantageous for studying land–atmosphere interactions, since vegetation plays a central role in regulating energy and water fluxes. Therefore, this study adopts ecoregion boundaries to better capture the vegetation related variability in precipitation–soil moisture relationship.” (Line 207-216)

Gerken, T., B.L. Ruddell, R. Yu, P.C. Stoy, and D.T. Drewry. 2019. Robust observations of land-to-atmosphere feedbacks using the information flows of FLUXNET. npj Climate and Atmospheric Science. 2:37.

Olson, D.M., E. Dinerstein, E.D. Wikramanayake, N.D. Burgess, G.V.N. Powell, E.C. Underwood, J.A. D'Amico, I. Itoua, H.E. Strand, J.C. Morrison, C.J. Loucks, T.F. Allnutt, T.H. Ricketts, Y. Kura, J.F. Lamoreux, W.W. Wettengel, P. Hedao, and K.R. Kassem. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. BioScience. 51:933-938.

• **Line 331:**

“The percentages of grid cells exhibiting negative dependence at these depths were 19.2%, 0.7%, and 2.3%, respectively.” Is 0.7% a meaningful value in this context? Also, the decrease in negative dependence with increasing depth is expected, but why does the middle layer exhibit less negative dependence than the deepest layer? This result seems counterintuitive. Can you provide a physical interpretation?

Response: Thank you for your comment. While a general decline in negative dependence with depth is expected due to reduced soil–atmosphere coupling, the notably low percentage in the middle layer may reflect the transitional role of this zone in the soil profile. The middle soil layer, generally between 7 and 28 cm depth in ERA5-Land, commonly corresponds to the main root zone of ecosystems like temperate deciduous forests, perennial grasslands, and shrublands., The plant water uptake is relatively consistent within this zone, resulting in low variability of soil moisture. This could weaken the precipitation-soil moisture feedback signal, leading to a few grid cells with significant negative dependence (Thompson et al., 2010). In contrast, the deep soil layers may retain some long-term memory of moisture deficits, especially under prolonged dry conditions, which could contribute to stronger negative dependence than in the more buffered middle layer.

We have added these interpretations in the Discussion section. (Lines 505-512)

Thompson, S.E., C.J. Harman, P. Heine, and G.G. Katul. 2010. Vegetation-infiltration relationships across climatic and soil type gradients. Journal of Geophysical Research: Biogeosciences. 115.

• Lines 341–349:

The variables λU and λL are formatted inconsistently. Please correct the notation. Additionally, you describe their behavior without providing any interpretation of what these patterns mean physically or statistically.

Response: Thanks, we have revised all formatted error, and added discussion to clarify the significance of the observed patterns.

"This decreasing trend likely reflects the weakening of extreme precipitation–soil moisture coupling in deeper soil layers, except for arid regions where vegetation is sparse or absent." (Line 354-356)

"It revealed that the negative correlation was kept between precipitation-soil moisture in long-term scale over arid regions." (Line 361-362)

• Monthly vs. Yearly Maps:

How do you interpret the differences between the maps based on monthly data and those based on yearly data? This comparison is presented, but not adequately discussed.

Response: Thank you for your comment. To improve clarity, we have revised the manuscript to explicitly emphasize this contrast and its physical interpretation in the section 4.1 as follows.

"Different from monthly scale, the negative dependence at annual scale is primarily generated in regions such as deserts, xeric shrublands, montane grasslands and shrublands. These ecosystems are specifically characterized by arid conditions, and particularly sensitive to environmental changes, making them much responsive to long-term climatic variability." (Line 523-527)

• Seasonality:

Time series of climatological data are typically affected by seasonal cycles.

However, you do not seem to have removed seasonality in your analysis. This is a standard procedure when applying copula models and tail dependence metrics. See, for instance:

Neumeyer, N., Omelka, M., & Hudecov., Š. (2019). A copula approach for dependence modeling in multivariate nonparametric time series. Journal of Multivariate Analysis, 171, 139–162.

Durante, F., Fuchs, S., & Pappad., R. (2025). Clustering of compound events based on multivariate comonotonicity. Spatial Statistics, 66, 100881.

You acknowledge the presence of seasonality, so why not attempt to de-seasonalize the data and compare the results? This would add robustness to your analysis.

Response: Thank you for your valuable comment. We agree that removing seasonal cycles prior to dependence analysis could help isolate the intrinsic relationship between precipitation and soil moisture, and improve the statistical robustness. We have revised the manuscript to state this limitation and added more explanations.

"The copula method can access the dependence between different time series, after removing influences of the conditional means and variances as well as marginal distributions (Neumeyer et al. 2019; Durante et al. 2025). In this study, although precipitation–soil moisture dependence was assessed across different time scales, the monthly series were not de-seasonalized. As a result, the residual seasonal signals may influence short-term dependence structures. This limitation will be addressed in future work through seasonal adjustment." (Line 619-625)

• **Line 379:**

"The results from ridge regression revealed more distinct patterns at the seasonal scale compared to the monthly scale (Fig. 5)."

This observation further highlights the influence of seasonality. It reinforces the concern that the analysis may benefit significantly from seasonal adjustment across the board.

Response: Thank you for raising this point. While our analysis includes results at the seasonal scale, it is important to clarify that the dependence measurements were computed for each season separately on an annual basis (e.g., spring 2000, spring 2001, ... , spring 2019), rather than aggregating all seasons together or combining all months across years. Therefore, each seasonal estimate is based on data with a one-year interval, which reduces the influence of intra-annual periodicity and helps to mitigate the effect of strong seasonal cycles.

Therefore the influence of seasonality on the ridge regression results is not overstated, and that the generated dependence patterns can reflect the differences in precipitation–soil moisture coupling behavior across different time scales. We have clarified this point in the revised manuscript to avoid misunderstanding.

• **Figure 7 and Clustering Approach:**

How are you performing clustering? In Figure 7, clusters appear to overlap. This suggests the use of fuzzy clustering, yet you previously stated (line 319) that K-means was used, which does not allow for overlapping clusters. Please clarify and correct any inconsistencies in your methodology description.

Response: Thank you for your comment. The K-means clustering was used in this study, which assigns each data point to a single, non-overlapping cluster. The appearance of overlapping clusters in Figure 7 is likely due to visual effects caused by spatial aggregation or the dominance of a single cluster in some regions. We have clarified this point in the revised manuscript and figure caption to avoid misunderstanding.

• **Section 4.3 – Data Reliability:**

This section feels largely redundant with Section 2.1. Consider consolidating or cross-referencing to avoid repetition.

Response: Thanks for your advices. We have revised section 4.3 based your comment as follows. (Lines 608-631)

“In this study, multiple observational datasets were employed to reduce model-driven uncertainty and enhance data reliability. CRU TS, ESA CCI, and GPCP were selected due to their direct reliance on ground-based or satellite observations, in contrast to the reanalysismodel-based ERA5-Land product. Although ERA5 does offer a wide range of meteorological variables, it can introduce model uncertainties. Therefore, the datasets used in this study have independent source, which can avoid the potential false relationships between soil moisture and precipitation that may be caused by the same model architecture and input parameters. To investigate spatial heterogeneity, all data were spatially aggregated by ecoregion boundaries from the Conservation Biology Institute. These boundaries may introduce regional biases, which should be considered when interpreting the results.

The copula method can access the dependence between different time series, after removing influences of the conditional means and variances as well as marginal distributions (Durante et al., 2025; Neumeyer et al., 2019). In this study, although precipitation–soil moisture dependence was assessed across different time scales, the monthly series were not de-seasonalized. As a result, the residual seasonal signals may influence short-term dependence structures. This limitation will be addressed in future work through seasonal adjustment. In the Bayesian modeling, GPP, LST, and air temperature were examined as drivers of negative dependence. Evapotranspiration was excluded due to its dependence on both soil moisture and temperature. We acknowledge that additional factors—such as wind, topography, and soil physical properties—may also modulate precipitation–soil moisture coupling but were not in the scope of this analysis. Future research incorporating these variables would provide a more comprehensive understanding of the underlying mechanisms."

• **Figure Quality:**

Some figures still appear to be of low resolution or poor quality. Please ensure all figures are adequately rendered and suitable for publication

Response: Thank you for your comment. In the revised manuscript, we have provided all figures with high qualities.