Journal: Hydrology and Earth System Sciences

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 anonymous reviewer for the very helpful and insightful comments that lead to the significant improvement of the quality of this manuscript. We have checked our work carefully according to these comments and made the requested changes. For point to point response, we indicate the comments and use blue font for our responses.

Anonymous Referee #2

The authors examine the dependences between soil moisture and precipitation, and their drivers across the northern hemisphere. They find substantial negative dependences, which are mostly attributed to evapotranspiration and vegetation conditions. The topic is intriguing and the methodology interesting. However, I think this paper could benefit from refinement in areas like novelty declaration, method justification, presentation quality, and enhanced supporting evidence for conclusions. Therefore, I would recommend a major revision.

Response: We sincerely thank you for your valuable comments. Based on your suggestions, the Results and Discussion sections were reorganized for improving clarity. Some quantitative summery was added to the Abstract and Conclusion sections. Figure 2 was re-plotted and Figures S3 and S4 were added for considering the time lag. These modifications have improved the overall quality of the manuscript.

1. Below are major concerns that expect to authors to address in the revised manuscript. The authors need to identify the research gaps and specify any novel findings or methodology not reported in earlier studies. Negative correlations between soil moisture and precipitation and their causes have previously been identified, a fact acknowledged by the authors (Line 66-73). The authors seem to claim their novelty in terms of climate change and climate extremes (Line 101-106). However, I find the two points only loosely related to this study.

Response: Thanks for your comment. We have rewritten the related sentences to identify the research gaps and specify novel in abstract as follows.

"Although previous studies have identified the mechanisms of soil moisture variation across different time scales (Shen et al. 2018; Vidana Gamage et al. 2020), the interaction among precipitation, evapotranspiration and soil water under climate change may have changed. The dependence of soil moisture to precipitation and its interactions with evapotranspiration under conditions of climate change require further investigation."

"This study clarifies the regional differences and driving mechanisms of the negative correlation between precipitation and soil moisture.”

Shen, S., and Coauthors, 2018: Persistence and Corresponding Time Scales of Soil Moisture Dynamics During Summer in the Babao River Basin, Northwest China. Journal of Geophysical Research: Atmospheres, 123, 8936-8948.
Vidana Gamage, D. N., A. Biswas, and I. B. Strachan, 2020: Scale and location dependent time stability of soil water storage in a maize cropped field. CATENA, 188, 104420.

2. There is a lack of quantitative summary of the findings throughout the paper, especially in the abstract and conclusion sections. For instance, the authors should indicate the proportion of positive/negative correlations across various soil layers/ecoregions and quantify the contribution of controlling factors.

Response: Thanks for your suggestion. We have revised abstract and conclusion, and the quantitative summary was added.

“……Nonlinear negative dependencies of soil moisture to precipitation were revealed. The monthly scale negative dependence proportion reached 19.2%, 0.7%, and 2.3%, while the annual scale was 1.8%, 3.8% and 6.4%, respectively.”

“……Among them, temperature most strongly drives the deep-layer negative dependence in the tundra over annual scale, with the absolute difference between the posterior estimates of temperature on precipitation and soil moisture reaching 0.32.”

“……The results suggest that, at the monthly scale, negative dependence proportion reached 19.2%, 0.7%, and 2.3%, while the annual scale was 1.8%, 3.8% and 6.4%, respectively.”

3. The Results and Discussion section reads too imbalance. Currently, there is a lack of reasoning of the findings shown in the Results section, making the results a bit dull to read. The reasoning in Discussion is too spread and redundant, causing readers having to flip between the two sections. Also, I think a schematic diagram might help.

Response: We appreciate your comment about the readability of the manuscript. We have substantially revised the structure of the Results and Discussion sections to enhance logical flow and readability. In particular, we have reorganized subsection 4.3

based on the driving mechanisms and strengthened the interpretation of our findings directly within the Results section to reduce redundancy. We hope these changes can address your concerns effectively.

4. The ridge regression and Section 3.2 seem off topic, as the main scope is to study the dependences between precipitation and soil moisture as well as their drivers. As a key driver of the dependences, why ET is not added to the Bayesian model. The soil property, another key controlling factor according to the authors, is also not considered in the Bayesian model as well (Line 116).

Response: The ridge regression model was established to quantify the driving intensity of precipitation-evapotranspiration on soil water, which is a complementary analysis for joint distribution. Considering evapotranspiration is generally correlated with soil moisture and air temperature, while soil moisture is used as the dependent variable in the Bayesian model, air temperature and ground temperature are considered as driving factors. So it is not necessary to consider ET as the driving factor separately. Soil factors include many factors such as soil depth, soil texture, etc., and this study mainly explores the dependence in different depths. These were further explained in Section 4.3 in the revised version.

"In addition to the factors discussed in this study, other variables such as wind patterns and topography may also influence the negative dependence between precipitation and soil moisture. Soil properties—such as texture, organic matter content, and hydraulic conductivity—represent another set of important controls that were not explicitly included in the current Bayesian models. While this study provides a foundational analysis of the negative dependencies across different ecoregions, future research should explore these additional environmental factors to gain a more comprehensive understanding of the mechanisms underlying precipitation–soil moisture interactions."

5. The authors should justify their use of eco-region boundaries over the more well-known climate region, e.g., Köppen climate classification system.

Response: Ecoregions are divided based on an integrated consideration of vegetation types, soils, substrate, and climate. Compared to climate zones, they can better capture the heterogeneity of regional water feedback processes. Therefore, ecoregion boundaries were used instead of climate zones. The explanation for this choice was added in the revised manuscript.

"In this study, the ecoregion boundaries rather than Köppen climate zones were used to investigate the spatial patterns of precipitation–soil moisture feedbacks. Ecoregions are divided based on a combination of factors including vegetation types, soil characteristics, substrate, and climate conditions. This multi-factor approach allows ecoregions to better reflect ecological and hydrological processes than classifications based solely on climate variables. Since soil moisture dynamics and their feedbacks with precipitation are strongly influenced by vegetation structure, root systems, and edaphic properties, the ecoregions can provide a more mechanistic and spatially relevant framework for our analysis."

6. The dependence between soil moisture and precipitation might not be concurrent, and could have a lag time. There are little consideration and discussion of this point.

Response: We appreciate your insightful comment regarding the potential non-concurrent relationship between precipitation and soil moisture, and we fully agree with this point.

In the revised version, we have re-evaluated the dependence between precipitation and soil moisture by incorporating time-lagged effects. Specifically, for each grid cell, a maximum lag of up to 12 months was used to calculate the lagged correlation between precipitation and soil moisture. Then the optimal lag for each grid cell was determined by identifying the time lag that yielded the maximum Kendall's tau within this 0–12 month window. To assess model adequacy, the Akaike Information Criterion (AIC) was calculated for each lag.

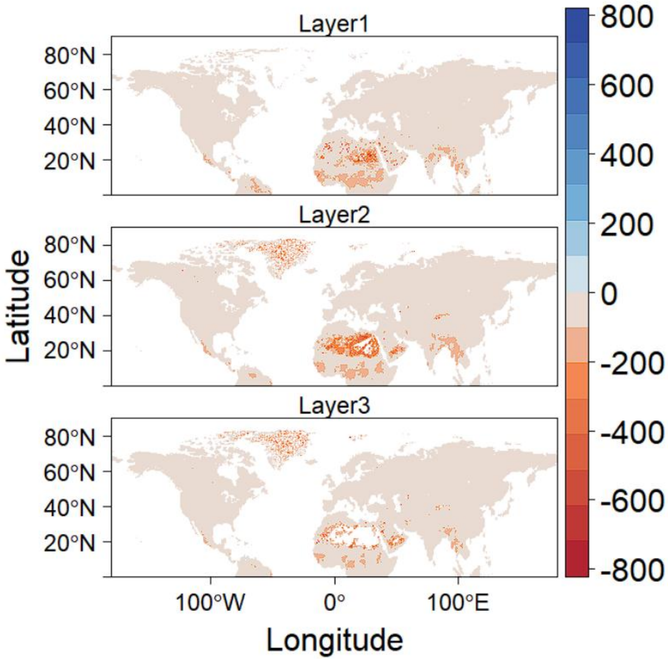

Fig. S3 The AIC value for each grid in the selection of copula function.

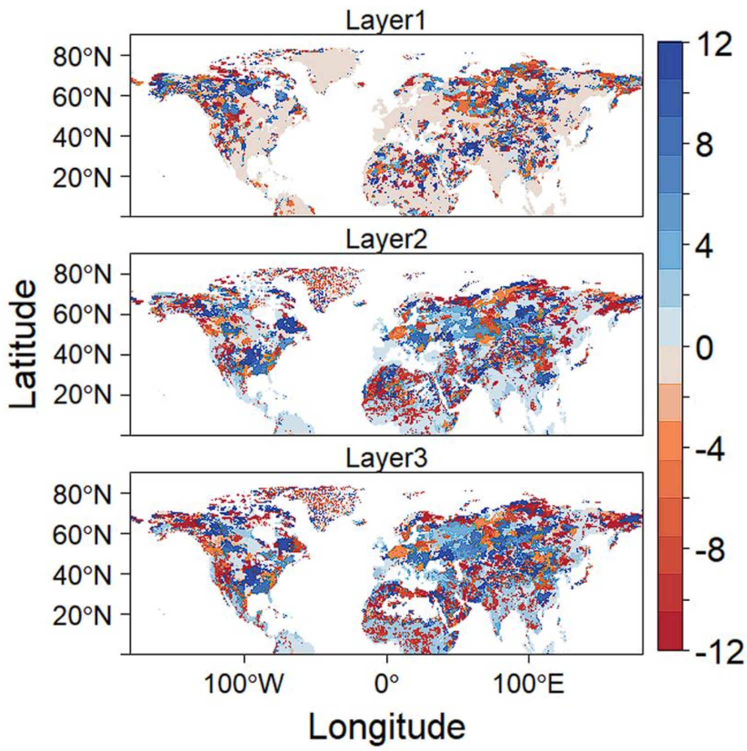

Fig. S4 The estimated number of lagged month for each grid in the the Kendall's tau correlation.

The related text was added in revise manuscripts as follows.

"To address the potential delayed response of soil moisture to precipitation, lagged correlation analysis was conducted. For each grid cell, the AIC value was calculated to select copula function (Fig. S3), then the Kendall's tau correlation was calculated between precipitation and soil moisture with time lags ranging from 0 to 12 months (Fig. S4). The lag corresponding to the maximum absolute correlation was identified as the optimal lag.”

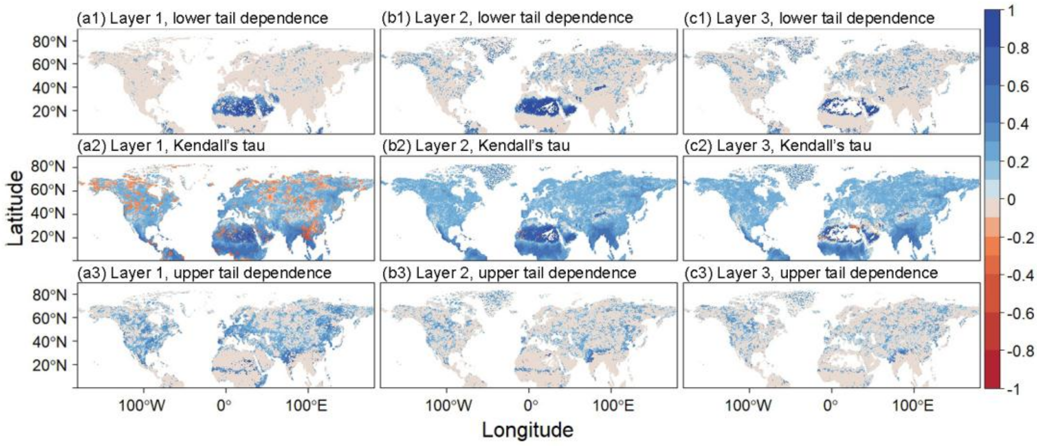

Fig. 2 Spatial distribution of Kendall’s tau (τ), the upper tail dependence (λ_U), and the lower tail dependence (λ_L) on the 0.25 ° × 0.25 °grids between monthly precipitation volume and soil moisture with the time lag during 2000 to 2019. The three columns are for the soil moisture from depths of 0 to 7 cm, 7 to 28 cm, and 28 to 100 cm, respectively.

“The copula analysis of monthly average soil moisture and total monthly precipitation volume revealed a clear negative dependence at all three soil depths (a2, b2, and c2; Fig. 2). The percentages of grid cells exhibiting negative dependence at these depths were 19.2%, 0.7%, and 2.3%, respectively. The negative dependence between precipitation and soil moisture is more prevalent in the surface soil layer, where the grid cells exhibiting are more widespread. In contrast, at the middle and deep soil layers, these negative dependence patterns are primarily confined to the margins of the Sahara desert, the montane grasslands and shrublands, and parts of the deserts and xeric shrublands regions. In the surface layer, the negatively dependent grid patches are more spatially scattered, mainly distributed across the tundra, montane grasslands and shrublands, deserts and xeric shrublands, as well as the tropical and subtropical moist broadleaf forests.

Regions exhibiting high λL values were primarily located in the deserts and xeric Shrublands, as well as in parts of India, where λL reached values as high as 0.99(a1, b1, c1; Fig. 2). With increasing soil depth, λL values gradually increased across the

Eurasian continent. Similarly, λ_U exhibited a clear reduction in spatial extent with increasing soil depth, with the majority of these regions located in the temperate broadleaf and mixed forests and the southern margin of the Sahara desert. With increasing soil depth, λU values consistently decreased, resulting in a lack of clear correspondence between these regions and specific ecological zones (a3, b3, c3; Fig. 2)."

7. I also have concerns about the time scale. I agree with reviewer #1 that the time scale (monthly, seasonal, annual) should be unified. Since the authors did not eliminate seasonal variations from monthly data, seasonal signals affect the monthly-scale results. The patterns and mechanisms during seasons appear clearer. I would suggest the authors to narrow the analyses by only focusing on one or two scales.

Response: Thanks for your suggestion. The results of annual scale have been added in Section 3.2 as follows.

"At the annual scale, results are consistent with those at the monthly scale, with precipitation amount continuing to exert a dominant influence across all three soil depth layers, accounting for more than 40% of the total area (Fig. 6). The spatial extent of areas dominated by precipitation amount, precipitation frequency, and evapotranspiration remains largely consistent with that observed at the monthly scale. In terms of spatial distribution, regions dominated by precipitation frequency are still primarily located in high-latitude areas, particularly in Greenland and the Queen Elizabeth Islands, although no distinct ecological zone patterns are observed in these areas. Regions dominated by precipitation amount are mainly distributed across boreal forests, temperate grasslands, savannas and shrublands, temperate broadleaf and mixed forests, as well as tropical and subtropical moist broadleaf forests. In temperate regions, soil moisture is primarily controlled by precipitation amount due to moderate temperatures and limited rainfall, making substantial precipitation inputs essential for soil moisture replenishment. In contrast, tropical and subtropical regions experience high temperatures and intense evapotranspiration, requiring substantial precipitation to maintain a water balance."

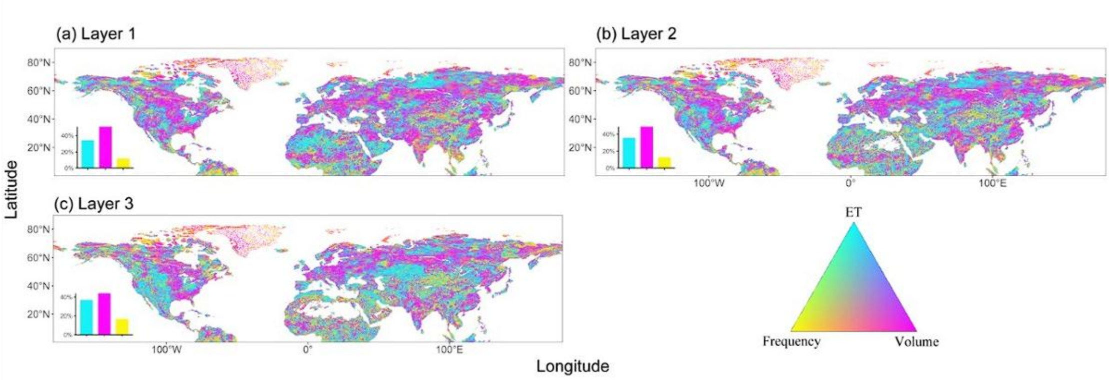

Fig. 6 Ternary map of factors controlling soil moisture at annual scale, for the period 2000 to 2019. The bottom-left histogram in the subgraph represents the proportion of grid cells where one variable exerts strong univariate control (with a regression coefficient greater than 75% of the total sum of the three variables), suggesting that soil moisture was predominantly controlled by that specific variable."

Minor comments:

1) Line 489: the "Arctic amplification" appears abruptly. How are the climate pattern associated with the dependences? Why not other climate patterns?

Response: Our intention means that, the heterogeneity in global warming among different regions can affects GPP and drives precipitation-soil water feedback. However, climate pattern are not the focus of this study, which aims to explore the driving characteristics of GPP, air temperature, and ground temperature in different regions.

2) Line 517-519: not clear, need rephrase.

Response: The sentence was deleted in revised manuscript.

3) Line 747-748: need quantitative measures to support this point.

Response: Revised.

"Evapotranspiration was the dominant driver of soil moisture dynamics during the growing season, with a regression coefficient proportion greater than 75%. In contrast, precipitation volume played a more significant role in the surface and middle layer of non-growing season, with areas under strong univariate control accounting for over 40% of the total area. Additionally, the influence of precipitation frequency on soil moisture increased with latitude, the proportion of the regression coefficient averaging from 36.5% to 91.3%, highlighting a shift in controlling factors across climatic gradients."

4) Line 764-769: these reasoning needs quantitative support.

Response: Thanks for your suggestion. Since this point is not the focus of our study, we have revised this sentence in the manuscript to better reflect our reasonable speculation.

"A possible explanation is the long-term variability in precipitation and temperature, which may have influenced geomorphology, vegetation structure, and soil water retention capacity."