Authors' responses to RC1' comments

Hydrology and Earth System Sciences

https://doi.org/10.5194/egusphere-2025-6195-RC1

Title: Weakening Correlation and Delaying Response Time of Ecosystem Water Use Efficiency to Meteorological Drought

Dear RC1:

Thank you very much for carefully reviewing our manuscript and helping us improve its quality. On behalf of my co-authors, we thank you very much for giving us an opportunity to revise our manuscript. We have made significant revisions to our manuscript to address the comments. Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches.

Below, we provide a detailed point-by-point response to the comments. Text by the reviewer is indented and in black font. Our reply is in blue font and not indented. The "References" are in green and italic, and follow immediately after the reply. For ease of referencing our replies, we numbered them. All changes in the revised manuscript have been highlighted with a colored background for your convenience.

We believe that through these revisions, the quality of the manuscript will meet the publication standards of the journal *Hydrology and Earth System Sciences*. If you have further suggestions, we are happy to continue discussing them with you.

> [r1,1] Title: The current title, particularly the phrase "weakening correlation of WUE to drought", is grammatically awkward and unclear.

Thank you for your valuable comment. Following your suggestion, we have revised the wording of the title. To clearly explain the meanings of "Sensitivity" and "Resistance Time" in the revised title, we have also updated the corresponding descriptions in the Abstract and Introduction. We hope that this revision satisfactorily addresses your concern. We would also be grateful for any further suggestions you may have.

The specific modifications can be found in Title, Abstract and Introduction (see Lines **1-2**, Lins **26-28** Lines **90-104**, Lines **106-107** in manuscript (marked version)).

> [r1,2] Abstract and short summary: The abstract is currently too lengthy, which makes the key findings and main storyline difficult to identify. In contrast, the short summary is too brief and does not provide sufficient context for readers to understand the overall significance of the study.

Thank you for this constructive comment. We agree that the original abstract was relatively lengthy, which may have obscured the main storyline and key findings, while the short summary did not provide sufficient background and significance. In response, we have substantially revised both sections. Specifically, we shortened and reorganized the abstract to more clearly highlight the research gap, methods, key findings, driving mechanisms, and implications. We also expanded the short summary to provide clearer context. Because the previous short summary lacked a clear statement of the study significance and was constrained by the 500-character limit, we removed some details of the results and added information on the broader value of the study in this revision. We believe that these revisions improve readability and help readers better understand the main contribution of the study.

The specific modifications can be found in Abstract and Short summary (see Lines **17-54** in manuscript (marked version)).

> [r1,3] Study period: Since this study investigates temporal variations in WUE–drought relationships, the study period should ideally be extended to the most recent years, provided that the datasets used in the analysis have been updated. This would improve the timeliness and relevance of the results.

Thank you for your valuable comment. We acknowledge that the relatively short study period is an important limitation of this study. The main reason why we did not extend the analysis to the most recent years is the limited availability and temporal coverage of suitable datasets. For example, GLASS provides the latest MODIS GPP product at 500 m resolution up to 2025, but this product is only available from 2000 onward. In contrast, the GLASS AVHRR GPP product provides a longer time series from 1982 to 2018, but does not cover the most recent years. A similar issue exists for GLASS ET products: MODIS ET covers 2000-2024, whereas AVHRR ET covers 1981-2022. Recently, Xu et al. (2026) released the Penman-Monteith-Leuning Evapotranspiration v2.2 dataset, which provides GPP and ET data from 1980 to 2024. Although this dataset has the advantages of a longer temporal coverage and higher accuracy, systematic uncertainties may still be introduced by sensor degradation (Tian et al., 2015; Zhang et al., 2017), and by the generation algorithms of reanalysis datasets (Yan et al., 2021). Uncertainties in GPP (Zhang and Ye, 2021) and ET (Cai et al., 2024) products have also been widely reported. Meanwhile, the ability of multi-product ensemble means to reduce systematic uncertainties has been demonstrated (Zhang et al., 2023). Therefore, after careful consideration, we retained the multi-product mean approach to reduce systematic uncertainties.

Reference:

[1] *Xu, Z., Zhang, Y., Kong, D., Ma, N., and Zhang, X.: Extended global terrestrial evapotranspiration and gross primary production dataset from 1982 to near present, Earth Syst. Sci. Data Discuss., 2026, 1-41, 10.5194/essd-2026-94, 2026.*

[2] *Tian, F., Fensholt, R., Verbesselt, J., Grogan, K., Horion, S., and Wang, Y.: Evaluating temporal consistency of long-term global NDVI datasets for trend analysis, Remote Sensing of Environment, 163, 326-340, https://doi.org/10.1016/j.rse.2015.03.031, 2015.*

[3] *Zhang, Y., Song, C., Band, L. E., Sun, G., and Li, J.: Reanalysis of global terrestrial vegetation trends from MODIS products: Browning or greening?, Remote Sensing of Environment, 191, 145-155, https://doi.org/10.1016/j.rse.2016.12.018, 2017.*

[4] *Yan, K., Pu, J., Park, T., Xu, B., Zeng, Y., Yan, G., Weiss, M., Knyazikhin, Y., and Myneni, R. B.: Performance stability of the MODIS and VIIRS LAI algorithms inferred from analysis of long time series of products, Remote Sensing of Environment, 260, 112438, https://doi.org/10.1016/j.rse.2021.112438, 2021.*

[5] *Zhang, Y. and Ye, A.: Would the obtainable gross primary productivity (GPP) products stand up? A critical assessment of 45 global GPP products, Science of The*

Total Environment, 783, 146965, https://doi.org/10.1016/j.scitotenv.2021.146965, 2021.

[6] *Cai, Y., Xu, Q., Bai, F., Cao, X., Wei, Z., Lu, X., Wei, N., Yuan, H., Zhang, S., Liu, S., Zhang, Y., Li, X., and Dai, Y.: Reconciling Global Terrestrial Evapotranspiration Estimates From Multi-Product Intercomparison and Evaluation, Water Resources Research, 60, e2024WR037608, https://doi.org/10.1029/2024WR037608, 2024.*

[7] *Zhang, Y., Li, C., Chiew, F. H. S., Post, D. A., Zhang, X., Ma, N., Tian, J., Kong, D., Leung, L. R., Yu, Q., Shi, J., and Liu, C.: Southern Hemisphere dominates recent decline in global water availability, Science, 382, 579-584, doi:10.1126/science.adh0716, 2023.*

In addition, this study aims to reveal an ecohydrological phenomenon, which is relatively less sensitive to the exact endpoint of the study period. If the significant changes detected during 1982-2018 were extended to the present, even a trend reversal after 2018 would be unlikely to substantially alter the overall long-term tendency. For example, despite the intensification of climate change in recent years, the Budyko framework is still widely applied.

Nevertheless, we fully acknowledge the limitation associated with the relatively short study period. In future research, we will extend the analysis to the most recent years when longer and more reliable datasets become available. We will also consider incorporating Coupled Model Intercomparison Project (CMIP) datasets to clarify future changes in WUE-drought coupling and their driving mechanisms under different development scenarios. We have added a discussion of this limitation and future research direction in Section 5.4, "Limitations and future prospects" We hope this explanation is acceptable.

The specific modifications can be found in Discussion (see Lines **552-557** in manuscript (marked version)).

[r1,4] Significance testing: Statistical significance tests should be included in both the analysis and the interpretation of the results. For example, when discussing temporal trends, changes in correlations, or spatial patterns, the authors should clearly indicate whether these changes are statistically significant.

Thank you for your valuable comment. In our previous analysis, we had included statistical significance for temporal trends, for example by indicating $p < 0.01$ in Fig. 1. However, we did not sufficiently describe this significance in the interpretation of the results. In addition, the significance of spatial patterns was not marked in the original figures. Therefore, we have revised Fig. 2 to indicate statistical significance and have updated the corresponding descriptions of the results.

In summary, we have revised the spatial distribution maps and explicitly indicated statistical significance throughout the manuscript wherever changes in temporal trends, correlations, or spatial patterns are discussed.

The specific modifications can be found in Abstract, Results and Conclusion (see Line **30**, Figure **2**, Line **320**, Lines **567-572** in manuscript (marked version)).

> [r1,5] Focus on meteorological drought: The study focuses mainly on meteorological drought, but soil moisture drought may be more directly relevant to vegetation water use and ecosystem water-use efficiency. The authors should justify why meteorological drought was selected as the primary drought indicator, or consider including soil moisture drought to provide a more mechanistic understanding of vegetation responses.

Thank you for your valuable comment. As one of the most widely used drought indices, SPEI not only accounts for the cumulative water balance but also incorporates the effects of temperature (Beguería et al., 2014), and has therefore been extensively applied to monitor and quantify the spatiotemporal characteristics of drought at both regional and global scales (Beguería et al., 2010). In addition, SPEI combines the sensitivity of the Palmer Drought Severity Index (PDSI) to evaporation demand and the multi-temporal nature of the standardized precipitation index (SPI) (Vicente-Serrano et al., 2010). Hence the SPEI is considered to have good performance to capture drought impacts on ecosystems (Vicente-Serrano et al., 2012; Vicente-Serrano et al., 2013). Moreover, previous studies have demonstrated that meteorological drought is the initial drought type occurring in the drought propagation cascade, making it the most critical component that exerts the most profound impacts on ecosystems (Yan et al., 2025). This is one of the core rationales for our focus on the SPEI in this study.

Reference:

[1] *Beguería, S., Vicente-Serrano, S. M., and Angulo-Martínez, M.: A Multiscalar Global Drought Dataset: The SPEIbase: A New Gridded Product for the Analysis of Drought Variability and Impacts, Bulletin of the American Meteorological Society, 91, 1351-1356, https://doi.org/10.1175/2010BAMS2988.1, 2010.*

[2] *Beguería, S., Vicente-Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, International Journal of Climatology, 34, 3001-3023, https://doi.org/10.1002/joc.3887, 2014.*

[3] *Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming*
The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696-1718, 2010.

[4] *Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., and Sanchez-Lorenzo, A.: Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications, Earth Interactions, 16, 1-27, https://doi.org/10.1175/2012EI000434.1, 2012.*

[5] *Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., and Sanchez-Lorenzo, A.: Response of vegetation to drought time-scales across global land biomes, Proceedings of the National Academy of Sciences, 110, 52-57, 10.1073/pnas.1207068110, 2013.*

[6] *Yan, W., Zhou, J., Lin, H., Luo, J., Duan, X., and Wu, R.: Drivers of the pre-season drought thresholds triggering earlier autumn foliar senescence in the Northern Hemisphere, Nature Communications, 16, 7568, 10.1038/s41467-025-62847-y, 2025.*

In studies on the relationship between WUE and drought, SPEI has commonly been used as the drought indicator. For example, Yang et al. (2025) used global flux observations to comprehensively investigate whether different WUE metrics respond consistently to drought (SPEI) and how drought intensity, duration, and timing affect their responses.

Reference:

[7] *Yang, S., Zhang, J., Han, J., Bai, Y., Xun, L., Zhang, S., Cao, D., and Wang, J.: The ratio of transpiration to evapotranspiration dominates ecosystem water use efficiency response to drought, Agricultural and Forest Meteorology, 363, 110423, https://doi.org/10.1016/j.agrformet.2025.110423, 2025.*

Overall, the focus of this study is meteorological drought rather than soil drought. Nevertheless, we acknowledge the important role of soil drought in influencing WUE, as well as the limitation of not explicitly considering soil drought. Therefore, we have further clarified in the Introduction the rationale for selecting meteorological drought as the primary drought indicator. In addition, when discussing the mechanisms underlying the relationship between meteorological drought and WUE, we have addressed the role of soil drought. We have also discussed this limitation in the "Limitations and future prospects" section and noted that future studies should incorporate soil drought to more systematically elucidate vegetation response mechanisms. We hope that these revisions satisfactorily address your concerns.

The specific modifications can be found in Introduction and Discussion (see Lines **62-72**, Lines **491-498** and Lines **547-548** in manuscript (marked version)).

> [r1,6] "Significant threshold effects": The meaning of "significant threshold effects" is not sufficiently clear. The authors should define this term more explicitly and explain how the thresholds were identified, tested, and interpreted in the context of WUE responses to drought.

We apologize for the confusion caused by our incomplete description. In fact, using SHAP dependence plots to reveal the relationships between feature values and SHAP values has been widely applied for threshold identification (Yan et al., 2025; Chen et al., 2026) .To further improve the readability of the manuscript, we have added a description in the Methods section explaining how the thresholds were identified and interpreted. We hope that these revisions satisfactorily address your concern.

Reference:

[1] *Chen, Y., Qu, W., Zohner, C. M., Peñuelas, J., and Wu, C.: Increased artificial illumination delays urban autumnal foliar senescence, Nature Communications, 17, 1526, 10.1038/s41467-025-68246-7, 2026.*

[2] *Yan, W., Zhou, J., Lin, H., Luo, J., Duan, X., and Wu, R.: Drivers of the pre-season drought thresholds triggering earlier autumn foliar senescence in the Northern Hemisphere, Nature Communications, 16, 7568, 10.1038/s41467-025-62847-y, 2025.*

The specific modifications can be found in Methods (see Lines **246-250** in manuscript (marked version)).

[r1,7] Novelty and knowledge gap: The novelty of the study is not clearly articulated. The authors should better clarify the current knowledge gap regarding WUE responses to drought. For example, it would be helpful to explain what remains uncertain about the temporal evolution, response time, threshold behavior, or causality of WUE-drought relationships, and how this study advances beyond previous work.

Thank you very much for pointing out these shortcomings in our manuscript. Following your suggestion, we have strengthened the description of the knowledge gap and the novelty of this study to improve the clarity and readability of the manuscript.

The specific modifications can be found in Introduction (see Lines **90-104** in manuscript (marked version)).

[r1,8] Importance of response time: The manuscript should better explain why the response time of WUE to drought is scientifically important. For instance, does response time provide insight into ecosystem sensitivity, drought resistance, recovery capacity, or early-warning signals of vegetation stress? Clarifying this point would strengthen the motivation of the study.

Thank you for your valuable comment. In our response to Comment [r1,7], we have also more clearly explained the scientific significance of the response timescale of WUE to drought, thereby strengthening the rationale and foundation of this study. We hope that these revisions satisfactorily address your concern.

The specific modifications can be found in Abstract and Introduction (see Lines **26-28**, Lines **90-104**, Lines **106-107** in manuscript (marked version)).

> [r1,9] Causality diagnosis framework: The causality diagnosis framework should be clearly stated in the abstract. Since this appears to be an important methodological component of the study, the authors should briefly describe what causal method was used, what variables were included, and how this framework helps distinguish causal relationships from simple correlations.

Thank you very much for your valuable comment. Following your suggestion, we revised the description of the causality diagnosis framework. In the Abstract, we now specify the causal method employed and the key variables included in the framework. We also further refined the Methods to improve clarity and accessibility. Specifically, we removed excessive technical details and added more explanation of the underlying rationale, thereby emphasizing how this framework helps distinguish causal relationships from simple correlations. Since PCMCI+ is a well-established and widely used method, we also cited the original references for PCMCI+ in the revised manuscript.

The specific modifications can be found in Abstract and Methods (see Lines **35-38** and Lines **260-280** in manuscript (marked version)).

Reference:

Beguería, S., Vicente-Serrano, S. M., and Angulo-Martínez, M.: A Multiscalar Global Drought Dataset: The SPEIbase: A New Gridded Product for the Analysis of Drought Variability and Impacts, Bulletin of the American Meteorological Society, 91, 1351-1356, https://doi.org/10.1175/2010BAMS2988.1, 2010.

Beguería, S., Vicente-Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, International Journal of Climatology, 34, 3001-3023, https://doi.org/10.1002/joc.3887, 2014.

Cai, Y., Xu, Q., Bai, F., Cao, X., Wei, Z., Lu, X., Wei, N., Yuan, H., Zhang, S., Liu, S., Zhang, Y., Li, X., and Dai, Y.: Reconciling Global Terrestrial Evapotranspiration Estimates From Multi-Product Intercomparison and Evaluation, Water Resources Research, 60, e2024WR037608, https://doi.org/10.1029/2024WR037608, 2024.

Chen, Y., Qu, W., Zohner, C. M., Peñuelas, J., and Wu, C.: Increased artificial illumination delays urban autumnal foliar senescence, Nature Communications, 17, 1526, 10.1038/s41467-025-68246-7, 2026.

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Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming

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Vicente-Serrano, S. M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J. J., López-Moreno, J. I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., and Sanchez-Lorenzo, A.: Performance of Drought Indices for Ecological, Agricultural, and Hydrological Applications, Earth Interactions, 16, 1-27, https://doi.org/10.1175/2012EI000434.1, 2012.

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., and Sanchez-Lorenzo, A.: Response of vegetation to drought time-scales across global land biomes, Proceedings of the National Academy of Sciences, 110, 52-57, 10.1073/pnas.1207068110, 2013.

Xu, Z., Zhang, Y., Kong, D., Ma, N., and Zhang, X.: Extended global terrestrial evapotranspiration and gross primary production dataset from 1982 to near present, Earth Syst. Sci. Data Discuss., 2026, 1-41, 10.5194/essd-2026-94, 2026.

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Yan, W., Zhou, J., Lin, H., Luo, J., Duan, X., and Wu, R.: Drivers of the pre-season drought thresholds triggering earlier autumn foliar senescence in the Northern Hemisphere, Nature Communications, 16, 7568, 10.1038/s41467-025-62847-y, 2025.

Yang, S., Zhang, J., Han, J., Bai, Y., Xun, L., Zhang, S., Cao, D., and Wang, J.: The ratio of transpiration to evapotranspiration dominates ecosystem water use efficiency response to drought, Agricultural and Forest Meteorology, 363, 110423, https://doi.org/10.1016/j.agrformet.2025.110423, 2025.

Zhang, Y. and Ye, A.: Would the obtainable gross primary productivity (GPP) products stand up? A critical assessment of 45 global GPP products, Science of The Total Environment, 783, 146965, https://doi.org/10.1016/j.scitotenv.2021.146965, 2021.

Zhang, Y., Song, C., Band, L. E., Sun, G., and Li, J.: Reanalysis of global terrestrial vegetation trends from MODIS products: Browning or greening?, Remote Sensing of Environment, 191, 145-155, https://doi.org/10.1016/j.rse.2016.12.018, 2017.

Zhang, Y., Li, C., Chiew, F. H. S., Post, D. A., Zhang, X., Ma, N., Tian, J., Kong, D., Leung, L. R., Yu, Q., Shi, J., and Liu, C.: Southern Hemisphere dominates recent decline in global water availability, Science, 382, 579-584, doi:10.1126/science.adh0716, 2023.