Responses to editors and reviewers

We sincerely thank the reviewer for the thorough evaluation of our manuscript and for the constructive comments. We appreciate the recognition of the regional significance, multi-scale framework, and methodological rigor of our study. Below, **we respond to each comment in detail and describe the corresponding manuscript revisions**, including their specific locations in the manuscript. All changes and responses made are highlighted *in blue* color in the following remarked manuscript.

1. Summary and General Assessment

Reviewer comment:

I have significant concerns regarding the statistical reliability of the conclusions drawn at the inter-annual scale. The primary issue is the sample size (N = 6 years) used to determine climatic drivers via regression analysis. While the daily and seasonal analyses appear sound, the inter-annual results carry a high degree of uncertainty that needs to be addressed or re-framed before publication.

Response:

We thank the reviewer for highlighting this important methodological concern. We acknowledge that the small number of years inevitably introduces uncertainty into regression-based analyses of climatic drivers. Therefore, the inter-annual results are interpreted with caution and are intended to indicate general tendencies rather than robust causal relationships. To avoid over interpretation, we have revised the manuscript to explicitly acknowledge this limitation and to re-frame the inter-annual analysis as exploratory and supportive, rather than definitive, evidence.

Manuscript revision (Section 3.5; Section 4.2**):**

Original text (see Section 3.5, lines 409-411):

"…, annual NEE exhibited strong correlations with annual PRE and SWC (R^2 = 0.85 and 0.56, respectively), indicating that water-related variables exert a significant influence on NEE at the inter-annual timescale."

Revised text:

"…, annual NEE showed relatively strong co-variability PRE and SWC (R^2 = 0.85

and 0.56, respectively). These relationships suggest that inter-annual variations in ecosystem carbon exchange may be closely linked to changes in water-related conditions."

Original text (see Section 3.5, lines 411-415):

"Ecosystem Re was more strongly correlated with PAR and LAI at the inter-annual timescale, whereas it was more closely associated with temperature at daily and monthly scales."

Revised text:

"Annual Re showed weaker and variable associations with most environmental factors at the inter-annual timescale. The relatively scattered relationships suggest that Re may be influenced by multiple interacting factors, including temperature, and moisture conditions, whose combined effects may vary among years. As a result, inter-annual variations in Re appear less tightly coupled to any single climatic driver."

Original text (see Section 3.5, lines 415-418):

"Annual GPP showed stronger correlations with PRE and LAI, suggesting that both water availability and vegetation exert greater controlled over GPP at the inter-annual timescale."

Revised text:

"Annual GPP exhibited relatively higher co-variability with PRE and LAI compared to other environmental variables. Such co-variability likely reflects the integrated effects of climatic conditions on vegetation growth and canopy structure over the entire growing season, rather than short-term environmental controls."

Original text (see Section 3.5, lines 418-419):

"ET displayed significant inter-annual timescale correlations with LAI and Ta."

Revised text:

"ET displayed apparent inter-annual co-variability with LAI and Ta."

Original text (see Section 3.5, lines 419-420):

"WUE was more strongly correlated with PRE at the inter-annual timescale, highlighting the dominant role of PRE in regulating WUE."

Revised text:

"Inter-annual variations in ecosystem WUE were more closely associated with

PRE than with other environmental variables."

2.Specific Comments

(1) Reviewer comment:

With only six data points, regression analysis risks spurious correlations. The emphasis should be reduced, with greater focus on qualitative or process-based interpretation.

Response:

We fully agree with this assessment. In the revised manuscript, we have taken the following actions:(1) Avoided language implying strong predictive or causal inference at the inter-annual scale. (2) Shifted the emphasis from regression coefficients to observed co-variability patterns. (3) Strengthened the discussion by comparing the inter-annual results with regions investigated in previous multi-year studies, supported by published studies with longer records. No additional regression models were introduced, in order to avoid overstating the statistical certainty.

Manuscript revision (Abstract; Section 4.2):

Original text (see Abstract, lines 25-26):

"At the inter-annual timescale, precipitation (PRE) and leaf area index (LAI) were the dominant factors influencing carbon and water fluxes."

Revised text

"At the inter-annual timescale, carbon and water fluxes exhibited clear co-variability with precipitation (PRE) and leaf area index (LAI)."

Newly added statement (see Section 4.2, lines 503-506):

"It should be noted that the inter-annual analysis is based on a relatively short observational record (6 years), which limits the statistical robustness of regression-based inference. Therefore, our interpretation focuses on qualitative consistency with established process-based understanding."

(2) Reviewer comment:

The site is characterized as a "humid" alpine meadow. The results suggest that soil temperature drives fluxes at the daily scale, which is consistent with energy-limited environments. However, the conclusion that Precipitation drives inter-annual variability

is somewhat counter-intuitive for a humid ecosystem where water is typically not the limiting factor.

Question: Could this dominance of precipitation be an artifact of the short time series (e.g., one significantly dry year skewing the regression)? The authors need to provide a deeper biological explanation for why a humid ecosystem would be so sensitive to annual precipitation amounts.

Response:

We appreciate the reviewer's thoughtful concern and agree that our conclusion appears, at first glance, to differ from the conventional expectation that humid ecosystems are primarily energy-limited. We acknowledge this inconsistency and provide the following explanations:

(1) The designation of the study site as "humid" is based on a climatology, which reflects long-term (typically 30-year) averages of meteorological variables such as precipitation, temperature, and atmospheric conditions. This classification describes the background climate state rather than the actual water availability experienced by ecosystems at specific timescales or during individual growing seasons. Consequently, being located in a humid climatic zone does not preclude the occurrence of seasonal or inter-annual water stress that can influence ecosystem carbon and water fluxes.

(2) Carbon and water fluxes at the study site exhibit pronounced seasonal cycles. Although the annual precipitation amount is relatively high, precipitation is highly concentrated in summer, and its intra-seasonal distribution plays a critical role in regulating soil moisture dynamics and vegetation activity. Variations in the timing, frequency, and intensity of rainfall events within the growing season can strongly affect plant physiological processes and cumulative annual carbon exchange, even under generally humid conditions.

(3) Previous studies in alpine meadow ecosystems have shown that when soil moisture drops below a threshold (approximately $0.28 \text{ m}^3 \text{ m}^{-3}$)(Wang et al., 2024), net ecosystem exchange (NEE) is significantly suppressed. This indicates that ecosystem carbon uptake is sensitive not only to absolute precipitation amounts but also to episodic reductions in soil water availability. Such threshold behavior provides a mechanistic basis for precipitation-related inter-annual variability in carbon fluxes.

(4) During the study period, short-term dry spells occurred almost every year during the peak growing season, when vegetation growth and photosynthetic activity are most vigorous. These dry periods coincide with the phase of maximum carbon

fixation potential, making the ecosystem particularly sensitive to water availability. Even brief soil moisture deficits during this critical period can constrain photosynthesis and reduce annual carbon uptake, thereby amplifying the influence of precipitation at the inter-annual timescale.

(5) Similar inter-annual sensitivities to precipitation have been reported in other humid and alpine meadow ecosystems based on longer-term observations. For example, studies have shown that seasonal precipitation patterns can significantly influence annual net ecosystem exchange even under overall humid conditions (Zheng et al., 2022), and that inter-annual variability of carbon fluxes in alpine grasslands is often associated with changes in soil moisture and vegetation dynamics rather than direct water limitation (Xi et al., 2017; Xu et al., 2022). These findings support the biological plausibility of the observed co-variability in our study while underscoring the need for cautious interpretation given the limited time series.

Manuscript revision:

Newly added explanation (see Section 3.5, lines 421-425):

At the inter-annual timescale, apparent associations were observed between annual carbon and water fluxes and precipitation-related variables. These relationships suggest that inter-annual variations in ecosystem fluxes may be closely linked to changes in hydroclimatic conditions. However, given the limited number of observation years, these associations should be interpreted as indicative patterns rather than statistically robust relationships.

Newly added explanation (see Section 4.2, lines 507-515):

"Although the study site is climatically classified as humid, this classification reflects long-term mean conditions and does not preclude seasonal or inter-annual water constraints on ecosystem functioning. Carbon and water fluxes exhibited strong seasonal cycles, and inter-annual variability was closely linked to the intra-seasonal distribution of precipitation, particularly during the peak growing period. Previous studies have shown that reduced soil moisture can suppress NEE when falling below critical thresholds(Wang et al., 2024), and short dry spells during the most active growth stages occurred frequently in our study period, amplifying the influence of precipitation on annual carbon uptake. Therefore, precipitation should be interpreted as a long-term integrative driver of inter-annual variability, while energy availability remains the dominant control at shorter timescales."

References:

Wang, S., Zhang, Y., Meng, X., Shang, L., Li, Z., and Li, S.: Water availability control the seasonal and inter-annual variability of CO2 fluxes in an alpine meadow on the eastern Tibetan Plateau, Agric. For. Meteorol., 356, 110187, https://doi.org/10.1016/j.agrformet.2024.110187, 2024.

Xi, C., Peili, S., Ning, Z., Ben, N., and Et., A.: Biophysical regulation of carbon flux in different rainfall regime in a northern tibetan alpine meadow, J. Resour. Ecol., https://doi.org/10.5814/j.issn.1674-764x.2017.01.005, 2017.

Xu, M., Sun, Y., Zhang, T., Zhang, Y., Zhu, J., He, Y., Wang, L., and Yu, G.: Biotic effects dominate the inter-annual variability in ecosystem carbon exchange in a tibetan alpine meadow, J. Plant Ecol., 15, 882–896, https://doi.org/10.1093/jpe/rtac005, 2022.

Zheng, Y., Liu, H., Du, Q., Liu, Y., Sun, J., Cun, H., and Järvi, L.: Effects of precipitation seasonal distribution on net ecosystem CO2 exchange over an alpine meadow in the southeastern tibetan plateau, Int. J. Biometeorol., 66, 1561–1573, https://doi.org/10.1007/s00484-022-02300-7, 2022.

(3) Reviewer comment:

While the choice of Ridge Regression is praised, the manuscript should provide more details on how the regularization parameter was optimized. Did the authors use cross-validation? Providing a trace plot of the coefficients would strengthen the methodological description.

Response:

We appreciate the reviewer's request for further methodological details. In our revised manuscript, we have expanded the description of the Ridge Regression approach, specifically including how the regularization parameter was selected and interpreted.

Ridge Regression is implemented by adding an L2-norm penalty term to the ordinary least squares objective function, which shrinks coefficient estimates and mitigates multicollinearity among predictors (Hoerl and Kennard, 1970). The regularization parameter α controls the strength of this penalty. Because the optimal value of α is generally unknown a priori and can substantially affect model performance, it is commonly chosen using data-driven procedures (e.g., cross-validation).

In this study, the Ridge Regression regularization parameter was optimized using 5-fold cross-validation, in which multiple candidate values of were evaluated and the

value minimizing the cross-validated mean squared error (MSE) was selected. Cross-validation is one of the most widely accepted strategies for tuning ridge regularization, as it seeks to balance bias and variance and improve out-of-sample predictive performance(Hoerl and Kennard, 1970; Golub et al., 1979; Liu and Dobriban, 2020). In the revised Methods (section 2.3), we now explicitly state this procedure and report the selected α values.

To further illustrate the behavior of coefficients across the range of α, we have generated a coefficient trace plot in which each predictor's estimated coefficient is plotted as a function of α. This visualization helps demonstrate how coefficient shrinkage evolves with increasing regularization strength and supports the robustness of our model interpretation.
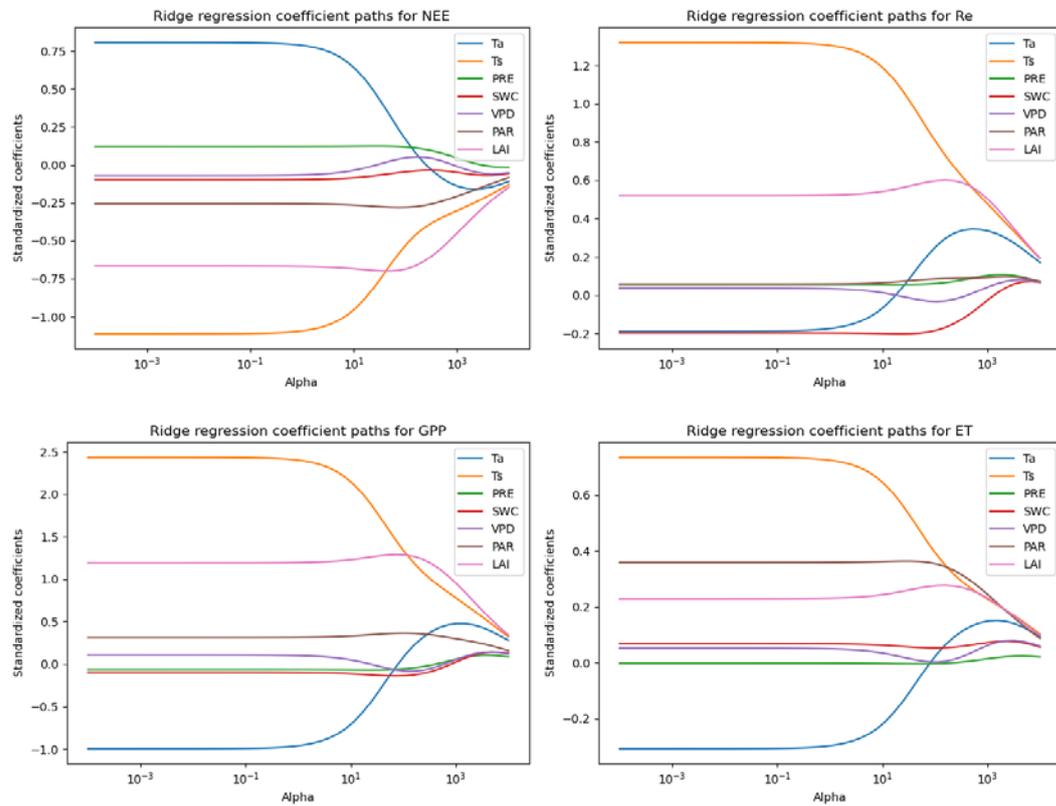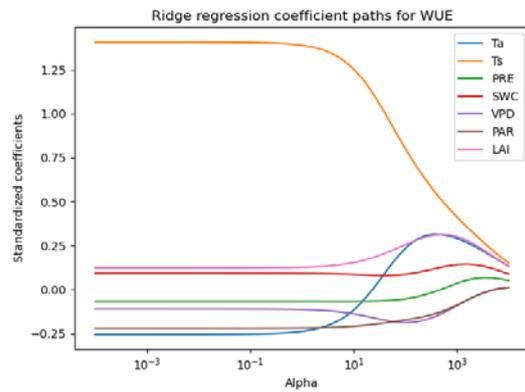
Figure R1 Ridge regression coefficient paths

Manuscript revision:

Added text (see Section 2.3, lines 184-192):

"The regularization parameter α in ridge regression was selected using 5-fold cross-validation. A grid of logarithmically spaced α values ranging from 10^{-4} to 10^4 was evaluated, and the optimal α was determined by minimizing the cross-validated mean squared error (MSE). Cross-validation is a standard procedure for selecting the ridge regularization parameter and helps balance model bias and variance while enhancing predictive performance. Additionally, we generated coefficient trace plots showing how regression coefficients varied across α values, which were inspected to confirm the stability and interpretability of the estimated coefficients. The trace plots are provided in the Supplementary Materials."

References:

Golub, G. H., Heath, M., and Wahba, G.: Generalized cross-validation as a method for choosing a good ridge parameter, Technometrics, 21, 215–223, https://doi.org/10.2307/1268518, 1979.

Hoerl, A. E. and Kennard, R. W.: Ridge regression: biased estimation for nonorthogonal problems, Technometrics, 12, 55–67, https://doi.org/10.1080/00401706.1970.10488634, 1970.

Liu, S. and Dobriban, E.: Ridge regression: structure, cross-validation, and sketching, https://doi.org/10.48550/arXiv.1910.02373, 29 March 2020.

(4) Reviewer comment:

For any study based on Eddy Covariance, reporting the Energy Balance Closure (EBC) is standard practice to assess data quality. I could not find a clear evaluation of

the EBC (slope of $LE+H$ vs. $Rn-G$) for the observation period. Please add this information to the Materials and Methods or Results section.

Response:

We thank the reviewer for this valuable comment. Following the reviewer's suggestion, we have now explicitly evaluated the energy balance closure (EBC) of the eddy covariance measurements. The EBC was assessed using the slope of the linear regression between the sum of turbulent fluxes (LE + H) and the available energy (Rn − G), based on quality-controlled half-hourly data.

Energy balance non-closure is a widespread issue on the Tibet Plateau. The degree of EBC in the Maqu region exhibits pronounced differences among the frozen period, pre-growing season, growing season, and post-growing season, with values of 0.81, 0.92, 0.91, and 0.72, respectively. Significant diurnal contrasts are also observed: during nighttime, the EBC generally remains below 0.6. From approximately 08:00 the closure gradually increases, reaching a maximum around 17:00. Notable jumps in the EBC occur around sunrise and sunset.

The EBC evaluation has been added to the Materials and Methods section (Section 2.2).

Manuscript revision:

Added text (see Section 2.2, lines 139-143):

"To assess the overall quality of the eddy covariance measurements, the energy balance closure (EBC) was evaluated following standard practice, using half-hourly daytime data after quality control. The degree of EBC in the Maqu region exhibits pronounced differences among the frozen period, pre-growing season, growing season, and post-growing season, with values of 0.81, 0.92, 0.91, and 0.72, respectively. Significant diurnal contrasts are observed: during nighttime, the EBC generally remains below 0.6. From approximately 08:00 the closure gradually increases, reaching a maximum around 17:00. Notable jumps in the EBC occur around sunrise and sunset."

(5) Reviewer comment:

Please specify the percentage of missing data for the carbon and water fluxes and describe how the uncertainty introduced by gap-filling was handled or evaluated, especially given the harsh environmental conditions that often lead to instrument failure.

Response:

Thank you for this important and constructive comment. In harsh alpine environments, frequent instrument malfunction and strict quality control procedures often lead to substantial data gaps in eddy covariance measurements.

After standard quality control procedures, only about 40% and 80% of the half-hourly NEE and LE data were retained(Wang et al., 2024). In addition, studies focusing on Maqu and Zoige alpine meadow sites have shown that the annual missing rates typically range from ~30–50% for NEE, and are generally lower for energy fluxes (H and LE), particularly during the growing season (Nieberding et al., 2020; Wang et al., 2022).

We evaluate the uncertainty of interpolation through the following scheme(Wang et al., 2020):

First, multiple gap-filling methods were applied and inter-compared. This study employed the widely used Marginal Distribution Sampling (MDS) method together with three machine-learning algorithms (Random Forest, Support Vector Machine, and Artificial Neural Networks). By comparing fluxes filled using different methods, we were able to quantify the method-dependent uncertainty,

Second, independent validation using observed data subsets was conducted. For each machine-learning algorithm, 75% of high-quality observations were used for training and the remaining 25% for validation. This step ensured that gap-filled values were constrained by real observations rather than extrapolated arbitrarily.

Third, temporal patterns of gap-filling performance were explicitly analyzed. The study showed that gap-filling uncertainty is not temporally uniform: all methods performed worse during nighttime, sunrise/sunset transitions, and winter–spring periods, when turbulence is weak and environmental controls are complex.

Fourth, the sensitivity of annual cumulative fluxes to gap-filling methods was quantified. While annual sensible heat (H) and latent heat (LE) fluxes were relatively insensitive to the choice of gap-filling method, annual NEE differed by up to ~42 g C m^{-2} among methods. This range was interpreted as an estimate of gap-filling–induced uncertainty, demonstrating that carbon budgets are much more sensitive to data gaps than energy fluxes under alpine conditions.

We therefore recommended using multiple gap-filling methods and treating annual NEE estimates as ranges rather than exact values, especially for sites experiencing frequent data loss due to harsh climatic conditions. We explicitly acknowledge that gap-filling may introduce uncertainty in annual carbon budgets, and this limitation has been clarified in the revised manuscript.

Manuscript revision:

Added text (see Section 2.2, lines 130-138):

"Due to instrument malfunction, harsh climatic conditions, and strict quality control filtering, data gaps were common at the alpine meadow site. Approximately 60% of half-hourly NEE data were missing after quality control, which is comparable to other alpine ecosystems on the eastern Tibetan Plateau (Wang et al., 2024). It should be noted that gap-filling uncertainty may affect absolute estimates of annual NEE, particularly during periods of weak turbulence and harsh environmental conditions (Wang et al., 2020, 2022). Uncertainty associated with gap-filling was assessed by comparing fluxes obtained using different gap-filling methods and by evaluating model performance against independent subsets of observed data. We further recognizing that uncertainties are larger during nighttime, transition periods, and cold seasons when data gaps are more frequent(Wang et al., 2020). "

References:

Nieberding, F., Wille, C., Fratini, G., Asmussen, M. O., Wang, Y., Ma, Y., and Sachs, T.: A long-term (2005–2019) eddy covariance data set of CO2 and H2O fluxes from the tibetan alpine steppe, Earth Syst. Sci. Data, 12, 2705–2724, https://doi.org/10.5194/essd-12-2705-2020, 2020.

Wang, S., Zhang, Y., Meng, X., Shang, L., Su, Y., and Li, Z.: Fill the Gaps of Eddy Covariance Fluxes Using Machine Learning Algorithms, Plateau Meteorology, 39, 1348–1360, 2020.

Wang, W., Wu, Y., Wang, S., Yin, H., Li, W., and Zhao, S.: Seasonal Variations of Ecosystem Water Use Efficiency and Their Responses to Climate Factors in Inner Mongolia of China, Atmosphere, 13, 2085, https://doi.org/10.3390/atmos13122085, 2022.

Wang, S., Zhang, Y., Meng, X., Shang, L., Li, Z., and Li, S.: Water availability control the seasonal and inter-annual variability of CO2 fluxes in an alpine meadow on the eastern Tibetan Plateau, Agric. For. Meteorol., 356, 110187, https://doi.org/10.1016/j.agrformet.2024.110187, 2024.