Dear Editor, this is the point-by-point response to Reviewer1's comments and suggestions.

We thank the reviewer for providing such thorough and constructive feedback on our manuscript. We believe the revisions we have made have substantially improved the clarity, rigor, and impact of our paper.

The referee's comments are shown in black. Our responses are shown in blue and the added or modified texts are shown in blue italics.

Main concerns

• Concerns 1 and 2:

1. "From the Title and Abstract, we expected to see sufficient evidences about "recent intensification of hydroclimatic extremes", but there is few in Results and Discussion about it. Most of the results are about the reconstruction development and comparisons with rogation-derived drought indices.
2. From Fig.7, we can see a little bit increase in frequency and intensity of wet and drought extremes after 2000 CE, but it is not proven. The variance of the reconstructed precipitation should be a good indicator to show it. Additionally, the running RABR should be shown in Fig. 6 to help evaluating the impacts of sample depth and inter-series correlations on variance of precipitation."

In order to address concerns 1 and 2, we have now implemented two major improvements to show sufficient evidence of recent intensification of precipitation extremes:

a) **Quantitative analysis of extremes**: we have created a new table that quantifies the frequency of extreme dry and wet years per century as follows:

"Visual inspection of ***Error! Reference source not found.*** *highlights periods characterized by distinct wet or dry conditions, as well as shifts in variability. For instance, the reconstruction identifies notable drought periods, with years like 1526, 1527, 1879, 1931, 2005 and 2012 falling below the 5th percentile, and exceptionally wet periods, with years such as 1534, 1546, 1575, 1645, 1716, 1940, 2010 and 2013 exceeding the 95th percentile. To further investigate the temporal dynamics of hydroclimatic variability, we calculated a 51-year running standard deviation of the reconstructed precipitation series. This metric, which quantifies the magnitude of year-to-year fluctuations (Von Storch and Swiers, 1999), is displayed in Fig. 7 (green dashed line, right-hand axis). The running SD reveals a period of pronounced climatic stability with low variability centred around the mid-19th century. This contrasts sharply with a subsequent, persistent rise in volatility that begins around the start of the 20th century and accelerates markedly after 1975, reaching values that are unprecedented in the context of our 519-year reconstruction.*

To provide robust quantitative evidence for this observed intensification, we analyzed the frequency of extreme events per century (Table 1). The analysis reveals a high contrast between the hydroclimatically stable 19th century, which recorded only nine events outside the P10–P90 range, and the recent period. The 21st century, though spanning only 24 years, has already accumulated eight such events. This intensification is most pronounced for the rarest occurrences: the 2001–2024 period has registered four exceptionally rare events (two <P01 and two >P99). This corresponds to an occurrence rate of 16.7 %, an order of magnitude higher than the 1.6 % average rate for such events across the preceding five centuries (1505–2000). These numerical results offer strong statistical support for the visual evidence from the running SD and confirm the recent and anomalous intensification of hydroclimatic extremes in our study region."

Table 1: Frequency of extreme events per century, with breakdown by severity.

Period (CE)	Total years	Dry years (<P10)	<P05	<P01	Wet years (>P90)	>P95	>P99	Total extremes
1505–1600	96	10	4	2	12	5	1	22.9 %
1601–1700	100	13	7	0	9	6	1	22.0 %
1701–1800	100	8	3	0	9	3	1	17.0 %
1801–1900	100	6	3	1	3	1	0	9.0 %
1901–2000	100	12	6	1	14	8	1	26.0 %
2001–2024	24	3	3	2	5	3	2	33.3 %

b) **Visualization of variability**: We have revised our main reconstruction figure (Figure 7) to include a 51-year running standard deviation of the reconstructed precipitation. This new curve visually demonstrates the marked increase in precipitation volatility in recent decades, corroborating the findings from our new Table 2.

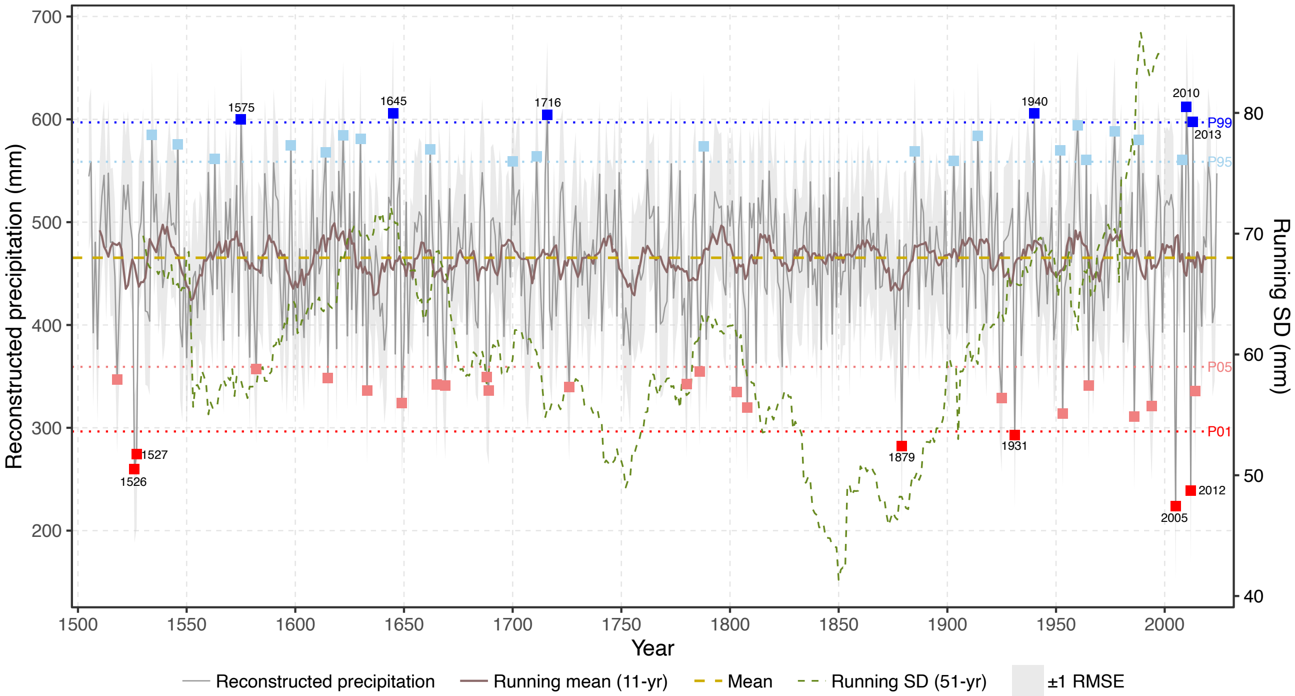

Figure 7: Annual rainfall reconstruction between August 16 of the previous year and June 30 of the current year back to 1505 (grey curve). A 11-year rolling mean is shown in brown. Dark blue squares represent years above 99th percentile, light blue squares between 95th and 99th percentiles, dark red below 1st percentile and light red between 1st and 5th. The variability in the reconstructed values is shown with a green dashed line showing a 51-year running standard deviation.

We have also revised the figure showing the chronology statistics (Figure 2; we believe the referee's mention of Fig. 6 was a typo). This figure now includes a 51-year running Rbar, as suggested, to provide a clearer picture of the stability of the common signal over time, alongside SSS and sample depth. We are confident that these additions provide the quantitative evidence required to fully support our conclusions.

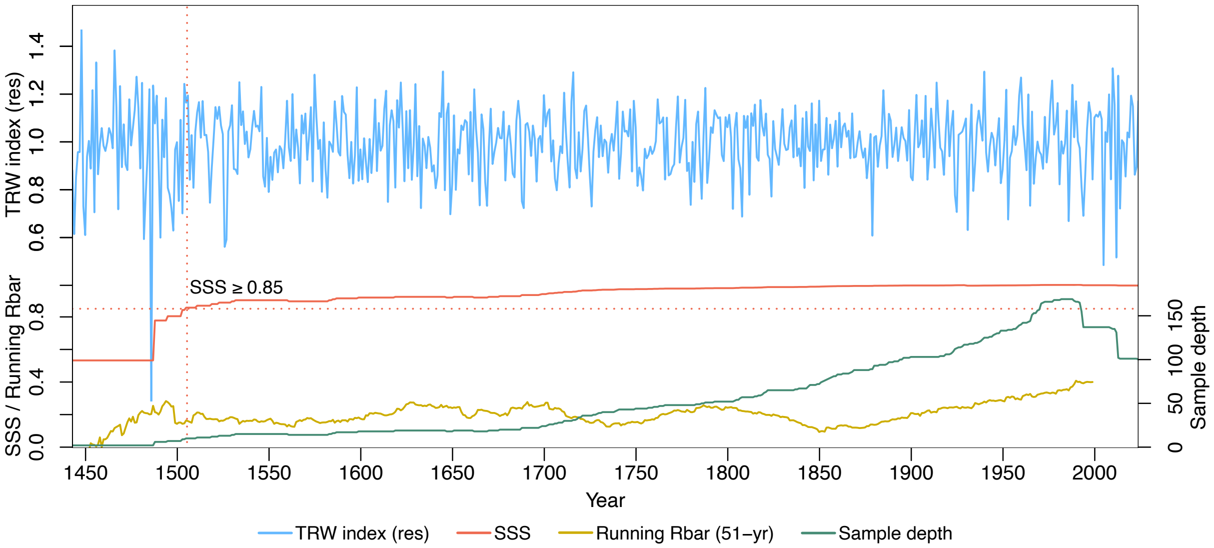

Figure 2: Residual chronology (blue), SSS (red), running 51-year Rbar (yellow) and number of samples per year and SSS (green).

<u>• Concern 3:</u> "Line 340-407, there are so many results (or discussion) about the comparisons between precipitation reconstruction and rogation-derived drought event, even including some correlations (Line 361, 366, 373,…), but no one figure and table to show these results. By using the method of giving the examples (a lot of "For instance") to show the alignment of tree-ring based precipitation reconstruction with rogation ceremony records is not sufficient to support the precipitation influence on ecosystem and society, as maybe more disagree years happened."

Fair enough. Our approach was chosen to carefully handle the fundamental differences between these two proxy types: a continuous, annually-integrated biological record (tree rings) versus a discrete, event-triggered societal response (rogations), which makes a simple year-to-year correlation plot potentially misleading. To address the reviewer's point directly and improve clarity, we have now added Table 3 after line 375, which summarizes the periods of statistically significant correlation from our moving window analysis. We acknowledge the inherent limitations of such a comparison, but the documented periods of significant alignment provide valuable historical evidence, demonstrating that our reconstruction captures hydroclimatic extremes that were severe enough to impact the socioeconomic and natural systems.

Table 2: Main periods of significant correlation between reconstructed precipitation and regional rogation-derived drought indices. The table highlights the core intervals where a statistically significant negative correlation (Spearman r, $p < 0.05$) was identified between the reconstructed precipitation and the two main regional rogation clusters, based on a 50-year moving window analysis. For each regional index, the table displays the period of significance, the average Spearman coefficient across that period and a measure of data density, expressed as the number of years with recorded rogation ceremonies relative to the total duration of the interval.

Area	Period (CE)	Mean Spearman correlation	Number of years with rogation ceremonies within the period
Mediterranean Coast (DIMED)	1738–1801	–0.32	58/64
Ebro Valley (DIEV)	1747–1808	–0.35	56/62

<u>• Concern 4:</u> " The organization of the manuscript is poor. (1) First, there are some repeat information in Discussion part. Such as, Line 416-419, "The resulting regional residual chronology demonstrates strong internal coherence (Rbar = 0.273), similar to those from other Mediterranean hydroclimatic reconstructions such as Esper et al. (2021); Klippel et al. (2018); Tejedor et al. (2016) (Rbar = 0.28; 0.31; 0.29). Our chronology retains a reliable common signal back to 1505 CE, as indicated by an SSS value consistently exceeding the 0.85 threshold (Buras, 2017; Cook and

Kairiukstis, 1990; Wigley et al., 1984)", which is repeat with Results. (2) Line 489-492, "Visual inspection of Fig. 7 highlights periods characterized by distinct wet or dry conditions, as well as shifts in variability. For instance, the reconstruction identifies notable drought periods, with years like 1526, 1527, 1879, 1931, 2005 and 2012 falling below the 5th percentile, and exceptionally wet periods, with years such as 1534, 1546, 1575, 1645, 1716, 1940, 2010 and 2013 exceeding the 95th percentile." should be represented in Results part, as actually there is no discussion about it here. (3) The paragraph of Line 478-487 should be moved to the second paragraph from bottom as a summary to highlight the key aspects of this paper. Now, it is in the middle of discussion and disturbed the discussion about reconstructed precipitation."

We have done the following:
-Removed the repeated information on chronology statistics from the Discussion (lines 416–419):
"The resulting regional residual chronology demonstrates strong internal coherence (Rbar = 0.273), similar to those from other Mediterranean hydroclimatic reconstructions such as Esper et al. (2021); Klippel et al. (2018); Tejedor et al. (2016) (Rbar = 0.28; 0.31; 0.29). Our chronology retains a reliable common signal back to 1505 CE, as indicated by an SSS value consistently exceeding the 0.85 threshold (Buras, 2017; Cook and Kairiukstis, 1990; Wigley et al., 1984)."

-Moved the description of specific extreme years from the Discussion to the Results section (former lines 489–492; now moved to where Figure 7 is first introduced):

*"Visual inspection of **Error! Reference source not found.** highlights periods characterized by distinct wet or dry conditions, as well as shifts in variability. For instance, the reconstruction identifies notable drought periods, with years like 1526, 1527, 1879, 1931, 2005 and 2012 falling below the 5th percentile, and exceptionally wet periods, with years such as 1534, 1546, 1575, 1645, 1716, 1940, 2010 and 2013 exceeding the 95th percentile".*

Relocated the paragraph (lines 478–487) summarizing the study's strengths to the end of the Discussion, as it provides an excellent foundation for the subsequent interpretation.

*"The strength of this study lies in several key aspects. First and foremost, the exceptional length of the reconstruction (over 500 years) provides a rare and valuable long-term hydroclimatic perspective for the Iberian Range. Second, a critical strength stems from the rigorous approach to climate data evaluation and target variable identification: we assessed multiple gridded precipitation datasets (Sun et al., 2018; Tapiador et al., 2012; Xiang et al., 2021), including high-resolution products specific to Spain, and utilized daily correlation analysis (Torbenson et al., 2024) with the chosen high-resolution dataset to precisely define the optimal growth window. This approach is particularly relevant in this precipitation-limited environment and allows for a more nuanced capture of the climate signal compared to relying solely on pre-defined monthly periods. Third, the resulting reconstruction focuses on quantitative precipitation, offering direct estimates of past weather conditions rather than relying on derived drought indices. Furthermore, the clearly defined spatial representativeness (**Error! Reference source not found.**) centred on eastern and central Iberia, provides a solid basis for the interpretation and application of the reconstruction."*

Response to minor problems
1. About the Title, "precipitation extremes" is more exact than "hydroclimatic extremes" to highlight the study gap.

As both reviewers have suggested to replace hydroclimate with precipitation, we have modified the title to read: *"A five-century tree-ring record from Spain reveals recent intensification of western Mediterranean precipitation extremes"*

2. Line 89, "June is the month with the highest pluviosity, followed by May" is inconsistent with Fig.1B, which shown precipitation in May is the highest, followed by April.

Thank you for spotting this error. Corrected to: *"May is the month with the highest pluviosity, followed by April"*

3. Tree-ring series from five sites and two species were used for developing one chronology. How about the correlations between sites and species, and the uniformity of five chronologies at high frequency and low frequency variability? These informations could be plotted in Supplementary materials.

As suggested, we have now added two new tables in the Supplementary materials showing the correlations between the five individual site chronologies to demonstrate their coherence. Also, there's a new paragraph in the main text, at the end of the 2.2 (Tree chronology development) subsection.

"To justify the creation of a regional chronology, inter-site correlations were calculated on the standardized residual series (see Supplementary Table S1A and S1B). The analysis shows positive correlations across the entire network during the common instrumental overlapping period, with the all the sites being statistically significant ($p < 0.05$). The correlations for the full interseries overlapping period also show high correlations between sites, except between Javalambre and Valdecuenca sites ($r = 0.19$), which does not reach the 0.05 significance level, the overall strong coherence, with 9 out of 10 inter-site correlations being highly significant, indicates a robust common climatic signal across the network and validates their combination into a regional composite. These correlations are based on robust overlapping periods between sites, ranging from 78 to 520 years (Table S2), with Javalambre and Valdecuenca overlapping only 97 years."

Table S3: Intersite Pearson correlation matrices for the five residual site chronologies. Two different time periods are presented to assess the temporal coherence of the network. A) Common instrumental period (1952–1993): correlations are calculated for each site pair using all of their available common years. B) Full individual overlapping periods: correlations are calculated for all sites over a single, consistent period. All correlations are statistically significant ($p < 0.05$), with the exception of the JAR-VAN pair in the full overlapping period analysis.

A. Common overlapping period during the calibration period (1952-1993)					
	BEL	JAR	LIN	MOS	VAN
BEL	1.00	0.75	0.66	0.6	0.6
JAR	0.75	1.00	0.55	0.44	0.47
LIN	0.66	0.55	1.00	0.55	0.70
MOS	0.60	0.44	0.55	1.00	0.79
VAN	0.60	0.47	0.70	0.79	1.00

B. Individual overlapping periods					
	BEL	JAR	LIN	MOS	VAN
BEL	1.00	0.38	0.50	0.52	0.33
JAR	0.38	1.00	0.33	0.33	0.19
LIN	0.50	0.33	1.00	0.38	0.32
MOS	0.52	0.33	0.38	1.00	0.40
VAN	0.33	0.19	0.32	0.40	1.00

Table S4: Overlapping periods between site chronologies. Number of overlapping years between each pair of site chronologies used for the correlation analysis in Table S1. The diagonal (in bold) shows the total length of each individual site chronology.

	BEL	*JAR*	*LIN*	*MOS*	*VAN*
BEL	***581***	*520*	*297*	*314*	*109*
JAR	*520*	***520***	*297*	*302*	*97*
LIN	*297*	*297*	***297***	*283*	*78*
MOS	*314*	*302*	*283*	***314***	*109*
VAN	*109*	*97*	*78*	*109*	***109***

4. Line 412-413, "capture the critical moisture accumulation phase influencing annual growth (late summer, autumn, winter and spring/early summer)," how to understand the autumn and winter precipitation influence on tree radial growth considering trees dormancy in winter.

We have added a sentence to clarify the physiological mechanism, explaining that autumn and winter precipitation is crucial for recharging soil moisture, which supports earlywood growth at the start of the following season.

"Physiologically, this window was strategically selected through detailed correlation analysis to capture the critical moisture accumulation phase influencing annual growth. This extended period is crucial because

autumn and winter precipitation, often accumulating as snowpack at these mountain sites, recharges soil moisture during tree dormancy. The release of this water during spring snowmelt then directly supports earlywood formation (Pasho et al., 2011a, b), while the window still excludes the peak summer drought period (July to mid-August) where growth is typically limited by intense water stress (Camarero et al., 2013)."

5. Line 445, "comparing our Fig. 6 extremes with their findings", should be Fig. 7, right?

This was a typo and it is *"Fig. 7".*

6. Line 472-474, "The lack of strong correlation in earlier periods… influenced by biological memory, …" seems inconsistent with the feature of RES chronology with "pre-whitening to reduce autocorrelation".

The paragraph has now been rephrased to:

"The lack of strong correlation in earlier periods or variable wet-year correspondence may stem from several factors. Firstly, and most importantly, while our chronology meets the SSS > 0.85 threshold for reliability throughout, the inherent decrease in sample replication in the early part of the record leads to a statistically weaker common signal compared to the well-replicated recent period (Buras, 2017; Wigley et al., 1984). This reduced signal strength naturally makes robust correlations with any external proxy, including rogation records, more challenging to achieve. Secondly, fundamental distinctions between the proxies remain: our reconstruction represents an annually integrated, 320-day signal, whereas rogation records are event-triggered responses to perceived agricultural and social stress, which may not always align seasonally."

7. 5 is not clear and takes up too much space.

We appreciate the feedback on this figure. While we acknowledge it is dense, we believe it is crucial for demonstrating the rigour of our data-driven approach to defining the optimal climate window, which is a key strength of the study, since we are using daily precipitation data. We have refined the figure caption to better guide the reader in its interpretation and we have also considered reducing the period shown (and the window length shown) to make it more compact.

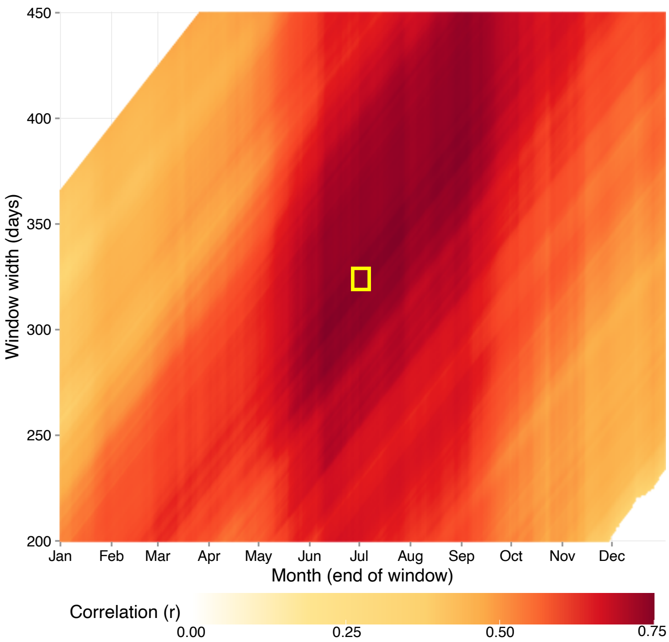

Figure 5: Daily climate-growth response analysis showing Pearson correlation coefficients between the residual tree-ring chronology and daily accumulated precipitation. The heatmap explores a vast parameter space to identify the optimal climate window influencing tree growth. The y-axis represents the width of the precipitation window in days (from 200 to 450 days). The x-axis represents the ending day of this window, spanning from January to December of the current growth year.

The colour of each pixel indicates the strength of the correlation (r). Only statistically significant correlations ($p < 0.05$) are shown. The yellow box highlights the pixel with the maximum positive correlation ($r = 0.749$), which corresponds to a window of 324 days ending on July 1st.