Response to Reviewer 3:

Comments/Text of reviewer posted in **black;** our answers are posted in blue.

RC3:

General comments

The authors studied trends in hydroclimatic extremes using a 40-year time series from the boreal Krycklan catchment in Sweden, in the context of 130 years of climate data from a nearby site. They looked at how different extreme climate indices changed and how they affected seasonal low flows in winter and summer. The authors also identified the best climate indices for predicting both summer and winter minimum flows. The authors have carried out an interesting study that is certainly scientifically relevant. I see the novelty both in the focus on a boreal region, where not so many studies exist and in the robust testing of different predictors of minimum flow. Therefore, I believe that the study has the potential to be published in HESS. However, I have some comments listed below that I would like to be addressed.

Response: We would like to thank reviewer 3 for the constructive comment and the acknowledgement of the novelty of this research. Please see below our detailed response to all the comments raised by the reviewer.

Major comments

1) I think the research gaps and novelty could be better described. Although the entire introduction is clear and comprehensive, I miss the "so what" message. What is new in the study and how does it go beyond current knowledge?

Response: In response to the research gaps and novelty, we will add more details to highlight the novelty and gaps in the research as follows in the third paragraph:

We now suggest adding “Despite previous studies showing the effects of earlier snowmelt on spring floods (Irannezhad et al., 2022; Venäläinen et al., 2020; Hrycik et al., 2024), as well as decreasing baseflow trends in succeeding summers (Murray et al 2023), is a link of how winter climate affects winter hydrological processes and subsequent summer runoff lacking. This is critical to understand how climate change will alter winter conditions and consequently catchment recharge and runoff processes in light of future climate warming predictions. “

We will also restructure the final paragraph of the introduction as follows: “This research addresses how changes in winter climate affect seasonal runoff in the boreal Krycklan catchment using trends analysis and interconnectivity with a large number of long-term hydroclimatic variables and isotopic analysis to improve the predictability of future climate warming impacts on hydrological processes. Our first objective was to identify any significant changes in temperature trends and test the relation to a much longer time series (130 years) in the region. We then used a more detailed time series (30 years) to identify seasonal climate extreme indices. With this analysis, we tested how climate is changing using both the 30-year and 130-year time series in terms of seasonal variability. Our second objective was to evaluate how changes in extreme climate indices affect key hydrological processes during winter and summer. This analysis allow*ed* us to quantitatively identify what hydroclimatic extremes are most important for regulating runoff across the seasons and an opportunity to improve the predictability of future climate warming. Our final objective was to use seasonal origin index analysis of water isotopes to verify whether the changes in runoff corresponded with the climate analysis *by testing the* relative contributions of winter precipitation to winter and summer runoff. *"*

2) L157: Please describe the linear regression model in more detail. The linear regression models also have some requirements for the input data, such as normality and uncorrelated predictors. Were these conditions met? If not, were the data transformed? Did the authors also consider other methods for detecting trends, such as Mann-Kendall's correlation (which can be used for non-normal distributions thanks to its ranking) or Sen's slopes? How might the interpretation of the results change if different methods of trend analysis were used?

Response: We will change the analysis to Mann-Kendall's trend test, which does not affect the results (see also response to Reviewers 1 and 2). Initially, this test was initially used to identify the significant trends among the indices but was not included in the previous manuscript. However, with this reviewer's suggestion and others, we will include the analysis.

3) L270, section Model of changes in runoff: I think the text in this section should be better supported by the results. For example, the authors state that AFDD<0 is the best explanatory variable, but I cannot see it in any of the figures (Fig. 5 only shows its relationship with winter/summer runoff). Perhaps you could at least show the correlation matrix of all predictors (heat map or similar) to support your statements.

Response: Great suggestion! We will add a correlation matrix to the supplementary material to show the coefficient of regression value with winter minimum Q (WQmin) and Summer minimum Q (S_Qmin). For the winter Qmin, we can see that AFDD had the highest regression coefficient, r^2 (0.63) as identified by the stepwise linear regression model. For the summer Qmin, the strongest r^2 can be seen with summer max temperature S_MaxTMax (-0.56) and winter AFDD<0 (0.27) indicating that warmer summers lower the Q min while warmer winters contributed to lower Qmin during the summers.

	r^2	
Significant climate extreme indices	W_Qmin	S_Qmin
W_AFDD <0	0.63	0.27
W_Frost days	-0.39	0.21
W_Icing Days	-0.55	0.01
W_Diurnal temp. range	0.45	-0.13
W_Coldspells	-0.39	-0.02
W_Coolnights	-0.45	0.03
W_Snowdays	-0.03	0.13
S_MaxTMax		-0.56
S_ Coolnights		-0.2
S_Warmnights		-0.05
S_Warmdays		0.09

Table that will added to the new version of the manuscript.

4) My general concern is that more could be done to investigate the potential effects of individual climate indices on runoff. For example, how does climate variability affect

the observed relationship between climate and hydrological variables, in particular the role of warm/cold, wet/dry or snow-poor/snow-rich years? I believe this direction would provide new insights into catchment behaviour.

Response: We agree that the correlation to years with both temperature and moisture variability with runoff will be an interesting step forward, which could be addressed in a follow-up study, for example using the PLS models to show the most important variables in predicting runoff. However, in this study, the majority of the precipitation variables did not show significant trends, and hence we did not include them in any future modelling steps.

5) While I like the idea of supporting the results of the time series data analysis with a more detailed analysis using stable water isotopes (especially for the Krycklan catchment with long-term and detailed isotope data), I feel that this part is not well connected to the other results and seems quite separate from the rest of the text. In addition, there is only one short paragraph and one figure in the results section relating to this part. I would encourage the authors to expand this part by adding more visualisations and results, and try to better connect it to the results of other analyses.

Response: In regards to the isotope analysis we will improve the text in the introduction as follows

"A powerful technique for assessing changes in stream flow involves using the differences in the water isotopic signatures of $\delta^{18}O$ in precipitation across seasons (Allen et al., 2019). Previously, Peralta-Tapia et al 2016 showed strong seasonality in precipitation signals during the winter and summer where $\delta^{18}O$ isotopes with more depleted (lighter) isotopes in winter min (-24.4 ‰) and enriched (heavier) in summer precipitation max (-4.4 ‰) while stream $\delta^{18}O$ varied between -15.4 ‰ winter and -10.5 ‰ in later summer. This distinction in the seasonal isotopic signals presents the possibility of tracing the fraction of water arriving as snow in the winter that can either be potentially stored in the catchment or become streamflow in the current or proceeding seasons. Similarly, in the summer, the precipitation can be traced to contribute to either storage, streamflow or evapotranspiration (ET). Using isotopic signals to understand the water partitioning in catchments offers a possibility to trace water contributions from different sources that are not possible by using only the water balance or measuring seasonal total precipitation volumes. This can be done by adapting the seasonal origin index (SOI) to implicitly test whether winter precipitation or summer precipitation is overrepresented in stream water with $\delta^{18}O$ isotopes using the methods outlined in Allen et al., (2019). The results from the SOI analysis can then be used to support whether increases in winter runoff are a result of winter precipitation and whether this signal is seen during the summer baseflow. "

We will also add a connection of the runoff analysis to the SOI section as follows.

"The great fraction of winter signal represented in winter runoff corresponds with the results from the runoff analysis that showed higher Qmin during the winter across the years."

Specific comments

6) Section 2: It would be good to provide a map of the Krycklan catchment and its position within Europe/Sweden.

Response: A map will be added based on all reviewer's comments.

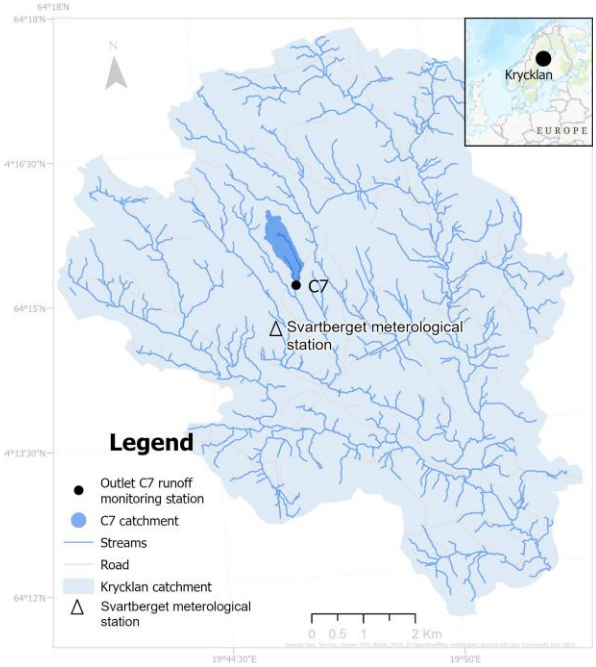
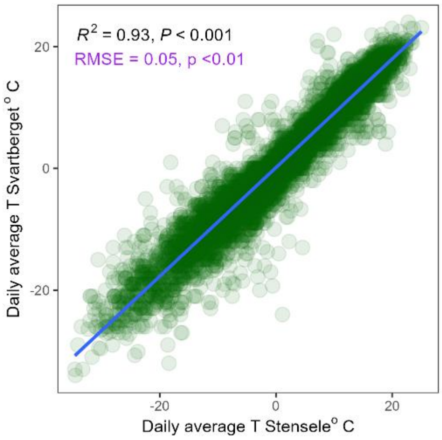


Fig 1 Map showing the location of the study site in the Krycklan catchment in relation to Northern Countries

7) L110: Is there a reason why the study only uses data up to 2004 for the Stensele climate station? Later, in some figures, the data are plotted together with data from the Krycklan catchment (by different colours). Have the two-time series been homogenised somehow in order to plot them together as a single time series? The distance between Krycklan and Stensele is 150 km, so one would expect different conditions at the two stations.

Response: The meteorological station in Stensele was closed in 2004 and no longer provided data hence we could not continue the long-term analysis with one dataset. We will add this to the methods to make it more clear. Additionally, we have tested the homogeneity of the two datasets using regression analysis and root mean square error (RMSE), which showed that the Stensele and Svartberget synchronise with an r^2=0.92, RMSE 0.05 for the overlapping period 1982-2004 using the daily average time series. The systematic bias in the dataset lies in the extremes where maximums are higher in the Svartberget than the Stensele dataset while minimums are lower in the Stensele than the Svartberget dataset. However, these differences are small and do not affect the general trends in the dataset used in this study. Based on these results, we expect that the trends observed in the long-term Stensele dataset can be used to reflect similar trends in Svartberget. We have included this in the supplementary information section to support the data analysis (R Fig 13).



R Fig 2 The correlation between daily mean temperature from the Stensele meteorological station and the Svartberget meteorological station between 1982-2004 showing the r^2 and root mean square (rmse) between the two datasets

8) L134: What is meant by “Temperature intensity”?

Response: Temperature intensity refers to a measure of the degree to which a season is warm or cold as measured by the 7 indices. This is described as exceeding a threshold as described in Sanches et al 2023. We ´will add this description to improve the clarity.

- the coldest daily maximum temperature (Min Tmax),
- the coldest daily minimum temperature (Min Tmin),
- the warmest daily maximum temperature (Max Tmax),
- the warmest daily minimum temperature (Max Tmin),
- the mean difference between daily maximum and daily minimum temperature (diurnal temperature range),
- the number of days when Tmax < 0°C (icing days), and
- (vii) the accumulated degree days below 0°C (AFDD<0).

9) L144: Since Table S1 is very important for the methods and results interpretation, I would prefer to put it directly to the main text to avoid jumps between the two files. I think it would be beneficial for the readers.

Response: Thank you for the suggestion, we will move table 1 to the main document

10) L154: How exactly has baseflow been calculated? If baseflow is only represented by minimum streamflow, I would suggest not calling it baseflow (use just minimum streamflow or similar). If you agree, this terminology would need to be changed throughout the text and figures.

Response: Agreed! We will change this to be a minimum runoff

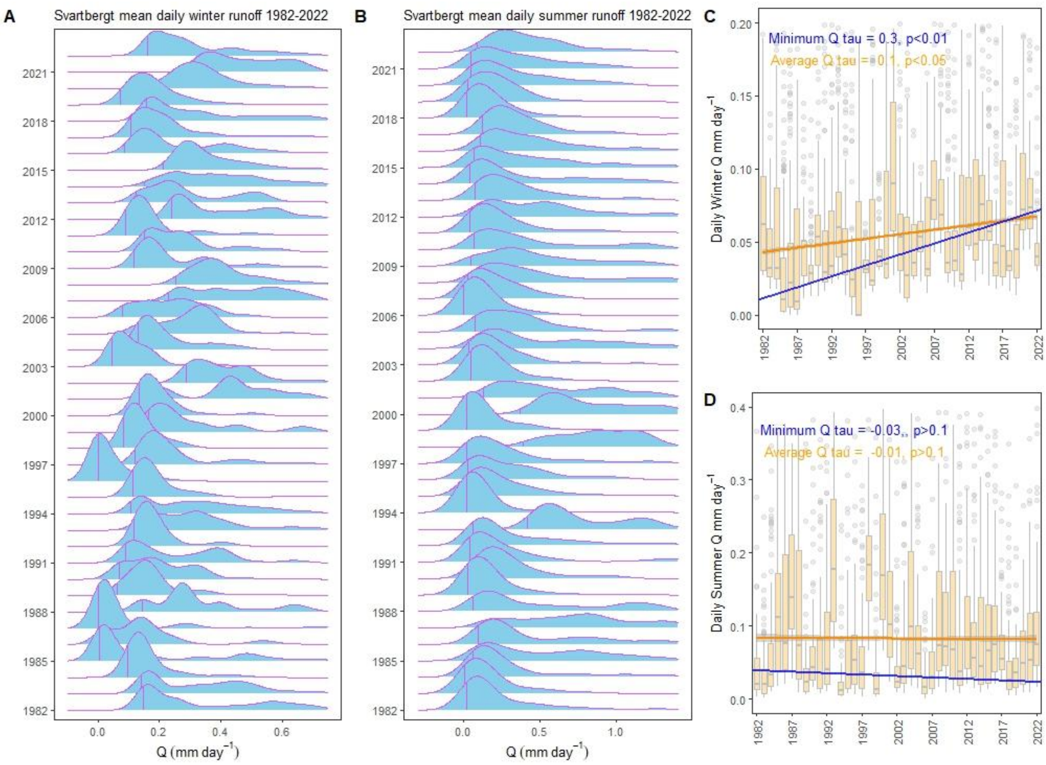
11) Fig. 1: Please explain the grey background colours in the B) (probably confidence or prediction intervals). Same for Fig. 2, 3, 5 and 6. Besides, B) and C) descriptions in Fig. 1 caption are probably switched.

Response: This will be added based on all reviewer's suggestions

12) Fig. 4: Please describe what is in individual panels in the figure caption

Response: We will add labels and describe each plot as follows

“Figure 4 Variability in winter and summer runoff showing hydrograph during the winter (A) and Summer (B) in the C7 catchment. The minimum flow in each year during the winter and summer are identified as vertical lines in each year. The annual variability of winter runoff is shown as boxplots (C) and trends in minimum (blue line) and average (orange) runoff across the years. In panel D, the boxplots show the annual variability of summer runoff (D) and trends in minimum (blue line) and average (orange) runoff across the years.



R Fig 3 New proposed figure

13) Fig. 5: There are a couple of years considerably outside the prediction range. Is there any explanation for what might be the reason for this?

Response: This was explained in line 280:202 in the manuscript “The three years (1993, 1998 and 2000) were the largest outliers in the model because these were the wettest years when minimum runoff was above 0.35 mm day-1 (Fig. 5B).”

14) Fig. 5, caption: I think the resulting equation of the linear model should be placed in the main text together with some further description (see also my major comment related to the linear regression model).

Response: Thank you for the suggestion, we will add the equation to the main text and include further descriptions

15) L298: I would be rather cautious about attributing the results to baseflow, as baseflow was not calculated/simulated in your study (unless I missed something). An increase in Qmin in winter doesn't necessarily mean that baseflow also increases (although I agree that it is likely). If there are more melting periods in winter (higher fast flow component), Qmin will of course also increase, but the effect on baseflow may not be so straightforward. I'm not saying it's not true (as I expect the close connection of streamflow and baseflow in the Krycklan catchment, although I don't know the study area), but I would ask the authors to address this issue in the discussion (e.g. by adding some studies investigating this effect).

Response: Agreed, we will keep this consistent by using minimum flow

16) L324: Again, please consider whether you mean baseflow or Qmin.

Response: Agreed, we will rephrase to be consistent.

17) L354-368: This paragraph is perhaps rather the introduction.

Response: We will consider in cooperation this paragraph in the introduction.

18) In my opinion, the conclusions can be formulated more specifically and with clear take-home messages. Additionally, the sentence in L372 (“shrinking snowpacks that melt earlier”) is not a conclusion coming from this study (although the statement itself is true), so please consider reformulation.

Response: We will reword the conclusion based on this suggestion

“In this study, we found significant trends in many warming-related climate extreme indices over the last 30 years during both winter and summer. The warming observed in the last 30 years corroborates with the longer 130-year time series that dates back to the 1890s showing progressive warming temperatures across time. Evaluating how these changes affect key hydrological processes during the same period, we observed higher runoff during the winter while decreasing runoff during the summers (1992-2022). Using the significant trends in the extreme indices to better evaluate the effects on catchment seasonal runoff, we found that winter variables were best at explaining winter minimum runoff while winter and summer maximum temperatures could explain much of the variability in the summer minimum runoff. These findings were supported by water isotopic analysis that showed an increasing seasonal origin index during the winter indicating higher contributions of winter precipitation to winter runoff and consequently lower winter precipitation in summer runoff. With the decreased catchment water storage due to increased winter runoff before the occurrence of the true spring flood, the potential for maintaining summer base flow runs the risk of being exhausted in the future. This work highlights the importance of understanding future hydro-climatic trends where changes in the seasonal distribution of water could further affect low-flow conditions, with implications for drought-related issues in light of future climate change. “

19) Fig. S2, S5: Please explain the background colours (S2, S5) and the red line (S3) in the figure captions.

Response: These captions will be corrected based on this and the reviewer's 2 comments

Technical corrections

20) L8 and 18: Should there be “subsequent” rather than “preceding” (seasons; streamflow)?

Response: Agreed, we will change the terminology to subsequent

21) L111: Please specify the exact time period to be consistent with the previous text.

Response: We will add the runoff timeframe to this section. Thank you for the comment

22) L154-155: Coefficient of determination (rather coefficient of regression).

Response: We will change these to tau using the Mann Kendal trend test based on this reviewer's and others' suggestion

23) L174: The abbreviation SOI should be defined here for the seasonal origin index.

Response: Thank you for the comment, we will add this