egusphere-2025-2982: Responses to Anonymous Referee #1, 05 Dec 2025

We are grateful to both reviewers RC1 and RC2, for the time and care they devoted to evaluating our manuscript. Their comments were exceptionally helpful and, in many places, provided the kind of guidance and direction one would expect from a dedicated supervisor.

Both reviews pointed to a consistent set of issues that we address through the following principal changes in the revised manuscript.

(1) All six phase change timing metrics will be renamed and reframed:

FUD/BUD → DSO/DSE (Discharge Stabilization Onset/End),

SBD/SMD → CSO/CSE (Continuous Snow Onset/End), and

TTP^{-}/TTP^{+} → CCT/CWT (Cumulative Cooling/Warming Transition),

explicitly framed as proxy-based regime transitions distinct from ice phenology definitions (IAHR, 1980).

(2) The "periods" mentioned in the discussion manuscript will be replaced by Intra-Variable Intervals (IVIs) and Cross-Variable Intervals (CVIs); the CSP algorithm will be renamed LSS (Longest Snow Sequence).

(3) The "loss of seasonal synchrony" framing and the associated title will be revised; the central narrative will be reframed around asymmetric proxy-based timing shifts, with CVI trend analysis providing the quantitative basis.

(4) The record will be extended from 57 to 59 water years (WY1966–WY2024).

(5) The single reference-year result (section 3.1) will be replaced by full-period summary statistics and an early (WY1966–WY1994) versus late (WY1995–WY2024) sub-period comparison.

(6) RiTiCE will be described as a rule-based detection framework. Limitations for regulated and hydropeaking rivers will be explicitly acknowledged.

(7) Overstated language will be removed or moderated. Results will be interpreted within the scope of what the proxy framework and single-site record can support.

(8) Research questions will be added at the end of the Introduction.

(9) FDD/TDD diagnostics, seasonal air temperature trends, and independent observational context from ice thickness and water temperature records will be added.

(10) Timings detected through RiTiCE will be separated into onset-group (CCT, CSO, and DSO) and release-group (CWT, CSE, and DSE) for autumn/winter and springtime, respectively.

The underlying detection algorithms remain unchanged throughout. Point-by-point responses to RC1's comments follow below.

- Abolfazl Jalali Shahrood on behalf of co-authors.

In the following document, reviewer comments are in black, and author responses are in blue.

RC1: This manuscript applies the RiTiCE (River Ice Timing Characteristics and Extremes) framework to 57 years (1966–2023) of daily discharge, air temperature, and snow depth data from the River Oulankajoki, a boreal/sub-Arctic river in northeastern Finland. Building on earlier RiTiCE work that focused mainly on break-up, the authors extend the framework to detect six phase change timing (PCT) features (FUD, BUD, SBD, SMD, and two temperature transition points TTP^{-} and TTP^{+}) and derive associated seasonal durations (cold and warm seasons, ice cover, open water, snow cover, no-snow period). The authors then analyze long-term trends, correlations among PCT features and seasonal periods, and temporal lags between atmospheric transitions and cryo-hydrological responses. A central qualitative conclusion is the asymmetry between autumn and spring. The order and timing of autumn features (SBD, TTP^{-}, FUD) exhibit substantial year-to-year variability, whereas spring features (TTP^{+}, BUD, SMD) retain a highly stable sequence. This behavior is interpreted as a loss of seasonal synchrony driven by climate warming.

Response: In the revised manuscript we will extend the analysis to 59 water years (1 Oct 1966–30 Sep 2025) of mean daily data. We will present the detected timings as **proxy-based transitions** rather than as **direct visual freeze-up or break-up dates**.

The phase change timings (PCTs) referred to in the discussion manuscript as FUD/BUD, SBD/SMD, and TTP^{-}/TTP^{+} will be renamed to DSO/DSE (Discharge Stabilization Onset/End), CSO/CSE (Continuous Snow Onset/End), and CCT/CWT (Cumulative Cooling/Warming Transition), respectively. **The underlying detection rules will remain unchanged** but will be addressed with supporting independent data (timings of ice thickness and water temperature measurement operations).

In addition, the "periods" which will be treated as a legacy terminology for RiTiCE will be replaced with Intra-Variable Intervals (IVIs) and Cross-Variable Intervals (CVIs) to avoid them from getting mixed with actual ice events. Additionally, the PCTs in autumn/winter season will be referred to as "Onset-group" and those in springtime will be referred to as "release-group". We also divide the 59-year period into halves of WY1966-WY1994 (early) and WY1995-WY2024 (late) periods to better reflect the long term changes. Please note that the middle year is chosen arbitrarily to nearly divide the period into half. We will not use breakpoint tests (e.g., Pettitt test) as it may be different between variables and the scope of the study may drift.

Our point-by-point replies here, use this updated terminology throughout. The CSP algorithm will be renamed to LSS (Longest Snow Sequence) to avoid it from being mixed with CSP (Continuous Snow Period) as an IVI. Please note that with these reframing, the underlying algorithms remain untouched in terms of their implementation and logic. Please find the tables 1-3 below for your reference. Table 1 will be in the main manuscript and table 2 and 3 will be moved to supplements.

Table 1 Redefining the PCTs and replacing CSP with LSS.

PCT	**Legacy PCT**	**Definition**	**Variable**	**Method**
DSO (Discharge Stabilization Onset)	FUD	Start of the longest period of reduced discharge variability	Discharge	DVD (Daily Value Difference)
DSE (Discharge Stabilization End)	BUD	End of the longest period of reduced discharge variability	Discharge	DVD (Daily Value Difference)
CSO (Continuous Snow Onset)	SBD	Start of the longest continuous period of non-zero snow depth	Snow depth	LSS (Longest Snow Sequence)
CSE (Continuous Snow End)	SMD	End of the longest continuous period of non-zero snow depth	Snow depth	LSS (Longest Snow Sequence)
CCT (Cumulative Cooling Transition)	TTP^{-}	Transition to cumulative cooling dominance	Temperature	ZCAT (Zero-Referenced Cumulative Area Transition)
CWT (Cumulative Warming Transition)	TTP^{+}	Transition to cumulative warming dominance	Temperature	ZCAT (Zero-Referenced Cumulative Area Transition)

Table 2 Redefining "Periods" with intera-variable intervals.

Intra-variable Interval (IVI)	Legacy period	Definition	Variable
DSP (Discharge Stability Period)	Ice cover	Period between DSO and DSE	Discharge
DVP (Discharge Variability Period)	Open water	Complementary period to DSP	Discharge
CSP (Continuous Snow Period)	Snow cover	Period between CSO and CSE	Snow depth
NSP (Non-Continuous Snow Period)	No-snow	Complementary period to CSP	Snow depth
CDP (Cooling-Dominant Period)	Cold season	Period between CCT and CWT	Temperature
WDP (Warming-Dominant Period)	Warm season	Complementary period to CDP	Temperature

Table 3 Defining Cross-variable intervals.

Cross-variable interval (CVI)	Definition	Variables	Phase
DSO–CSO	Signed timing offset between discharge stabilization onset and continuous snow onset	Discharge–Snow	Onset-group
DSO–CCT	Signed timing offset between discharge stabilization onset and cumulative cooling transition	Discharge–Temperature	Onset-group
CSO–CCT	Signed timing offset between continuous snow onset and cumulative cooling transition	Snow–Temperature	Onset-group
DSE–CSE	Signed timing offset between discharge stabilization end and continuous snow end	Discharge–Snow	Release-group
DSE–CWT	Signed timing offset between discharge stabilization end and cumulative warming transition	Discharge–Temperature	Release-group
CSE–CWT	Signed timing offset between continuous snow end and cumulative warming transition	Snow–Temperature	Release-group

General Comments:

Although this manuscript falls within the scope of TC and is based on a valuable data set, it requires substantial revision before it can be considered for publication. My main concerns are:

RC1: 1- The central narrative relies on the sequence and relative timing of the six PCT markers. A key and potentially confusing result is that in some years FUD occurs earlier than both SBD and TTP$^-$. This is counter-intuitive if one understands “freeze-up” as the date when the river is first observed to be completely ice-covered.

Response: We will revise the terminology to avoid interpreting FUD as physical freeze-up, we will be replacing it with a discharge-based transition metric (DSO) and we will clarify its meaning as a proxy not direct freeze-up date. Please note that DSO<CCT (legacy FUD<TTP$^-$) cases are not driven by early DSO, but by delayed CCT in years with fewer sub-zero air-temperature days in early winter (OCT-DEC). DSO < CCT occurs in 14 out of 59 water years.

RC1: 2- The manuscript states in Sect. 2.3 that FUD and BUD are hydrological signatures, distinct from IAHR visual definitions. However, later sections routinely interpret FUD as freeze-up in the physical sense. The paper needs to be more precise and transparent here, especially given the unusual orderings of events.

Response: We agree and will ensure consistent terminology throughout, clearly distinguishing hydrological proxies from physical ice conditions. We will frame the PCTs properly to avoid them from being interpreted as actual freeze-up/break-up defined in IAHR 1980 terminology (IAHR, 1980). The revised manuscript will use clearer terminology and definition.

RC1: 3- I suggest adding an explicit clarification such as "FUD is a discharge-based proxy for the onset of the winter low-flow regime, which is typically associated with sustained ice cover in this river, but does not necessarily coincide with the date when the channel is first completely ice-covered in a visual sense."

Response: Thanks for your suggestion. The revised manuscript will use the new terminology for all metrics, specifically for the discharge-based metrics to be interpreted as a proxy for flow regime transition rather than visual ice cover. Discharge Stabilization Onset (DSO) will be a replacement for the legacy Freeze-up day (FUD) to avoid it from being mixed with IAHR 1980 terminology. We will similarly redefine the terminology and definitions for all 6 PCTs, intra-variable and cross-variable intervals (legacy Periods) in this study.

RC1: 4- In Fig. 7, the authors should explicitly discuss the years when FUD precedes SBD and/or TTP^{-}. It would help to show one or two example years (similar to Fig. 6) with T, Q, S and all six PCT markers overlaid, and to guide the reader through how an early FUD can arise physically, for example a very dry autumn, early stabilization of baseflow, delayed continuous snow cover at the nearby terrestrial station, and a late zero-crossing in the cumulative temperature curve.

Response: We agree. Figure 1 below is an example of an atypical year (1975) where the short snow duration was not captured as the CSO timing as CSO -by LSS method definition- is the start of "continuous snow", therefore the rank is CCT < DSO < CSO.

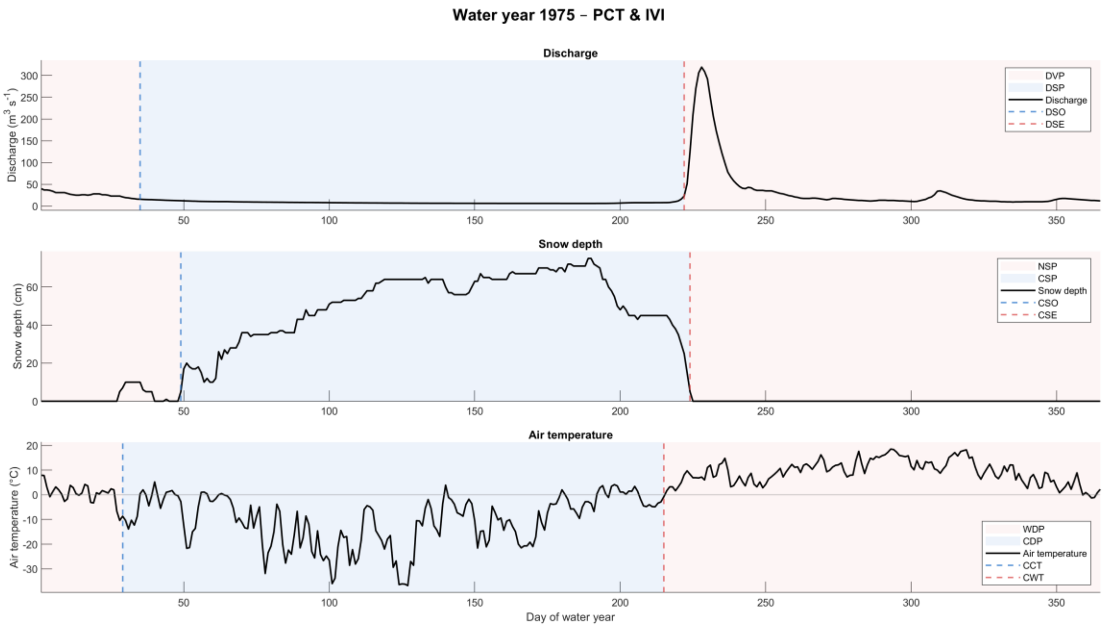


Figure 1 DSO precedes CSO.

Similarly, Figure 2 is an example of another atypical year (2011) where the CCT timing is delayed while discharge was already stabilized. Therefore, the rank is CSO < DSO < CCT.

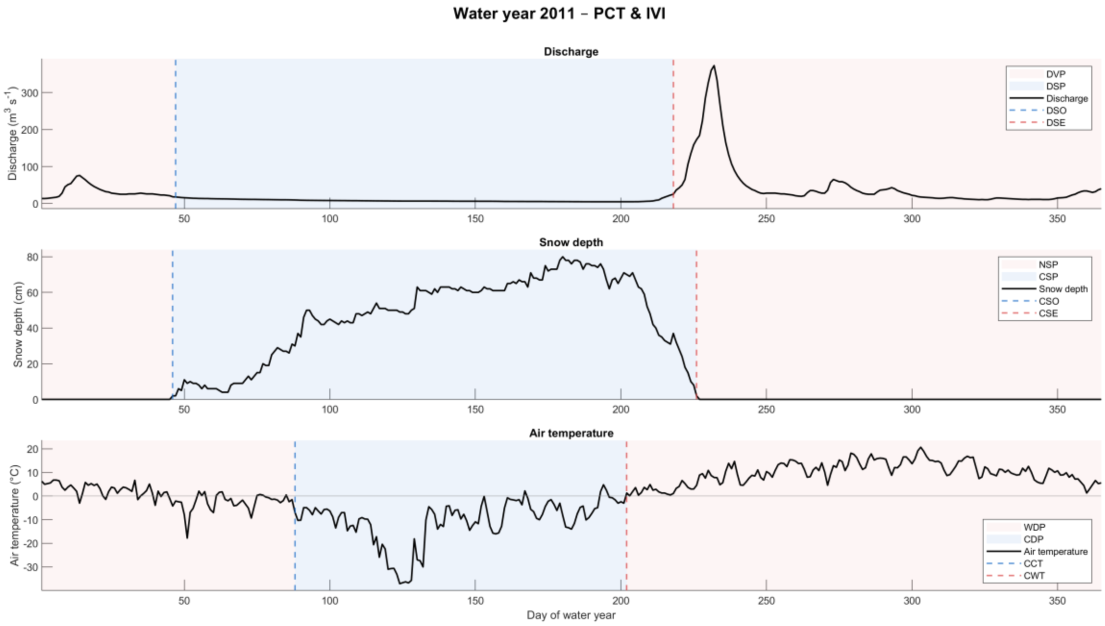


Figure 2 DSO and CSO almost at the same time while CCT delayed.

Figure 3 is an example of another atypical year (2020) where the CCT timing is delayed, initial snow data not captured by LSS (not inside the continuous segment) while discharge was already stabilized. Therefore the rank is DSO < CSO < CCT. We will discuss these in the revised manuscript.

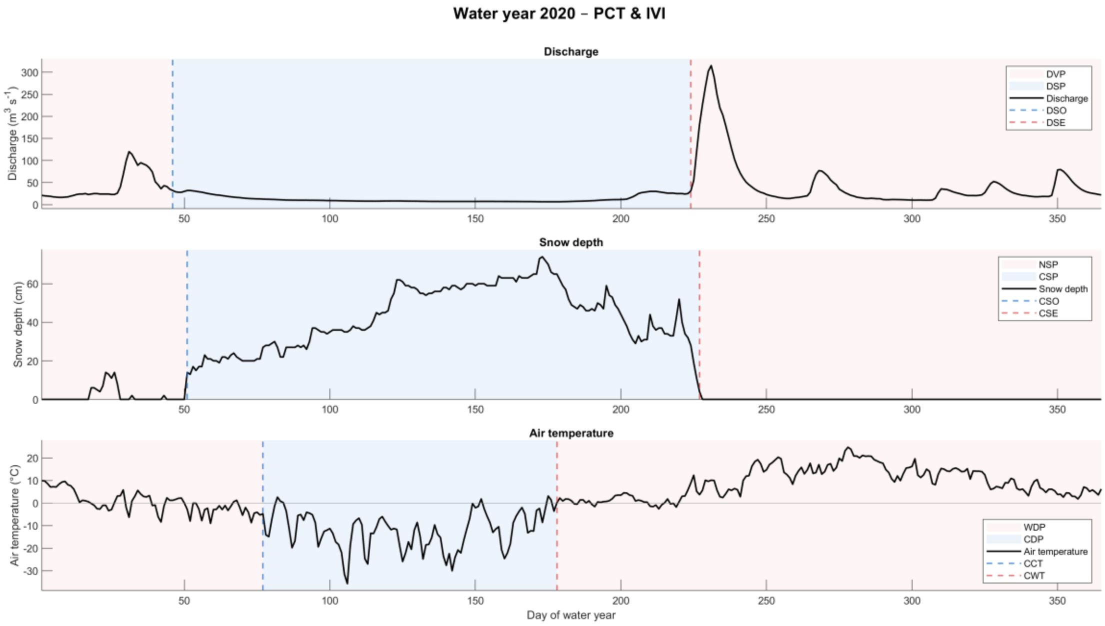


Figure 3 DSO precedes both CSO and CCT.

RC1: 5- I think the authors need to acknowledge more explicitly the limitations of the hydrological proxy and to demonstrate that these cases are physically plausible and reasonably rare, for instance X out of 57 years, rather than artefacts of the detection algorithm.

Response: We agree that a discharge-based timing is wrongly framed as direct observation of river freeze-up in the discussion manuscript, and we now state this limitation explicitly by redefining the

FUD/BUD as DSO/DSE and frame them properly as proxies. We therefore revise our terminology and interpretation: DSO is a hydrologic regime-transition proxy derived from the onset of reduced day-to-day discharge variability, and it is not equivalent to “freeze-up” as defined in observational river-ice terminology (e.g., IAHR 1980).

Across the full record (59 water years), the cases where DSO precedes the air-temperature transition (DSO<CCT) occur in 14/59 years (23.7%), and where DSO precedes continuous snow onset (DSO<CSO) occur in 7/59 years (11.9%). Please not that the DSO<CCT cases are primarily associated with delayed CCT during warm early-winter conditions.

Therefore, we explicitly acknowledge that DSO can be sensitive to hydro-meteorological conditions (e.g., autumn wetness/baseflow stabilization) and to methodological choices (DVD and its variability threshold). We therefore treat DSO as a proxy timing marker within the proxy-transition framework, not a universal freeze-up date.

RC1: 6- The phrase “loss of seasonal synchrony” is prominent in the title, abstract, and conclusions, but there is no clear quantitative definition of synchrony and no consolidated figure that directly supports this claim. What exactly does "seasonal synchrony" mean here in this study?

Response: We agree that the term “seasonal synchrony” was not defined quantitatively in the original manuscript and that the supporting evidence was not presented in the discussion manuscript. In the revision, the synchrony definition will be replaced by the CVI trend analysis (Figure 4).

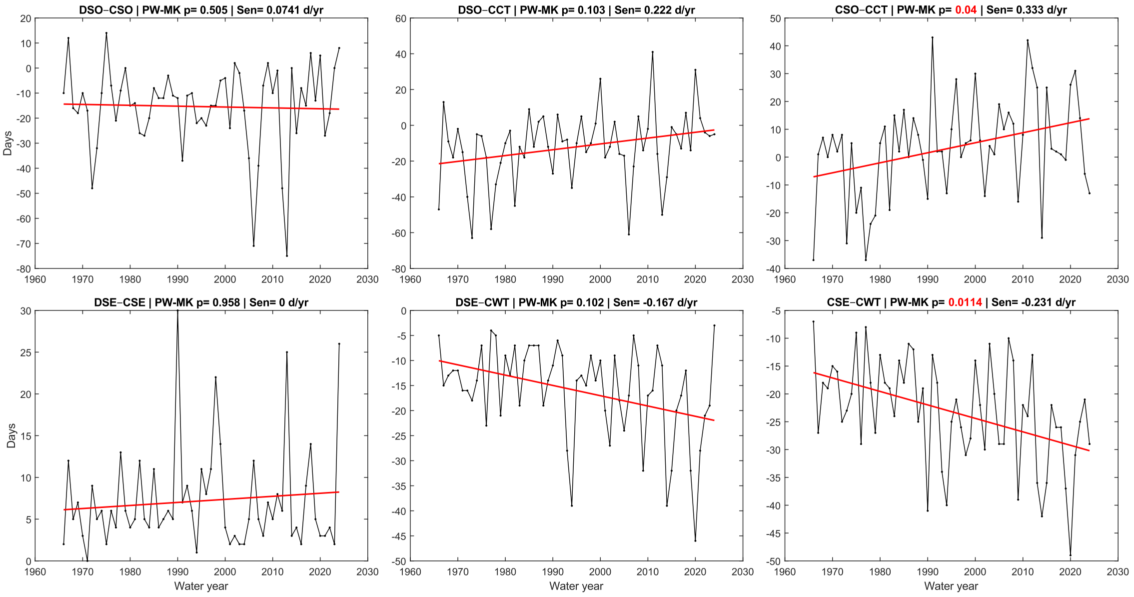


Figure 4 Cross-Variable Intervals (CVIs) showing the

RC1: 7- The study relies on one air and snow station (Kuusamo Kiutaköngäs, about 500 m from the river gauge) and one discharge gauge to characterise the whole sub-Arctic river system. This is understandable given data availability, but it has direct consequences for the interpretation of the PCT features. SBD and SMD are based on terrestrial snow depth at the weather station rather than snow on the river. Vegetation and wind redistribution can lead to systematic differences between station snow and river ice or river-adjacent snow conditions.

Response: We agree. The snow depth data represents local terrestrial snow conditions near the gauge rather than snow conditions on the river surface and we will acknowledge the limitation in the revised manuscript. We will interpret CSO/CSE accordingly as proxy timing rather than direct river ice metrics as stated earlier in our responses.

RC1: 8- Air temperature is also a single-point measurement, whereas freeze-up, break-up, and hydrological responses integrate the entire upstream basin. I suggest that in Sect. 4, when discuss cases where FUD precedes SBD or TTP^{-}, or where snow and ice duration diverge, authors should explicitly mention this spatial representativeness issue as one plausible explanation.

Response: We agree. This spatial representativeness mismatch can therefore contribute to scatter in the relative timing of our proxy transition markers and to occasional ordering reversals (e.g., DSO preceding CSO or CCT). In the revised manuscript we will state that air temperature is measured at a single location, whereas discharge integrates the upstream basin.

Our diagnostics for the revised manuscript also indicate that some counter-intuitive cases are linked to late CCT under warm early-winter conditions, which can shift the ZCAT-based atmospheric transition later. We will incorporate this limitation into Sect. 4 (Discussion) when interpreting DSO<CSO and DSO<CCT cases and when discussing divergence among snow, thermal, and discharge PCTs.

Specific comments:

RC1: 9- Line 11: Calling RiTiCE a "process-based detection tool" may be misleading. It is a statistical rule-based method using thresholds on Q, T, and S, not a physical energy-balance or hydrodynamic model.

Response: We agree and will revise the wording to describe RiTiCE as a rule-based detection method rather than process-based as you suggested.

RC1: 10- Line 95: At present the manuscript moves into the Methods in a descriptive way and does not clearly state two or three guiding scientific questions. I suggest adding a short paragraph with explicit research questions, for example "Specifically, we ask how the timings of six key PCT features have changed over 1966–2023, how the duration of cold, warm, ice-covered and snow-covered seasons have been reorganised, and how the lags between atmospheric transitions and surface hydrological and cryospheric responses have evolved."

Response: Thank you for your suggestion. We will add a paragraph at the end of the introduction that states RQs. The RQs in the revised manuscript will be:

(1) How have the PCTs shifted over the observational record?

(2) How have the derived IVIs and CVIs changed, and do these changes differ between the onset-group and the release-group?

(3) How has the temporal coupling between thermally-derived PCTs and their surface response evolved in terms of the direction and magnitude of cross-variable timing offsets?

RC1: 11- Line 104: The water year is defined from 1 October to 30 September. Based on Fig. 4, negative temperatures can already occur in October. For some colder water years this choice might prevent capturing the full evolution of Ct within a water year. It would be helpful to comment on this point. In addition, the figures linked in Appendix A are currently provided in emf or eps format. If possible, providing tif versions would make them easier to view.

Response: In our record, CCT defaulted to day 1 only once (WY 2009) because the cumulative curve did not exhibit a zero-crossing within the water-year window. The cumulative curve starts negative already so we inspected the adjacent-year curve (Figure 5), and it indicates that the corresponding zero-crossing occurs at the end of the preceding water year (30 Sep 2008). For consistency and simplicity, we will keep the ZCAT implementation unchanged. We will provide figures in .tif format.

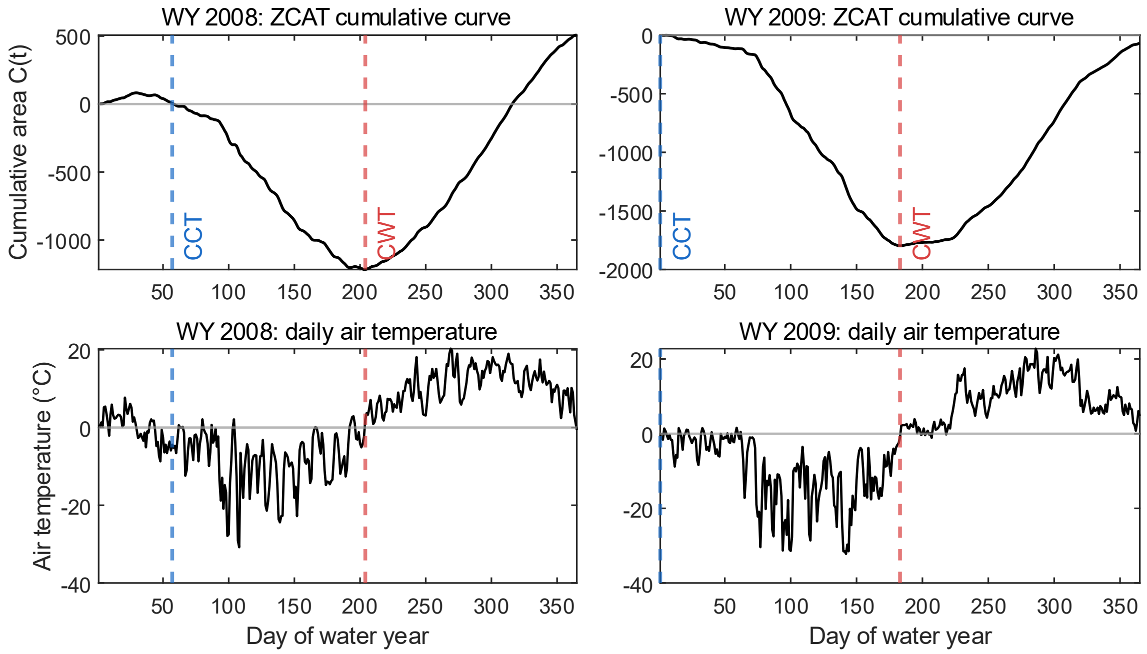


Figure 5 Single case of ZCAT method defaulting CCT to day 1 (1 OCT 2009), the actual CCT day is 30 Sep 2008.

RC1: 12- Equation 1: the authors define DVD as $\Delta Q_t = Q_{t+1} - Q_t$. Mathematically, using $Q_t - Q_{t-1}$ would only shift indices by one day, so the stable segment and FUD/BUD would be essentially unchanged. However, from a physical perspective it may be more intuitive to define "change from day t−1 to t" instead of "from t to t+1".

Response: We agree. We will clarify in methods that DVD is computed using forward differences $\Delta Q_t = Q_{t+1} - Q_t$ for consistency with the implementation in MATLAB (**diff(Q)**). We will also note explicitly that the backward-difference form $\Delta Q_t = Q_t - Q_{t-1}$ is equivalent up to a one-day index shift and does not materially alter the detected DSO or DSE.

RC1: 13- Equations 5 and 6: authors treat any $S_t > 0$ as "snow present" in the CSP algorithm. Please state the measurement resolution. This is especially relevant for short early/late snow events and could affect SBD/SMD in marginal years.

Response: We state the ±2 cm accuracy given in FMI guidance for snow depth, and the fact that the series is reported in whole centimetres. Snow cover for CSO/CSE is detected by $S_t > 0$ after preprocessing; this identifies days classified as ≥ 1 cm snow depth (there is no fractional category between 0 and 1 cm in the archive).

Prior to applying the LSS rule we recoded FMI "−1" to "0" (no snow) and interpolated a small number of missing calendar days to build a complete daily series (12 missing non-consecutive days over 59 water years). CSO and CSE are the start and end of the longest continuous snow interval; shorter early- or late-winter snow spells that are not part of that longest segment do not set CSO/CSE, which is the main limitation in marginal years. The ±2 cm uncertainty should be read as observational error on the reported depth, not as a reason to change the 1 cm-class rule in the code.

Figure 5 shows the monthly distribution of raw FMI "−1" values in our raw dataset. They are largely absent in mid-winter and dominate in summer.

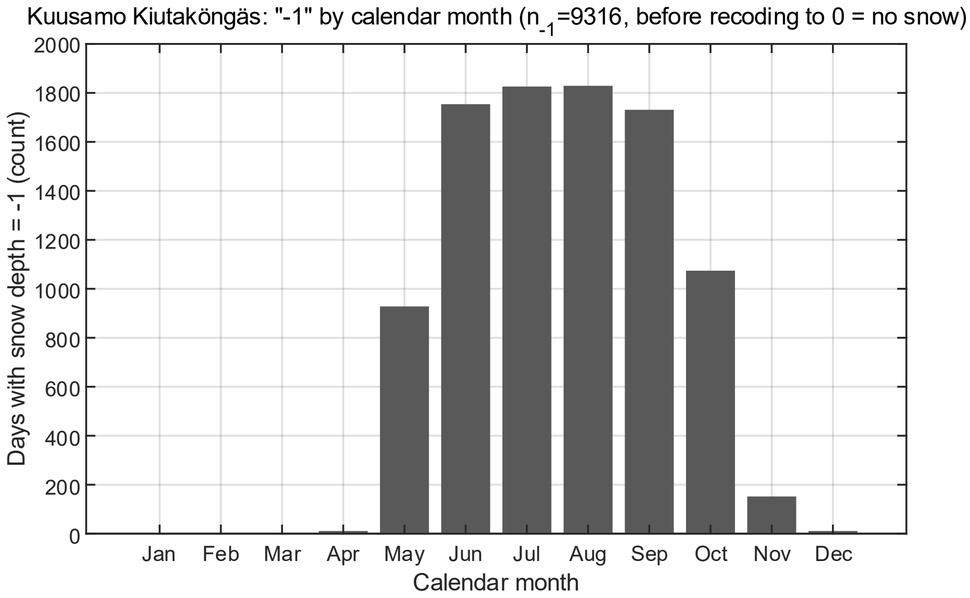


Figure 6 Monthly counts of FMI snow-depth codes −1 at Kuusamo Kiutaköngäs for the downloaded daily record, prior to setting −1 → 0 (no snow) for RiTiCE.

RC1: 14- Section 2.5: It is not entirely clear why authors do not directly use the more classical and widely used FDD and TDD metrics. A short explanation of why the ZCAT approach is preferred here would be helpful.

Response: We distinguish **timing detection** from **energy accumulation** metrics. We use ZCAT to identify two within-year transition timings (CCT/CWT) directly from the cumulative temperature curve, whereas classical FDD/TDD are cumulative degree-day sums (°C-days) that quantify thermal energy accumulation but do not, on their own, define a unique transition date **without introducing an additional threshold or breakpoint rule.** For this reason, we retain ZCAT as the primary temperature-based timing detector in RiTiCE, and we will refer to FDD/TDD as complementary results for physical context rather than as replacement **timing** definitions. We will be using the following (Figure 7) for FDD/TDD analysis.

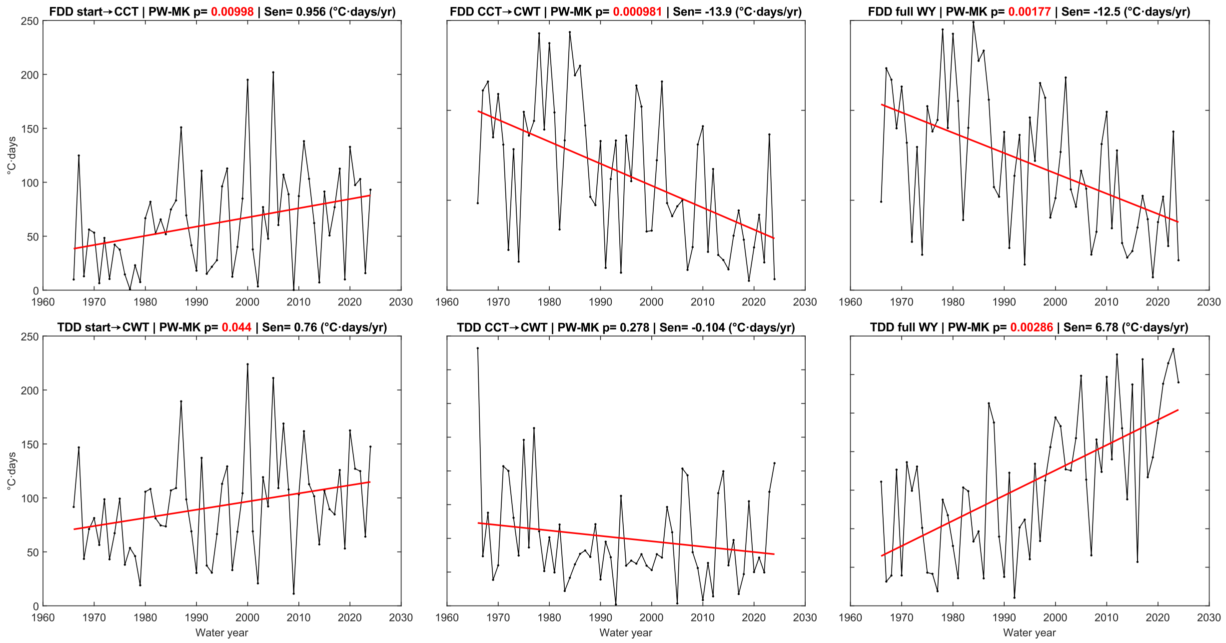


Figure 7 Trends on FDD and TDD.

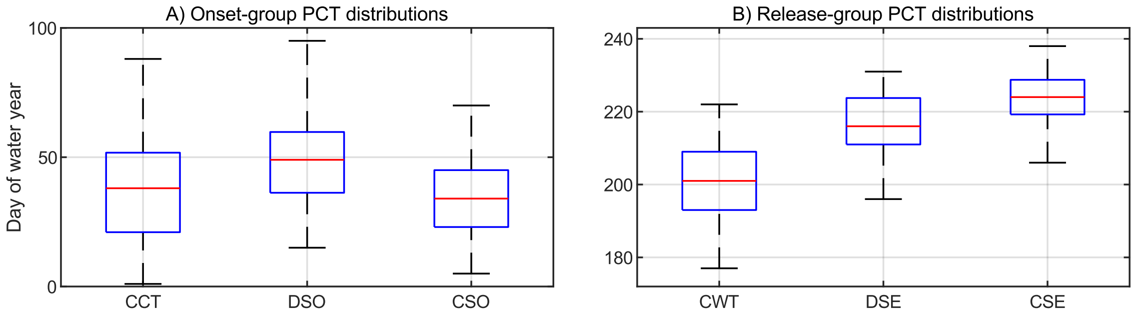
RC1: 15- Line 225: "The manuscript states that it provides "one of the most comprehensive long-term assessments". However, authors have already published related work in Water titled "RiTiCE: River Flow Timing Characteristics and Extremes in the Arctic Region", where the DVD method was developed and applied to 100-year discharge series in sub-Arctic rivers. I suggest softening the current claim to something like "a detailed 57-year assessment for a well-monitored sub-Arctic river".

Response: Thank you for your suggestion on reframing the claim. "most comprehensive" phrasing is too much to reflect the scope of this **site-specific study**, and we will rephrase the claim. The revised manuscript's Results section no longer opens with a scope claim.

RC1: 16- Line 228: Please explain why 1966 was chosen as the reference year. For example, is it simply the first year of the record, or was it selected because it is particularly representative?

Response: We agree and we should clarify that the reference year (1966) is indeed the first available water year in the observational record, and **it is not assumed to represent "typical" or stable cryo-hydrological conditions**. As year-to-year visualizations will be provided in the Appendix A, we will rework the sect. 3.1 to include the summary of full period and early vs late periods rather than reporting a single year. This will be addressed carefully in the revised manuscript as per your concern and RC2-13 & 15.

We will add the following full-period summary statistics for our timing results (Figure 8) in sect. 3.1, while keeping the complete year-by-year visualizations in Appendix A.



PCT	Mean ± SD	Median [p10–p90]	Min	Max
DSO	50.0 ± 17.5	49 [27–72]	15	95
DSE	216.3 ± 8.6	216 [205–226]	196	231
CSO	34.6 ± 14.4	34 [19–51]	5	70
CSE	223.5 ± 7.0	224 [214–233]	206	238
CCT	38.0 ± 20.9	38 [12–66]	1	88
CWT	200.3 ± 10.9	201 [184–214]	177	222

Figure 8 Full-period summary statistics for PCTs detected by RiTiCE for WY1966–WY2024.

In addition, we replace the single-year example (1966) with multi-year reference periods, including

(i) an early (WY1966–WY1994) versus recent (WY1995–WY2024) comparison (Figure 9), and

(ii) decade-binned distributions across the full record (Figure 10).

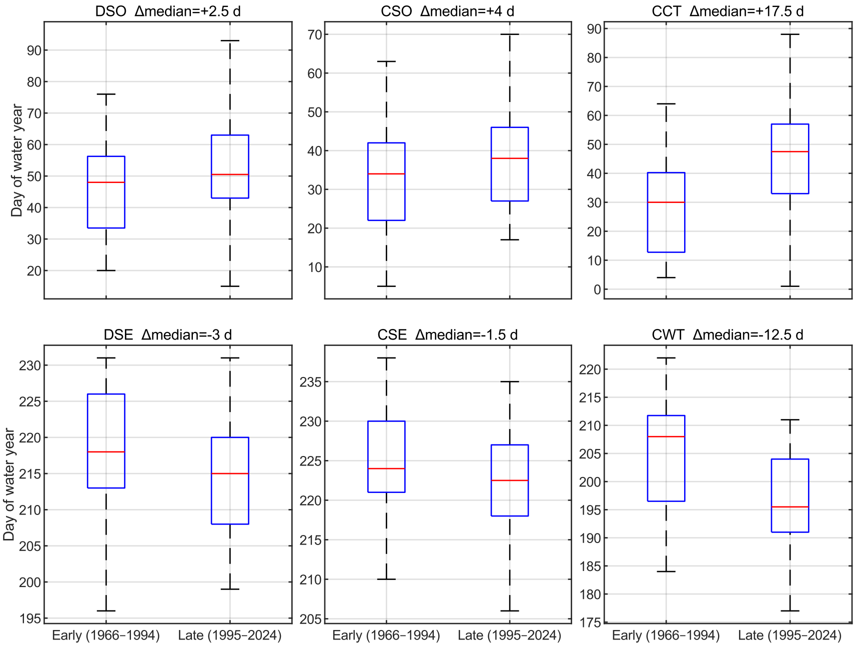


Figure 9 Early vs recent decade distributions of PCT timings. WY1966–WY1994 vs WY1995–WY2024.

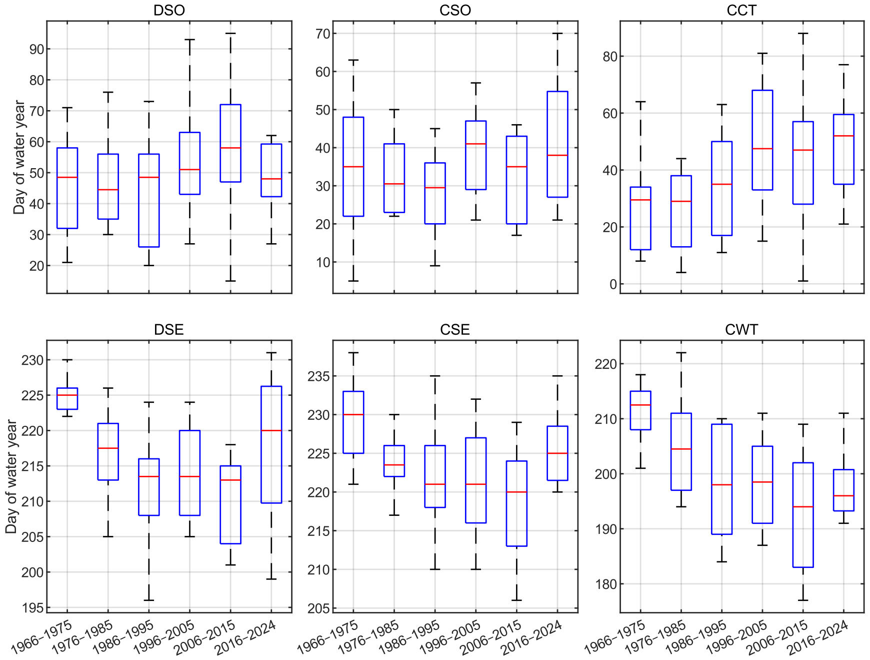


Figure 10 Decadal-scale distributions of PCT timings (day of water year) across the full record (WY1966–WY2024), shown as 10-year blocks (last block WY2016–WY2024 contains 9 years).

RC1: 17- Figure 9: The figure is not very clear in its current layout and would benefit from being rearranged or redrawn. In addition, important information is missing, such as the Sen slope and the Mann–Kendall p value for each variable.

Response: We agree and we will redraw the trend summary figure(s) to improve readability (layout, spacing, and font sizes). We also will add the missing statistical information to each panel. The layout in the revised manuscript will be as follows:

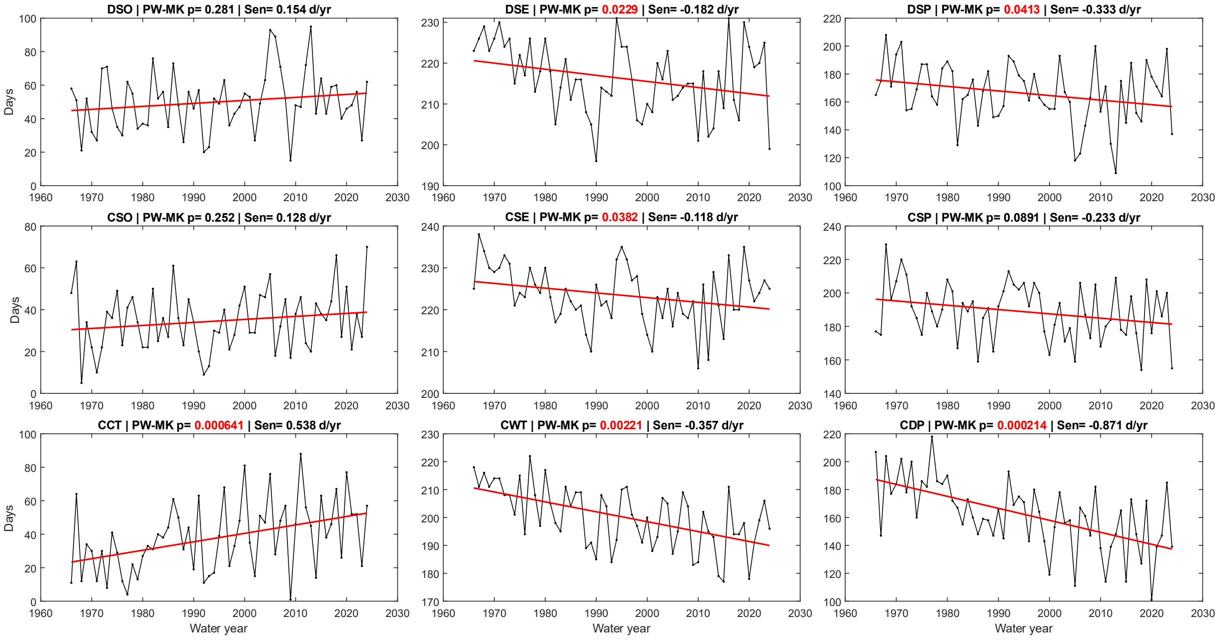


Figure 11 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

References

IAHR, 1980. International Association for Hydraulic Research Association. MULTILINGUAL ICE TERMINOLOGY. URL https://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVP/Reports/ice/iahr_ice_terminology.html (accessed 4.30.26).