egusphere-2025-2982: Author response to the Editor

Dear Dr. Kheyrollah Pour,

Thank you for handling our manuscript and for the constructive evaluations provided by both referees. We have revised the manuscript substantially in response to all of the comments raised.

The principal changes are as follows. The six detection timings and their derived intervals have been reframed and renamed as proxy-based transitions, so that they are no longer interpreted as direct observations of freeze-up, break-up, or snowmelt. The title and central narrative have been revised away from the loss-of-synchrony framing toward asymmetric, quantitatively supported shifts in transition timing. The record has been extended to 59 water years (WY1966 to WY2024). The single reference-year results have been replaced with full-period statistics and an early versus late comparison. Overstated statements have been removed or moderated, and all interpretation is now scoped to this single site. Research questions, freezing and thawing degree-day diagnostics, seasonal air-temperature trends, and independent observational context from ice-thickness and water-temperature records have been added. The original underlying dataset and detection algorithms are unchanged.

A point-by-point response to each referee follows below, with the reviewer comments in black and our responses in blue. We hope that the revised manuscript is now suitable for publication in The Cryosphere.

On behalf of all authors,

Abolfazl Jalali Shahrood

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."

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.

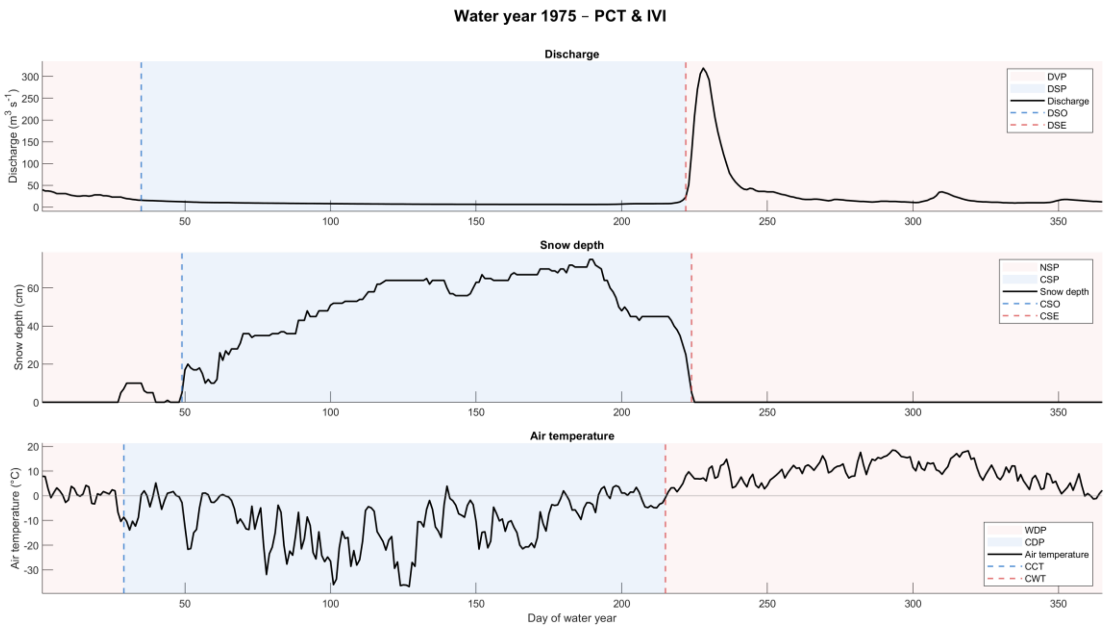


Figure 1 DSO precedes CSO.

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.

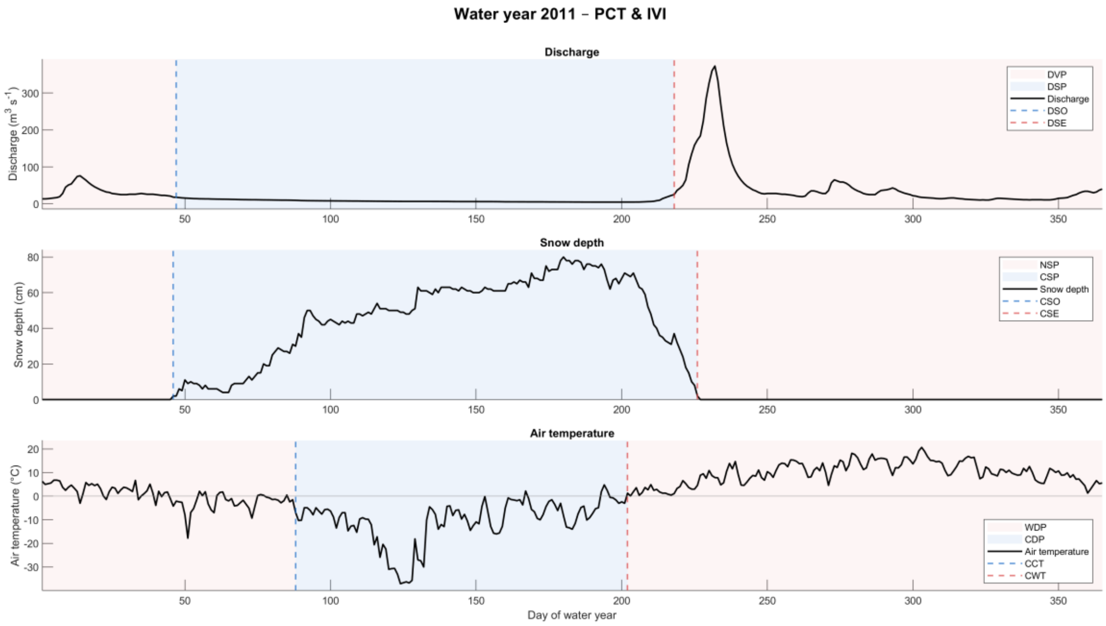


Figure 2 DSO and CSO almost at the same time while CCT delayed.

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.

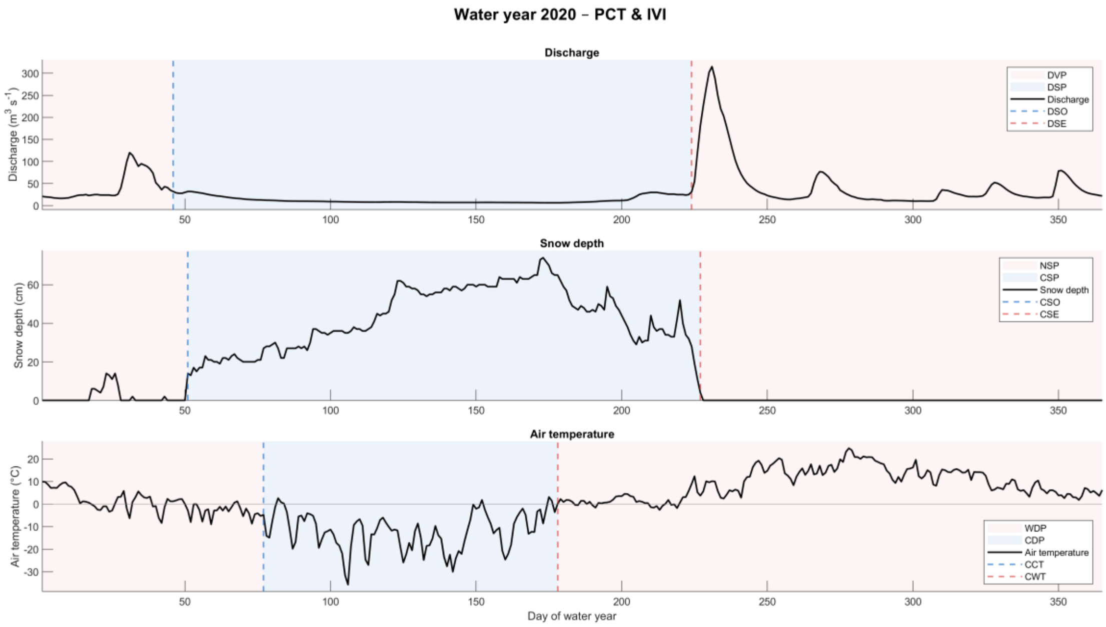


Figure 3 DSO precedes both CSO and CCT.

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 note 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).

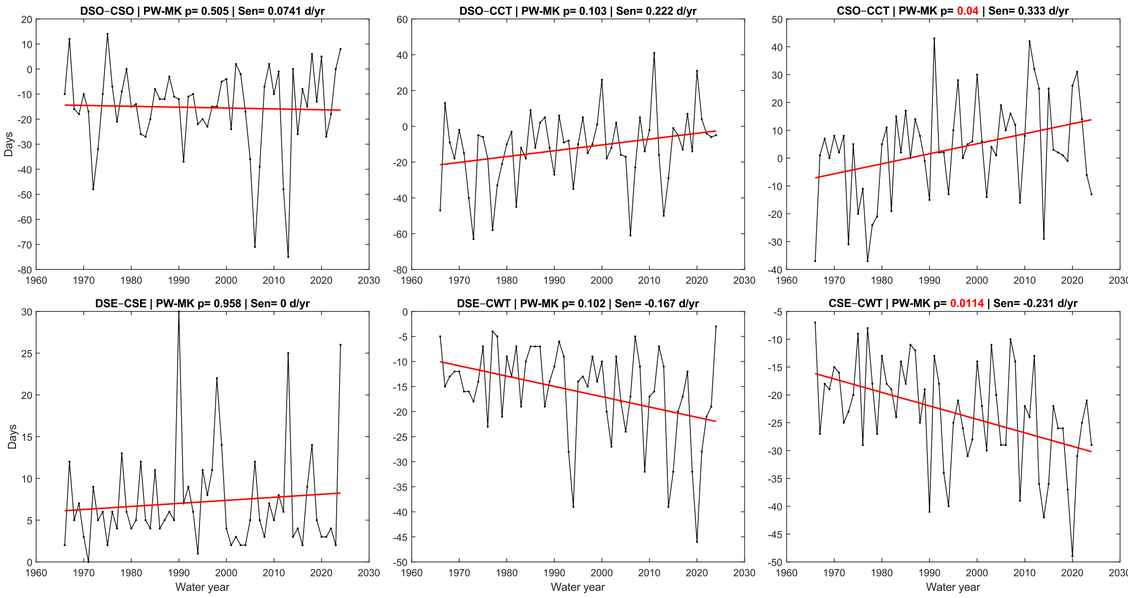


Figure 4 Cross-Variable Intervals (CVIs) showing the long-term trends in cross-variable timing offsets between PCT pairs (WY1966–WY2024; n=59). Significant trends (PW-MK $p<0.05$) are highlighted in red.

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.

<u>Specific comments:</u>

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.

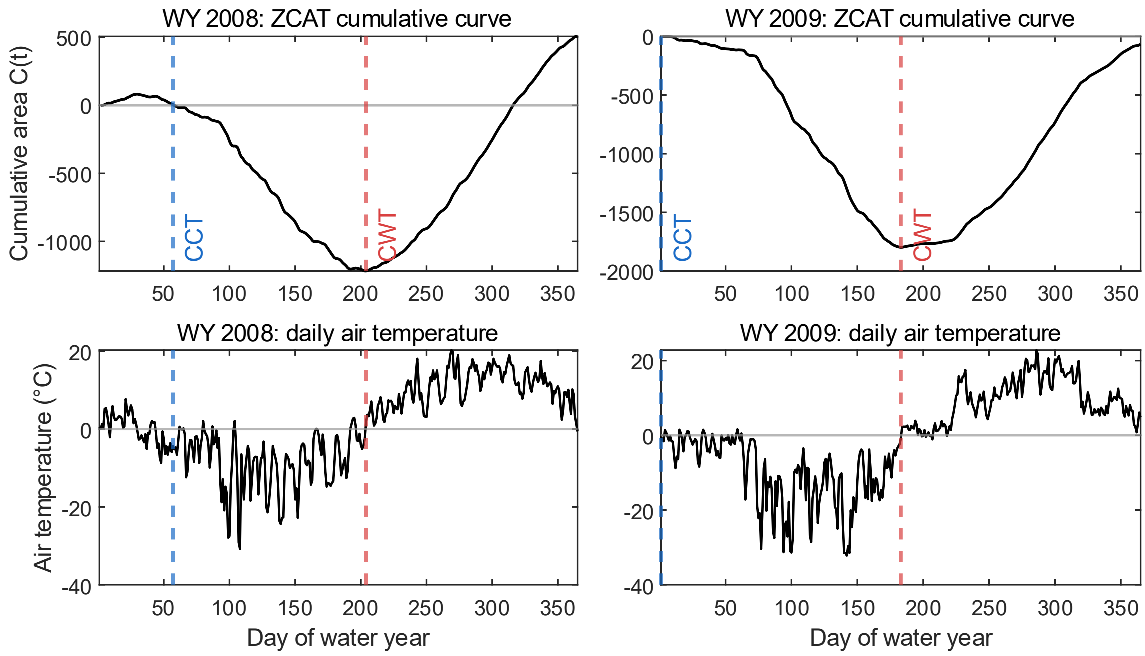


Figure 5 Single case of ZCAT method defaulting CCT to day 1 (1 OCT 2009), the actual CCT day is 30 Sep 2008.

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.

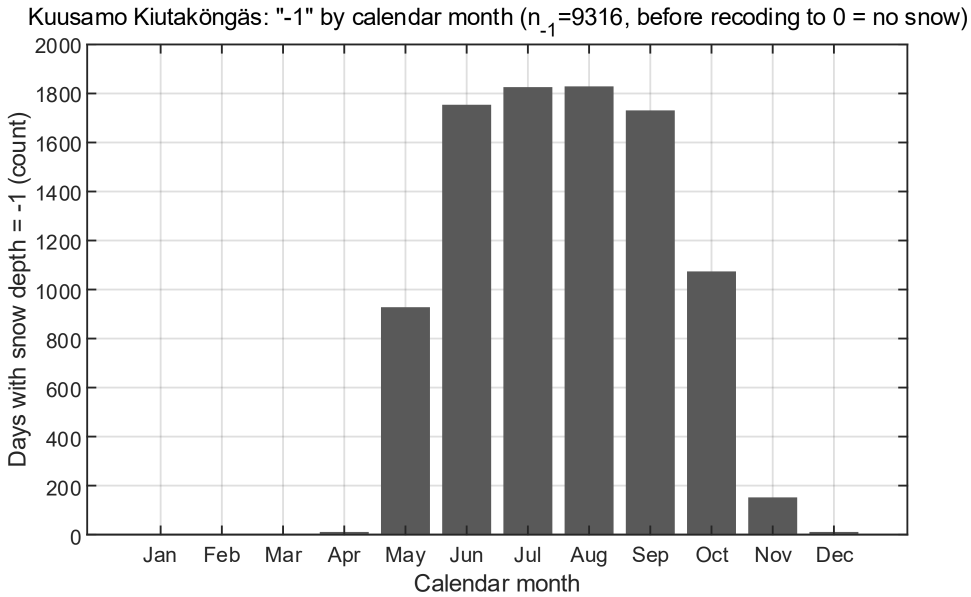


Figure 6 Monthly counts of FMI snow-depth codes −1 at Kuusamo Kiutaköngäs for the downloaded daily record, prior to setting −1 ⟶ 0 (no snow) for RiTiCE.

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.

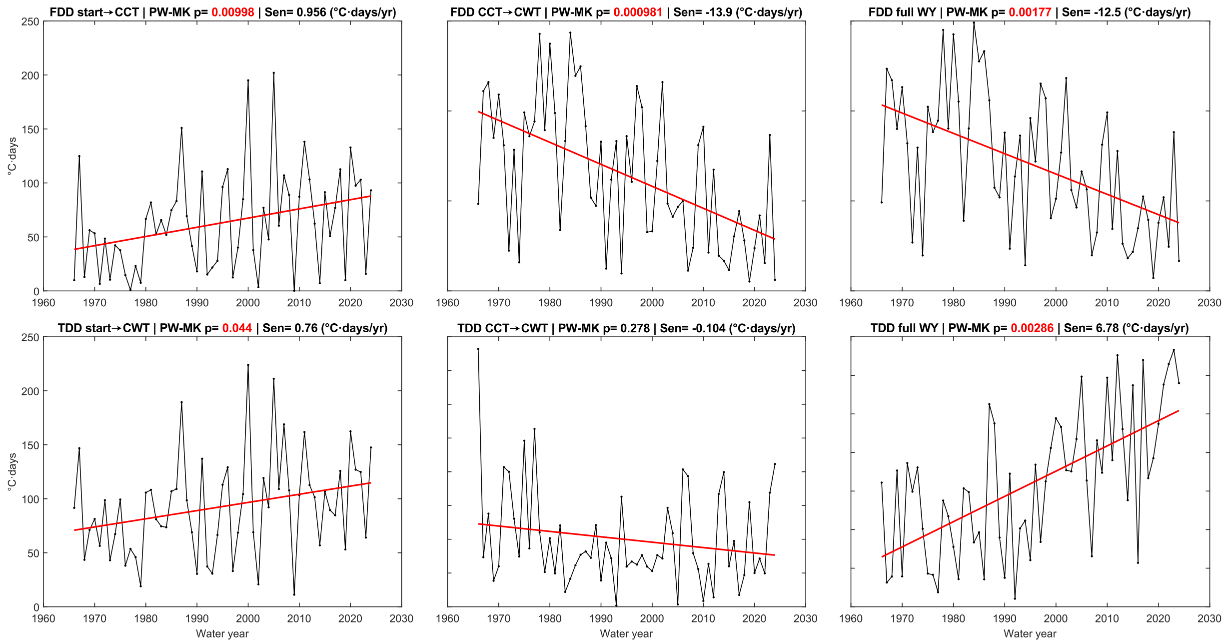


Figure 7 Trends on FDD and TDD.

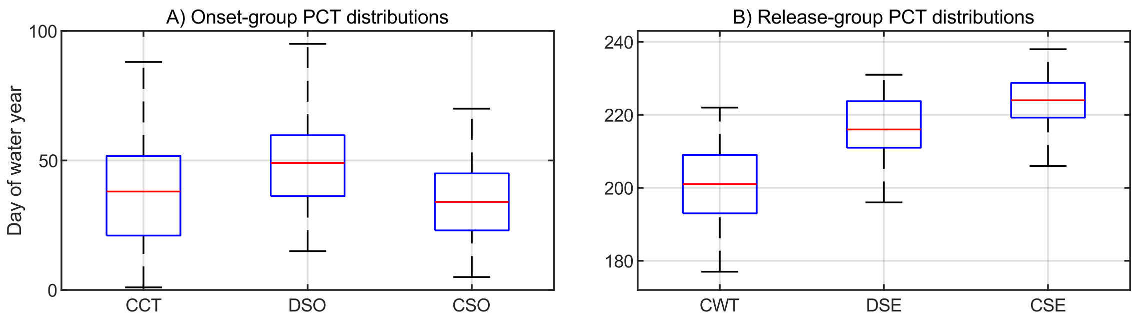
RC1: 15- Line 225: “The manuscript states that it provides “one of the most comprehensive long-term assessments”. However, authors have already published related work in Water titled “RiTiCE: River Flow Timing Characteristics and Extremes in the Arctic Region”, where the DVD method was developed and 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).

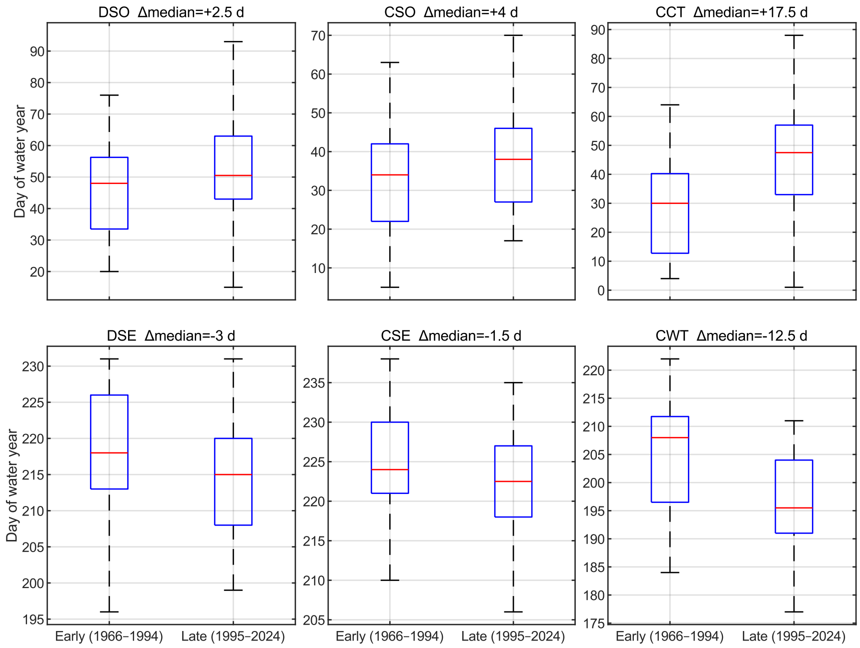


Figure 9 Early vs recent decade distributions of PCT timings. WY1966–WY1994 vs WY1995–WY2024.

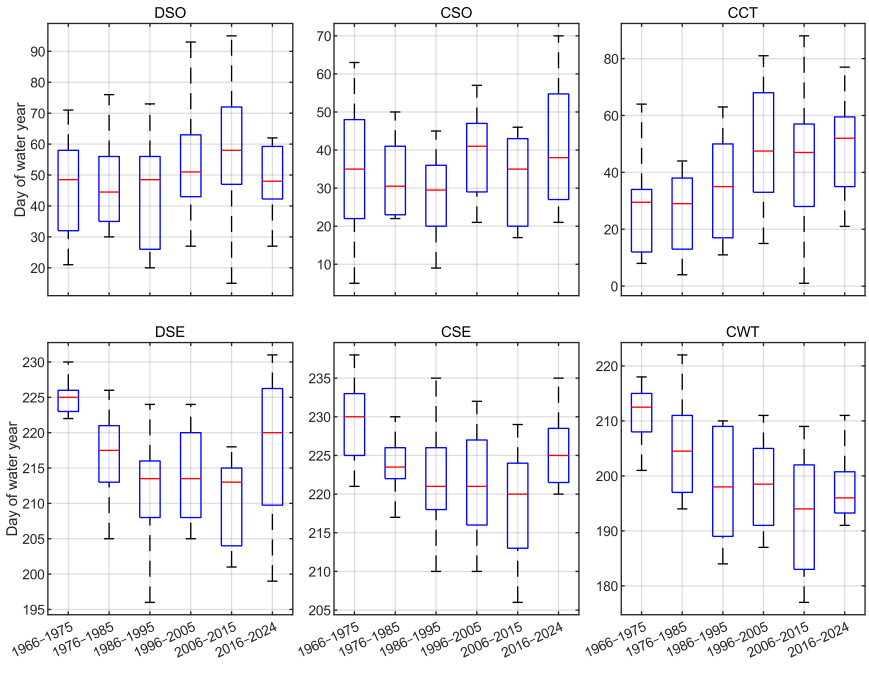


Figure 10 Decadal-scale distributions of PCT timings (day of water year) across the full record (WY1966–WY2024), shown as 10-year blocks (last block WY2016–WY2024 contains 9 years).

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:

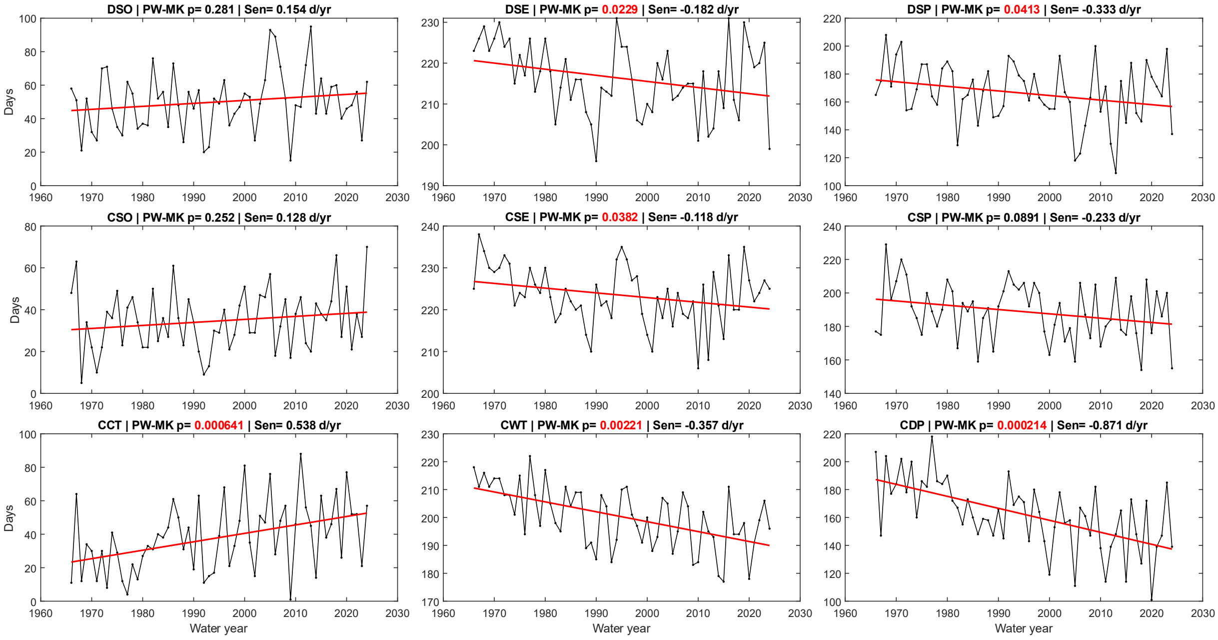


Figure 11 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

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).

egusphere-2025-2982: Responses to Anonymous Referee #2, 30 Mar 2026

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),

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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 title will be revised to “Asymmetric shifts in seasonal transition timing in a sub-Arctic river system under climate warming”

(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.

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(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 RC2'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.

RC2: The authors are commended for their work and analysis presented which made for an interesting read. The manuscript provides an analysis of a 57-year daily record (1966-2023) of the River Oulankajoki using a process-based detection tool building on the River Ice Timing Characteristics and Extremes (RiTiCE) tool previously developed by the Authors. Analysis presented is based on identified Phase Change Timing (PCT) features of freeze-up dates (FUD), break-up dates (BUD), snow-build up days (SBD), snow melting day (SMD), and two temperature transition point (TTP) metrics. The results highlight asymmetric seasonal changes to parameters, with those defining spring-based processes showing statistically significant trends relative to the selected baseline year of 1966. Several correlations were discussed amongst the PCT metrics. The results are of significance to the scientific community for understanding long-term trends in river ice processes in sub-arctic/arctic systems and fit within the scope of The Cryosphere. There are several concerns however regarding the presented results which warrant significant changes to the manuscript prior to publication.

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 4 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 5 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 6 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:

RC2: 1- The definitions of FUD and BUD based solely on discharge are problematic. While they may apply fairly well to this river system, the authors suggest a scalability of the RiTiCE framework, which, would may be problematic for rivers with frequent mid-winter freeze-thaw events, increases in discharge, or regulated rivers (e.g. hydropeaking). Further, under ice discharge values are notoriously challenging to accurately measure. It is unclear what post-processing methods (if any) have been used on the winter-time discharge data presented since 1966. Do the authors have visual ice phenology data for the river that can be used to compare to the discharge-based delineations?

Response: In the revised manuscript, this will be addressed in three ways:

1- Terminology and interpretation

We explicitly adopt proxy-oriented terminology and redefine DSO/DSE (previously referred to as FUD/BUD) as discharge regime transition proxies, rather than visual ice phenology dates. We clarify that all PCTs (DSO/DSE, CSO/CSE, CCT/CWT) represent transition markers in their respective variables, not direct observations of freeze-up or break-up.

2- Limitations and data provenance

We add a clear limitation statement regarding uncertainty in under-ice discharge measurements, We also clarify the processing metadata availability of the discharge record used in this study. Additionally, in the "Discussion" we will clarify the limitation of RiTiCE on regulated regimes.

3- Independent observational context

As there is no available freeze-up/break-up record for the Oulankajoki, we incorporate an analysis using available independent observations from the same station:

(i) Ice thickness measurement records (limited overlap period, WY1980–WY1994), which represents periods when ice conditions were sufficient and possibly safe for field observations,

(ii) Water temperature data (WY1970-WY2024), which contains a recurring winter measurement gap.

We do not treat datasets as true ice records, but as operational / observational proxies of ice presence. We will provide a supporting diagnostic (Figure 1) that quantifies their temporal relationship (timings) with our PCTs.

Based on these data, onset of ice measurement window is mostly after discharge stabilizes (DSO – legacy Freeze-Up Day FUD), continuous snow onset (CSO – legacy Snow Build-up Day SBD), and Cumulative Cooling Transition (CCT – legacy TTP-). While the end of ice measurement window is before DSE (legacy Break-Up Day BUD), CSE (legacy SMD), and around the time of Cumulative Warming Transition (CWT – legacy TTP+). Similarly, the start and end of the winter gap in water temperature measurements generally delineate the cold season. The gap start tends to occur slightly before DSO, around CCT and CSO, while the gap end tends to occur near DSE and CSE and after CWT. We will address these results in the main text and move the visualization to the supplements.

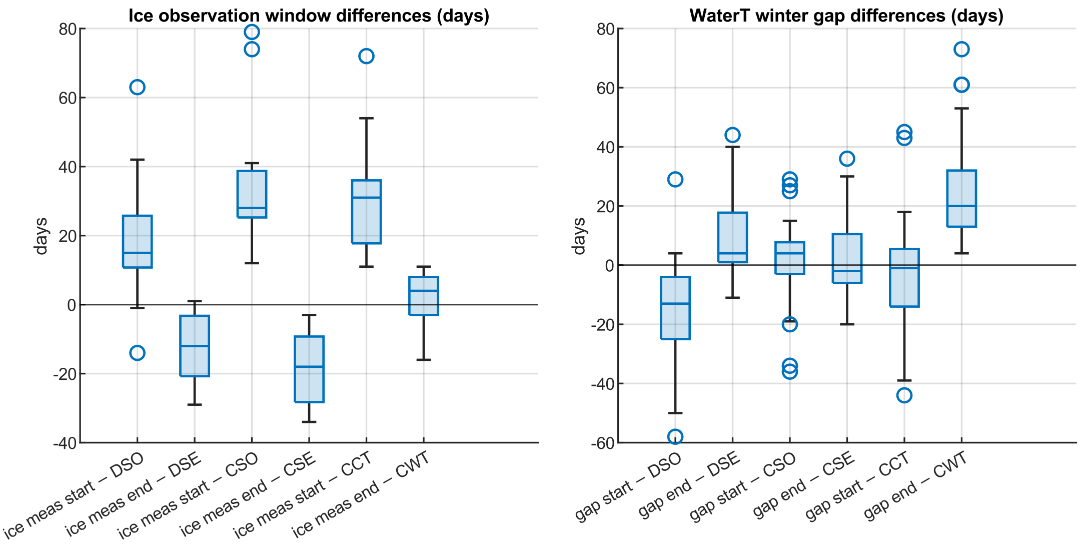


Figure 12 Differences between independent observation windows and proxy timings. (A) Distributions of timing differences (days) between ice observation start/end and proxy timings (PCTs: DSO/DSE, CSO/CSE, CCT/CWT) for years with ice measurement data (n=15). (B) Distributions of timing differences between the winter data-gap endpoints in water temperature (gap start/end) and PCTs for available years (n=55).

RC2: 2- The authors do not need to reintroduce acronyms in each section. They should be introduced once and used thereafter. Figures are often confusing to understand. Figures should always be introduced in text before they appear- this was missing for several figures.

Response: In the revised manuscript we streamline acronym usage by defining acronyms once (at first use; except for headings and captions) and we will use them without repeated re-introduction. We will also improve figure readability by ensuring that each figure is introduced and briefly explained in the text before it appears.

RC2: 3- Section 3.2 is confusing. It is unclear what is meant by ranks and order and how the presented figure and analysis follow the presented claim: "A central finding of this study is the

asymmetry between spring and autumn transitions. The sequence of seasonal cryo-hydrological features revealed a clear separation between early- and late-year events (Fig. 7).”

Response: We will rework the Fig. 7 in the discussion manuscript to better convey the meaning of asymmetry between onset-group transitions and those in release-group (Figure 2).

We will revise Sect. 3.2 to define rank and order explicitly. For each water year, the six PCT markers (CCT, CSO, DSO, CWT, DSE, CSE) are sorted by day-of-water-year; the earliest event is assigned rank 1 and the latest rank 6. The order refers to the resulting within-year sequence (e.g., CSO → CCT → DSO). The revised figure is reworked to show (i) the frequency of dominant order patterns for full period (ii) the frequency of dominant order patterns for early vs late, separately for the onset-group (CCT/CSO/DSO) and the release-group (CWT/DSE/CSE) (iii) and year-to-year ranking.

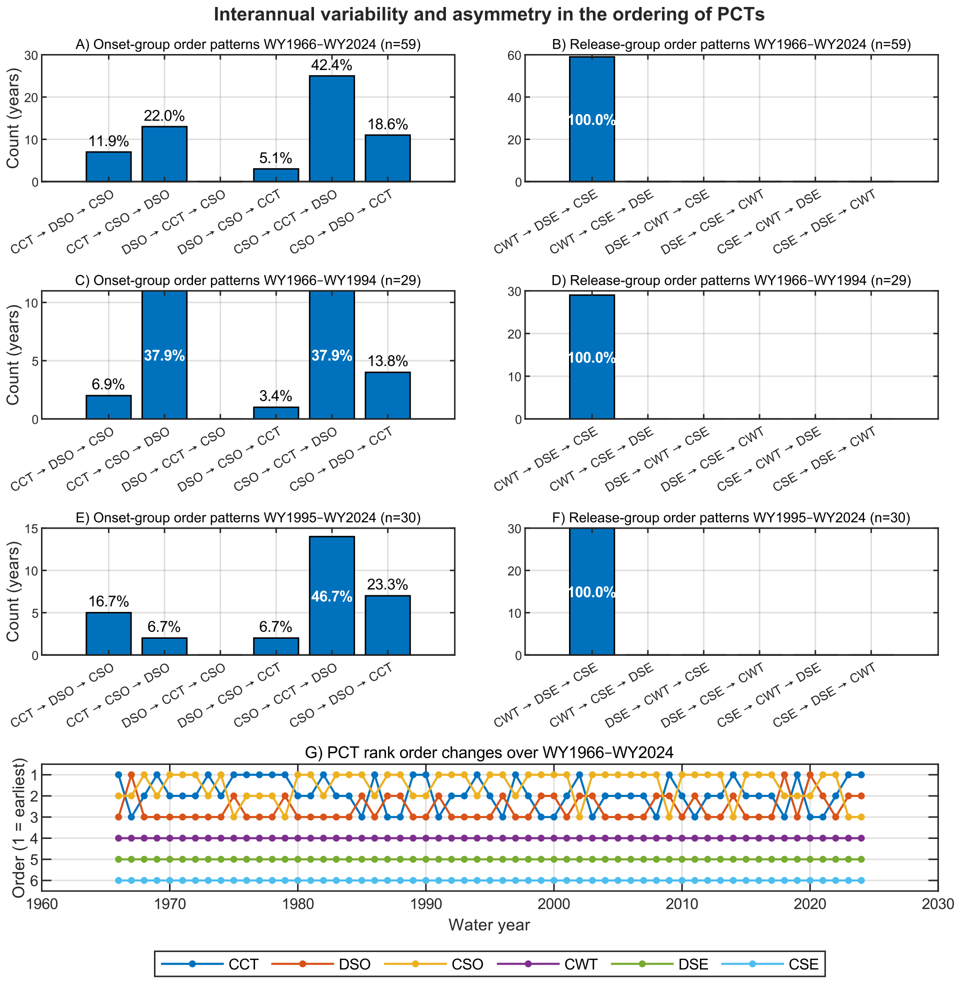


Figure 13 Seasonal sequencing asymmetry of PCT proxies (WY 1966–2024; n=59): (Top) PCT timing distributions, (Middle-left) onset-cluster order-pattern frequencies (CCT–DSO–CSO), (Middle-right) spring release order-pattern frequencies (CWT–DSE–CSE), and (Bottom) year-to-year rank order changes.

RC2: 4- Results need to be better contextualized. One gauge station is used to represent a moderately sized river system with decently large basin. This should be considered when asserting conclusions and attempting to generalize to larger Arctic and sub-arctic river systems.

Response: We agree and we will explicitly frame our conclusions as **site-specific** to the Oulankajoki River and moderate any statements that imply direct extrapolation to larger Arctic/sub-Arctic rivers.

RC2: 5- Several large claims are made throughout the paper which, in my opinion, are not justified based on the results presented. Examples include L324, L334-335, L350-351, and L369-370. On the latter: the results presented in the study do not support a "fundamentally reorganized" cryo-hydrological system" as the authors' argue.

Response: We agree that some statements in the discussion manuscript overstate the scope of what can be concluded from the presented results, although durations of IVIs and timing of some PCTs show statistically meaningful changes over the study period (Figure 3). For instance, statistically significant trends for DSP (legacy ice cover), CDP (legacy cold season), and CSE-CWT (legacy snowmelt) are what stated in L324 in discussion manuscript. However, we agree with RC2 that if we frame it as "we have found evidence of a broader redistribution of seasonal durations" it might be a large claim. Instead, we will frame the results more narrowly as statistically supported trends in a limited set of timing and duration metrics (PCTs and IVIs) within our proxy framework. We will report these changes metric-by-metric (with Sen slopes and PW-MK p-values) and interpret them as changes in particular components of the seasonal cycle, without claiming a uniform or basin-wide redistribution of seasonal durations.

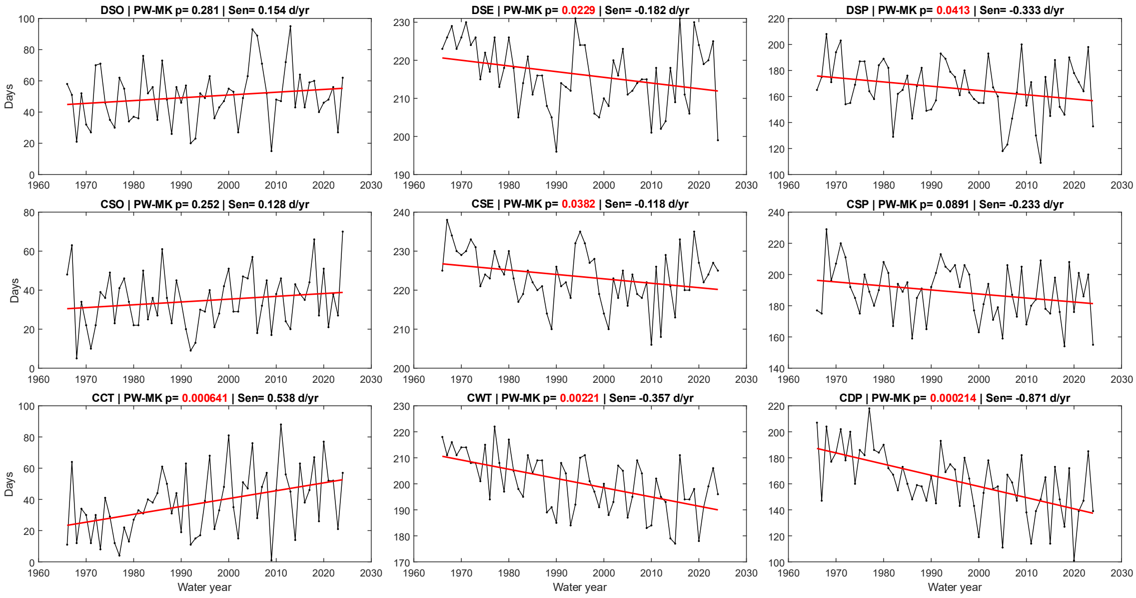


Figure 14 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

L350-351 in discussion manuscript was overly speculative and not directly supported by the analyses presented in this manuscript. We will therefore remove this sentence and revise the surrounding discussion to limit interpretation to what our results demonstrate.

L369-370: We agree that our wording ("fundamentally reorganized") was too strong relative to what is supported by the presented analyses. We therefore remove this statement to avoid implying a system-wide reorganization. In the revised manuscript we describe the results more narrowly as statistically supported changes in selected timing (PCT), duration (IVI), and timing offsets between variables (CVIs).

RC2: 6- The title has too much jargon and is inappropriate for the presented analysis. It is recommended to just use "Loss of Seasonal Synchrony in a Sub-Arctic River System Under Warming Climate" or something similar.

Response: Thank you for your suggestion. We agree with the fact that the title should be clearer. Based on RC1: 6- the "loss of synchrony" is not supported. In the revised manuscript we will revise the title to “Asymmetric shifts in seasonal transition timing in a sub-Arctic river system under climate warming”.

Specific comments:

RC2: 7- L95: The scalability of “RiTiCE” is questionable for regions that experience mid-winter melting and increased discharge using the given definitions of the metrics for BUDs and FUDs, SMD and SBD, and TTP+/-.

Response: RC2 is right and we agree. The proxy definitions used here are most appropriate for systems without frequent mid-winter melt-driven discharge increases and without strong regulation/hydropeaking as RC2 suggested. In the revised manuscript we will moderate the scalability language and will add a limitation statement. We will also frame RiTiCE as rule-based framework (as RC1 recommended).

RC2: 8- L122-124: “Instead, BUD refers explicitly to the timing of the river ice break-up day which is defined as the day when the river’s flow begins to rise after a long period of low and stable discharge, corresponding to the start of ice break-up and the transition toward spring flow conditions”. This would only apply to a particular subset of unregulated rivers in which mid-winter increases in discharge (or hydropeaking in the regulated case) are not expected. Your statements on L212-215 regarding shifting seasonality in discharge values point to potential problems in defining your metrics in the approach outlined.

Response: We agree that based on what has been cited in L212-215 can reduce the prevalence of a uniquely “stable winter discharge” period in some years. We hereby clarify that the DVD-based PCTs (DSO/DSE) identify the **boundaries** of the longest relatively low (based on SD) day-to-day discharge variability segment within each water year, rather than assuming an invariant winter low-flow regime. In years with more winter runoff events, this segment may be shorter, and its physical interpretation may be less specific, which we acknowledge as a limitation for RiTiCE. Nevertheless, the method remains useful for quantifying within-year regime structure consistently through time using the same objective rule.

RC2: 9- L130- DVD used as daily variation in discharge but is defined as Daily Value Difference elsewhere. Additionally, is the discharge used in this study the mean daily or max daily? What about post-processing corrections?

Response: In the revised manuscript we will use consistent terminology for DVD (Daily Value Difference) throughout.

The discharge data used in this study are **mean** daily discharge values obtained from the Finnish Environment Institute (Hertta system) (SYKE, 2026), discharge from water level measurements via rating curve. During winter conditions, these values are subject to standard operational post-processing corrections to account for rating curve limitations. Most winter-time discharge values in Hertta are flagged as 'Redukoitu' (quality code '=') meaning “reduced”.

Therefore, we acknowledge that winter discharge values are not purely raw observations but estimates derived through corrections. This means part of the winter low-variability signal is already embedded in the dataset prior to applying the DVD method. A limitation of this approach is that the derived DSO/DSE timings are partly influenced by the underlying correction procedures. Accordingly, they are interpreted in this study as discharge regime transition proxies, not direct observations of ice phenology.

The consistency of timing shifts across independent variables, including air temperature (CCT, CWT) and snow-based metrics (CSO, CSE), supports that the observed patterns are not solely artifacts of discharge correction procedures.

Therefore, the data from Hertta system is only leap year corrected and organized by water year for RiTiCE input. We do not apply additional winter-time post-processing beyond what is provided in the source record.

RC2: 10- DVD definition: perhaps instead of the standard deviation, a more robust metric such as an IQR or 75th percentile could be used to handle distribution skewness.

Response: Thank you for your suggestion. We tested an alternative threshold while keeping the DVD logic unchanged. We replaced the SD-based stability threshold with an IQR-based spread estimate (IQR/1.349).

For the Oulankajoki record this IQR-based threshold is much smaller than the SD threshold (median ratio = 0.055, n=59), which makes the stability criterion far stricter and causes large timing shifts (median DSO shift = +91 days; median DSE shift = −7 days). The DSO timing changes drastically under the IQR threshold, as shown in Table 4.

Table 7 Seasonal distribution (counts) of discharge-based transition timings detected using the standard-deviation versus IQR/1.349 DVD stability thresholds (WY1966–WY2024; n=59).

Method	Oct–Nov	Dec–Jan	Feb–Mar	Apr–May	Jun–Sep
SD-based DSO	45	14	0	0	0
IQR-based DSO	1	20	35	3	0
SD-based DSE	0	0	0	59	0
IQR-based DSE	0	0	1	58	0

Because this alternative materially changes what “stable discharge” represents and substantially alters DSO/DSE, we retain the SD-based definition for consistency, but we will add an explicit limitation noting the dependency of DSO/DSE on the threshold choice.

RC2: 11- Section 2.5- what is the advantage here of using a “Zero-Referenced Cumulative Area Transition (ZCAT)” rather than a traditional Cumulative freezing degree days approach but correcting for temperatures greater than 0°C? It is confusing why a new metric needed to be defined here.

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 for FDD/TDD analysis.

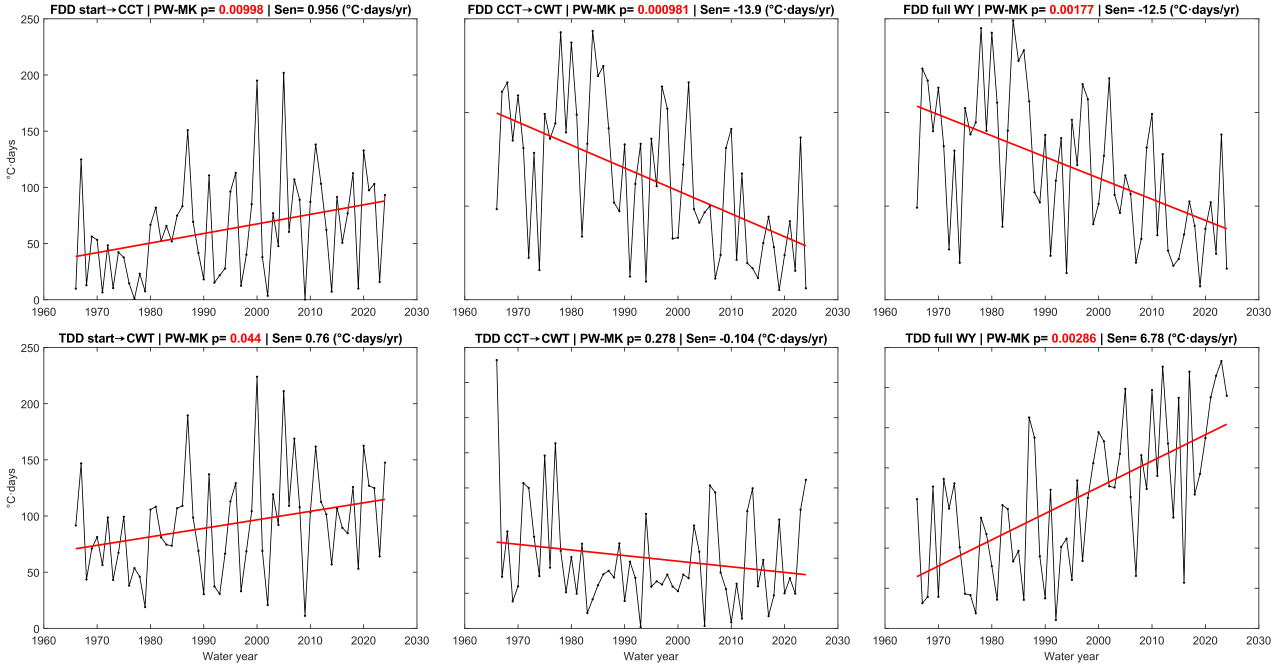


Figure 15 Trends on FDD and TDD.

RC2: 12- L227- remove brackets for PCT

Response: Correct. We remove the unnecessary bracket.

RC2: 13- L228-229: I would suggest rephrasing the sentence "The 1966 reference…" It has not been shown in this study that 1966 conditions were under stable cryo-hydrological conditions. The 1966 year is simply used as a baseline and should be treated as such without generalization.

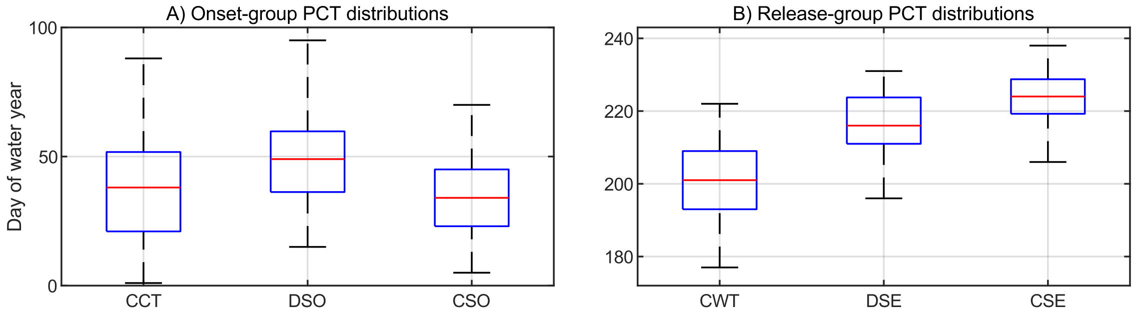
Response: We agree and we should clarify that the reference year (1966) is simply the first available water year in the observational record, and **it is not assumed to represent "typical" or stable cryo-hydrological conditions**. As year-to-year visualizations will be provided in the Appendix A, we 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 RC1-16. Please see RC2: 15- for broader response.

RC2: 14- L231- "These results…" Provide references for this statement.

Response: Multiple river and lake studies explicitly document later freeze-up, and earlier spring melt (breakup) as a long-term trend (Fukś, 2023; Newton and Mullan, 2021; Podkowa et al., 2023; Sharma et al., 2016; Wang and Feng, 2024). We will move this line to the discussion and provide references accordingly.

RC2: 15- L240: No specifics are presented for the full period. The reader simply points to "full-year characterizations for all 57 years are provided in Appendix A." Include a brief description of the full period in the text. For example, what was the average FUD, BUD, SMD, etc. To strengthen section 3.1, it is perhaps more prudent to use a reference period (e.g. 5-10 years) rather than one particular year which may have conditions outside the climate normal.

Response: We will add the following full-period summary statistics for our timing results (Figure 5) 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 16 Full-period summary statistics for PCTs detected by RiTiCE for water year 1966–2024.

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

(i) an early (1966–1994) versus recent (1995–2024) comparison (Figure 6), and

(ii) decade-binned distributions across the full record (Figure 7).

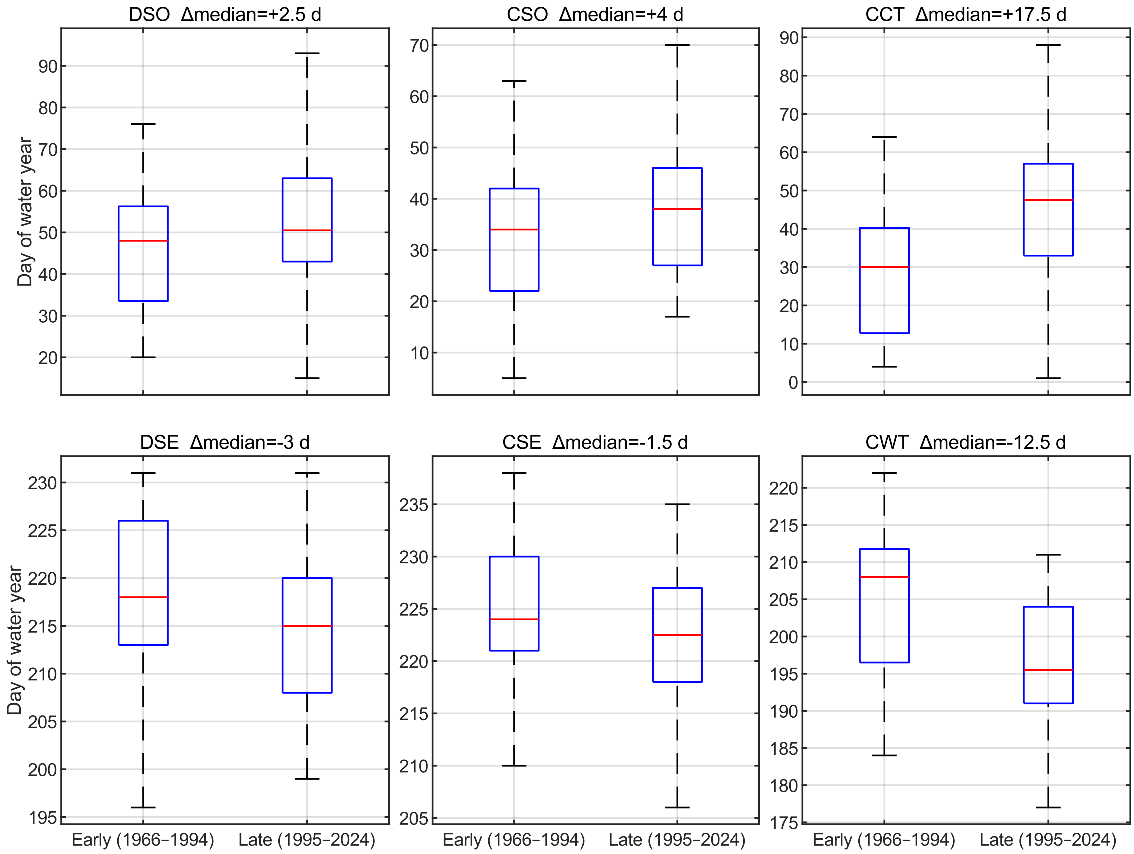


Figure 17 Early vs recent decade distributions of PCT timings. WY1966–1994 (n=29) vs WY1995–2024 (n=30).

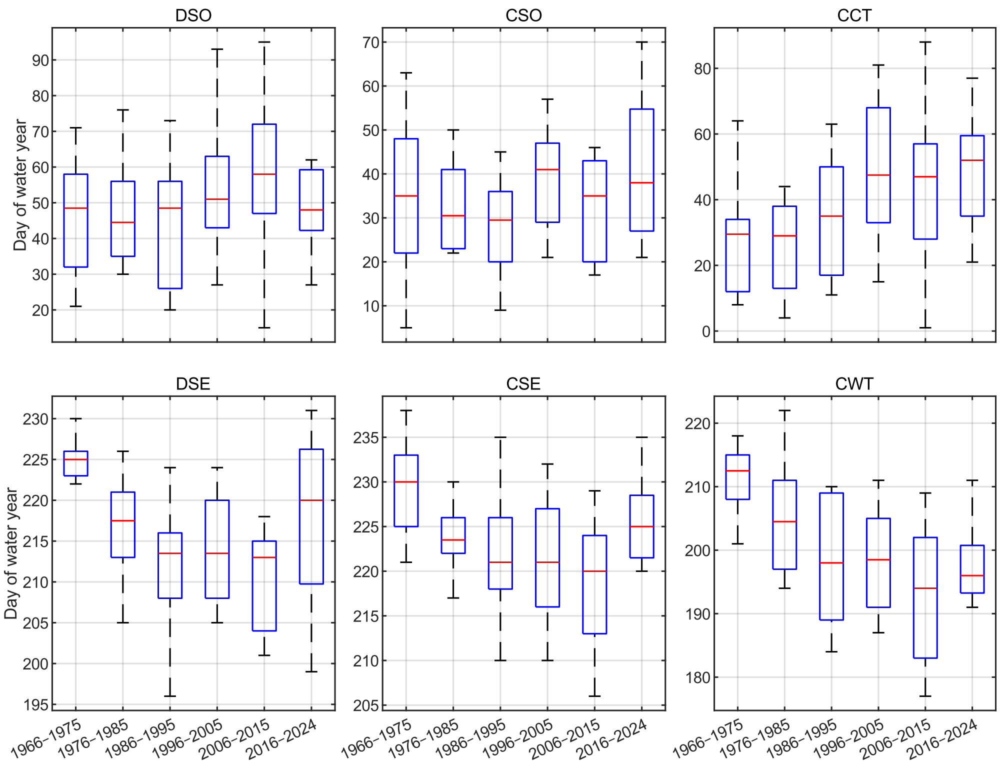


Figure 18 Decadal-scale distributions of PCT timings (day of water year) across the full record (WY 1966–2024), shown as 10-year blocks (last block 2016–2024).

RC2: 16- L295- It is interesting how your BUD, SMD, and TTPs showed statistically significant trends but your air temperatures did not (discussed on L293-296). How do you explain this? Perhaps looking at monthly air temperature trends for the should periods of freeze-up and break-up would show significant trends, as has been shown elsewhere in the literature.

Response: Our statistically significant results are for **timing metrics** (day-of-water-year), whereas the statement that "air temperature did not trend" referred to annual extreme values (°C).

We now add FDD/TDD diagnostics and trends. In addition, following your suggestion, we analyze seasonal mean air-temperature trends. We find significant warming in both Oct–Dec (Sen = 0.066 °C/yr; PW-MK p = 0.0011) and Mar–May (Sen = 0.037 °C/yr; PW-MK p = 0.0076). These results are shown below, and we will add it to the revised manuscript.

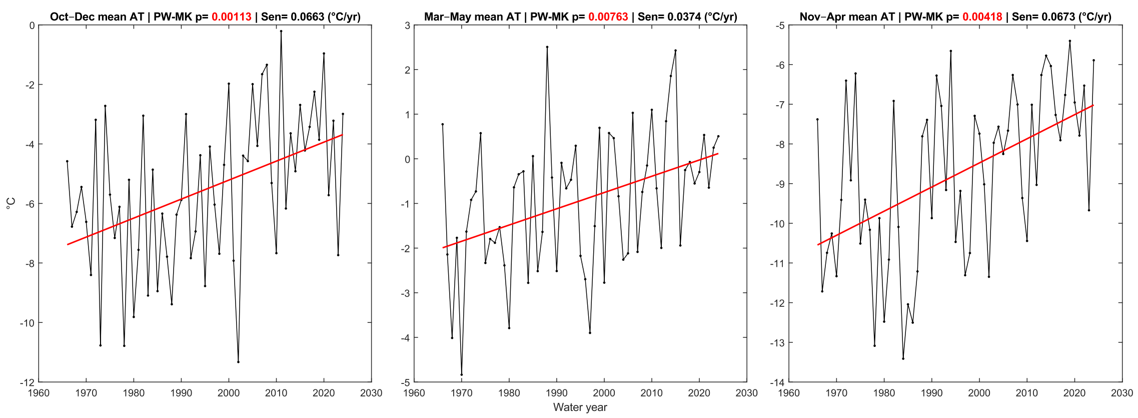


Figure 19 Trends on seasonal mean air temperature.

RC2: 17- Figure 9 is rather difficult to read. Text is too small and trends are difficult to interpret.

Response: We improve the readability of this figure in the revised manuscript with a better layout. Example layout as follows (Figure 9).

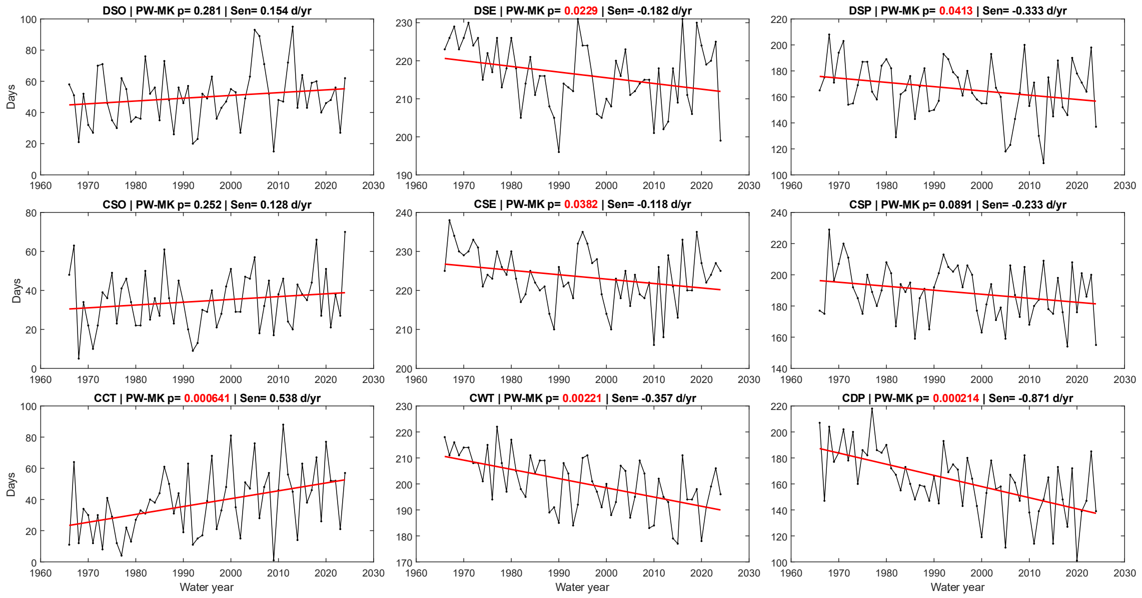


Figure 20 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

RC2: 18- L312-313: You state that spring PCT metric trends are from consistent warming, but your air temperature trends do not agree with this statement. Please explain this claim (see previous comment also).

Response: Our statistically significant results are for **timing metrics** (day-of-water-year), while the "air temperature did not trend" statement refers to extreme (max/min) annual temperature values (°C). We add FDD and TDD as well as seasonal air temperature trends to the study.

RC2: 19- L350-351: The results presented from one gauged station (presented here) cannot be extrapolated to speculate on most sub-Arctic systems.

Response: We agree and will limit extrapolation and clearly state the study's scope.

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