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),

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 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.

(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 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 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:

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.

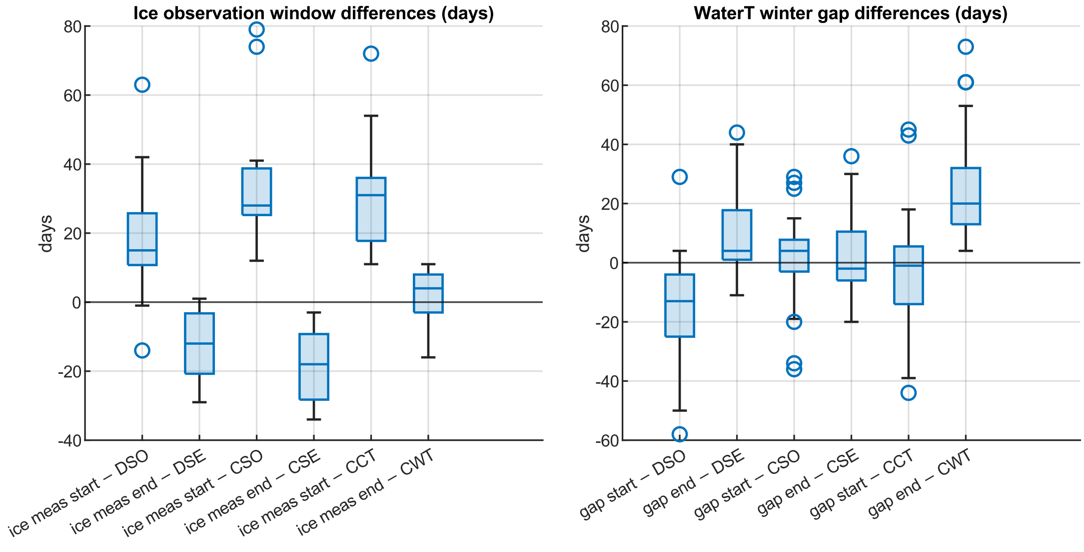


Figure 1 Differences between independent observation windows and proxy timings. (A) Distributions of timing differences (days) between ice observation start/end and proxy timings (PCTs: DSO/DSE, CSO/CSE, CCT/CWT) for years with ice measurement data (n=15). (B) Distributions of timing differences between 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.

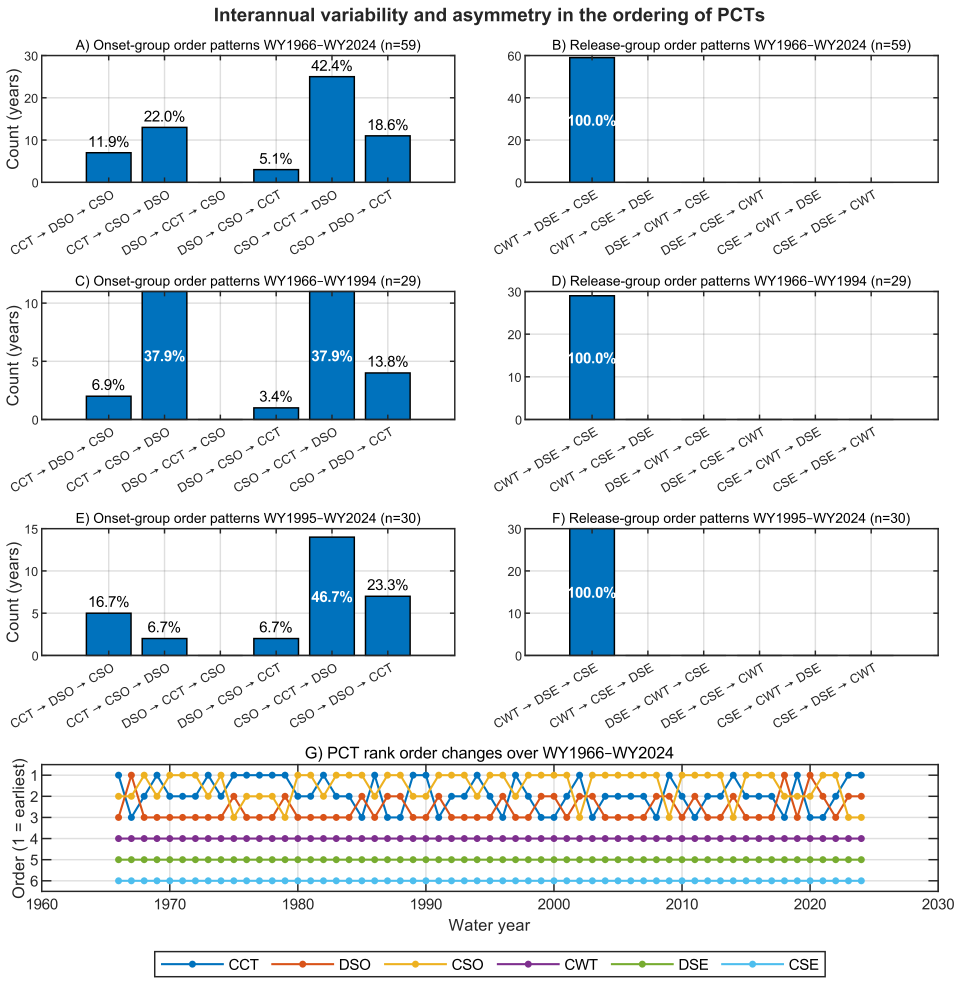


Figure 2 Seasonal sequencing asymmetry of PCT proxies (WY 1966–2024; n=59): (Top) PCT timing distributions, (Middle-left) onset-cluster order-pattern frequencies (CCT–DSO–CSO), (Middle-right) spring release order-pattern frequencies (CWT–DSE–CSE), and (Bottom) year-to-year rank order changes.

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.

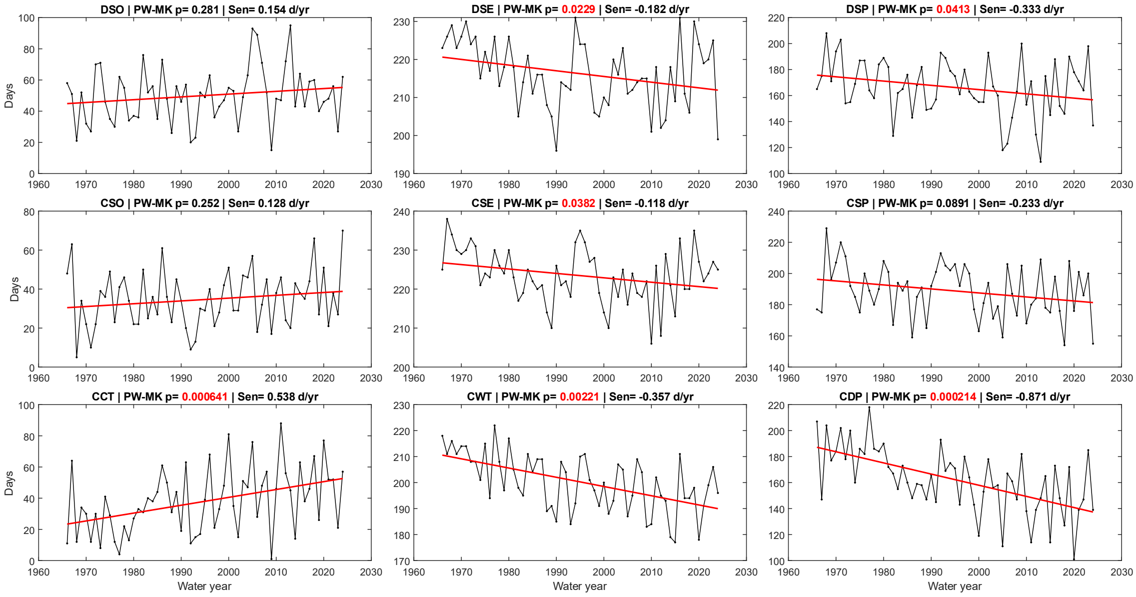


Figure 3 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

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 4 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.

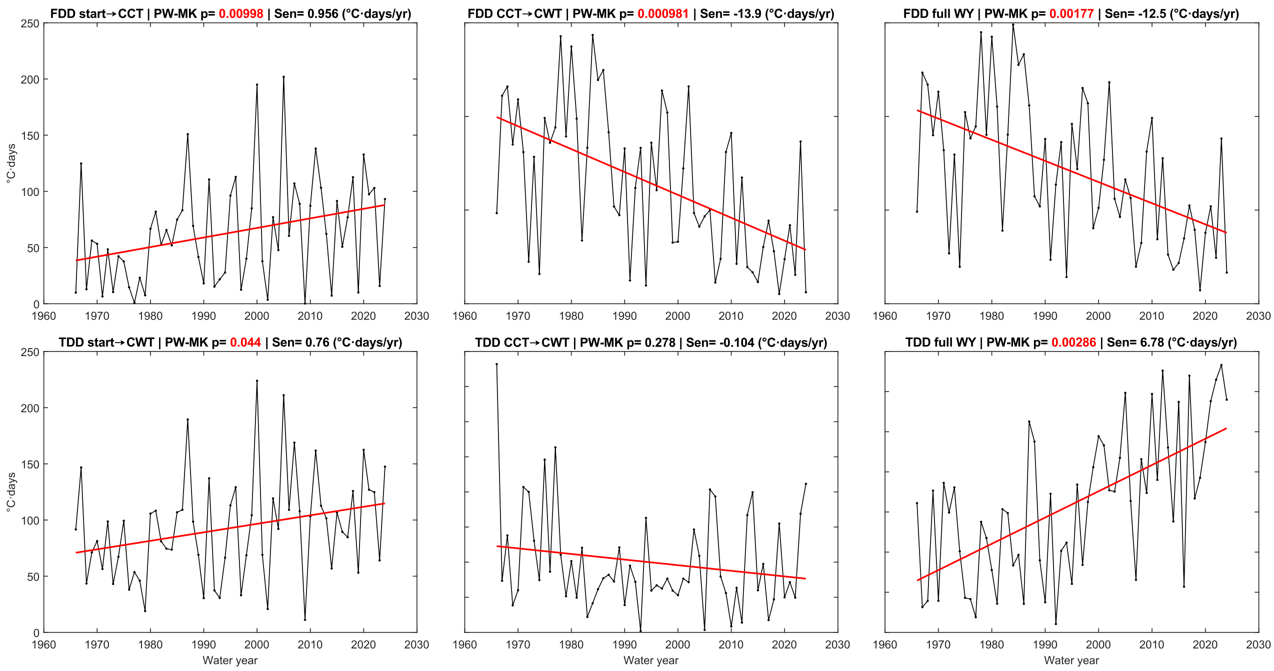


Figure 4 Trends on FDD and TDD.

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.

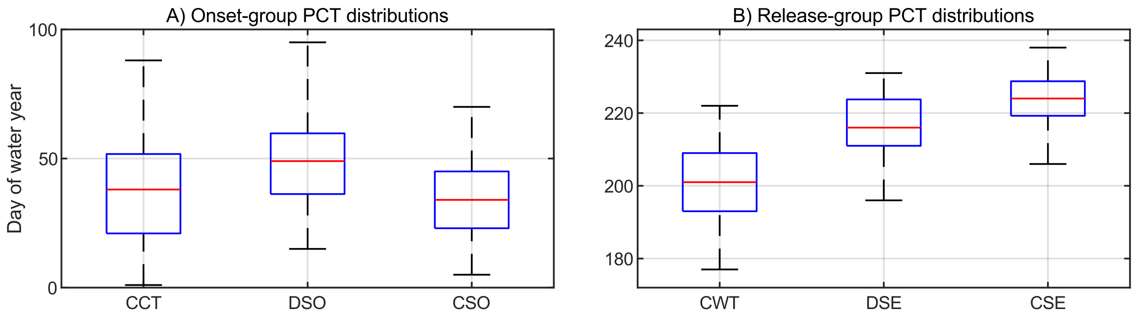
Response: We agree and we should clarify that the reference year (1966) is simply the first available water year in the observational record, and **it is not assumed to represent "typical" or stable cryo-hydrological conditions**. As year-to-year visualizations will be provided in the Appendix A, we 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 5 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).

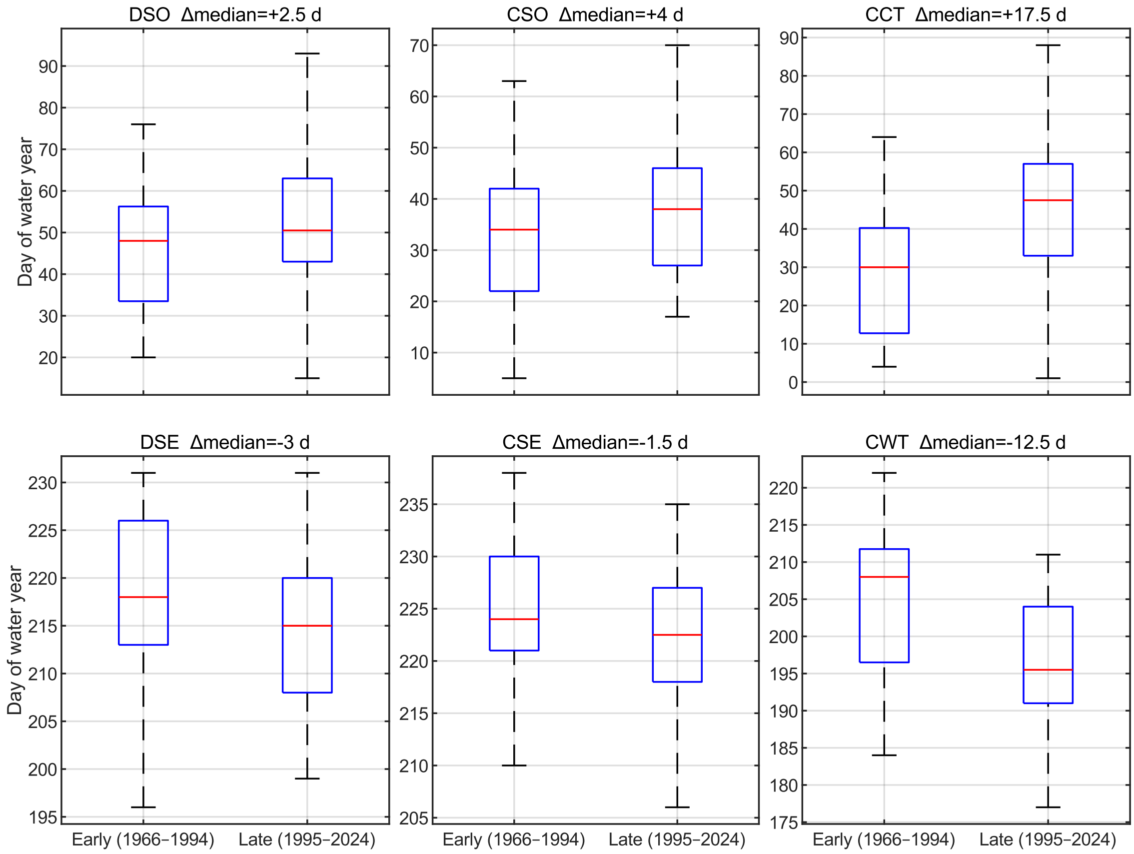


Figure 6 Early vs recent decade distributions of PCT timings. WY1966–1994 (n=29) vs WY1995–2024 (n=30).

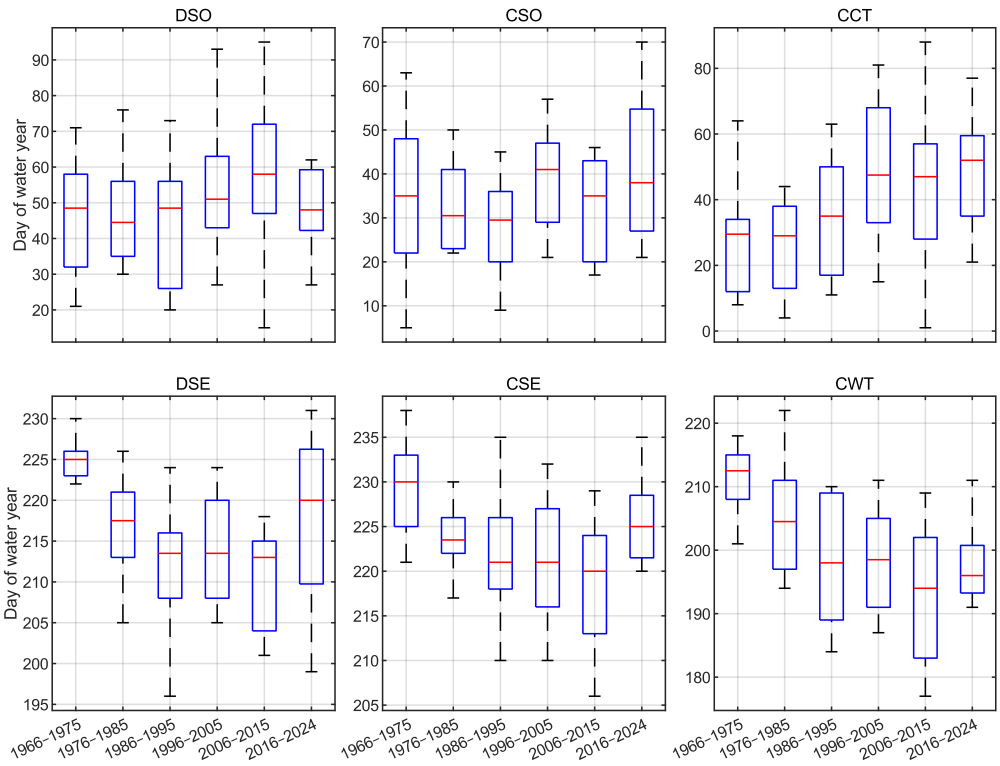


Figure 7 Decadal-scale distributions of PCT timings (day of water year) across the full record (WY 1966–2024), shown as 10-year blocks (last block 2016–2024).

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.

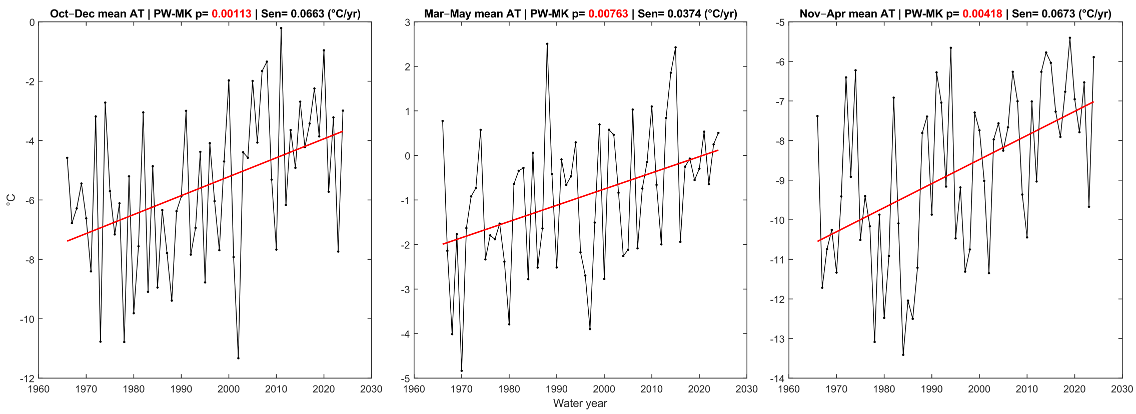


Figure 8 Trends on seasonal mean air temperature.

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).

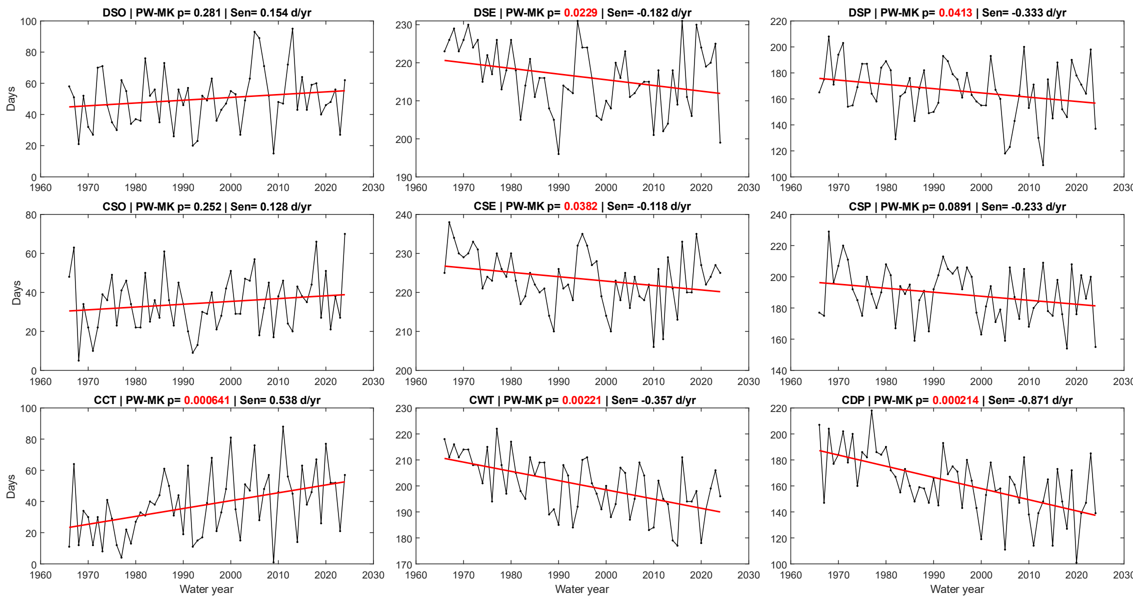


Figure 9 Trends on PCTs and IVIs. Row 1: Discharge-based, Row 2: Snowdepth-based, Row 3: Air Temperature based metrics. Column1: PCT Onset markers, Column 2: PCT End markers, and Column3: IVIs.

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.

References

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