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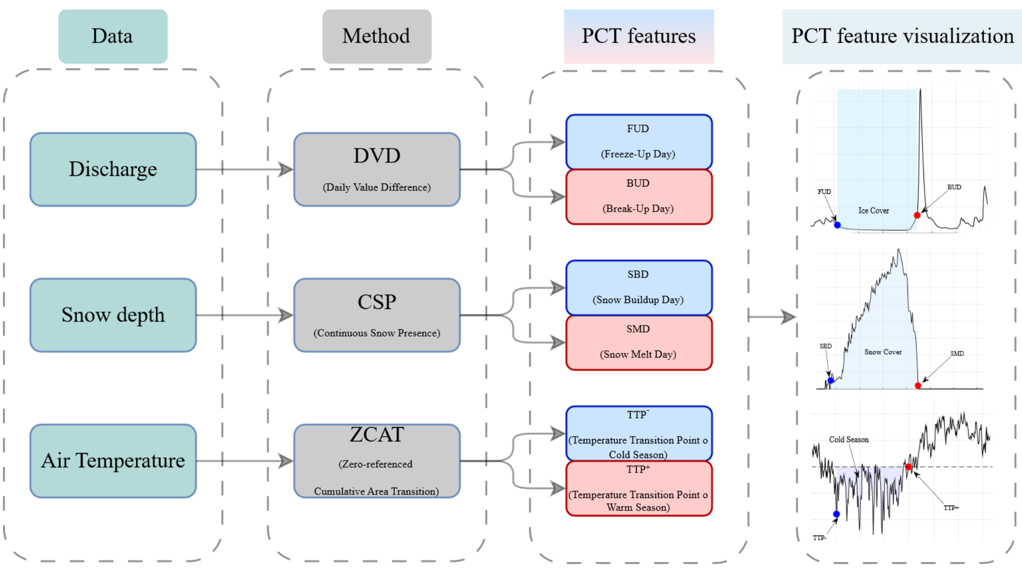
No longer on schedule, the pattern Is breaking apart: The Loss of Seasonal Synchrony in a Sub-Arctic River System Under Warming Climate

Abolfazl Jalali Shahrood[1], Amirhossein Ahrari[1], Ali Torabi Haghighi[1]

[1]Department1Water, Energy and Environmental Engineering Research Unit, University of Oulu, Pentti Kaiterankatu 1, Oulu, P.O.Box 8000, 90570, Finland

Correspondence to: Abolfazl Jalali Shahrood (a.jalali.civil@gmail.com)

Abstract. Climate warming is altering the timing and synchrony of snow and ice processes across northern river systems, yet long-term shifts in their seasonal dynamics remain insufficiently resolved. Here, we analyze a 57-year daily record (1966–2023) from the River Oulankajoki in northeastern Finland to characterize freeze-up, break-up, snow accumulation and melt, and key atmospheric temperature transition points. Using a process-based detection tool, we identify significant advances in spring-related events, including snow melt, ice break-up, and the seasonal shift from cold to warm temperatures. In contrast, autumn transitions such as freeze-up and snow onset exhibit higher year-to-year variability and no consistent trends. The durations of cold season, ice cover, and snow melt periods have shortened, while warm and open-water seasons have lengthened. Moreover, the temporal gap between atmospheric warming and surface responses has increased in spring but contracted in autumn. These findings suggest not only a shift in seasonal timing but also a growing desynchronization between atmospheric conditions and cryo-hydrological processes, with implications for Arctic river ecology, ice forecasting, and flood risk under continued climate change.



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1 Introduction

The Arctic's cryo-hydrological systems are experiencing significant changes driven by climate warming. Arctic regions are warming at a rate approximately two to four times faster than the global average, with the most pronounced warming occurring during autumn and winter months (García Criado et al., 2025; Masson-Delmotte et al., 2021; Prowse et al., 2007). Annual average temperatures in the Arctic are expected to rise by approximately 3.7°C by 2050, relative to the 1981–2000 baseline (Prowse et al., 2007). Snow cover extent and duration have generally declined across the Northern Hemisphere in recent decades (Bring et al., 2016), with snow depth and duration projected to continue their downward trends (Burrell et al., 2023). Specifically, Arctic snow cover duration has shortened by approximately 2–4 days per decade over the past 30–40 years, and spring snow cover extent has declined by over 30% since 1971 (Box et al., 2019). Snowmelt is occurring earlier in many regions, often accompanied by more frequent rain-on-snow events (Park et al., 2016). These changes have also affected the timing of spring freshets, which have shifted earlier in Eurasian basins at a rate of about 1.1 days per decade, while North American basins show no significant trends (Feng et al., 2021).

Cryo-hydrological processes in Arctic river systems are experiencing significant transformations driven by climate change. These widespread changes in river flow patterns are primarily driven by rising air temperatures (Pavelsky and Zarnetske, 2017). The timing and magnitude of spring river flows are shifting, with many Arctic rivers transitioning from a nival to a pluvial regime (i.e., snowmelt-dominated to rainfall-dominated) (Prowse et al., 2006). River ice, a critical element of the cryosphere that significantly impacts the global hydrological system, is highly sensitive to weather and hydrological conditions (Shen, 2016). This sensitivity is particularly evident in the Northern Hemisphere, where by 2010, major ice cover existed on 29% of total river lengths, and seasonal ice affected approximately 58% of river lengths (Bennett and Prowse, 2010). Globally, the duration of river ice cover has declined Specifically over the past three decades (Newton and Mullan, 2021; Yang et al., 2020), with studies attributing these changes to global warming (Fukś, 2023).

An example is the Danube River, where increasing winter temperatures have reduced its ice cover duration by about 28 days per century (Ionita et al., 2018). Broader analyses using more than 400,000 Landsat images reveal a global average reduction in river ice extent from 10% to 7.5% over the last 30 years (Yang et al., 2020). The most substantial reductions in ice cover duration have occurred in northeastern North America, Central Europe, and areas surrounding the Tibetan Plateau (Fukś, 2023). Ice thickness has also shown widespread decline. For instance, major Arctic rivers in Russia experienced reductions in maximum ice thickness ranging from 2.3 to 12.6 cm per decade between 1955 and 2012 (Fukś, 2023). Numerous studies report overall decreases in river ice thickness across various regions (Nalbant and Sharma, 2023; Vuglinsky, 2017; Vuglinsky and Valatin, 2018).

The timing of river ice freeze-up and break-up has been significantly shifting. Many rivers and lakes around the world exhibit later freeze-up dates and earlier break-up times, which leads to a shorter annual ice cover period (Janowicz, 2010; Newton and Mullan, 2021; Rokaya et al., 2019; Sharma et al., 2022; Shiklomanov and Lammers, 2014; Takács and Kern, 2015; Yang et al., 2020). Long-term records spanning the past 150–200 years provide clear evidence of these trends across

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Northern Hemisphere lakes and rivers, with freeze-up occurring approximately 5.8 days per century later and break-up about 6.5 days per century earlier (Burrell et al., 2023). On average, ice break-up has moved earlier by about 0.6 days per decade since 1850, correlating with a global temperature increase of about 0.12°C per decade (Fukś, 2023; Magnuson et al., 2000). Freeze-up timing shows greater regional variability, which shows both delayed and earlier occurrences depending on location; however, the dominant global trend is toward later freeze-up dates (Fukś, 2023). Spring and autumn temperatures play critical roles in determining break-up and freeze-up timing, respectively (Brown et al., 2018). Research conducted in the Mackenzie River Delta suggests increasingly earlier spring break-up, with Siberian rivers exhibiting even more pronounced changes than rivers in North America (Kugler et al., 2010). These shifts are driven primarily by rising springtime air temperatures and indirectly by enhanced river discharge from increased snowmelt (Bieniek et al., 2011; Brown et al., 2018).

Shifts in river ice regimes are disrupting both ecosystems and human activities in the Arctic. Earlier ice break-up and reduced ice cover alter seasonal flooding, nutrient transport, and thermal conditions in aquatic systems, that might affect fish habitats and species composition (Prowse et al., 2006; Yang et al., 2020). These changes also threaten traditional practices, winter transportation, and water resource availability in northern communities (Brown et al., 2018; Fukś, 2023). On land, permafrost thaw is reshaping vegetation, while aquatic ecosystems experience species shifts and declines in fish condition (Lehnherr et al., 2018; Liljedahl et al., 2016).

River ice and cold-climate hydrological processes are important indicators of climate change in Arctic regions, yet their potential is limited by persistent data gaps. River discharge data offer a useful proxy, with the timing and magnitude of spring flows reflecting changes in ice break-up. Increased spring discharge typically accelerates break-up, while autumn and early winter flows influence freeze-up timing (Feng et al., 2021; Park et al., 2016). Among climate variables, air temperature is the dominant driver of ice regimes, strongly correlating with both freeze-up and break-up events (Ionita et al., 2018; Shiklomanov and Lammers, 2014). The freezing index, based on cumulative sub-zero temperatures, is commonly used to estimate ice thickness and seasonal transitions. Specifically, spring temperatures play a critical role in predicting break-up dates (Park et al., 2016). Snow cover is another key proxy, with declining winter snow depths and shorter durations contributing to earlier break-up through reduced surface albedo and enhanced melt (Bring et al., 2016; Lesack et al., 2014). Together, these variables indicate the value of integrating hydrological and climatic data to monitor cryospheric change.

There is a significant shortage of consistent hydrological observations related to river ice across the Arctic, particularly in remote regions (Kugler et al., 2010). Long-term records of freeze-up and break-up dates, as well as ice thickness, are scarce and often fragmented, that limits the ability to detect robust climate trends (Feng et al., 2021; Park et al., 2016). The decline in river gauging stations since the mid-1980s, especially in Russia and Canada, has further reduced the availability of continuous datasets (Prowse et al., 2007). Inconsistencies in data collection methods and definitions, such as differing criteria for the start or end of ice events, complicate trend analysis and comparisons across regions (Sharma et al., 2022; Yang et al., 2020). For example, some observations record initial break-up, while others note complete ice clearance, a process that may span several weeks (Prowse et al., 2007). These methodological disparities, combined with reduced

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ground-based monitoring, hinder efforts to separate climate change signals from natural variability and challenge the integration of datasets at the pan-Arctic scale.

Given the persistent data gaps and inconsistencies in direct river ice observations, proxy indicators such as air temperature, river discharge, and snow cover have become essential for assessing changes in ice dynamics. These proxies are particularly important in regions where long-term observational records are sparse or incomplete. In response to this challenge, the present study builds on the River Ice Timing Characteristics and Extremes (RiTiCE) tool (Jalali Shahrood et al., 2023) to evaluate long-term ice break-up trends in the River Oulankajoki in northern Finland. RiTiCE estimates break-up timing using daily discharge data and has been validated across multiple Arctic and sub-Arctic river systems, including the Tornionjoki, Kiiminkijoki, Kemijoki, and Tana rivers (Jalali Shahrood, 2023; Shahrood et al., 2024). RiTiCE provides a consistent and scalable method for monitoring river ice phenology in regions lacking direct measurements.

2 Methodology

2.1 Phase Change Timing (PCT) Detection

To identify the onset of seasonal transitions in river and climate-related variables, we used the RiTiCE (River Ice Timing Characteristics and Extremes) framework, developed and implemented in MATLAB. RiTiCE requires annual daily time series, prepared under consistent preprocessing rules and analyzed using variable-specific transition detection methods.

2.2 Data Preparation

The datasets must be prepared as follows:

- Leap days (29 February) must be removed to maintain a uniform 365-day structure across all years.
- Data were reorganized by water year, defined from October 1st to September 30th.

Primary aim of RiTiCE is to detect the timing of an event (or known as Feature in this study) on annual daily time series with a generic mathematical approach. The timing is when a parameter changes its phase known as Phase Change Timing (i.e., PCT). The terms "Features" and "Periods" are defined in Table 1 and Table 2.

Table 1 Summary of Phase Change Timing (PCT) events detected by RiTiCE.

Event	Abbreviation	Definition in RiTiCE	Parameter	Method to detect
break-up day	BUD	The day when river flow begins rising after a long low-flow period, which signals the start of ice break-	Discharge	DVD (Daily Value Difference)

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		up.		
freeze-up day	FUD	The start of the longest period of stable discharge before the break-up day,	Discharge	DVD (Daily Value Difference)
Snow build-up day	SBD	The start of the longest continuous period of non-zero snow depth	Snow depth	CSP (Continuous Snow Presence)
Snow melting day	SMD	The end of the longest continuous period of non-zero snow depth	Snow depth	CSP (Continuous Snow Presence)
Temperature Transition Point	TTP^+	The day on which transition from cold to warm season occurs	Temperature	ZCAT (Zero-Referenced Cumulative Area Transition)
Temperature Transition Point	TTP^-	The day on which transition from warm to cold season occurs	Temperature	ZCAT (Zero-Referenced Cumulative Area Transition)

110 **Table 2 Definitions of seasonal periods used in the analysis.**

Period	Definition	Parameter
Cold Season	Period between TTP^- and TTP^+	Temperature
Warm Season	Complementary period to the cold season	Temperature

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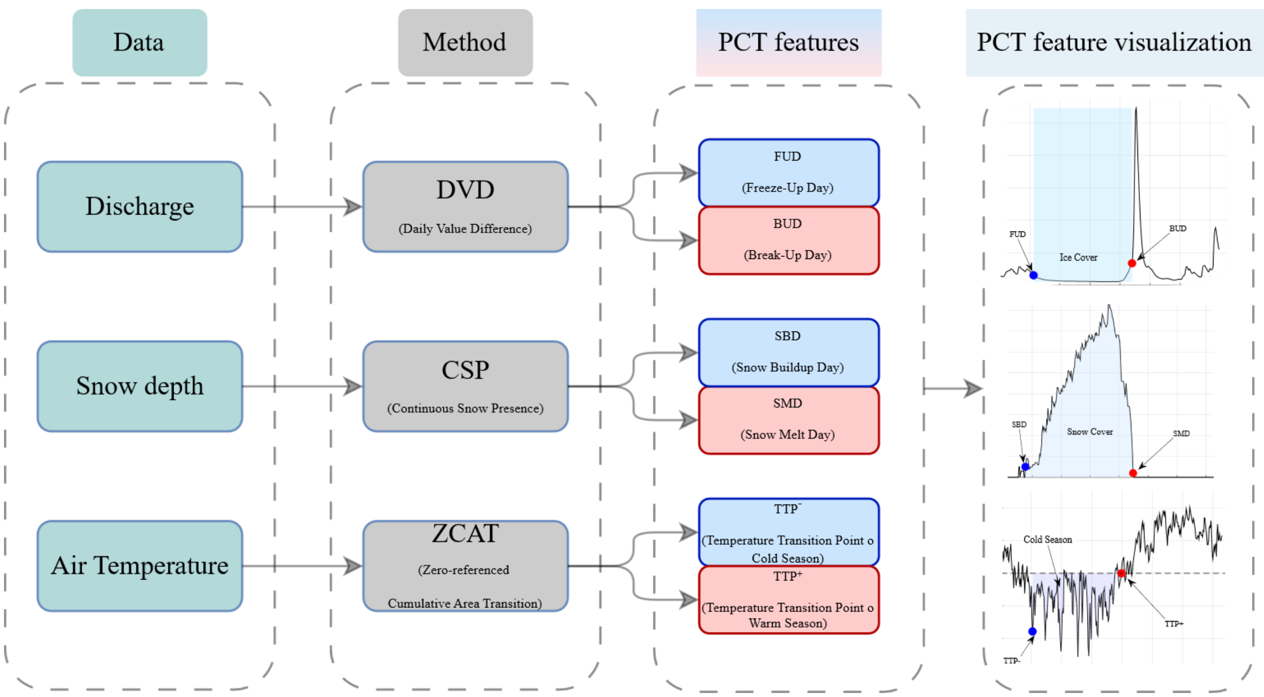
Ice Cover	Period between FUD and BUD	Discharge
Open Water	Period between BUD and FUD	Discharge
Snow Cover	Period between SBD and SMD	Snow depth
No Snow	Period between SMD and SBD	Snow depth



115 **Fig. 1 Overview of the PCT (Phase Change Timing) feature extraction framework.**

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2.3 River Ice Features: Freeze-Up and Break-Up Days (FUD & BUD)

In RiTiCE, FUD and BUD refer to the hydrological signature of river ice freeze-up and break-up. This is distinct from the visual or observational break-up date (e.g., the first day a river is entirely ice-free) and freeze-up date (e.g., The date on which the water body was first observed to be completely frozen over), as defined by the International Association for Hydraulic Research (IAHR, 1980). 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. On the other hand, RiTiCE defines FUD as the day of year on which the flow enters the stable (i.e., least fluctuations) before BUD occurs.

BUD is detected using the Daily Value Difference (DVD) method. The change in discharge is calculated between each pair of consecutive days:

$$\Delta Q_t = Q_{t+1} - Q_t \quad (1)$$

The stable segment, bounded by the FUD and BUD, reflects sustained ice presence. To isolate this period, we computed the daily variation in discharge (DVD) and applied a threshold defined by the standard deviation (±σ). A binary mask was then generated for |DVD| ≤ σ, from which the longest continuous segment was extracted to represent the ice-covered season.

$$\sigma_{\Delta Q} = \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\Delta Q_t - \overline{\Delta Q}\right)^2}, \quad (2)$$

$$\text{BUD} = max\{t_k\} + 1 \quad \text{where} \quad \left|\Delta Q_{t_k}\right| < \sigma_{\Delta Q} \quad (3)$$

$$\text{FUD} = min\{t_k\} + 1 \quad \text{where} \quad \left|\Delta Q_{t_k}\right| < \sigma_{\Delta Q} \quad (4)$$

Where:

Q_t = Discharge on day t (m³/s)

ΔQ_t = Daily change in discharge, $Q_{(t+1)} - Q_t$ (m³/s)

N = Number of daily ΔQ_t values in the water year (364)

$\overline{\Delta Q}$ = Mean of all ΔQ_t values over the water year

$\sigma_{\Delta Q}$ = Standard deviation of the ΔQ_t series

t_k =Time-indices of the longest contiguous run satisfying $|\Delta Q_t| < \sigma_{\Delta Q}$

BUD = Break-Up Day, defined as the day index max$\{t_k\}$ + 1

FUD = Freeze-Up Day, defined as the day index min$\{t_k\}$ + 1

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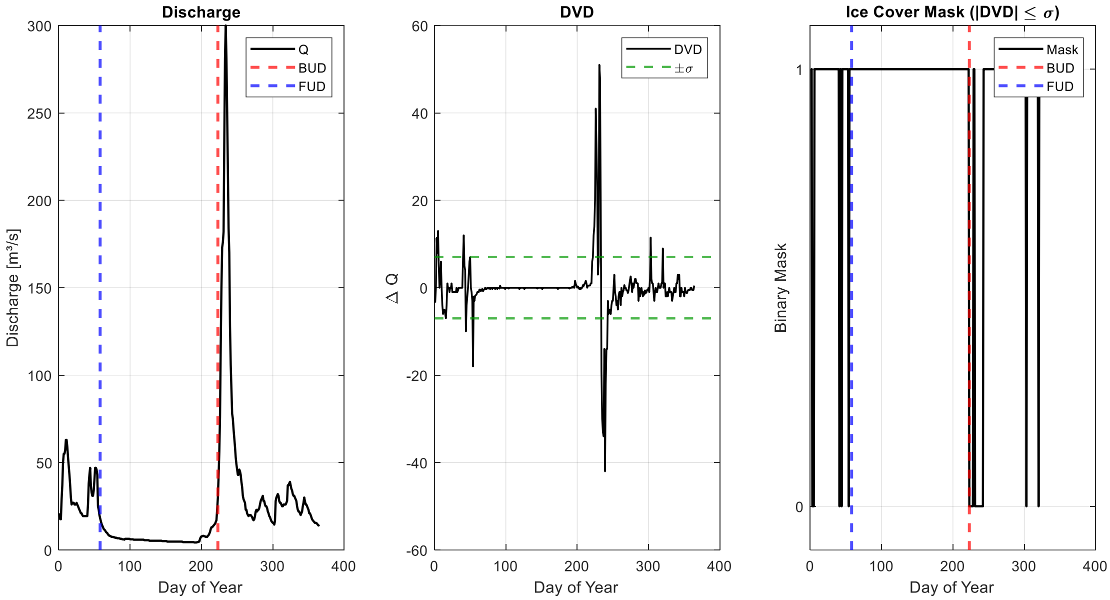

Fig. 2 Detection of BUD (Break-Up Day) and FUD (Freeze-Up Day) using discharge data. (Left) Daily discharge with BUD (blue dashed line) and FUD (red dashed line). (Center) Daily Value Difference (DVD) method showing changes in discharge. (Right) Binary ice cover mask derived from periods where |DVD| ≤ σ, used to define stable low-flow (ice-covered) periods between BUD and FUD.

2.4 Snow Features: Build-Up and Melt Days (SBD & SMD)

To determine the timing of persistent seasonal snow cover, we apply the Continuous Snow Presence (CSP) method. A binary mask is generated based on daily snow depth values, where each day is assigned a value of 1 if snow is present ($S \neq 0$) and 0 otherwise. The longest continuous segment of days with a value of 1 in this mask identifies the main snow cover period. The first day of this segment is defined as the Snow Build-Up Day (SBD). The last day of this segment is defined as the Snow Melt Day (SMD).

$$M_t = H(S_t), \quad \text{where} \ \ H(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \end{cases} \tag{5}$$

Longest continuous subsequence of days where $M_t = 1$,

$$[\mathrm{SBD} = t_{\mathrm{start}}, \quad \mathrm{SMD} = t_{\mathrm{end}}] \qquad M_t = 1 \quad \forall\, t \in [t_{\mathrm{start}}, t_{\mathrm{end}}] \tag{6}$$

Where:

S_t = Snow depth on day t (in cm), for t ∈ {1, 2, ..., 365}

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M_t = Binary snow presence mask

$[t_{start}, t_{end}]$ = Indices of the longest continuous subsequence such that $M_t = 1$ for all $t \in [t_{start}, t_{end}]$

$SBD = t_{start}$ (Snow Build-Up Day)

$SMD = t_{end}$ (Snow Melt Day)

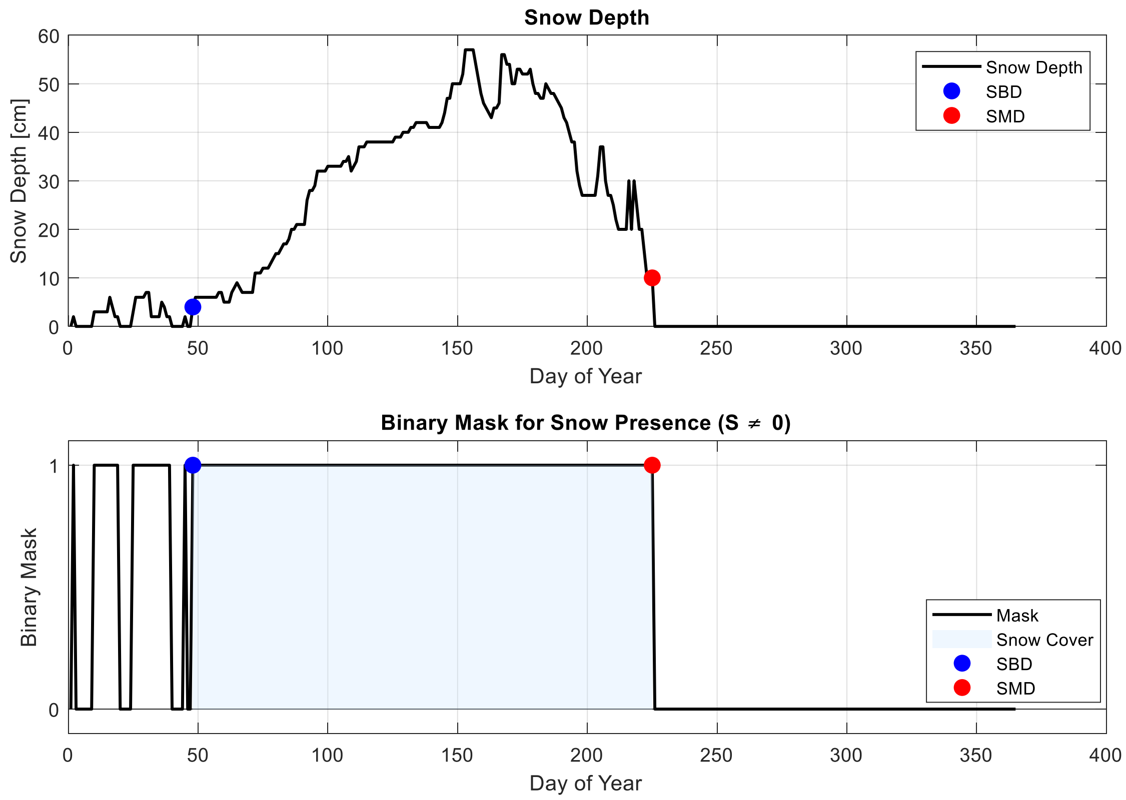

Fig. 3 Detection of SBD (Snow Build-Up Day) and SMD (Snow Melt Day) from snow depth data. (Top) Daily snow depth with SBD (blue dot) corresponding to the start of continuous snow cover and SMD (red dot) corresponding to the end. (Bottom) Binary snow presence mask (1 if snow depth > 0, else 0) used to identify the longest continuous snow-covered period.

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2.5 Temperature Features: Transition Points (TTP⁻ & TTP⁺)

To characterize the seasonal temperature transition, we apply the Zero-Referenced Cumulative Area Transition (ZCAT) method. This approach captures the integrated thermal state by accumulating daily areas between the temperature curve and the 0 °C baseline.

For each day t, the area between day t and t + 1 is computed using the trapezoidal rule with a unit time step:

$$A_t = \frac{T_t + T_{t+1}}{2} \tag{7}$$

$$C_t = \sum_{i=1}^{t} A_i \tag{8}$$

where:

- T_t= daily mean temperature on day *t*
- A_t = area contribution between day *t* and *t + 1*
- C_t = Cumulative curve
- TTP⁺ = the day corresponding to the minimum of the C_t , the transition from cold season to warm season.
- TTP⁻ = timing of the last zero-crossing of the C_t before TTP⁺, the transition from warm season to cold season.

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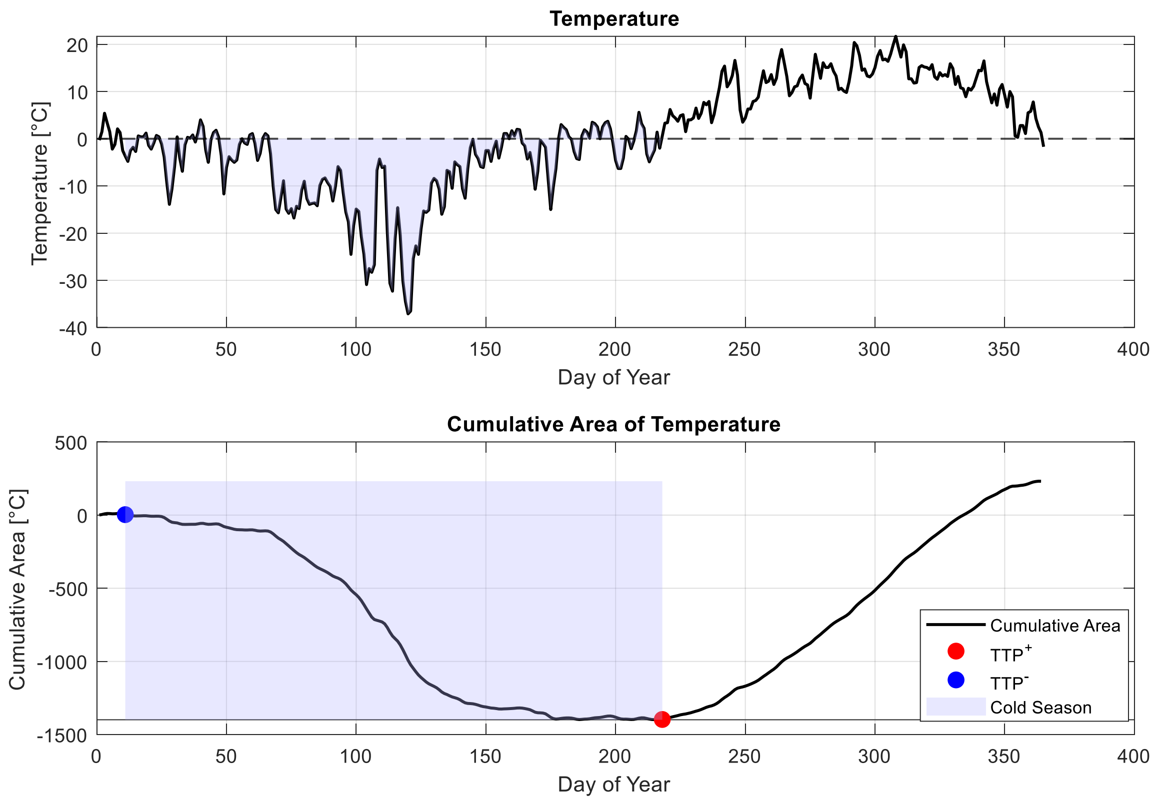

Fig. 4 Identification of temperature transition points (TTP⁻ and TTP⁺) using cumulative temperature analysis. (Top) Daily air temperature with cold season highlighted; TTP⁻ (blue dot) signals the start of cumulative cooling, and TTP⁺ (red dot) signals the transition to cumulative warming. (Bottom) Cumulative temperature curve used to detect these inflection points.

To detect long-term monotonic trends in the key variables, we applied the Mann-Kendall trend test, a non-parametric method widely used in hydrology and climatology. The significance of observed trends was evaluated at conventional confidence levels (P-Value < 0.05). To further explore the relationships between seasonal PCT features, we calculated the Spearman correlation coefficients among all six PCT markers including BUD, FUD, SMD, SBD, TTP^{+}, and TTP^{-}, over the full 57-year record.

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2.6 Study Area

River Oulankajoki, is a boreal river system located in northeastern Finland near the Arctic Circle (Arvola and Nurmesniemi, 2000; Saraniemi et al., 2008). Situated within the boreal zone, it displays cold-climate hydrological characteristics, including seasonal snow accumulation, extended ice cover, and distinct freeze-thaw cycles. Hydrologically, the river is strongly seasonal (Blåfield et al., 2024; Saraniemi et al., 2008). The mean annual discharge is approximately 25.5 m³/s, with low flows dropping to around 3 m³/s in late winter and peak flows reaching up to 249 m³/s during the spring snowmelt in May–June. The river typically freezes from mid-November to early May. Recent climatic trends show significant warming in the region, with average temperatures rising by 0.61°C per decade and summer temperatures by 0.41°C per decade. These trends are shortening the winter season and altering the basin's overall hydroclimatic regime. Over the past five decades, spring floods have weakened by 7%, while high-flow events in other seasons have increased by 10%. Annual minimum flows have risen by 28%, that reflects both climatic and hydrological shifts (Blåfield et al., 2024).

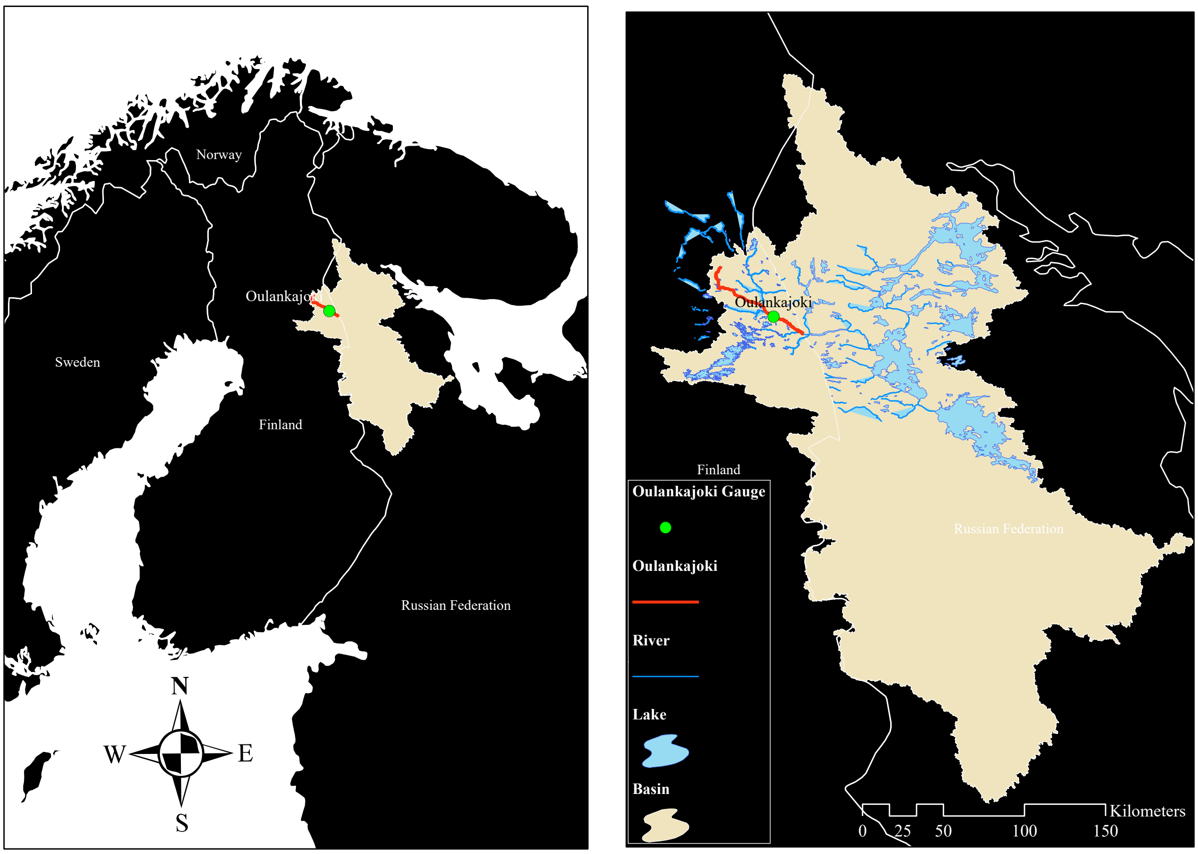

Fig. 5 Location and of the River Oulankajoki basin.

Daily air temperature and snow depth records were obtained from the Finnish Meteorological Institute (FMI) Open Data Portal, specifically from the Kuusamo Kiutaköngäs weather station (N66°22'4", E29°19'40"), about 500 meters away from

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the Oulanka Research Station. These records span from October 1966 to September 2023 and serve as key indicators of thermal and snowmelt dynamics affecting river ice phenology. Daily river discharge measurements were acquired from the Oulanka Research Station, hosted by SYKE (Finnish Environment Institute).

3 Results

3.1 Seasonal Hydroclimatic Patterns in a Reference Year

This study presents one of the most comprehensive long-term assessments of cryo-hydrological dynamics in a sub-Arctic river system, analyzing 57 years of in-situ observations from the River Oulankajoki. By defining and analyzing six seasonal (PCT) features and their corresponding durations, we observed a clear and systematic shift toward earlier thaw-related events and a broader restructuring of cold-season hydroclimatic regimes. The 1966 reference cycle illustrates the structurally ordered nature of seasonal transitions under stable cryo-hydrological conditions. In more recent decades, however, this sequence has grown increasingly variable. Rather than a simple forward shift of the seasonal calendar, we observe elongated transition windows. These results are consistent with Arctic-wide trends which shows earlier melt onset and later freeze-up.

In the reference year 1966, the seasonal progression of cryo-hydrological conditions showed distinct and coherent transitions in discharge, snow cover, and air temperature (Fig. 6). Freeze-Up Day (FUD) was identified on day 58 of the hydrological year, initiating a 166-day ice cover period that lasted until Break-Up Day (BUD) on day 223 (Fig. 6, top). Snow Build-Up Day (SBD) occurred earlier, on day 48, with snow depth remaining continuously above zero until Snow Melt Day (SMD) on day 225, resulting in a snow cover duration of 178 days (Fig. 6, middle). Air temperature dropped below freezing early in the year, with the warm-to-cold transition point (TTP^{-}) occurring on day 11. The cold-to-warm transition point (TTP^{+}) was reached on day 218, after which temperatures stayed consistently above freezing. This marked a 208-day cold season (Fig. 6, bottom). Full-year characterizations for all 57 years are provided in Appendix A.

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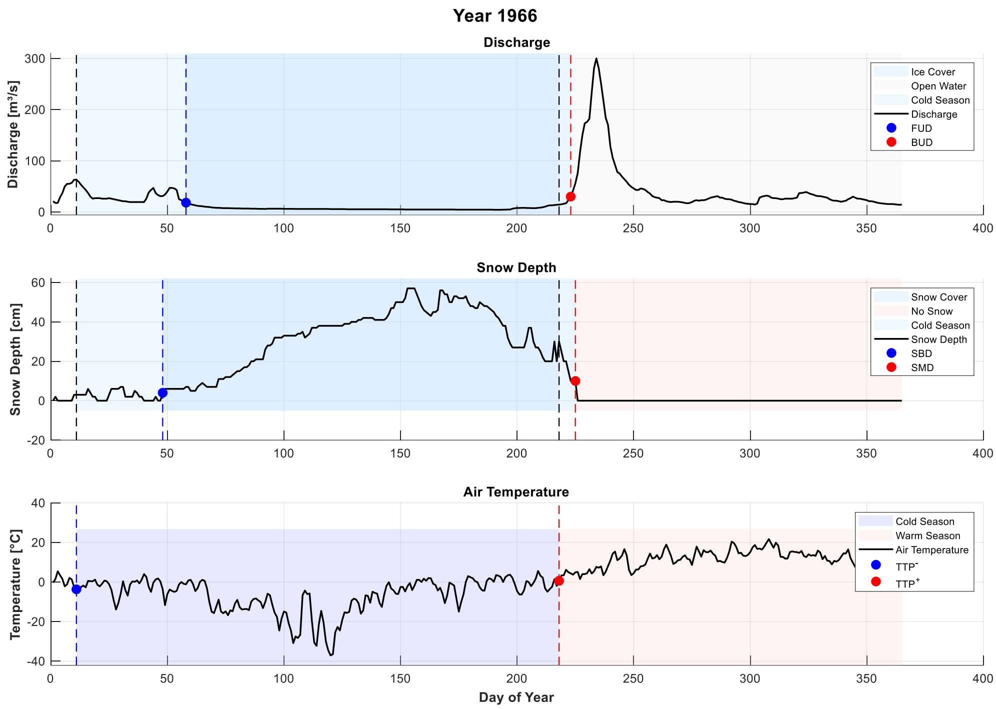

Fig. 6 Hydroclimatic conditions in 1966 showing seasonal transitions. (Top) Discharge with break-up (BUD) and flow rise (FUD) days. (Middle) Snow depth with build-up (SBD) and melt (SMD) days. (Buttom) Air temperature with cold-to-warm (TTP^{-}) and warm-to-cold (TTP^{+}) transitions.

3.2 Temporal Sequencing and Interannual Variability of Seasonal Features

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). Snow Build-Up Day (SBD), warm-to-cold transition (TTP^{-}), and Freeze-Up Day (FUD) showed considerable year-to-year fluctuations in both order and timing. In contrast, the cold-to-warm transition (TTP^{+}), Break-Up Day (BUD), and Snow Melt Day (SMD) maintained a fixed sequence across all 57 years.

SBD and TTP^{-} frequently alternated between the first and second positions, with FUD occasionally preceding both. Meanwhile, TTP^{+}, BUD, and SMD maintained a stable order, consistently appearing in the final positions of the seasonal progression. This persistent ordering reflects a strong temporal stability in spring-related markers compared to the more variable autumn features (Fig. 7, bottom). This difference illustrates that spring transitions are increasingly governed by consistent atmospheric warming, whereas autumn processes remain subject to localized and stochastic controls, such as precipitation phase, surface insulation, and early snowfall events.

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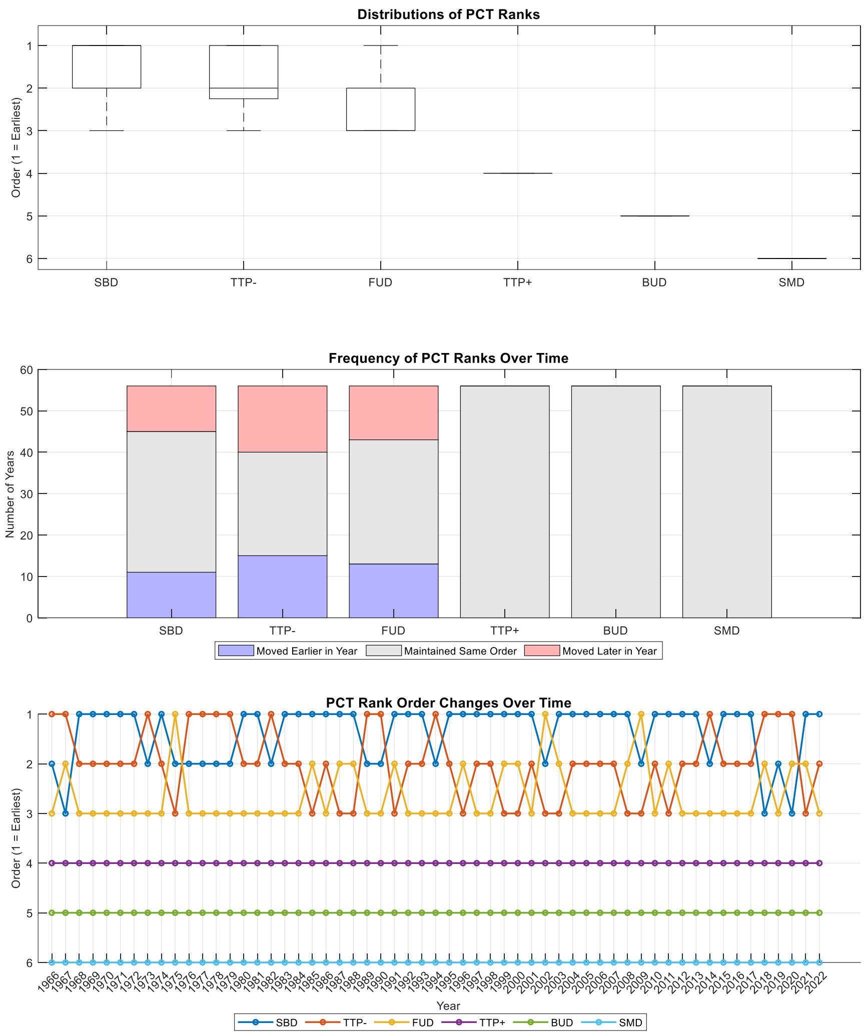

Fig. 7 Annual ranks and temporal shifts of six cryo-hydrological Phase Change Timing Features (1966–2022). (Top) rank distributions; (middle) frequency of shifts; (bottom) year-to-year order changes.

3.3 Correlations Among PCT Features and Seasonal Periods

Relationships among the six Phase Change Timing (PCT) features and seasonal period durations reveal structured associations across the 57-year record (Fig. 8). Among the PCT features, the strongest correlation was observed between Snow Melt Day (SMD) and Break-Up Day (BUD), with a coefficient of ($r = 0.76$). Both features were also positively correlated with the cold-to-warm temperature transition point (TTP^{+}), with values of ($r = 0.60$) for BUD and ($r = 0.54$) for SMD. In contrast, the warm-to-cold transition marker (TTP^{-}) showed weaker and negative correlations with spring events,

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including (r = −0.34) with SMD and (r = −0.28) with BUD. Correlations among cold-season features were more moderate. Snow Build-Up Day (SBD) was positively associated with both FUD (r = 0.44) and TTP⁻ (r = 0.48).

The seasonal period duration matrix showed a strong inverse relationship between Cold Season and both No Snow (r = −0.57) and Open Water periods (r = −0.55). Cold Season duration was positively associated with Snow Cover (r = 0.57) and Ice Cover (r = 0.55), while Snow Cover and Ice Cover were also correlated (r = 0.52). No Snow and Open Water durations were moderately correlated (r = 0.52), and both were negatively related to Ice Cover and Cold Season. In contrast, the duration of the Snow Melt period exhibited weak correlations with all other periods, ranging from −0.05 to 0.17.

Fig. 8 Correlation matrix of seasonal transition timing parameters. The values represent Spearman correlation coefficients between key phenological markers: BUD (Break-Up Day), FUD (Freeze-Up Day), SMD (Snow Melt Day), SBD (Snow Build-Up Day), TTP⁺ (Cold-to-Warm Temperature Transition), and TTP⁻ (Warm-to-Cold Transition).

3.4 Long-term Trends in Phase Change Timings, Seasonal Durations, Hydroclimatic Indicators, and Lag Metrics

Figure 9 summarizes long-term trends across four thematic categories of phase change timings, seasonal durations, hydroclimatic indicators, and lag metrics. In the phase change timings, statistically significant trends ($p < 0.05$) were detected for Break-Up Day (BUD), Snow Melt Day (SMD), and both positive and negative Temperature Transition Points (TTP⁺, TTP⁻). BUD and SMD showed a shift toward earlier dates, indicating earlier river ice break-up and complete snowmelt. TTP⁺ has shifted earlier, while TTP⁻ has delayed. No significant trends were observed for Freeze-Up Day (FUD) and Snow Build-Up Day (SBD), although both showed slight upward tendencies. For seasonal durations, significant shortening was detected in the Cold Season ($p < 0.000$), Ice Cover Duration ($p = 0.026$), and Snow Melt Duration ($p = 0.001$), while the Warm Season ($p < 0.000$) and Open Water Duration ($p = 0.042$) lengthened. Snow Cover and No Snow

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durations increased but did not reach statistical significance (p = 0.128). The hydroclimatic indicators section shows that Minimum Discharge increased significantly (p = 0.036), whereas Maximum Discharge remained stable (p = 0.918). Ice Cover Average Discharge showed a near-significant trend (p = 0.062). Neither Minimum (p = 0.073) nor Maximum Air Temperature (p = 0.184) had significant trends, although both increased slightly. Cold Season Average Temperature showed a non-significant rise (p = 0.346). Maximum Snow Depth remained stable (p = 0.660). In terms of lag metrics, the time lag between Cold Season Start and Snow Cover Start significantly decreased (p = 0.004), while the lags between Cold Season End and both Ice Cover End (p = 0.003) and Snow Cover End (p = 0.001) increased significantly. The lag between Cold Season Start and Ice Cover Start showed a non-significant decline (p = 0.096).

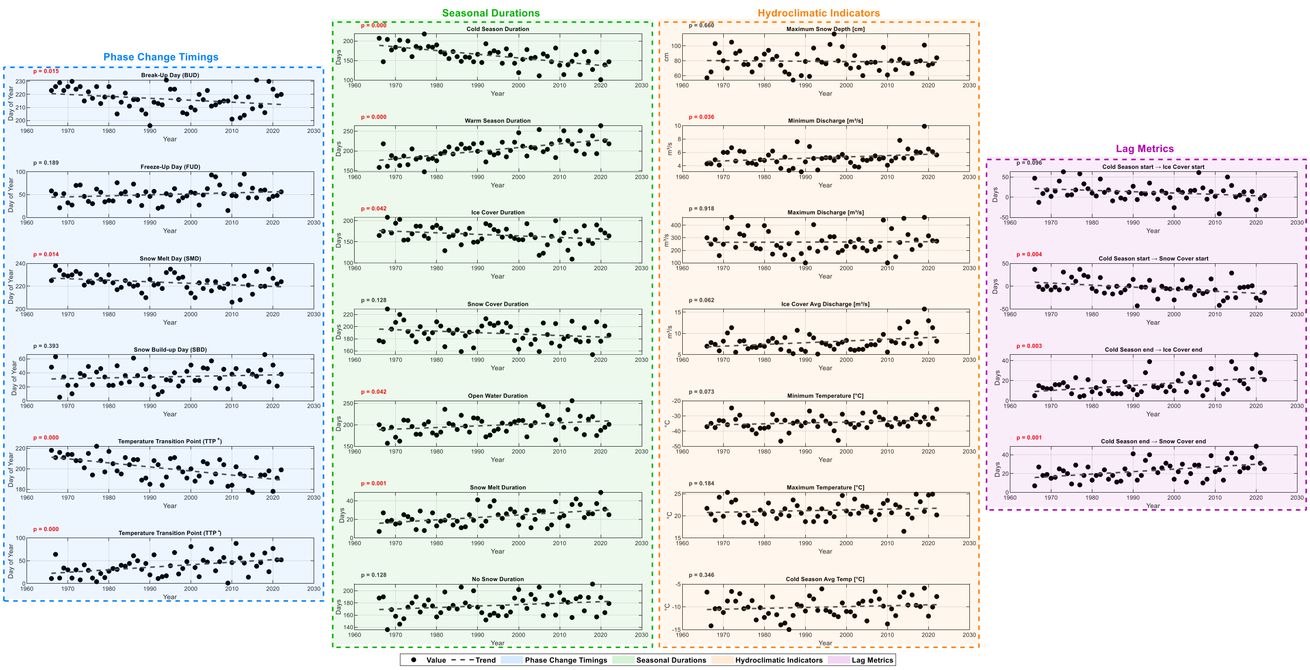

Fig. 9 Mann–Kendall trend analysis from October 1966 to September 2023.

4 Discussion

This study presents one of the most comprehensive long-term assessments of cryo-hydrological dynamics in a sub-Arctic river system, analysing 57 years of in-situ observations from the River Oulankajoki. By defining and analysing six seasonal (PCT) features and their corresponding durations, we observed a clear and systematic shift toward earlier thaw-related events and a broader restructuring of cold-season hydroclimatic regimes.

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A central finding of this study is the asymmetry between spring and autumn transitions. Spring PCT features including, SMD, BUD, and TTP⁺, showed statistically significant trends toward earlier timing. In contrast, autumn PCT features including, SBD, FUD, and TTP⁻, showed no significant long-term trends and demonstrated greater interannual variability, with frequent delays and timing fluctuations. This difference illustrates that spring transitions are increasingly governed by consistent atmospheric warming, whereas autumn processes remain subject to localized and stochastic controls, such as precipitation phase, surface insulation, and early snowfall events. This seasonal asymmetry is strongly supported by prior studies. Break-up dates across North America and Europe have advanced by ~0.6 days per decade, closely linked to spring warming (Chen and She, 2020; Newton and Mullan, 2021), while freeze-up trends remain spatially heterogeneous and weakly correlated with climate signals (Liston and Hall, 1995; Prowse and Bonsal, 2004). These dynamics are further evidenced in our feature sequencing analysis. SBD, TTP⁻, and FUD exhibit flexible interannual rankings, frequently switching order across years. In contrast, the sequence of TTP⁺, BUD, and SMD remains fixed. This consistency supports the interpretation that spring processes are more temporally constrained and climatically synchronized, while autumn markers retain internal autonomy. The correlation matrix reinforces this conclusion, strong interconnections among spring features (i.e., TTP⁺, BUD, and SMD) contrast with weak or inconsistent correlations among autumn indicators (i.e., SBD, TTP⁻, and FUD).

In addition to timing shifts, we have found evidence of a broader redistribution of seasonal durations. The cold season, ice cover, and snow melt periods have significantly shortened, while the warm season and open water durations have lengthened. Trends in snow cover and no-snow durations were weak but positive which suggests increasing variability. This uneven redistribution reflects a restructuring of seasonal phase coherence. Rather than a simple forward shift of the seasonal calendar, we observe elongated transition windows. These results are consistent with Arctic-wide trends which shows earlier melt onset and later freeze-up. This contributes to lengthened melt seasons of up to 2–3 weeks per decade (Dauginis and Brown, 2021; Markus et al., 2009). Satellite-based observations also highlight spatial heterogeneity in snow cover dynamics (Dye, 2002; Kim et al., 2018). The emergence of complex, nonlinear transitional phases, such as multi-stage ice freeze-up and snow melt onset without sustained thaw, reveals the increasing fragmentation of seasonal coherence across Arctic river systems (Kim et al., 2018; Markus et al., 2009).

We have detected evolving lag relationships between atmospheric temperature transitions and corresponding surface responses. The lag between cold season onset (i.e., TTP-) and snow accumulation (i.e., SBD) has decreased, this means a faster response to initial freezing. However, lags between the end of the cold season (i.e., TTP+) and the snow melt (i.e., SMD) and ice (i.e., BUD) have increased significantly, which means snow and ice are taking longer to respond to spring warming. A number of studies support this trend that despite earlier spring warming, snow melt has lagged expectations (Schwartz et al., 2006; Stone et al., 2002). This disconnection between air temperature and surface melt poses substantial challenges for both hydrological modeling and ecosystem forecasting. Traditional degree-day models may fail to predict the timing of snowmelt-driven runoff or spring ecological cues, as lagged surface responses become increasingly decoupled from atmospheric indicators (Bjorkman et al., 2015; Groisman and Easterling, 1994; Siegel et al., 2022).

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Despite the pronounced shifts in cryospheric timing and duration, our analysis reveals relatively stable trends in hydrological extremes. Minimum discharge has increased modestly, while maximum discharge and snow depth have remained statistically unchanged. We observed a nearly significant increase in river flow during the ice-covered period ($p = 0.062$), which may suggest more water is moving beneath the ice. These findings align with studies reporting regional resilience in streamflow metrics despite substantial hydroclimatic shifts (Harder et al., 2015; Shiklomanov et al., 2007). Increases in winter baseflow observed in northern basins have been attributed to permafrost thaw and deeper infiltration (St. Jacques and Sauchyn, 2009). Although some studies report increasing spring peaks in certain regions (Burn et al., 2010; Byun et al., 2019), our results suggest that in many sub-Arctic systems, hydrological extremes remain buffered, potentially due to offsetting influences like soil water retention, increased evapotranspiration, or groundwater recharge (Bring et al., 2016).
Ecologically, changes in freeze-up and break-up timing alter sediment and nutrient transport, affect aquatic habitat structure, and misalign biological cues. Earlier phytoplankton blooms and zooplankton peaks may benefit fast-growing species but disrupt food web synchrony for others with more complex life cycles (Janowicz, 2010; Prowse et al., 2011). From a societal perspective, shorter and less reliable ice seasons threaten winter road networks, vital for northern communities and industries (Prowse et al., 2007). Mid-winter break-up events pose risks to infrastructure, navigation, and hydropower operations (Beltaos et al., 2007). While extended open water periods may reduce icebreaking costs, they also disrupt traditional practices, fish migrations, and ecological timing. Changes in freeze-thaw sequences increase the likelihood of compound flood risks, particularly from rain-on-snow events or early break-up under high-flow conditions (Beltaos and Prowse, 2009) as our results show significantly increasing trend of minimum discharge during ice cover period. In that way we may observe more mechanical ice break-up in the near future, which leads to more hazardous floods than thermal ones. They tend to produce thicker ice jams and lead to higher water levels, which increases the risk of severe flooding and damage (Prowse and Stephenson, 1986). The dynamic nature of mechanical break-up events, which involves rapid discharge, moving ice, and powerful waves, can trigger intense erosion and sudden spikes in sediment transport (Beltaos and Burrell, 2021). Mechanical break-up events also involve large runoff volumes acting on thick, intact ice, that leads to extreme surges in water level (Prowse et al., 2007). Ecologically, ice-induced floods from mechanical break-up events can significantly disrupt both in-channel and riparian processes (Prowse and Culp, 2003).

Taken together, our results show that the cryo-hydrological system is not just shifting earlier in the year, it is being fundamentally reorganized. Instead of a simple seasonal shift, we see complex changes in how different processes (including timing, duration, and response delays) interact. In some cases, earlier melt doesn't mean faster melting it can actually stretch out the melt period but with less intensity (Pomeroy et al., 2015). This evolving cryo-hydrological complexity challenges the utility of temperature-based models and reinforces the need for improved process-based representations. Effective forecasting and resource management will require models that integrate thermal-hydraulic coupling, threshold effects, and lagged surface responses to remain robust under continued Arctic warming. We acknowledge persistent limitations in cryo-hydrological datasets. Long-term, spatially dense monitoring networks remain sparse across the Arctic, particularly in

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Eurasia (Feng et al., 2021; Ionita et al., 2018). This constrains the ability to generalize findings, attribute change drivers, or validate remote sensing products. Advancing our understanding will require sustained in-situ measurements, integration of high-resolution satellite data, and deployment of distributed sensor networks capable of capturing both surface and subsurface dynamics in cold environments.

5 Conclusions

This study provides a 57-year assessment of seasonal cryo-hydrological dynamics in a sub-Arctic river system using a structured detection approach across six key timing metrics. By applying the RiTiCE framework to the River Oulankajoki, we document a coherent and statistically significant shift in spring-related features—namely snow melt, river ice break-up, and the atmospheric cold-to-warm transition—toward earlier dates, while autumn-related features remain temporally unstable and trendless. This divergence highlights a growing seasonal asymmetry in how Arctic rivers respond to climate forcing.

The analysis reveals that changes in phase transition timing are not occurring in isolation. Cold season, ice cover, and snow melt durations have shortened, whereas the warm season and open water periods have expanded. Lags between atmospheric transitions and surface responses have also evolved: spring surface processes are increasingly delayed relative to the onset of warming, while autumn reactions occur more promptly following cooling. These trends suggest a breakdown in the internal synchrony of cold-season processes rather than a uniform seasonal shift.

Despite these structural changes, hydrological extremes such as peak discharge and maximum snow depth remain relatively stable. This suggests a buffered system response, possibly due to subsurface storage, evapotranspiration shifts, or groundwater compensation. However, a modest but consistent increase in minimum winter discharge points to enhanced under-ice flow, potentially linked to permafrost degradation or increased baseflow, which may elevate the risk of mechanical break-up events.

The results demonstrate that cryo-hydrological transitions in Arctic river systems are becoming less predictable and more fragmented. The progressive loss of seasonal coherence—both in timing and interprocess alignment—poses a challenge for forecasting river ice conditions, assessing flood risk, and managing aquatic ecosystems. These findings underscore the need for long-term observational records and improved process-based models that incorporate not only temperature thresholds but also lagged hydrological responses and transitional variability under continued Arctic warming.

Appendices

Appendix A

https://figshare.com/s/d6dc8875fd8151a80085

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Data availability

All data supporting the findings of this study are publicly available at:
410 FMI Open Data Portal: https://en.ilmatieteenlaitos.fi/open-data
Finnish Environmental Institute (SYKE): https://wwwp2.ymparisto.fi/scripts/kirjaudu.asp

Author contribution

A.J.S. conceived the study, developed the methodology, processed and analyzed the data, wrote the manuscript, and prepared all figures. A.A. contributed to the interpretation of results and manuscript preparation. A.T.H. supervised the study.

Competing interests

The authors declare that they have no conflict of interest.

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