Understanding Changes in Iceland’s Streamflow Dynamics in Response to Climate Change

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Abstract. The hydrological cycle in high-latitude regions is undergoing significant changes due to climate change. Iceland, with its extensive data from minimally disturbed catchments, provides a unique opportunity to study these changes. The country's heavy reliance on hydropower, without interconnections to other electricity markets, makes understanding these changes crucial. Recent decades have seen warming outpace global warming trends in Iceland, along with increased precipitation, reduced glacier mass, rising soil temperatures and expanded vegetation cover. The impacts of these environmental shifts on streamflow remain largely unexplored. We analyzed long-term records from minimally disturbed catchments (25 gauges since 1973 and 37 gauges since 1993) using the LamaH-Ice dataset to assess climate-driven shifts in streamflow. The analysis focuses on minimally disturbed rivers to isolate hydrological responses to climatic trends and variability. Results show high inter-annual variability, decadal fluctuations, and strong correlations with the Arctic Oscillation, as reported in earlier studies. Annual streamflow has increased in most Icelandic rivers, driven by increased precipitation, with particularly strong increases in fall and winter. Summer flows have decreased in most rivers, especially in surface-fed rivers, likely due to earlier and decreased snowmelt, lower summer precipitation and increased evapotranspiration. This study is the first to report coherent regional and seasonal trends in Icelandic streamflow. Annual low flows have increased, reflecting enhanced winter runoff, while changes in high flows are more variable. Glacial rivers show positive streamflow trends during the last 50 years, reflecting warming-induced melt, but have shifted to negative summer trends over the past 30 years due to a recent cooling anomaly. Streamflow variability within the year is decreasing, as indicated by decreasing coefficients of variation and flashiness index. The baseflow fraction has increased, which may be facilitated by reduced soil frost and enhanced subsurface connectivity. The findings offer crucial insights into Iceland's hydrological changes amid rapid climatic shifts, with broader implications for reservoir operations and water resources management. This study enhances our understanding of Icelandic hydrology and contributes to global knowledge on climate-induced hydrological changes.

1 Introduction

Anthropogenic climate warming, primarily driven by greenhouse gas emissions, has caused widespread environmental changes around the globe (IPCC, 2023). The Arctic has experienced particularly profound effects, with warming occurring at close to four times the rate of the global average between 1979 and 2021 (Rantanen et al., 2022). This has led to an intensification of the hydrological cycle in the region (Box et al., 2019; Rawlins and Karmalkar, 2024).

In Iceland, the average warming rate between 1980-2015 was 0.47°C/decade (Björnsson et al., 2018). Despite this significant warming, analyses of snow observations in Iceland have shown a significant increase in snow cover and snow depth in some regions of Iceland over the periods 1930-2021 and 2001-2021 (Eythorsson et al., 2023). This is attributed to increases in precipitation, as annual precipitation in Iceland increased by about 10% between 1980-2015, with substantial variations between locations (Björnsson et al., 2018).

In addition to changes in weather and snow conditions, various other environmental factors in Iceland have undergone significant changes that impact streamflow dynamics. Glaciers have lost 18% of their area and 16% of their mass since 1890, with the most rapid mass loss occurring between 1994 and 2010 (Aðalgeirsdóttir et al., 2020). Since 2010, the pace of glacier net mass loss has reduced (Aðalgeirsdóttir et al., 2020). Soil temperatures in Iceland have increased, soil frost depth and duration have decreased (Petersen and Berber, 2018; Zaqout et al., 2023; Zaqout and Andradóttir, 2023), and permafrost is warming at a high rate and showing signs of degradation, with evidence of disappearance in some areas (Etzelmüller et al., 2023). Since the 1980s, increases in vegetation cover have been observed in the arctic, with increases particularly high in Iceland (Raynolds et al., 2015).

It is, however, still unclear how these changes have affected streamflow in Icelandic rivers. No recent comprehensive studies exist in the literature on how streamflow dynamics have changed in Iceland in the past decades. Jónsdóttir et al. (2006, 2008) performed trend analyses for two streamflow series for the period 1942-2002 and ten streamflow series for the period 1961-2000 to determine long-term changes in streamflow. Modest and statistically insignificant trends were found for mean annual and seasonal streamflow. For the longer period, a positive trend of 4% per decade in annual streamflow was observed for one of the two rivers (Jónsdóttir et al., 2006). For the shorter period, no trends were found for annual streamflow. However, two out of ten stations showed a 6-7% increase per decade for summer streamflow, which was attributed to colder temperatures in spring, delaying snowmelt into the summer. The magnitude of floods had a positive trend in the spring and a negative trend in the autumn, and spring floods showed a trend towards later timing, though these findings were generally not deemed statistically significant. A key takeaway was that despite a substantial increase in precipitation, no corresponding increase was found in the flow of non-glacial rivers (Jónsdóttir et al., 2006). Wilson et al. (2010) analyzed trends in annual and seasonal streamflow in Icelandic rivers for 1961–2000 and found no significant trends in either annual or seasonal streamflow, confirming the findings by Jónsdóttir et al. (2006). Their analysis also showed no shift in the timing of the spring floods. Blöschl et al. (2017) examined the timing annual highest floods across Europe between 1960-2010 and showed that (spring) flooding in southwestern Iceland occurred later in the year, while flooding occurred earlier (or changed little) in the northeastern part of the country.

Crochet (2013) examined the sensitivity of ten river basins to climate variability by comparing streamflow patterns during cold and warm years, as well as wet and dry years, using data from 1971-2006. The analysis revealed that streamflow seasonality is highly sensitive to temperature increases, manifesting as reduced snowpack, earlier snowmelt, and greater streamflow in winter, with decreased flow in summer for non-glaciated catchments.

In this study, we investigate the multi-annual variability in Iceland's climate and analyze changes in streamflow, aiming to link these changes to shifts in hydro-meteorological drivers, catchment attributes, and changes in glacier extent. Unlike previous studies that analyzed only a limited number of streamflow stations, our study leverages a significantly larger observational network. The data we use is from the “LArge-SaMple Data for Hydrology and Environmental Sciences for Iceland” (LamaH-Ice) dataset (Helgason and Nijssen, 2024a) which provides streamflow measurements from an extensive network of mostly undisturbed watersheds, enabling a comprehensive study of changes in streamflow dynamics over recent decades due to climate change. We calculate trends for various climate and streamflow metrics while accounting for natural climate variability. Our research addresses three key questions: (1) How have precipitation, temperature, and streamflow varied from year to year since 1950? (2) Are there significant trends in annual and seasonal streamflow across Iceland over recent decades? (3) If so, what are the key drivers of these trends?

2 Data and methods

2.1 Study area

Iceland, positioned in the North Atlantic, features a unique landscape shaped by glaciers that currently cover 10% of the country, active volcanism, and distinctive hydrological characteristics. Geologically, Iceland is bisected by a volcanic rift zone, leading to varied bedrock conditions that significantly affect hydrological patterns. Rivers originating from areas with porous, young bedrock exhibit high baseflow, while those from regions with older, less permeable bedrock are primarily surface-fed. Despite the dominance of natural landscapes, with urban and agricultural areas comprising only a small fraction of the land, the hydrological system is complex. Rivers are categorized by their sources as glacial, direct-runoff, or spring-fed, although many receive contributions from multiple sources.

2.2 The hydrology and climate of Iceland

Iceland’s hydrology is profoundly influenced by its location, subject to frequent cyclones crossing the Atlantic from west to east and abundant precipitation, especially in winter. Iceland's climate is marked by high interannual variability, largely driven by broad-scale atmospheric circulation patterns. The Arctic Oscillation (AO) plays a significant role, with a strong polar vortex (positive AO) trapping cold air in the Arctic and leading to milder, wetter conditions in Iceland (Thompson and Wallace, 1998). The Icelandic Low (IL), a semi-permanent low-pressure system between Iceland and Greenland, significantly shapes the path of cyclones crossing the Atlantic. The North Atlantic Oscillation (NAO) index measures the pressure difference between the IL and the Azores High (Wanner et al., 2001). During a positive NAO phase, the IL intensifies, enhancing westerly winds that bring warmer, more humid air to Iceland, increasing precipitation, particularly in the south and west. Streamflow in Iceland from 1966 to 2004 has been shown to be correlated with the AO and the NAO, though the latter's influence is generally less significant (Jónsdóttir and Uvo, 2009). Studies have also identified a strong positive correlation between streamflow magnitude and the intensity of southerly winds at the 500 hPa level (Snorrason, 1990). Additionally, sea surface temperatures (SSTs) around Iceland further modulate surface air temperatures, with warmer SSTs increasing glacial melt and runoff in glacial rivers (Jónsdóttir and Uvo, 2009).

2.3 Data

In this study, we use streamflow measurements, atmospheric reanalysis data and catchment characteristics from the LamaH-Ice dataset (Helgason and Nijssen, 2024a). Most of the catchments in LamaH-Ice are unaffected by anthropogenic influence such as flow regulations, water withdrawals or diversions. The dataset thus enables a comprehensive study of changes in streamflow dynamics during the past decades due to climate change. We exclude streamflow data from gauges heavily influenced by anthropogenic activities (e.g. hydropower withdrawals) or natural changes, such as evolving watershed boundaries due to shifting river courses. However, gauges downstream of hydropower reservoirs are included in the analysis of annual average streamflow trends when the reservoirs do not significantly affect annual streamflow volumes. The locations of the streamflow gauges used in this study are shown in Fig. S24 in the Supplement, and Table S1 provides an overview of the gauges, including river names, gauge locations, observation periods, and a selection of catchment attributes. The uncertainty in the streamflow observations is discussed in detail in the LamaH-Ice data description paper (Helgason and Nijssen, 2024a). Streamflow measurements in Iceland are prone to interruptions (e.g., ice disturbances or instrument malfunctions), particularly during winter, which can reduce data availability and introduce additional uncertainty. Moreover, uncertainty in older streamflow periods is higher than in recent periods due to older instrumentation with greater uncertainty. While LamaH-Ice includes a pre-filtered version of the data that retains only high-quality observations, this study uses the full dataset, which contains periods that have been gap-filled by experts using auxiliary observations such as weather data or nearby gauges. However, some periods could not be reconstructed and remain missing. For the analysis of trends in streamflow magnitudes, we did not attempt to fill these remaining gaps. We allowed up to 10% of daily data to be missing per year (or season) and calculated averages from the available data without filling missing values. If more than 10% was missing, we excluded that year from the time series. We then calculated trends for time series with at least 80% temporal coverage in annual values between the defined start and end dates. While calculating trends for incomplete time series could affect the trend estimates and the significance test's power, the inclusion of more gauges and regions enables a broader and more representative analysis. The number of gauges we used in this study for streamflow trend analyses ranges from 25 to 37 depending on analysis period.

Some gauges represent nested sub-catchments of larger river systems. Specifically, gauges 46 (Jökulsá á Fjöllum at Upptyppingar) and 59 (Kreppa) are sub-catchments of gauge 45 (Jökulsá á Fjöllum at Grímsstaðir); gauge 86 (Tungnaá at Maríufoss) is nested within gauge 102 (Þjórsá at Þjórsártún); and gauges 8 (Brúará at Dynjandi), 36 (Hvítá at Fremstaver), and 79 (Sog at Ásgarður) are sub-catchments of gauge 98 (Ölfusá at Selfoss). Rather than exclude gauges 45, 98, and 102, we retain them in the analysis because they integrate substantial additional drainage areas downstream of their respective sub-catchments.

Meteorological time series in LamaH-Ice are derived from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021), which is driven by the ERA5 reanalysis (Hersbach et al., 2020). ERA5-Land has a spatial resolution of 0.1°×0.1° (approximately 5 × 11 km over Iceland). In this study, we use timeseries for total precipitation, snowfall, and temperature for all 107 catchments in LamaH-Ice. Catchment-average time series were computed by calculating an area-weighted mean of ERA5-Land grid cells intersecting each catchment polygon, including partially overlapping grid cells (Helgason and Nijssen, 2024a). Table S2 in the Supplement shows average streamflow, temperature and precipitation for the catchments. Trends in climate variables were calculated from these catchment-average time series. As noted in the LamaH-Ice data description paper, ERA5-Land tends to underestimate precipitation in Iceland, particularly in coastal and mountainous regions, due to the underrepresentation of orographic enhancement in the reanalysis model.

To evaluate the reliability of ERA5-Land data for climate trend analysis in Iceland, we compared catchment-averaged ERA5-Land time series with observed station data and with time series from other regional reanalysis datasets. The results show that ERA5-Land accurately reproduces observed temperature variability and long-term trends, as evidenced by strong agreement with station data from Reykjavík over the 1973–2023 period (Figure S1). Additionally, mean annual temperatures from ERA5-Land show strong correspondence with those from a higher-resolution regional reanalysis (RAV-II; Rögnvaldsson, 2020), reinforcing confidence in the dataset's representation of temperature patterns (Figure S2). For precipitation, ERA5-Land and the regional CARRA reanalysis (Schyberg et al., 2020) display broadly consistent spatial patterns in trend direction across catchments (Figure S3). While ERA5-Land tends to produce slightly stronger (more positive) precipitation trend magnitudes than CARRA, the overall agreement is robust (Pearson $r = 0.84$), indicating that ERA5-Land reliably captures relative spatial and temporal variations in precipitation across Iceland. A full description of the comparison methodology and results is provided in the Supplement (Sect. S2). It should be noted that in watersheds with a substantial glacierized area, a large fraction of precipitation that falls in the glacier accumulation zone does not immediately contribute to streamflow. Instead, it becomes part of the glacier mass and may be released as runoff only after years or even decades.

Timeseries for total evaporation (ET) we use in this study are also from the ERA5-Land reanalysis. The reanalysis uses the Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. Land characteristics, such as glacier and vegetation cover, are represented by static masks based on satellite observations from the 1990s (Muñoz-Sabater et al., 2021). As a result, changes in glacier cover and vegetation are not reflected in ERA5-Land. The uncertainty in the ERA5-Land series is discussed in the LamaH-Ice data description paper (Helgason and Nijssen, 2024a). The maps in Sect. 3 use a basemap shapefile from Hijmans (2015) and glacier outlines from Hannesdóttir et al. (2020).

2.4 Homogeneity of streamflow series

Streamflow measurement series may exhibit inhomogeneity, meaning their statistical properties, such as mean or variance, change over time due to factors like alterations in measurement practices or environmental conditions. To assess the homogeneity of the streamflow records in LamaH-Ice, we performed the standard Petitt test (Pettitt, 1979). Series identified as inhomogeneous were manually inspected for breaks in homogeneity that were either 1) linked to a documented change in measurement practices or to specific incidents that compromised data quality, or 2) distinctly observable in the data, and these breaks could not be accounted for by shifts in temperature or precipitation. The homogeneity analysis revealed that one timeseries needed to be omitted (Syðri-Bægisá river). The analysis is further described in the Supplement (Sect. S1).

2.5 Calculation of spring freshet timing, centroid of timing and peak flow timing

To calculate the timing of spring freshet and centroid of timing, complete and continuous series of streamflow were needed. Many methods have been used in the literature to fill gaps in streamflow records, ranging from simple linear interpolation to advanced statistical or hydrological modeling techniques (Dembélé et al., 2019). A commonly applied approach involves interpolation from analogue gauging stations (WMO, 2008). Instead of relying on data from nearby gauges, we opted to fill missing streamflow records using the inter-annual mean daily flow for the given gauge. This method leverages temporal averaging and scaling based on observed streamflow conditions. Specifically, for each missing value, a 31-day window (15 days before and after the target date) was used to extract observed values. A scaling factor was then calculated as the ratio of the median flow in this window to the mean daily flow over the same period. The missing value was subsequently estimated by applying this scaling factor to the mean flow for the same day of the year from other years. We used the median flow in the 31-day window instead of the mean, to minimize the influence of extreme values. We applied this method for all gaps with a duration of 60 days or less; longer gaps were not filled.

The centroid of timing was calculated as the day of the water year when 50% of the total annual flow volume has passed the gauge. The timing of the onset of spring freshet was calculated using a method developed by Cayan et al. (2001). This method tracks the accumulated difference from the average streamflow over a given water year. When the resulting curve reaches its lowest point, it indicates that the spring freshet has begun, and the current streamflow magnitude has surpassed the annual average. To pinpoint the actual onset of the freshet, we then identify the lowest point on the hydrograph from the preceding days. Calculating a trend in these metrics provides insight into how the timing of spring snowmelt and the annual flow mass has shifted over recent decades. The methodology was adopted from Berge et al. (2021). Peak flow timing was determined as the day of the water year with the highest flow.

2.6 Calculation of trends

Autocorrelation, which is often present in streamflow records, may influence the ability to detect trends (Yue et al., 2002). We thus used the modified Mann-Kendall trend test (Hamed and Ramachandra Rao, 1998) to assess the significance of trends in this study, with significance determined at $p < 0.05$. Unlike the traditional Mann-Kendall test, which assumes independence among the observations, the modified version adjusts the variance of the test statistic to account for autocorrelation. We calculated the magnitude of trends using the Theil-Sen (TS) estimator (Sen, 1968; Theil, 1950), which is calculated as the median of the slope of lines connecting all data point pairs. This trend estimation method is commonly used in hydrological studies as it is insensitive to outliers and suitable for skewed and heteroskedastic data.

We calculate trends for annual, seasonal and sub-seasonal averages. Annual trends are based on hydrological years, defined as the period from October 1 to September 30. Seasons are defined as fall (September to November), winter (December to February), spring (March to May) and summer (June to August). In addition to the summer season, we define a glacial melt season as July to September to better isolate runoff originating from glacier ablation. While the conventional summer period includes both snowmelt and glacier melt, the July to September window reduces the influence of seasonal snowmelt. This separation allows for clearer interpretation of glacier-specific contributions. In addition to calculating trends in average streamflow, we also calculate trends for the standard deviation, coefficient of variation, flashiness index, and baseflow index. The flashiness index quantifies the frequency and magnitude of short-term fluctuations in streamflow, defined as the sum of absolute day-to-day changes in streamflow divided by the total streamflow volume over the water year. The baseflow separation was performed with the method of Ladson et al. (2013)

While annual and seasonal trend analyses are valuable for identifying long-term hydrological changes, they may overlook important shifts occurring at finer temporal scales. Sub-seasonal trends can provide valuable insights even when no significant annual or seasonal trends are detected. Moreover, when seasonal trends are present, this analysis helps pinpoint when changes occur in greater detail. For calculating sub-seasonal streamflow trends, we employ a 21-day rolling mean (21DRM) centered on each day in the series, enabling us to determine a trend for each day of the year. This approach aligns with prior research, which has explored moving windows of varying durations, including 3-day (Kim and Jain, 2010), 10-day (Skålevåg and Vormoor, 2021) and 30-day periods (Kormann et al., 2015). Our selection of a 21DRM balances the demand for a relatively high temporal precision against the challenges that arise as the averaging period decreases and data variability intensifies. For an in-depth explanation of the methodology, we direct readers to the study by Skålevåg and Vormoor (2021).

The high natural climatic variability in Iceland makes streamflow patterns and hydrological processes in Iceland highly dynamic, leading to significant fluctuations in precipitation, temperature, and runoff, on both an annual and decadal scale. As a result, trend analysis in such a variable environment is highly sensitive to the period used. Shorter periods may capture trends that are not representative of longer-term changes, while long periods can obscure shorter-term fluctuations that are critical to understanding streamflow dynamics. This inherent variability complicates the detection of robust trends and the attribution of observed changes to specific climate drivers. To investigate the sensitivity of the time periods chosen and to leverage the availability of streamflow data in Iceland, we calculate trends for two time periods, October 1, 1973 to September 30 2023 (50 years) and October, 1 1993 to September 30, 2023 (30 years). The earlier period, 1973–2023, includes relatively few streamflow series (25), while more series extend back to 1993, allowing for a larger dataset in the 1993–2023 analysis (37 series).

To explore potential drivers of the observed streamflow trends, we calculated Pearson correlation coefficients (R) between streamflow trend magnitudes and both meteorological trends and catchment characteristics. Only statistically significant correlations ($p < 0.05$) are reported.

3. Results

3.1 Multiannual variability in temperature, precipitation and streamflow

3.1.1 Multiannual variability in temperature and precipitation

Since the late 19th century, Iceland has experienced significant warming, although this trend has not been continuous. A marked warming phase occurred during the second decade of the 20th century, followed by a cooling period that persisted until the late 1970s. From that point onward, rapid warming resumed and has continued into recent years (Björnsson et al., 2023). Figure 1 shows the annual average temperature and precipitation over Iceland since the mid-20th century, based on the ERA5-Land reanalysis. While temperature and precipitation vary across the country, the use of averages in Figure 1 helps simplify and interpret large-scale, multiannual variability in Iceland's weather conditions. Because precipitation in the ERA5-Land reanalysis is underestimated for Iceland (Helgason and Nijssen, 2024a), we present it as percentage deviations from the mean rather than absolute amounts. Note that the trendlines in Figure 1 provide a visual representation of overall long-term changes, while the trend analysis of streamflow and meteorological variables in sections 3.2 and 3.3 is based on different time periods.

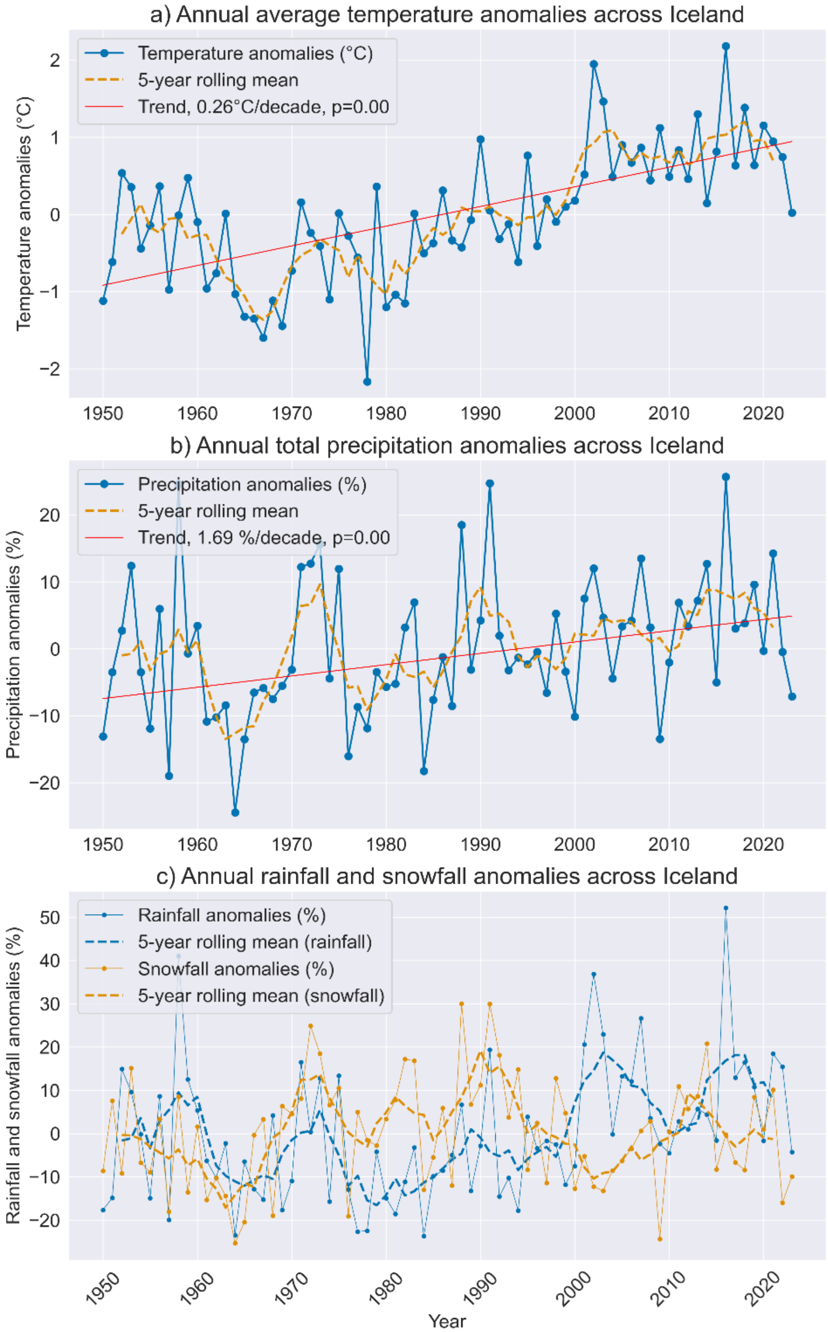

Figure 1: Anomalies from the long-term mean (1950-2024) in annual average temperature (°C), total precipitation (m), and precipitation partitioned into rainfall and snowfall over Iceland, derived from the ERA5-Land reanalysis. Averages are calculated for water years from October 1, 1950, to September 30, 2024. Solid lines represent water-year averages with circular markers for each year, while dashed lines show the 5-year centered rolling mean. Trendlines for temperature and precipitation are calculated using the Theil-Sen method, with statistical significance assessed using the Mann-Kendall test. Both trends are statistically significant ($p < 0.05$).

The temperature data reveals a clear warming trend over this period, with a long-term increase of 0.26°C per decade (Figure 1a). A period of colder years is evident in the late 1960s, a time marked by substantial sea ice around Iceland, followed by a warming phase beginning in the 1980s. The 5-year rolling mean highlights this warming, with temperatures notably higher after 2000 compared to previous decades. However, the warming appears to have slowed in recent years. For the period 2000–2024, the Theil-Sen slope indicates a near-zero trend of +0.01 °C per decade, and the Mann-Kendall test confirms that this trend is not statistically significant ($p = 0.98$).

Precipitation over Iceland exhibits significant interannual variability, characterized by distinct peaks and troughs throughout the study period. Despite this variability, a statistically significant long-term upward trend of 1.69 % per decade is evident. Shorter periods of sustained high or low precipitation are visible in the 5-year rolling average, which often align with fluctuations in the smoothed temperature average.

The 2024 water year recorded the lowest temperature since the turn of the century and the second lowest precipitation (Figure 1a and b). This deviation from the overall upward trend shows that short-term dips in precipitation can still occur, even against a backdrop of long-term increases. The 2024 water year is not included in the trend analysis in this paper due to lack of available streamflow data.

The partitioning of precipitation into rainfall and snowfall reveals that snowfall contributed significantly to total precipitation from around 1970 to 1995. From the early 2000s onwards, there is a shift towards more rainfall, with snowfall becoming less dominant. This shift coincides with the broader warming trend.

3.1.2 Multiannual variability in streamflow

Figure 2 illustrates the long-term variability in streamflow for Icelandic rivers with observational records dating back to before 1980. Distinct periods of streamflow variability are evident over the past several decades. The 1950s saw a high-flow period, followed by lower flows in the 1960s. Streamflow increased again during the 1970s, but the 1980s experienced another period of reduced flow. A brief high-flow period occurred in the early 1990s, after which streamflow declined until 2000. The 2000s marked a decade of high flows, particularly in glaciated catchments. Since the early 2010s, glaciated catchments have experienced near average or lower flows.

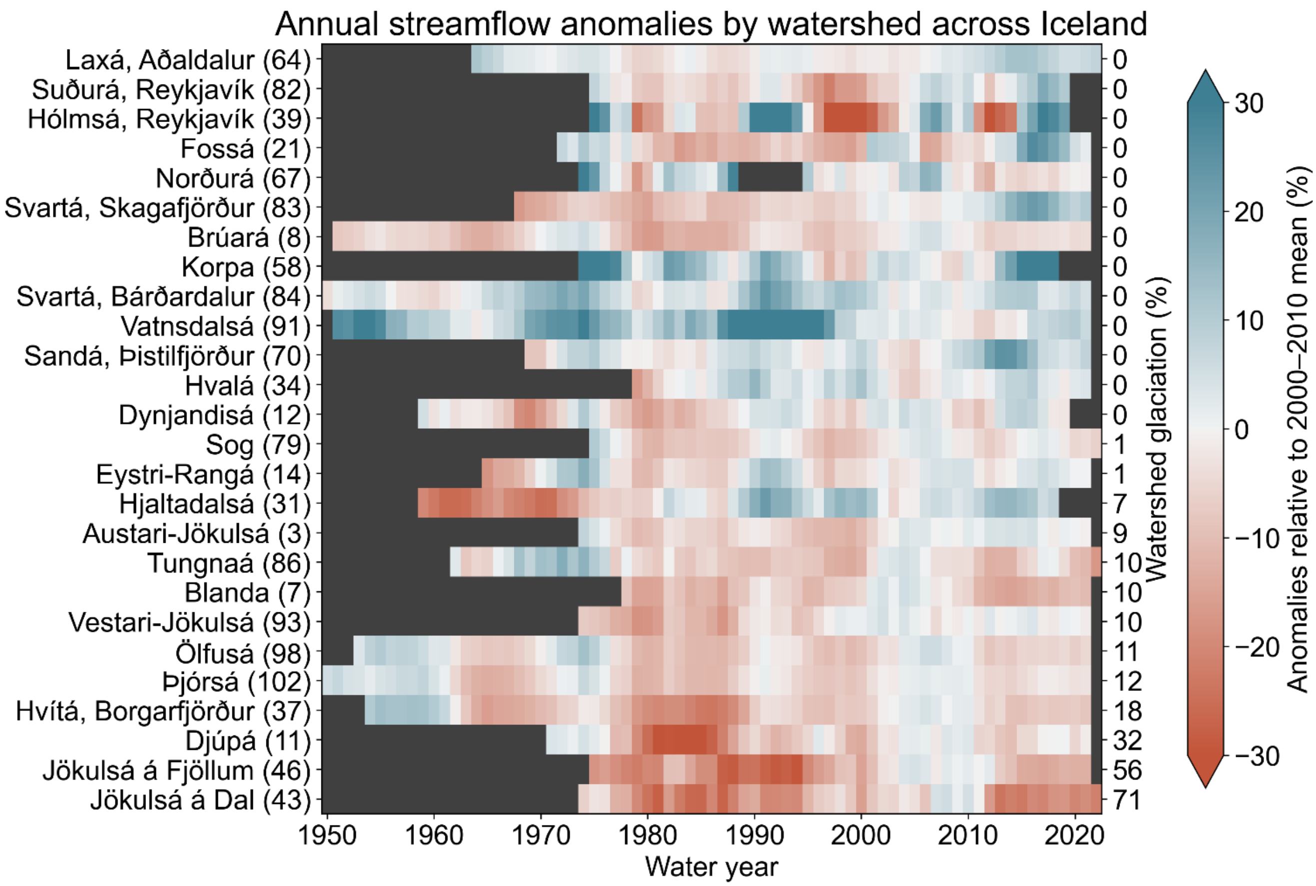

Figure 2: Annual streamflow anomalies for Icelandic gauges with extended measurement records. Anomalies are expressed as percentages relative to each gauge's mean streamflow during the common reference period (October 1, 2000 to September 30, 2010), allowing for direct comparison across watersheds. A 5-year centered rolling average is applied to smooth short-term variability. The color scale indicates percentage anomalies, with red representing below-average flows and blue representing above-average flows relative to the reference period. The left Y-axis lists river names and corresponding LamaH-Ice gauge IDs, while the right Y-axis displays watershed glaciation percentages.

These streamflow patterns align closely with the temperature and precipitation trends shown in Figure 1. The high-flow periods in the 1950s and early 1990s coincide with increased precipitation (Figure 1b), while the elevated flows in glaciated catchments during the 2000s align with warmer temperatures (Figure 1a). Additionally, enhanced glacier melt around 2010 was influenced by sub-glacial volcanic eruptions at Eyjafjallajökull (2010) and Grímsvötn (2011), with ash and tephra depositing on glaciers, reducing glacier albedo and increasing melt. Low-flow periods, such as in the 1960s, 1980s, and post-2010, correspond to reduced precipitation and/or lower temperatures.

3.1.3 Correlation of streamflow with climate indices

Figure 3 presents the correlation between water-year average streamflow in Icelandic rivers and the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) climate indices. The AO and NAO indices were obtained from the NOAA Climate Prediction Center (NOAA CPC, 2024). Streamflow with records dating back to before 1980 were used in the analysis (27 series). The streamflow series were normalized and de-trended before the correlation analysis. The climate indices, already in a normalized form, were de-trended.

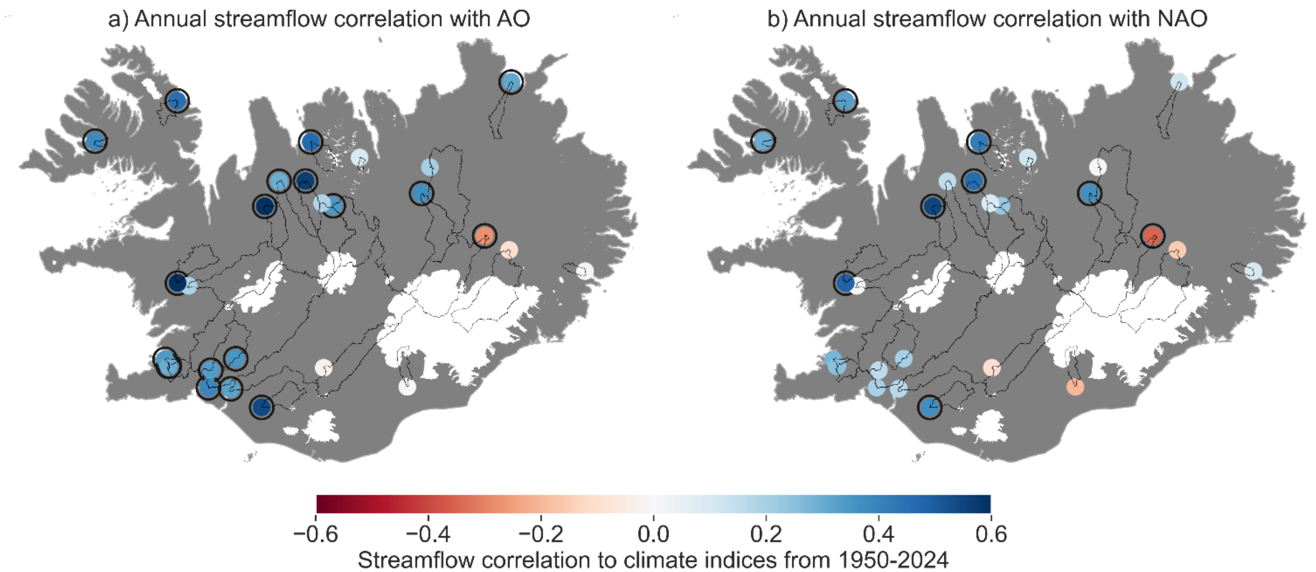

Figure 3: Annual streamflow correlation with the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) climate indices for streamflow gauges in Iceland. Black circles around gauges indicate statistically significant correlations ($p < 0.05$). The correlations were computed using Pearson's method, with the time series de-trended and normalized beforehand. The analysis covers available streamflow data, with the number of years in each series varying across 27 gauges. The average time series length is 58.7 years.

Figure 3a highlights the strong influence of the Arctic Oscillation (AO) on streamflow variability in Iceland, with significant positive correlations at 18 out of 27 gauges. In comparison, Figure 3b shows generally weaker but mostly positive correlations between streamflow and the North Atlantic Oscillation (NAO), with significant positive correlations observed at 8 gauges. This indicates that while the NAO's impact on streamflow is notable, it is less pronounced than that of the AO. These findings align with the results reported by Jónsdóttir and Uvo (2009). The rivers draining Vatnajökull glacier show negative or near-zero correlations to AO and NAO.

3.2 Trends in temperature, precipitation and evapotranspiration

We calculated annual and seasonal trends for catchment-averaged temperature, precipitation and evapotranspiration for all 107 catchments in LamaH-Ice. These timeseries are from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021).

3.2.1 Annual trends

Annual trends for the periods 1973-2023 (period 1) and 1993-2023 (period 2) are displayed in Figure 4.

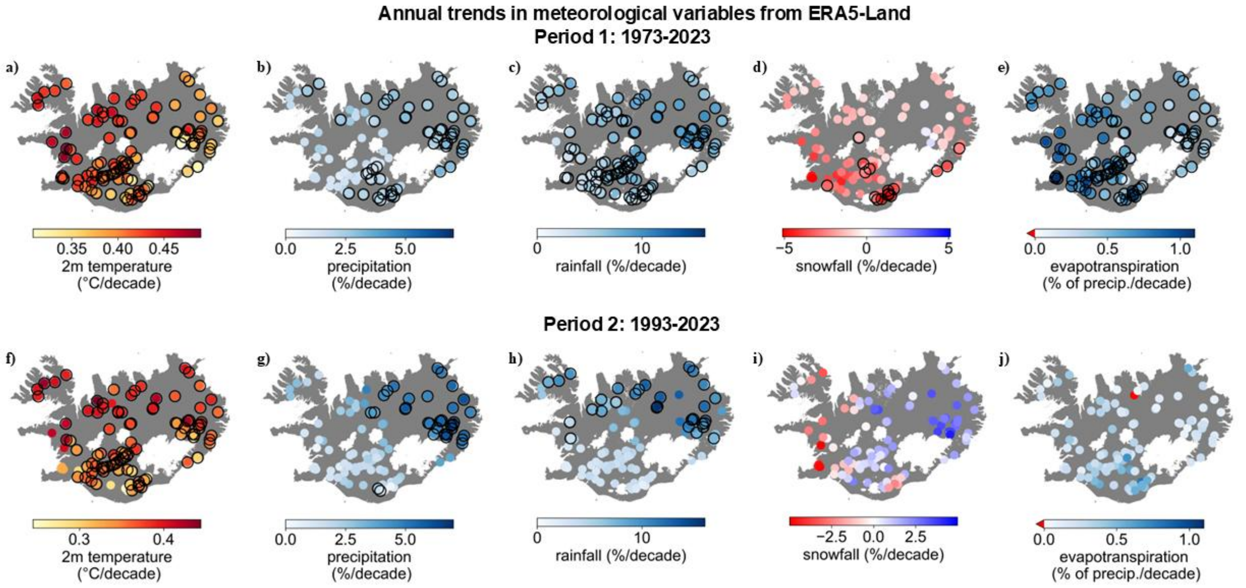

Figure 4: Trends in catchment-average 2m air temperature (a and f), precipitation (b and g), rainfall (c and h), snowfall (d and i) and evapotranspiration (e and j) from 1973-2023 and 1993-2023, with each point marking the streamflow gauge location. Evapotranspiration trends are shown as percentage of annual precipitation per decade. Black circles around gauge markers indicate statistically significant trends ($p < 0.05$). The data is from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021).

Figure 4a and f reveal significant increases in annual temperatures across all catchments in both periods, with stronger warming in the west, decreasing toward the east for period 1, and stronger warming in the north, decreasing towards the south for period 2. Precipitation trends are generally modest over these periods. In period 1, the strongest positive trends occur in the eastern part of the island (Figure 4b), and in period 2, trends are strongest in the northeast (Figure 4g). The magnitude of the trends is larger in period 2. Rainfall trends are positive and significant during period 1 (Figure 4c), but less pronounced in period 2 (Figure 4h). Snowfall displays near-zero or declining trends in all regions in period 1, with statistically significant decreases noted in the central south and southeast (Figure 4d). In period 2, snowfall increases are observed, although these trends are not statistically significant (Figure 4i). The strongest increases occur in the northeast, while decreases are observed in the west. Evapotranspiration (ET) trends are generally slightly positive but vary across regions. In period 1, ET increases are more widespread (Figure 4e) and statistically significant in almost all locations, while in period 2, ET trends are lower and not significant (Figure 4j). The overall increase in ET aligns with rising temperatures. However, these increases are small, accounting for less than 1% of annual precipitation per decade in most catchments. Figure S4 shows a comparison between the magnitude of trends in precipitation and ET in each basin (further discussed in Sect. 3.3.1).

3.2.2 Seasonal trends

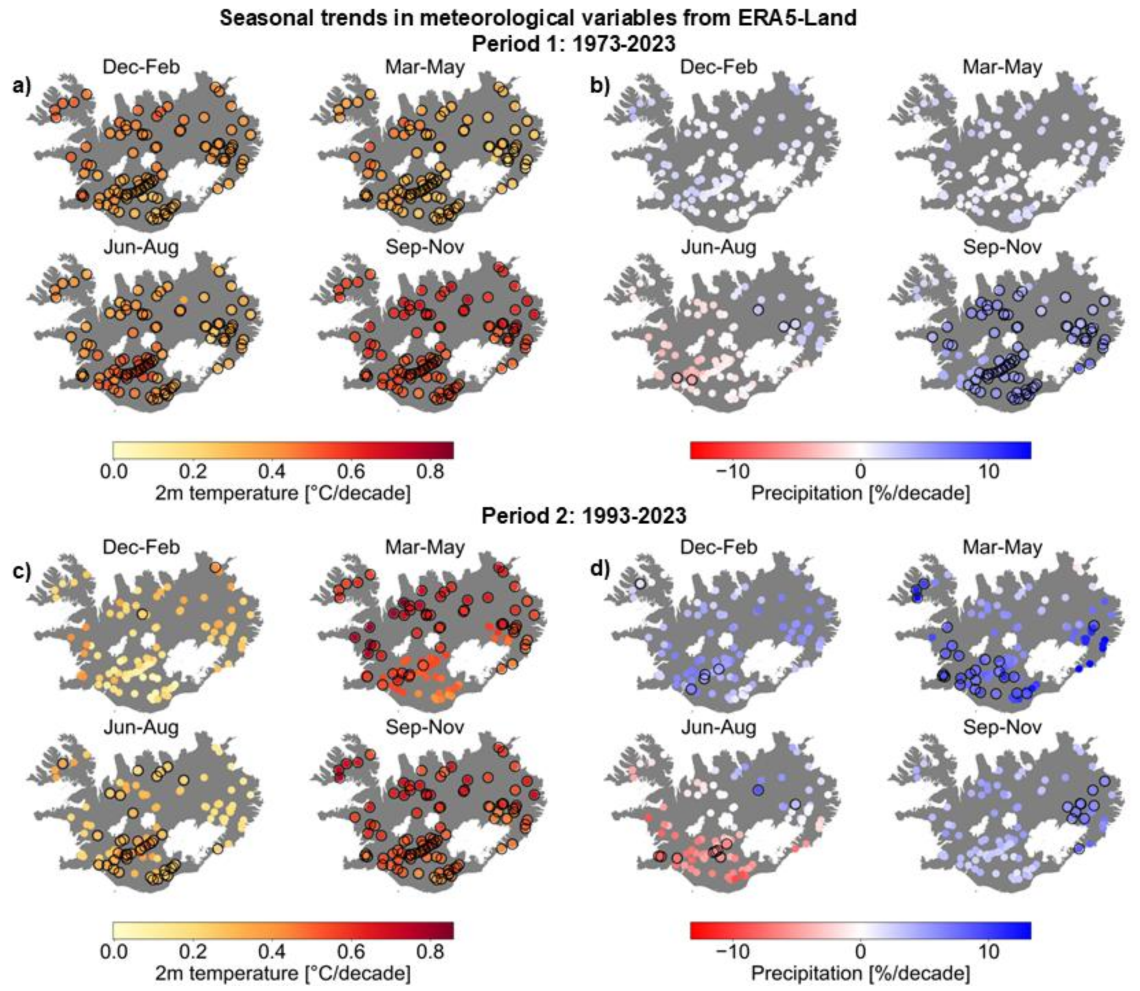

Figure 5: Seasonal trends in catchment-average 2m air temperature (a and c) and precipitation (b and d) from 1973-2023 and 1993-2023, with each point marking the streamflow gauge location. Black circles around gauge markers indicate statistically significant trends ($p < 0.05$). The data is from the ERA5-Land reanalysis (Muñoz-Sabater et al., 2021)**.**

Seasonal trends for 2m air temperature and precipitation for periods 1 and 2 are shown in Figure 5. The figure shows that, in almost all instances, temperature trends across all seasons for period 1 are statistically significant, displaying the highest increases in fall, whereas spring presents the smallest change. For precipitation (Figure 5b), significant positive trends are observed in the fall season for most catchments. The winter and spring seasons are characterized by modest positive or near-zero trends. In the summer season, precipitation increased slightly in the northeast region and decreased in the southwest.

Analysis of temperature trends for period 2 (Figure 5c) shows less statistical significance in seasonal temperature trends compared to period 1, with winter and summer exhibiting the least pronounced (and mostly insignificant) trends. Fall remains the season with the highest warming trend, but the spring season also has quite a high trend, which is a shift from period 1. As for precipitation (Figure 5d), the spring season shows the strongest positive trends in period 2, especially in the southwest. Winter and fall seasons exhibit positive trends, while summer persists in presenting an overall downward trend for precipitation as in period 1, with highest decreases in the southwest.

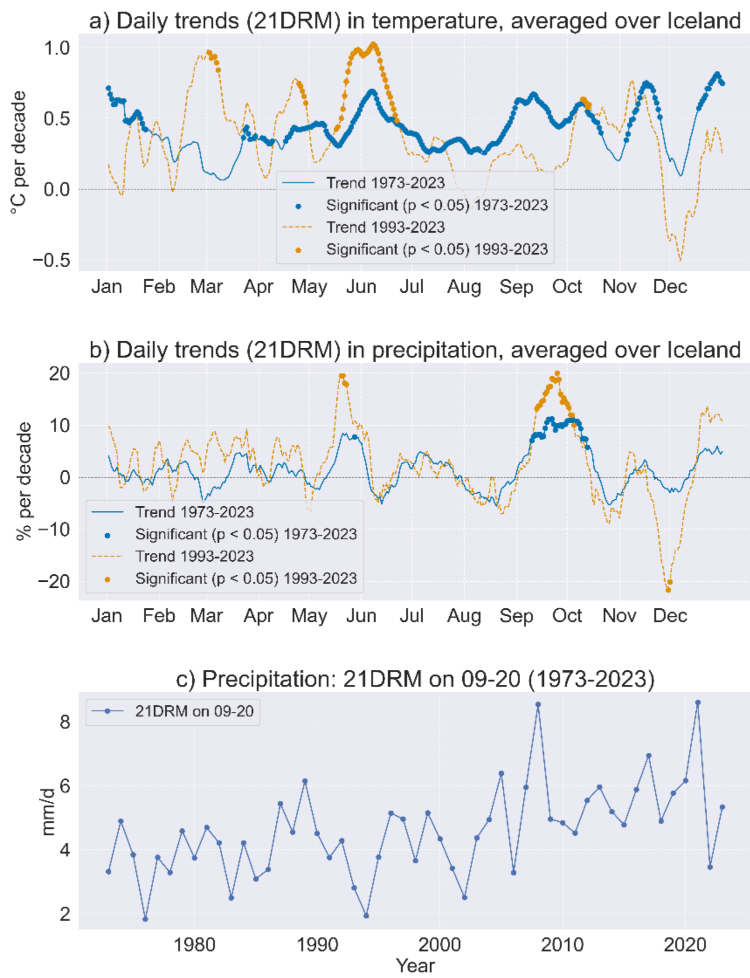

Figure 6: Daily trends in 21-day rolling means of 2m air temperature (a) and precipitation (b) from the ERA5-Land reanalysis for Iceland, shown for the periods 1973 to 2023 (blue) and 1993 to 2023 (orange). Precipitation trends for September 20th are highlighted separately in panel (c).

To better explain these variations within the year, Figure 6 shows average trend in 21DRM temperature and precipitation for all of Iceland for the two periods. The temperature trends in Figure 6a show that the values rarely fall below zero for either period. A notable exception for period 2 occurs in December, where decreasing trends are evident, corresponding to cooling during that month. Precipitation trends show a similar pattern (Figure 6b), with a decrease in December for period 2, indicating concurrent cooling and drying. Temperature exhibits statistically significant increases during most of the year for period 1. In contrast, statistically significant increases for period 2 are more limited, occurring mainly in two short periods in March and April and a more extended period from May to June.

For precipitation (Figure 6b), statistically significant increases are noted in May for both periods, although only a few data points meet the threshold for significance. A consistent period of significant increases is observed in September and October. The daily precipitation values for September 20 (Figure 6c) confirm these trends, showing notable increases, particularly since the mid-2000s, emphasizing the validity of the observed upward trend in autumn precipitation. In period 2, the highest sub-seasonal trends in temperature and precipitation are considerably stronger than the extremes in period 1, which could be due to an intensification of climatic extremes. Sub-seasonal trends in temperature and precipitation are shown for each catchment in Figure S5.

3.3 Trends in streamflow

Annual, seasonal, and sub-seasonal trends were calculated for streamflow records in LamaH-Ice with sufficient data coverage (Sect. 2.3), for the two periods, in the same manner as for the meteorological variables described in Sect. 3.2.

3.3.1 Annual and seasonal averaged streamflow

Figure 7 shows the annual and seasonal trends in streamflow for the gauges with sufficient data coverage for the two periods. Figure 8 shows a summary of these results in a heatmap. Figure S7 shows trends in annual and summer melt season streamflow for glacial rivers only. Figure S6 shows sub-seasonal trends in all rivers.

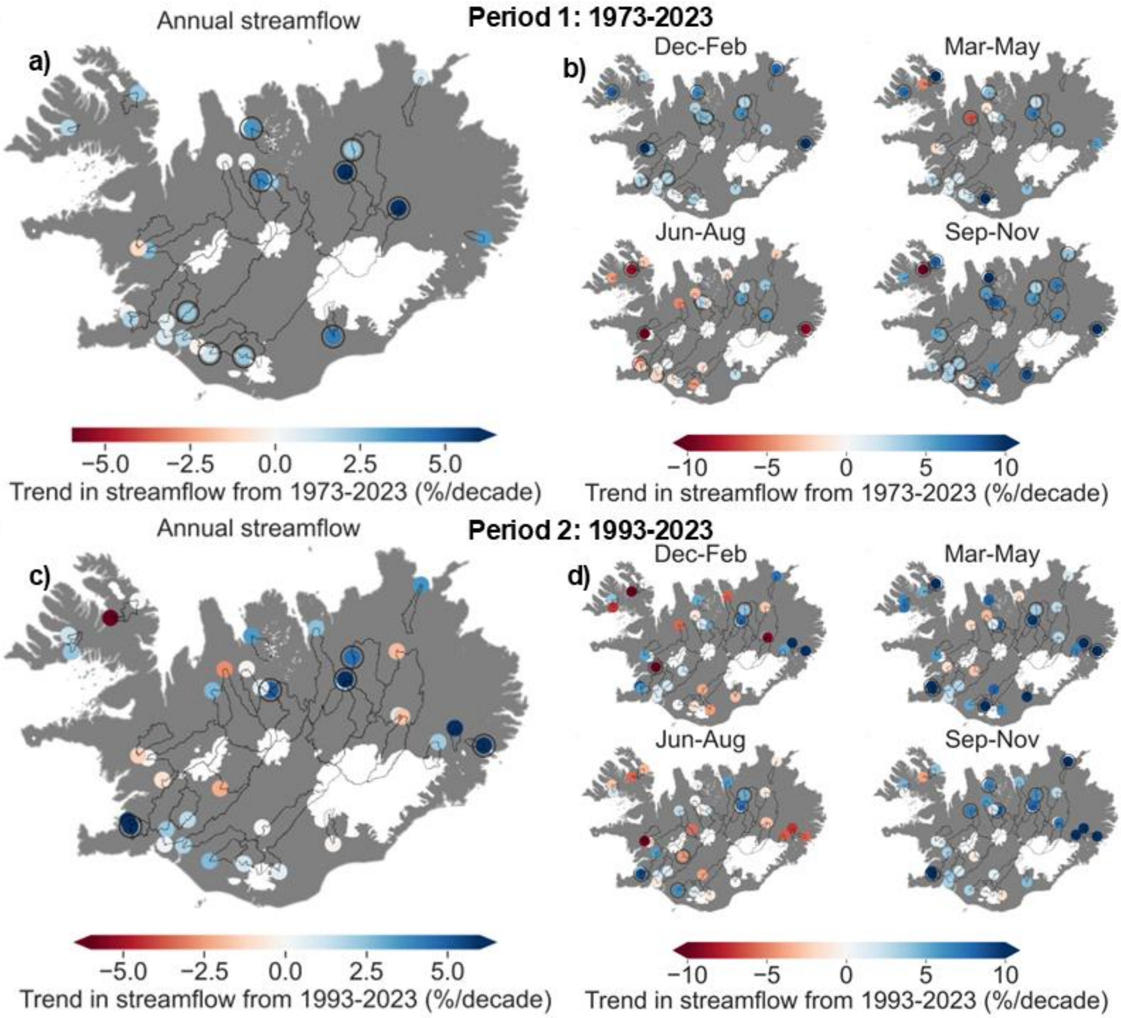

Figure 7: Annual (a, c) and seasonal (b, d) trends in streamflow from 1973-2023 (a, b) and 1993-2023 (b, d). Black circles around gauge markers indicate statistically significant trends ($p < 0.05$). Watershed outlines are shown for each gauge.

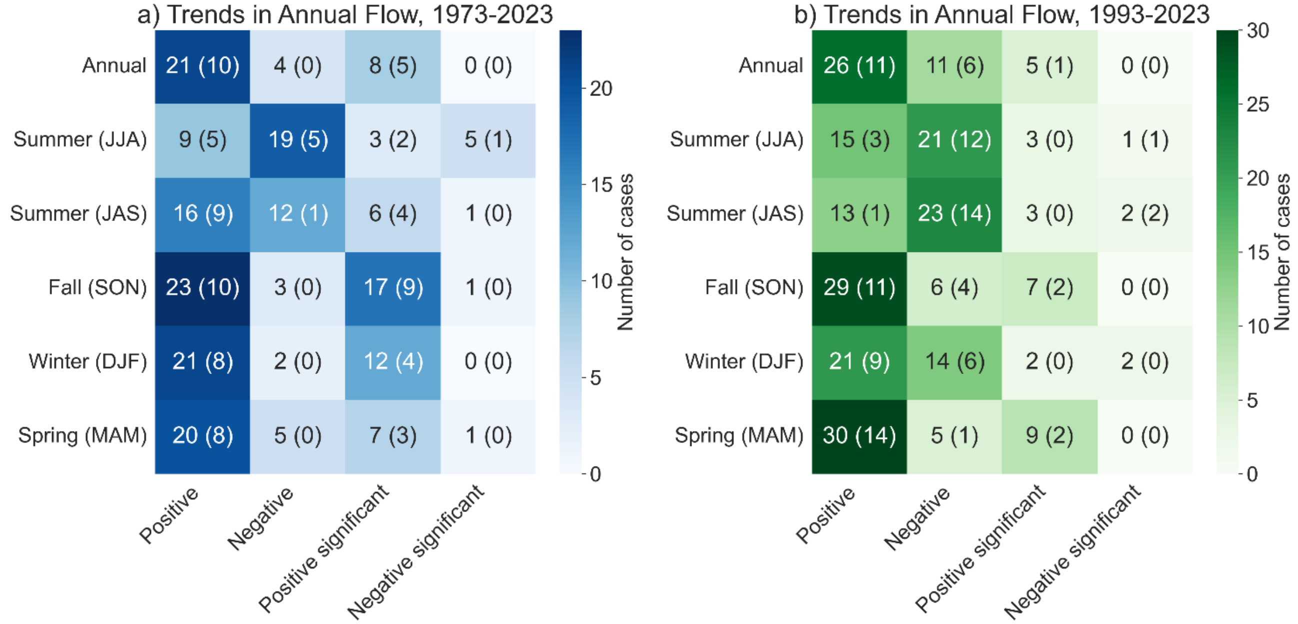

Figure 8: Heatmaps showing a summary of the results from analysis of annual and seasonal trends in streamflow for the periods 1973-2023 (a) and 1993-2023 (b). The numbers in parentheses indicate the count of basins with more than 5% glaciation.

Period 1:

Annual average streamflow for period 1 exhibits a positive trend in 21 out of 25 gauges (Figure 7a and Figure 8a), with increases ranging from 0.015% to 6.07% per decade. The trend in streamflow is highly correlated with the trend in rainfall (R=0.73, Figure S12). Further, the trend is also correlated with catchment mean elevation (R=0.67) and vegetation extent (yearly maximum NDVI) (R=-0.62) which are strongly interrelated (R=0.78). Despite the overall increase in streamflow, intra-annual variability is decreasing at a majority of gauges, as indicated by a decline in the annual CV and flashiness index (Figures S8a and S9a). The baseflow index is also increasing at a majority of gauges (Figure S10).

The seasonal analysis for period 1 (Figure 7b and Figure 8a) shows that most gauges exhibit increasing streamflow trends during the fall season, with 23 out of 26 gauges showing positive trends, 17 of which are statistically significant. These increases are moderately correlated with fall season precipitation increases (R=0.44, Figure S16) and catchment mean elevation (R=0.51). The strongest increases occur in September (Figure S6).

In winter, 21 out of 23 gauges show increasing trends, with 12 reaching statistical significance. Notably, rivers with lower baseflow index exhibit the largest proportional increases in streamflow (R=-0.69, Figure S13), reflecting more direct responses to increased rainfall and snowmelt.

In the spring season, 20 out of 25 gauges show positive trends, with 7 statistically significant. These trends are negatively correlated with changes in temperature (R=-0.58, Figure S14) and total ET (R=-0.56) and catchment mean root depth (R=-0.63), suggesting that higher evaporative demand and greater plant water uptake may reduce spring flows. Soil characteristics also seem influential: catchments with higher soil porosity exhibit stronger spring streamflow increases (R=0.68). The baseflow index increases during spring in 17 out of 25 gauges, and its trends show a correlation with soil characteristics (Figure S14), which may suggest that reduced frost in soils enables enhanced subsurface flow. In addition, streamflow becomes less flashy at the same number of gauges.

Summer (JJA) streamflow trends are negative at 19 out of 28 gauges, but only 5 of these trends are statistically significant. Summer streamflow trends are negatively correlated with spring temperature trends (R=-0.49, Figure S15) and positively correlated with catchment mean elevation (R=0.53), suggesting that earlier or decreased snowmelt may contribute to reduced flows in summer. There is also a strong correlation between summer streamflow trends and baseflow index (R=0.71), showing that surface-fed rivers are more prone to streamflow decreases in the summer. For rivers with less than 10% glacial coverage (n=20), this correlation is stronger (R=0.82).

All 10 glaciated basins exhibit positive annual streamflow trends during period 1, with statistically significant trends in 5 basins. The trend is positive during summer melt season (JAS) in most cases (9/10) as well, 4 of which are statistically significant.

Five rivers in the northern part of Iceland exhibit a significant trend in annual average streamflow. The positive trends observed in the two rivers that drain the large ice-caps Hofsjökull and Vatnajökull, Vestari-Jökulsá (gauge ID 93) and Jökulsá á Fjöllum (46), can be attributed to several factors: (1) increased glacier melt driven by rising temperatures and reduced snowfall, (2) a glacier surge in the Dyngjujökull glacier, which feeds the Jökulsá á Fjöllum river, occurring in 2000 and increasing glacier area at lower elevations, thereby accelerating melt rates, and (3) volcanic eruptions in Eyjafjallajökull (2010) and Grímsvötn (2011), which lowered glacier albedo and further enhanced melt. The positive trends in the remaining rivers, Hjaltadalsá (31), Laxá (64), and Sandá (70), are largely explained by a period of high precipitation from 2012 to 2015, which significantly influenced annual streamflow during this period.

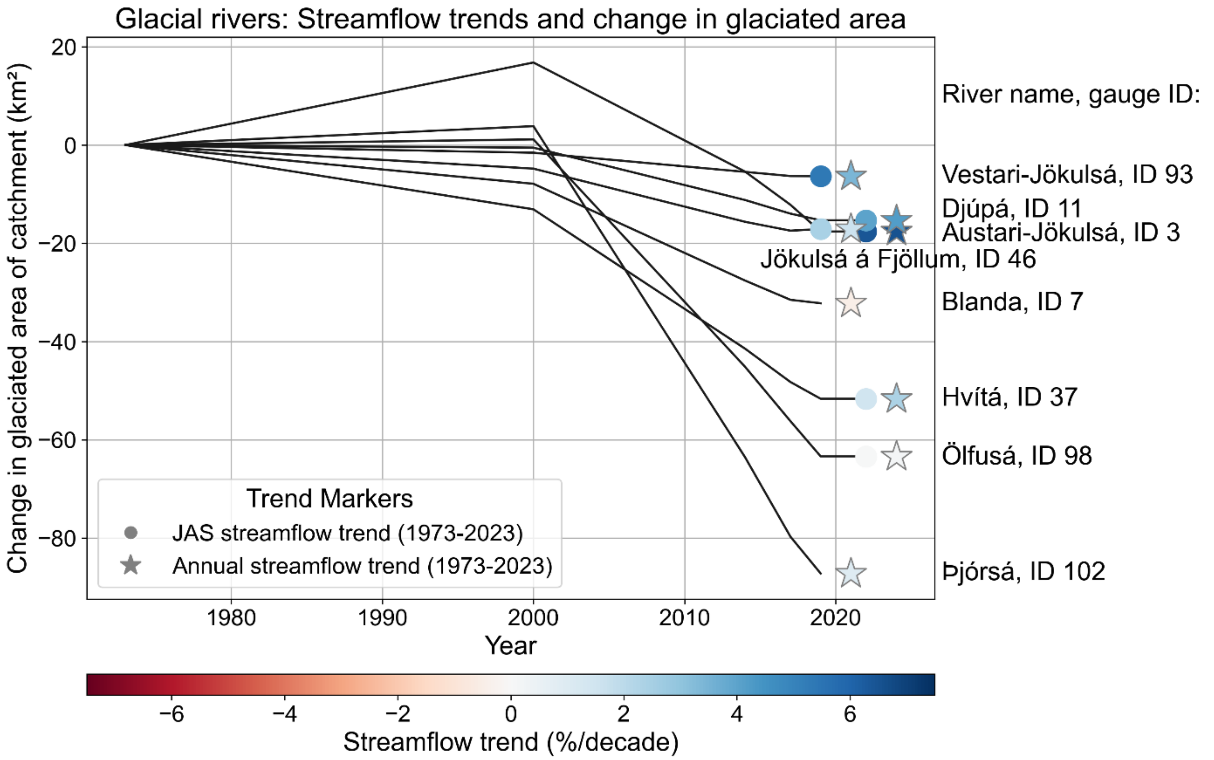

Figure 9: Streamflow trends in glacial rivers and their relationship to changes in glaciated area from 1973 to 2023. The figure highlights summer (JAS) streamflow trends and annual streamflow trends alongside changes in glaciated area, illustrating the dynamic interactions between glacial retreat and streamflow over the 50-year period. JAS season trends are omitted for Blanda and Þjórsá rivers since upstream reservoirs influence the seasonal flow in the river.

Figure 9 shows the relationship between streamflow trends in glacial rivers and the reduction in glaciated area from 1973 to 2023. The figure shows that rivers with minimal glacier area loss during period 1 show strong increases in streamflow, while those with more glacier area loss exhibit modest increases or even decreases. Although based data from few catchments, this suggests that reduced glaciated areas limit meltwater contributions, counteracting the effects of warming temperatures on streamflow. The figure emphasizes the critical role of glacial dynamics in shaping hydrological responses to climate change.

Period 2:

Annual streamflow increased at 26 out of 37 gauges, with positive trends ranging from 0.03% to 9.97% per decade. However, only 19% of these trends are statistically significant, compared to 38% in period 1. As in period 1, trends for annual coefficient of variation (CV) and flashiness are negative in period 2 for most gauges (Figures S8a and S9a), while baseflow index trends are positive (Figure S10a).

The seasonal analysis for period 2 shows that streamflow increased in the fall and spring at 29 and 30 out of 35 gauges, respectively, with statistically significant increases primarily observed in the north and east (Figure 7d). In fall, streamflow increases are most pronounced in late September and October (Figure S6b). Fall streamflow trends are moderately correlated with precipitation trends (R=0.41, Figure S21). In spring, streamflow trends are negatively correlated with baseflow index

(R=-0.53, Figure S19), indicating that surface-fed rivers tend to show stronger increases than groundwater-fed systems. Strong increases are particularly evident in April, followed by a decrease in May, indicating a potential shift in the timing of snowmelt (Figure S6).

During summer (JJA), streamflow trends are negative at 21 out of 36 gauges, although only one negative trend is statistically significant (Figure 7d). As in period 1, there is a correlation between summer streamflow trend and baseflow index (R=0.6, Figure S20), again suggesting that surface-fed rivers are more prone to streamflow changes.

The baseflow index shows positive trends in most gauges across all seasons, with the strongest signals in sumer (JJA): 28 out of 35 gauges show increasing trends, of which 6 are statistically significant (Figure S10.). In fall, the baseflow index trends correlate with soil attributes, potentially indicating that soil thawing contributes to increased baseflow. Similarly, in winter, declines in the flashiness index are correlated with soil attributes, implying changes in infiltration and runoff dynamics.

Most glaciated rivers have a negative trend for summer melt season (JAS) streamflow in period 2 (14 out of 15), but only 2 trends are statistically significant (Figure 8). The three rivers draining northern Hofsjökull glacier, Blanda, Vestari-Jökulsá and Austari-Jökulsá show divergent results. Blanda consistently shows negative or much smaller trends compared to the other two (Figure S7 c and d). This highlights the effects of local characteristics of the catchments on trend results.

To better understand the influence of changes in evapotranspiration on streamflow, and the main drivers of streamflow changes in the summer, Figure S4 shows a comparison between trends in precipitation and ET trends. Annually, precipitation increases exceed ET increases in both periods 1 and 2. Since ET in Iceland is energy-limited rather than moisture-limited (Helgason and Nijssen, 2024a), no clear relationship is observed between increases in precipitation and ET. In period 1, summer precipitation decreases, and ET increases are evident, suggesting that both factors contribute to streamflow reductions. In period 2, however, ET changes are minimal, aligning with small summer temperature trends, while precipitation decreases are more pronounced. This suggests that, among the two drivers considered, precipitation is more likely to explain the observed streamflow reductions. However, earlier or decreased spring snowmelt is also likely to contribute to these changes.

3.3.3 Trend in the timing of spring freshet onset, centroid of timing, and high/low flows

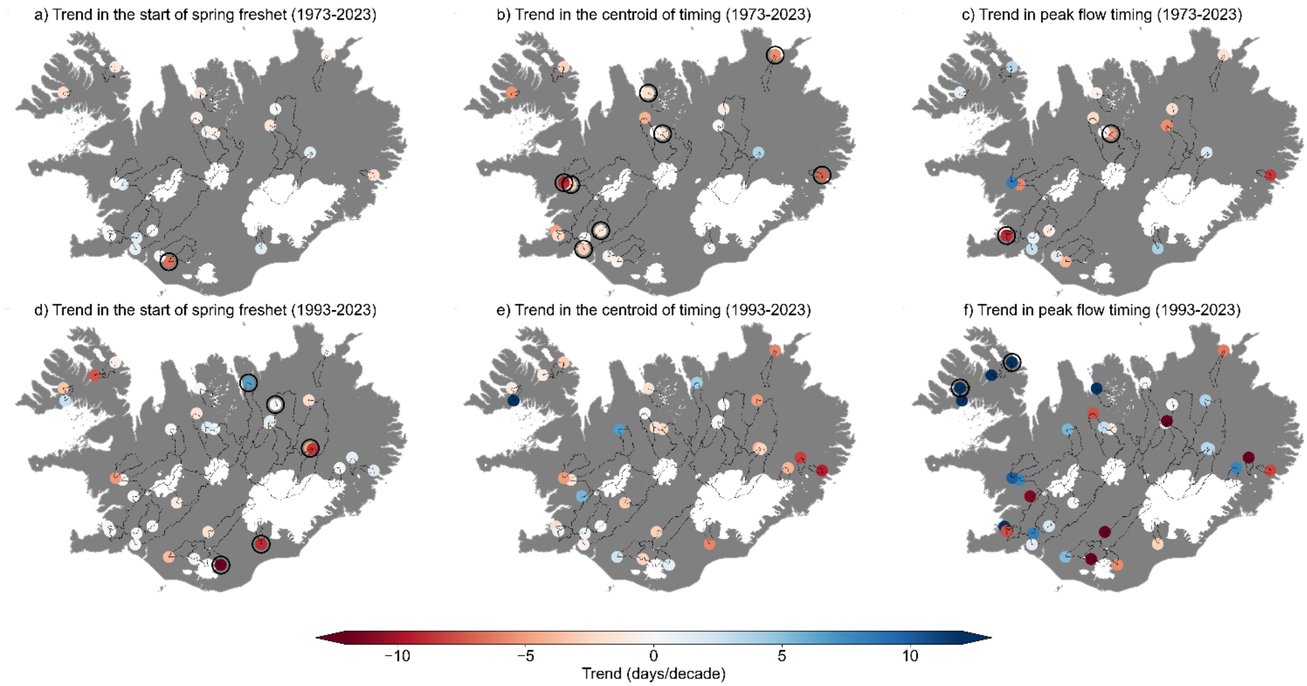

Figure 10: Trends in the timing of the spring freshet, the centroid of timing and peak flow timing for two periods: 1973–2023 and 1993–2023. Panels (a), (b) and (c) show the trend in the start of spring freshet, the centroid of timing and peak flow timing, respectively, for 1973–2023. Panels (d), (e), and (f) display the trends for 1993–2023. Trends are expressed in days per decade, with red indicating earlier timing and blue indicating later timing. Black circles around gauge markers indicate statistically significant trends ($p < 0.05$).

Figure 10 shows trends in the start of the spring freshet, centroid of timing, and peak flow timing for the two analysis periods. For both periods, trends in freshet onset are spatially variable, with both earlier and later shifts observed and no clear regional pattern. In period 1, trends in the freshet timing are generally weak and only one gauge shows a statistically significant trend toward earlier freshet (Eystri Rangá, ID 14, Figure 10a). In period 2, trend magnitudes are larger (Figure 10d), with three gauges showing statistically significant trends toward earlier onset and two toward later onset.

For the centroid of timing (the midpoint of annual flow), trends in both periods are predominantly negative, indicating earlier flow timing. In Period 1 (Figure 10b), 17 gauges show negative trends, 8 of which are statistically significant. Only 2 gauges exhibit positive trends, none of which are significant. In Period 2 (Figure 10e), negative trends persist at 22 gauges, but none are statistically significant; 8 gauges show positive trends. Notably, gauges in the eastern part of the country consistently exhibit earlier centroid timing in Period 2, while results are more mixed elsewhere. The trends in the timing of peak flow are mixed for both periods. Interestingly, all 4 gauges in the Westfjords exhibit strong positive trends in peak flow timing during Period 2 (Figure 10f), suggesting a shift toward later peak flows in that region.

Trends in spring freshet timing and peak flow timing showed no statistically significant or physically meaningful correlations with catchment characteristics in either period. In contrast, centroid of timing trends exhibited several notable relationships in period 1. Earlier centroid shifts were linked to surface-fed rivers, while shifts were smaller in groundwater-dominated catchments (R=0.71), consistent with the buffering effect of baseflow. Earlier shifts were also associated with low-elevation catchments (R=0.47). Increases in fall season precipitation likely contribute to this pattern, as rainfall at lower elevations enhances runoff generation early in the water year. Additionally, as temperatures rise, a greater proportion of precipitation falls as rain in low-elevation catchments, leading to increased winter flows and a further shift in the centroid of timing toward earlier in the year.

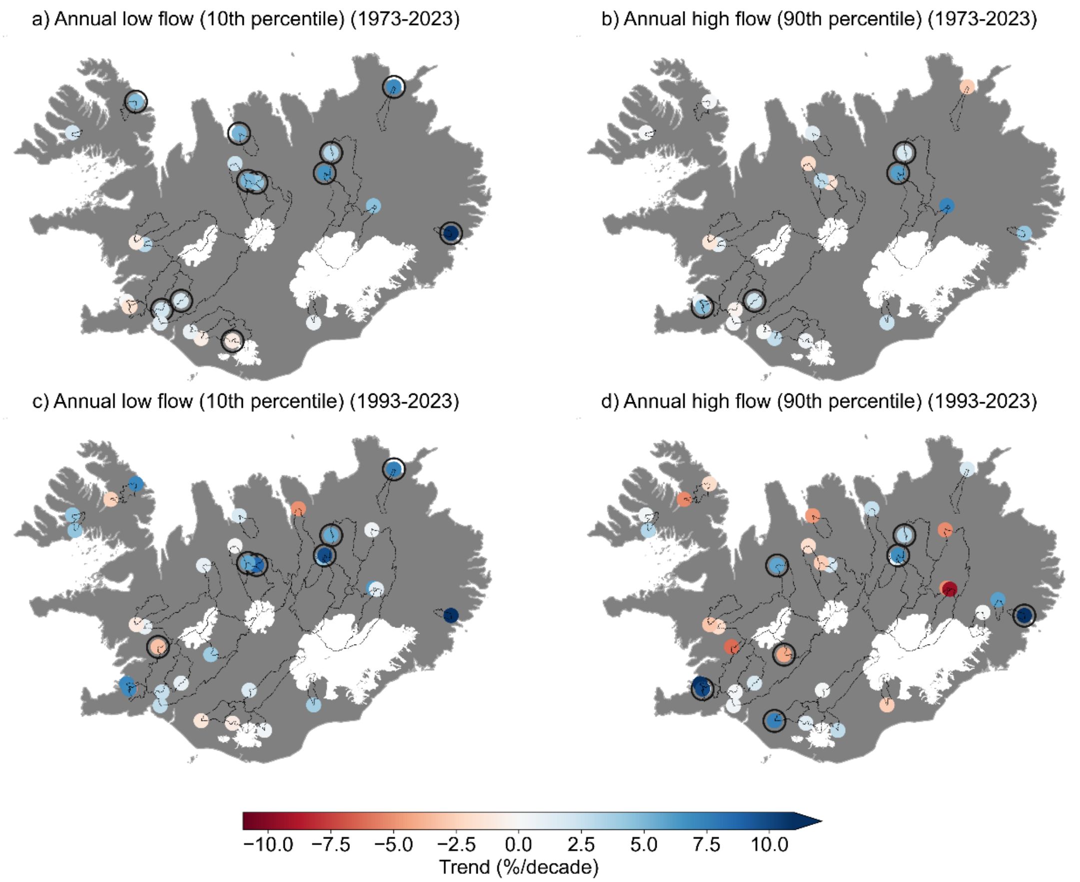

Figure 11: Trends in annual high and low flows for period 1 and 2. Annual low (a, c) and high (b, d) flows in streamflow from 1973-2023 (a, b) and 1993-2023 (b, d). Low and high flows are defined as the 10th and 90th percentiles of annual flow. Black circles around gauge markers indicate statistically significant trends ($p < 0.05$). Watershed outlines are shown for each gauge.

To investigate the change in the magnitude of low flows and floods, we extract the annual 10th and 90th percentiles of daily flow for each streamflow series. The trend in low and high flows is shown in Figure 11. For both periods, annual low flows show increasing trends for most streamflow gauges. Trends in high flows are mixed, with an almost even split between positive and negative trends for both periods (Figure 11 b and d), with fewer trends deemed significant. Trends for seasonal high and low flows are shown in the Supplement (Figure S11). For period 1, trends in high flows are positive and significant in most catchments in winter and fall, while summer and spring show mixed results. Trends in low flows are positive for most gauges in all seasons. For period 2, seasonal trends in low flows (Figure 8c) remain predominantly positive across most seasons and catchments, particularly in spring and fall, when many gauges show significant increases. Winter trends are more mixed, and summer trends are generally weak and spatially inconsistent, with fewer significant results. Trends in seasonal high flows (Figure S8d) are more spatially variable.

4. Discussion

4.1 Multiannual variability in streamflow in Iceland

Temperature, precipitation, and streamflow in Iceland exhibit pronounced multi-annual variability, driven largely by broad-scale atmospheric patterns. For example, streamflow in Iceland shows significant correlations with the Arctic Oscillation (AO) index (Figure 3). Fluctuations in streamflow reflect a complex interplay between precipitation, temperature, and glacier runoff, posing challenges for identifying long-term trends. Notably, streamflow in glaciated rivers increased significantly during the early 2000s, coinciding with an intense warming period and accelerated glacier melt. However, as the rate of warming has slowed in Iceland over the past decade, flows in most glaciated rivers have returned to near- or below-average levels. This aligns with glacier mass-balance measurements, which indicate a general slowdown in mass loss from 2011 onward compared to the rapid losses of the early 2000s (Aðalgeirsdóttir et al., 2020).

Glacier ablation has been shown to correlate with SSTs (Jónsdóttir and Uvo, 2009). Noël et al. (2022) attribute the reduced glacier mass loss after 2011 to the emergence of a regional cooling anomaly in the North Atlantic, southwest of Iceland, known as the 'Blue Blob'. This anomaly has dampened warming rates in Iceland, thereby reducing glacier meltwater runoff rates. The cause of formation of the 'Blue Blob' remains uncertain (Fan et al., 2024). Rahmstorf (2024) associates the ‘Blue Blob’ with a weakening Atlantic Meridional Overturning Circulation (AMOC), interpreting it as a symptom of reduced ocean heat transport to the region. Noël et al. (2022) project that the 'Blue Blob' will continue to mitigate glacier mass loss until at least the mid-2050s, based on simulations using the Regional Atmospheric Climate Model driven by the Community Earth System Model under the high-end SSP5-8.5 emission scenario. However, reliance on a single model scenario limits the robustness of such a projection, as alternative pathways could yield differing outcomes. Recent studies (Zanchettin and Rubino, 2024) document accelerated warming of SSTs in the North Atlantic in recent years, which may signal changes in the extent or influence of the 'Blue Blob' on regional climate patterns.

The 2024 water year was particularly challenging for Iceland's hydropower production. It was the coldest year since the turn of the century and the second driest (Figure 1), leading to significantly reduced inflows into hydropower reservoirs. Iceland’s National Power Company, Landsvirkjun, has a curtailment stipulation in its agreements with its largest industrial customers, so when reservoir inflows are low, energy deliveries can be reduced. These stipulations were activated in the 2024 water year, as well as in the following water year. Similar to the severe drought of 2013-2014, the combination of low precipitation and cold temperatures severely reduced runoff, highlighting the vulnerability of Iceland's hydropower system to prolonged dry

spells and limited reservoir inflows. Agriculture in Iceland was similarly affected: the 2024 potato harvest was the smallest since 1993, and carrot production reached an 11-year low, down 53% from the previous year (Statistics Iceland, 2025). In response to these widespread crop failures and production losses, the government issued financial compensation to farmers.
Overall, the strong variability in streamflow highlights the sensitivity of Icelandic hydrology to atmospheric and glaciological conditions. The findings emphasize the importance of integrating large-scale climatic influences, such as the AO and regional North Atlantic cooling, when interpreting multiannual variability and long-term streamflow trends in Iceland. These results align closely with findings by Jónsdóttir and Uvo (2009), who reported similar variability but based on data from fewer gauges.

4.2 Trends in meteorological drivers and streamflow

4.2.1 Trends in meteorological drivers

Our results show that temperature has increased significantly in Iceland during the past decades. Spring and fall seasons show the largest positive trends during the last 30 years, while fall shows the largest positive trend during the last 50 years. Our results also show that precipitation has increased in Iceland during both periods. These results are consistent with findings from previous studies (Eythorsson et al., 2023, Björnsson et al., 2023).
An interesting finding is the increase in precipitation during September, particularly for the last 30 years. This sub-seasonal increase in precipitation has not been highlighted before to the authors' knowledge, although Gunnarsson et al. (2019) reported a modest increasing trend in September snow cover between 2000 and 2018. These precipitation increases may reflect a shift in the timing of precipitation associated with regional atmospheric circulation changes. Even though the overall trend results were similar for the two periods, differences in the magnitude and spatial distribution of trends highlight the sensitivity of results to the period chosen for analysis. Eythorsson et al. (2023) showed that climate simulations project similar rate increases for both temperature and precipitation during the rest of the 21st century.

4.2.2 Trends in streamflow

4.2.2.1 Period 1: 1973-2023

Annual streamflow trends were predominantly positive during the 50-year period (1973-2023). This increase can primarily be attributed to rising precipitation, as well as enhanced glacier melt in glaciated catchments. The strongest positive trends were observed in the northeastern part of the country, where precipitation increases were most pronounced (Figure 4).
Seasonal trends reveal that fall and winter streamflow increased significantly across most catchments, reflecting higher precipitation during these seasons and warmer temperatures. Spring streamflow trends were more modest, and likely modulated by evapotranspiration and vegetation influences. Summer streamflow declined in non-glacial rivers, driven by reduced summer precipitation, elevated ET, and earlier or decreased snowmelt. Surface-fed rivers showed the greatest decrease in summer streamflow, while rivers with high baseflow showed minimal trends.

For glaciated rivers, trends during the summer melt season were predominantly positive over the 50-year period. Enhanced meltwater contributions during this time can be attributed to strong warming trends, with the period between 1973 and 2000 being much cooler than the period after 2000, as well as effects from volcanic eruptions and glacier dynamics. For example, eruptions at Eyjafjallajökull in 2010 and Grímsvötn in 2011 deposited ash on glaciers, reducing their albedo and temporarily increasing melt rates. Similarly, the Dyngjujökull surge in 2000 expanded the glacier at lower elevations, temporarily boosting summer flows in the Jökulsá á Fjöllum river. Our findings suggest that in catchments with large reductions in glacier area, the summer melt season streamflow has decreased. This is likely because less glacier area results in less surface available for meltwater production.

Low-flow trends during 1973-2023 were consistently positive across most gauges, likely driven by enhanced winter rainfall and snowmelt contributing to groundwater recharge. High-flow trends, on the other hand, were more variable, reflecting regional differences in snowfall and extreme precipitation.

4.2.2.2 Period 2: 1993-2023

Trends observed over the last 30 years were more variable and less spatially coherent compared to the longer period. Annual streamflow trends remained predominantly positive, but the relative number of gauges with statistically significant trends decreased. Notably, trends in glaciated rivers during the summer melt season were generally negative. The unusually warm period in the early 2000s amplified meltwater contributions, but this was followed by a cooler period after 2011, during which glacier melt was reduced. These cooler conditions, combined with reduced glacier area in some catchments, appear to have influenced the lack of a sustained increasing trend in the glacial rivers. It should however be noted that the relationship between glacier response to climate change and streamflow changes is complex and varies between different glacier types. The presence of both mountain glaciers and large ice caps further complicates this relationship due to differences in meltwater storage and dynamics.

Seasonal trends during the last 30 years also differ from the longer period, with fall and spring seasons showing the most pronounced increasing trends. In non-glaciated basins, streamflow reductions in summer were more pronounced during this period, likely driven by decreases in summer precipitation and earlier or decreased spring snowmelt. The sub-seasonal trends in both periods showed streamflow increases in September and October, coinciding with enhanced precipitation.

Additionally, both the coefficient of variation and flashiness index show declining trends over the 30- and 50-year periods, indicating a general reduction in within-year streamflow variability. A general increase in the baseflow index was evident across both periods, and correlations were found between baseflow index trends trends and catchment soil attributes in fall and spring. This could indicate that reduced soil frost enables greater sub-surface flow, thereby damping variations in streamflow.

4.2.3 Comparisons with previous studies

Past studies of streamflow trends in Iceland reported small or insignificant trends, despite increases in precipitation (Jónsdóttir et al., 2006, 2008). Our study uses a larger dataset than has been done before, and our results show significant positive trends in annual and seasonal streamflow in many rivers, particularly over the last 50 years. While a large majority of annual trends are positive (21 out of 25 streamflow stations), eight stations show statistically significant increases in streamflow for the period 1973-2023. The same holds true for 5 out of 37 for the period 1993-2023. Our analysis shows that the timing of the spring freshet has not systematically shifted, consistent with the findings of Wilson et al. (2010) for the period 1961–2000. The timing of the annual peak flows have also not systematically changed.

Our findings align with previous studies that showed a strong correlation between streamflow in Iceland and the AO (Jónsdóttir and Uvo, 2009). We provide new insights into sub-seasonal trends and identify increases in September and October precipitation and streamflow, which have not been reported before.

In the context of northern regions, our findings are consistent with studies that show increases in precipitation and streamflow (Box et al., 2019; Stahl et al., 2010). Many Arctic and sub-Arctic regions have observed rising winter flows due to increasing temperatures and/or precipitation (e.g. Skålevåg and Vormoor, 2021).

5. Conclusions

In this study, we analyzed streamflow variability and trends in Iceland, focusing on multi-annual, seasonal, and sub-seasonal changes. The results show a large inter-annual variability in streamflow and its main drivers, with notable multi-year fluctuations and a strong correlation with the Arctic Oscillation, consistent with previous studies. In recent decades, precipitation has increased in Iceland, which has led to increased flows in many rivers. Positive trends are found for most gauges for the last 30 and the last 50 years of annual and seasonal (fall, winter and spring) flows, thus making this the first study to report such consistent results for streamflow trends in Iceland. In contrast, summer flows have declined in most non-glaciated basins, albeit insignificantly, mainly due to decreasing summer precipitation, increased ET and earlier/decreased snowmelt.

Flow in glacial rivers was high in the early 2000s due to high temperatures, increased rainfall on glaciers, and enhanced melt, but has decreased again in recent years, reflecting a less negative glacier mass balance that is closer to equilibrium. Over the last 50 years, glaciated rivers exhibit positive trends in both annual (10 out of 10 gauges) and melt season (9 out of 10) flows, whereas in the last 30 years, they show negative trends during the melt season (14 out of 15) and more variable results for annual flows. This is linked to a regional cooling anomaly in the North Atlantic, which could possibly be caused by the weakening of the AMOC (Rahmstorf, 2024).

Despite warming, the timing of spring freshet has not significantly shifted earlier according to our analysis. However, streamflow centroid timing has advanced, particularly in the longer period (1973–2023), largely due to increased runoff in fall and winter.

The magnitude of annual low flows has increased in most rivers. Furthermore, intra-annual streamflow variability has decreased, as evidenced by declining trends in both the coefficient of variation and flashiness index. The proportion of baseflow in the total flow has increased, which may suggest that reduced soil frost enables enhances in sub-surface flows.

Our findings underscore that streamflow trend analyses are sensitive to the period considered, as decadal-scale fluctuations, such as those observed in glacial rivers, can substantially alter both the direction and strength of the detected trends. The results from this study have potential operational implications for reservoir management in Iceland. With an observed trend of increasing flows during the drawdown period (fall to spring), reservoir operators may consider adjusting seasonal operating rules to enable increased winter energy generation while maintaining storage capacity for spring snowmelt. In addition to hydropower operations, the changing streamflow regime may affect water availability for municipal, agricultural and ecological systems, particularly during the summer months when evapotranspiration is highest and flows are lowest in non-glaciated rivers. Resource managers should anticipate more frequent low-flow conditions in summer and consider developing drought contingency plans, anticipate an increased wildfire risk, and enhance monitoring of ecological minimum flows. Our results highlight the need for integrated seasonal planning that accounts for both increasing winter availability and heightened summer drought risks in a warming climate.

Investigating the relationship between streamflow and a broader set of climate indices, SSTs, and other large-scale atmospheric patterns could provide valuable insights into the climate drivers of streamflow variability, and potentially improve seasonal prediction skill. Additionally, an analysis of streamflow periodicity could help identify cycles that contribute to long-term variability. The ERA5-Land atmospheric reanalysis data used in this study uses static glacier and vegetation masks. To better understand the drivers of changing hydrological conditions in Iceland, a hydrological reanalysis using a process-based model that incorporates dynamic vegetation and glaciers would be beneficial. Such an approach could clarify the impacts of receding glaciers, changing glacier geometries, and expanding vegetation cover on streamflow patterns. Modeling soil-freeze thaw dynamics could clarify the role of reduced ground frost in the observed increases in baseflows.

6. Data availability

Streamflow observations and meteorological timeseries used in this study are part of the LamaH-Ice dataset (Helgason and Nijssen, 2024b), which is available for download on HydroShare.

7. Code availability

The code used in this study is available on GitHub, https://github.com/hhelgason/iceland-hydro-trends

8. Author contributions

HBH and BN designed the study. HBH performed the data analysis and wrote the manuscript. BN, ÓGBS and AG reviewed the results and the manuscript and provided consultations and contributions throughout the work.

9. Competing interests

The authors declare that they have no competing interests.

10. Acknowledgements

The authors used OpenAI's ChatGPT to assist with language refinement during manuscript preparation. All scientific content, structure, and interpretation were developed by the authors. ChatGPT was employed to improve grammar, clarity, and flow in select sentences and paragraphs. All AI-assisted text was critically reviewed, revised, and finalized by the authors, who take full responsibility for the content of the manuscript.

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