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LETTER

Increasing Alaskan river discharge during the cold season is driven by recent warming

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Abstract

Arctic hydrology is experiencing rapid changes including earlier snow melt, permafrost degradation, increasing active layer depth, and reduced river ice, all of which are expected to lead to changes in stream flow regimes. Recently, long-term (>60 years) climate reanalysis and river discharge observation data have become available. We utilized these data to assess long-term changes in discharge and their hydroclimatic drivers. River discharge during the cold season (October–April) increased by 10% per decade. The most widespread discharge increase occurred in April (15% per decade), the month of ice break-up for the majority of basins. In October, when river ice formation generally begins, average monthly discharge increased by 7% per decade. Long-term air temperature increases in October and April increased the number of days above freezing (+1.1 d per decade) resulting in increased snow ablation (20% per decade) and decreased snow water equivalent (−12% per decade). Compared to the historical period (1960–1989), mean April and October air temperature in the recent period (1990–2019) have greater correlation with monthly discharge from 0.33 to 0.68 and 0.0–0.48, respectively. This indicates that the recent increases in air temperature are directly related to these discharge changes. Ubiquitous increases in cold and shoulder-season discharge demonstrate the scale at which hydrologic and biogeochemical fluxes are being altered in the Arctic.

1. Introduction

The annual climate of Alaska has historically followed a predictable pattern of seasonal change. Mean daily air temperatures can remain below freezing for more than six months. During this time, the ground is frozen (Obu *et al* 2019), minimizing shallow groundwater runoff (Walvoord *et al* 2012), precipitation falls as snow and is stored on the land surface, and the rivers freeze. In spring, the days lengthen, and more solar energy reaches the surface melting the snow and ice. Rivers begin to flow when the ice breaks up and water temperatures rapidly increase. This seasonal increase in water temperatures allows fish to hatch and grow (Sparks *et al* 2019). Peak discharge occurs in May or June, at which time most of the snow has melted in the lowlands (Stone *et al* 2001) and the active layer above the permafrost has begun to thaw (Chen *et al* 2019). Summer rainfall runs off rapidly particularly in areas with underlying permafrost and can cause flashy discharge response. In the autumn, discharge decreases as temperatures drop below freezing, snowfall accumulates, the active layer refreezes, and river ice forms.

Rapid climatic warming has increased the mean annual air temperature (MAAT) in Alaska by 2.1 °C over the last 70 years (Walsh and Brettschneider 2019), which has altered hydrologic conditions via reduced snowpack, permafrost degradation (Li *et al* 2022), increased subsurface flow and soil moisture (Walvoord *et al* 2012), and altered precipitation (Bieniek *et al* 2014). These hydrologic responses to anthropogenic climate change are often reflected by the magnitude and seasonality of river discharge (Van

Vliet *et al* 2013). Across Alaska, increases in low flows and peak flows have been reported (Gudmundsson *et al* 2019), which have been attributed to alterations in the magnitude and phase of winter precipitation and higher spring temperatures (Bennett *et al* 2015).

Air temperatures have increased across Alaska, with increasing maximum and minimum temperatures (Bieniek and Walsh 2017). Since 1950, mean air temperatures during the cold-season have warmed more rapidly (4.1 °C) than the MAAT (2.1 °C) (Walsh and Brettschneider 2019). Winter warming has altered historically stable river ice causing increased mid-winter break-up events (Hori *et al* 2018), which poses flood risks to communities and isolates Indigenous people from neighboring communities as well as traditional hunting and fishing grounds (Burrell *et al* 2022). Alaskan river discharge is increasing significantly during the winter months due to thawing permafrost, which creates deeper flow paths and recirculation of sub-permafrost groundwater (Walvoord and Striegl 2007) increasing chemical fluxes to rivers (Toohey *et al* 2016). Autumn and spring discharge has also increased (Bennett *et al* 2015), however this change is attributed to higher temperatures, which shorten the snow-cover season and cause runoff to occur earlier in the year (Prowse *et al* 2010).

Previous studies have used a combination of observations and modeling to assess climatic changes and river discharge response (e.g. Walvoord and Striegl 2007, Prowse *et al* 2010, Bennett *et al* 2015). Low frequency climate variability can obscure long-term climate and discharge trends on short time scales (Hannaford *et al* 2013). A 30 year period is usually considered adequate to average out this short-term variability although longer term records are preferred (Hannaford *et al* 2013). A 60 year time period sufficiently averages out low frequency climate variability for trend analysis and it can also be disaggregated into two 30 year periods that can be analyzed separately for changing conditions. Long-term observational records are rare in Alaska, so most studies focus on few rivers and/or short time spans. Only recently has the observed discharge record exceeded 60 years of continuous data over a geographically diverse region of Alaska (U.S. Geological Survey 2022). Additionally, new climate datasets, such as the 5th generation reanalysis project from the European Centre for Medium-Range Weather Forecasts (ERA5), based jointly on observations and modeling have recently become available so that the hydroclimatic drivers of river discharge can be evaluated on a large scale (Muñoz Sabater 2019, 2021).

Here, we utilized long-term climate and river discharge datasets from nine basins spanning climate, meteorology, permafrost extent, and latitude in Alaska to evaluate the hydrometeorological drivers of changing river discharge. Many components of the hydrological cycle are sensitive to climate, so understanding how the climate has changed during the extended period of record is crucial to understanding past, present, and future changes.

2. Methods, data, study area

2.1. Study area and data sources

This analysis considered all United States Geological Survey (USGS) discharge gages in Alaska except for gages in the Aleutian Islands and in southeastern Alaska, which have different climate drivers than the rest of Alaska. Daily discharge data were extracted from the USGS National Water Information System (https://waterdata.usgs.gov/nwis/sw) (U.S. Geological Survey 2022), and each gage record was analyzed for data gaps. For this study, a record needed 350 d to be considered a complete year and 90% of the years needed to be complete from 1960–2019 for the record to be used. These criteria were met by 8 of the 114 currently active Alaskan gages. To achieve a geographic spread of river gages, the Kuparuk River on the North Slope of Alaska was added to the analysis even though it only had 48 years of continuous data available. Ultimately, nine USGS stream-gage records were analyzed in this study (figures 1 and S1) that span a range of size, permafrost extent, and climate and hydrologic conditions (table S1).

Three basins used in this study have regulation. The Chena River Lakes Flood Control Project was built in 1979 with the goal of preventing flooding in Fairbanks, AK. The diversion allows water to flow over the natural riverbank into the floodway when river elevation is $\geqslant$151 m mean sea level (roughly 340 $m^3 s^{-1}$ which will artificially flatten peak discharge (U.S. Army Corps of Engineers 2022). Ship Creek has a small run-of-the-river dam 240 m above the gage. This dam was put in place so that the City of Anchorage and the Joint Base Elmendorf-Richardson can pull drinking water from the river. There are no publicly available data on the amount of water withdrawn from the stream at this dam, but a U.S. Army Corps of Engineers study (Daly 2019) found that on average it is about 0.1 $m^3 s^{-1}$ (2% of mean annual discharge). Finally, the Kenai River watershed has a hydroelectric dam that imports transboundary water. An analysis by the U.S. Forest Service (Blanchet *et al* 2003) found that, on average, the hydroelectric plant has only caused discharge to increase by 0.42 $m^3 s^{-1}$ (<0.5% of mean annual discharge) at the Kenai River gage. This hydroelectric station reached full capacity in 1962, so water years 1960–1961 were dropped from the Kenai River record to account only for the years with the altered discharge. However, trends in winter discharge when river flow is at a minimum may be masked by the contribution of water due to the hydroelectric plant outweighing any changes due to changing hydroclimatic conditions.

ERA5 data, a gridded climatological dataset produced by the European Centre for Medium-Range

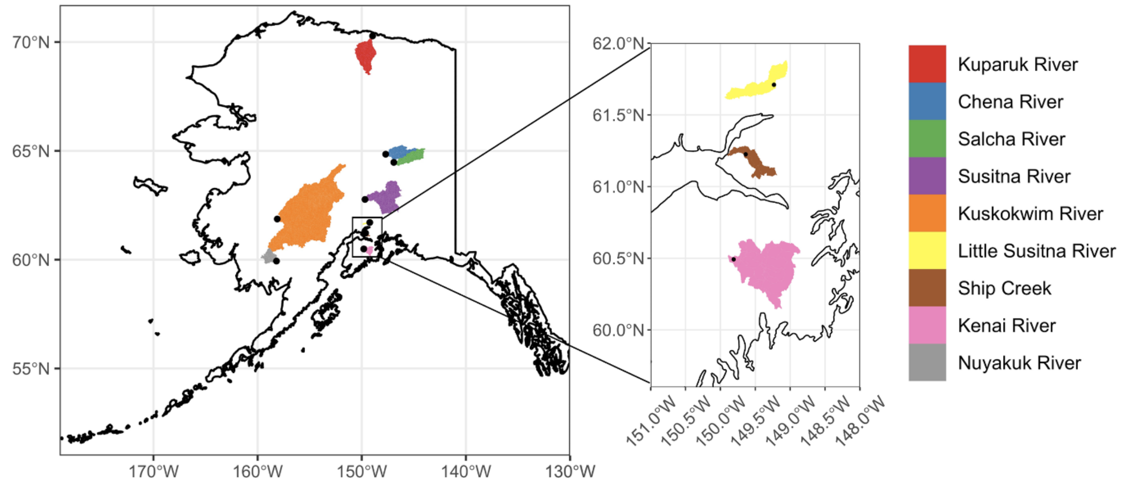

Figure 1. Location of nine U.S. Geological Survey gaging stations (U.S. Geological Survey 2022) for Alaskan rivers with long-term discharge records (black dots) and their corresponding watershed areas.

Weather Forecasts, were used for compiling historic climate patterns (Muñoz Sabater 2019, 2021). It provides hourly estimates of hydroclimatic variables on a 30 km grid by combining historic observations into global estimates using data assimilation and modeling. Quality assured data are available from 1979 to present and preliminary data are available from 1950–1978 (Muñoz Sabater 2021). Air temperature, precipitation, snow water equivalent (SWE), soil temperature (averaged from 0 to 100 cm), and soil moisture (in water equivalence averaged from a depth below the ground surface of 0–100 cm) were extracted from this dataset for each basin by taking the weighted average of every grid cell intersecting the basin. These hourly basin averages were then resampled to mean daily values. Soil moisture values are usually in excess of 90% so trends in this variable may be artificially reduced. These variables were used to calculate ancillary hydroclimatic metrics. The number of days above freezing were calculated for each month by adding any day where the mean daily temperature was above the freezing point. This serves as a conservative estimate of days when melt may occur. Snow ablation, which is the sum of daily snowmelt and sublimation, was calculated as the daily loss of SWE between consecutive days. Snow accumulation was calculated by summing the daily gain in SWE between consecutive days.

The Pacific North American (PNA) Pattern, the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO), and the El Nino Southern Oscillation (ENSO) index are used to assess low frequency climate variability in Alaska (L'Heureux *et al* 2004). Daily values of these climate indices were collected from the National Oceanic and Atmospheric Administration website (https://psl.noaa.gov/data/climateindices/list/) and averaged to obtain mean monthly values.

2.2. Statistical analyses

Monthly time series of climate variables and discharge were analyzed using the non-parametric seasonal Mann–Kendall test for monotonic trends (Mann 1945) as implemented in the *modifiedmk* package in R (Patakamuri and O'Brien 2021). This non-parametric test was chosen over a parametric test because the discharge data were skewed and to remain consistent with similar studies (e.g. Rennermalm *et al* 2010, Shrestha *et al* 2021a, Liu *et al* 2022). The seasonal Mann–Kendall test is unaffected by seasonality because it compares the same month throughout time. Auto-correlation is minimal on monthly data, so pre-whitening is not required (Zhang *et al* 2016). The results were compared to pre-whitened data to check this assumption and the results were similar. The Kuparuk River was analyzed using the 48 years of data available. For all other rivers, 60 years were used. Data gaps in the river hydrographs (figure S1) are relatively sparse (on average 3.3% (n = 60) of water-years), and the Mann–Kendall allows for data gaps (Gilbert 1987), so no attempt was made to in-fill data. Trend slopes were determined using the Sen method (Sen 1968).

The Spearman Rank correlation function in base R (R Core Team 2022) was used to evaluate how much of the discharge variance each climate index and hydroclimate variable could describe. Like the Mann–Kendall test, the Spearman Rank test is non-parametric and unaffected by seasonality when performed on monthly data. The correlation is assessed as very strong (absolute value of the correlation 0.8–1), strong (0.6–0.8), moderate (0.4–0.6), weak (0.2–0.4), and very weak (0.0–0.2). The timeseries was disaggregated into a historic (1960–1989) and recent (1990–2019) period to understand recent climatic changes.

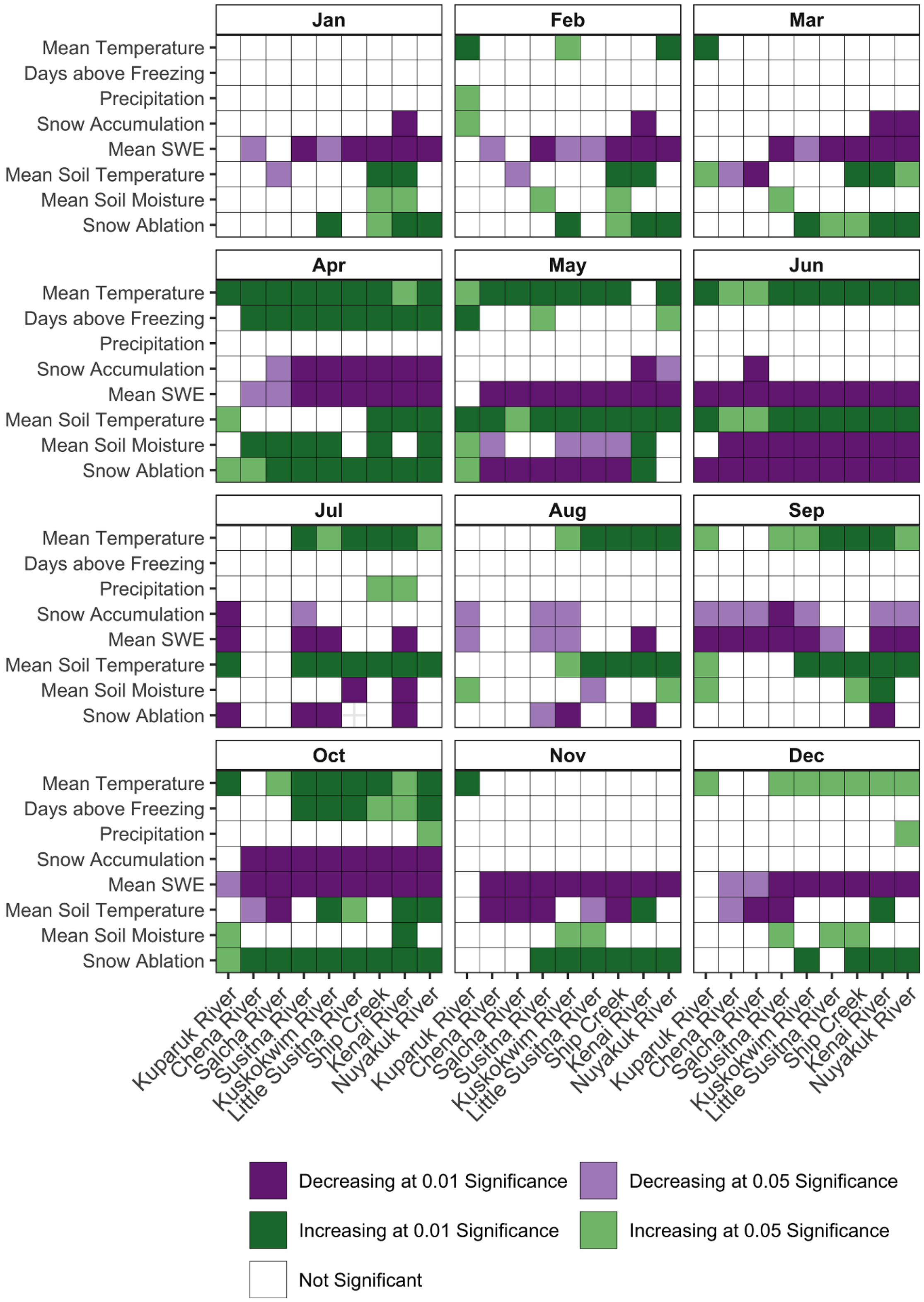

Figure 2. Trend and significance in monthly mean temperature, days above freezing, precipitation, snow accumulation, mean SWE, soil temperature, soil moisture, and snow ablation for each basin from 1960–2019 from ERA5 reanalysis (Muñoz Sabater 2019, 2021). River basins along the *x*-axis are ordered from north to south.

3. Results

3.1. Trends in hydroclimate variables

The most widespread and significant changes in all hydroclimatic metrics occurred during spring (April–June), as inferred from the number of darkly shaded cells in the monthly sub-plots of figure 2. For example, mean daily air temperature in April increased in all nine basins over the period of record (mean across all basins of +0.58 °C per decade), which was also reflected in the widespread trend toward more days above freezing in eight of nine basins, an average increase of 1.3 d per decade. The only basin without a significant increase in days above freezing in April was the Kuparuk River basin, the northernmost river in our study, where mean daily temperatures remain well below freezing (days above freezing increased in Kuparuk in May). SWE decreased in eight of the nine basins in April (−7% per decade), which is explained by increased snow ablation (+20.2% per decade) and reduced snow accumulation (−12.2% per decade). Similarly, mean air temperatures in May and June increased in eight and nine basins, respectively (+0.48 °C per decade). Mean SWE decreased across all basins in June and eight basins in May (−13.5% per decade). In June, all the basins have a trend toward higher soil temperature (+0.63 °C per decade) and less snow ablation, suggesting a trend toward earlier snowmelt and less June snow-cover.

In the autumn months of September and October, soil and air temperatures have increased in approximately two-thirds of the basins (+0.18 °C per decade and +0.47 °C per decade respectively), with corresponding and more widespread declines in snow accumulation (−11% per decade) and SWE (−11% per decade). Significant changes in hydroclimatic variables in October are similar to those seen in April except for soil moisture, which does not exhibit substantial change in October but increases significantly in April (+0.95% per decade). Together, April and October have undergone an increase of 1.1 d per decade of days above freezing, 20% per decade increase in snow ablation, 12.8% per decade decrease in snow accumulation, resulting in an 11.8% per decade decrease in mean SWE.

Widespread SWE declines (−7.1% per decade) are prominent throughout the months when ice consistently covers the rivers (November–March) despite few instances of snow accumulation reductions (figure 2). Increased snow ablation (+9.2% per decade) and soil moisture (+0.42% per decade) were observed during this time period. Air temperature also increased 0.49 °C per decade for November through March, with the largest increase occurring in December (+0.68 °C per decade).

3.2. Quantifying changes in river discharge

There were no significant changes in annual discharge in seven of the nine basins. The Nuyakuk and the Kenai have both increased in annual discharge by less than 4% per decade. The timing of peak discharge was significantly earlier in the year for only Kuparuk River (−2.1 d per decade). To understand the trends of monthly discharge, we plotted significance levels of $p < 0.01$ and $p < 0.05$ represented by various colors in figure 3. The percent change per decade as calculated by the Sens Slope is given in text for every significant trend.

Average discharge during October–April increased by 10% per decade across all watersheds. The months when ice freeze-up and break-up occur correspond to the months with the greatest increase in discharge (figure 3). October average monthly discharge increased by 7% per decade and April discharge increased by 13% per decade. The average date of ice-break up for the Kuparuk is in May, where discharge increases at 38% per decade.

The period between autumn freeze-up and spring break-up can be defined by two distinct periods: early and late winter. Median discharge in the early winter (November and December) increased by 6% per decade, with eight of nine gages recording increased discharge in at least one month (six had increased discharge in both months). Median discharge was used instead of the mean to account for the Kuparuk river discharge that is close to 0 $m^3 s^{-1}$, so large percent changes can occur. Later winter discharge (January–March) before ice break-up occurs has historically been assumed to be predominately baseflow. Discharge during this three month period increased by 6% per decade, with seven of nine gages recording significantly increased discharge in at least one month. Four of the gages had increasing discharge in all three months.

During the summer months, discharge decreased in at least one month in five of nine basins. The Chena River has a reduced May discharge, however the diversion that controls peak discharge on this river has been used 30 times since its construction which limits any results of this study during the summer months for this river. The Kuskokwim and the Salcha both decreased in discharge in June due to faster recession from peak discharge. The Little Susitna and Ship Creek both have reduced discharge during July. Late summer discharge in August and September increase in the Kuparuk River (+25% per decade) but there are no significant changes in any other gage during these months.

3.3. Climate drivers of changing discharge

PDO, AO, PNA, and ENSO were all very weakly or weakly correlated with discharge on a monthly (figures S2–S4) and a seasonal basis (figure S5). Sensitivities of discharge to interannual variations in air temperature and precipitation during various seasons are presented in figure 4, using the methods of Musselman *et al* (2021). Discharge data from each basin in every year of the study period were averaged over the percentile space for each month (figures S6–S14). Then all gages were averaged by each of the six percentile bins. The resulting centroids are plotted for each bin against the temperature and precipitation anomaly from the long term average. Months were visually inspected and grouped by similar slopes (figure S15). The slope of the lines

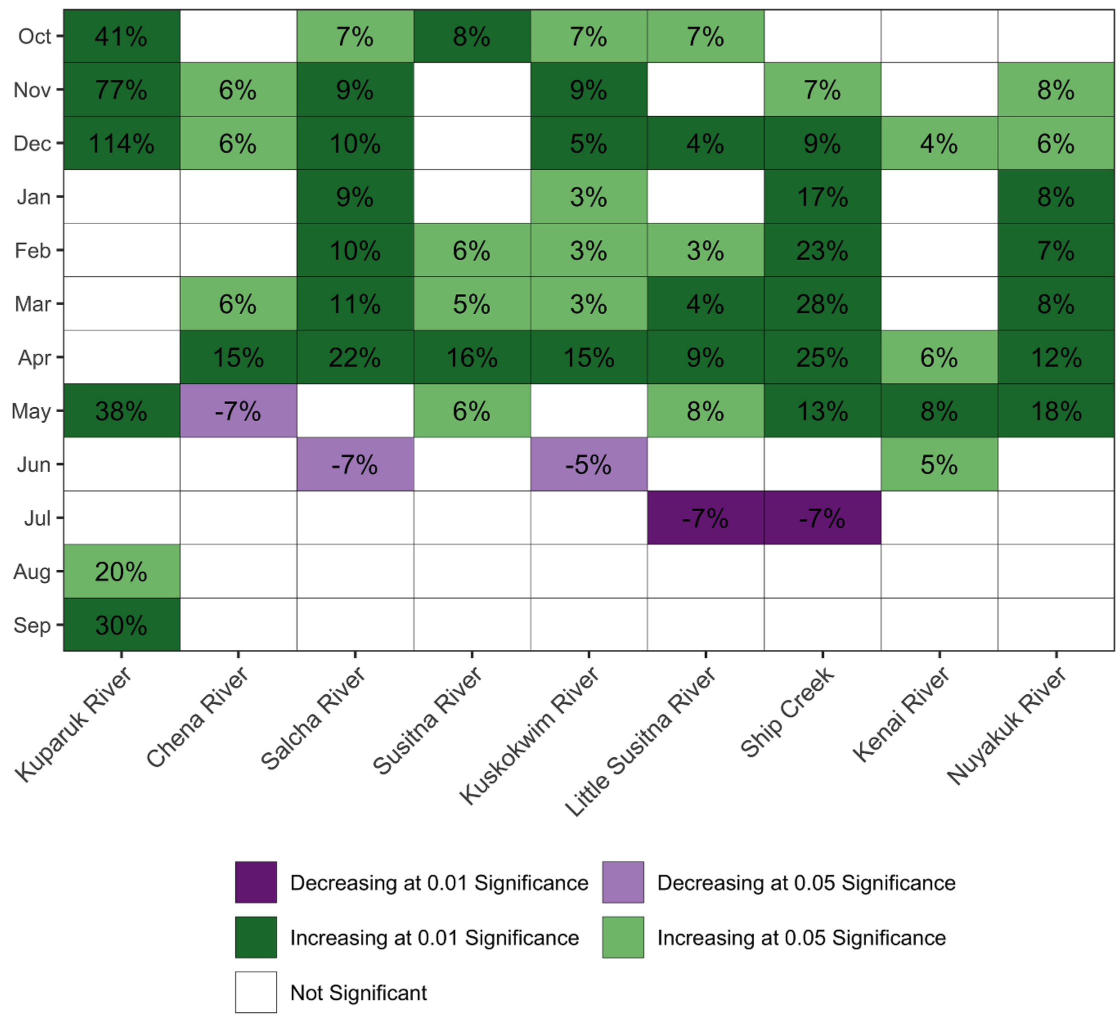

Figure 3. Trend and significance ($p < 0.01$ or <0.05) in mean monthly discharge (U.S. Geological Survey 2022) and the decadal percent change in discharge (values in the cells) for significant trends. The x-axis is ordered from north to south. Decreasing discharge during May for the Chena River is influenced by the flood control structure on the river (U.S. Army Corps of Engineers 2022).

connecting the centroid indicated the relative influence of precipitation and temperature. A more vertical line indicates a greater precipitation influence, and a horizontal line indicates a greater temperature influence.

The effects of air temperature and precipitation on discharge magnitude vary across the three primary hydrologic seasons (figure 4). The period of April–May is defined as the period spanning river ice break up and spring snowmelt/freshet. Discharge during this period depended almost exclusively on temperature as inferred by the near-zero slope of the line in figure 4(A). In contrast, the discharge centroids of the summer months, June–September, are aligned vertically, showing minor variation in temperature indicating a precipitation dependence, especially in higher discharge years (figure 4(B)). In years of low discharge, summer air temperatures are typically higher, but high discharge years are neither abnormally warm nor cold, suggesting that high discharge years are determined largely by winter precipitation. Discharge during the months of October–March (river ice freeze-up through late winter) depends on both temperature and precipitation as inferred from the diagonal line in figure 4(C).

Monthly mean soil and air temperature, precipitation, and soil moisture were correlated with river discharge for each river (figures S16 and S17) and then averaged (figure 5). Throughout the cold season (October–April) in the recent period (1990–2019), soil temperature has increased from a very weak correlation (0.12) to weakly correlated (0.34) with discharge (figure 5(C)). In October the air temperature correlation has increased from no correlation (0.0) to moderate correlation (0.47) between the historic and recent period (figure 5(A)). This temperature increase causes an increase in snow ablation and a decrease in SWE as shown in figure 3. During the early winter (October–December), air temperature has moved from a very weak correlation (0.07) to discharge in the historic period to a weak positive correlation (0.32) during the last 30 years, while precipitation remained roughly the same correlation (∼0.1) (figures 5(A) and (B)). Recent mean air temperature

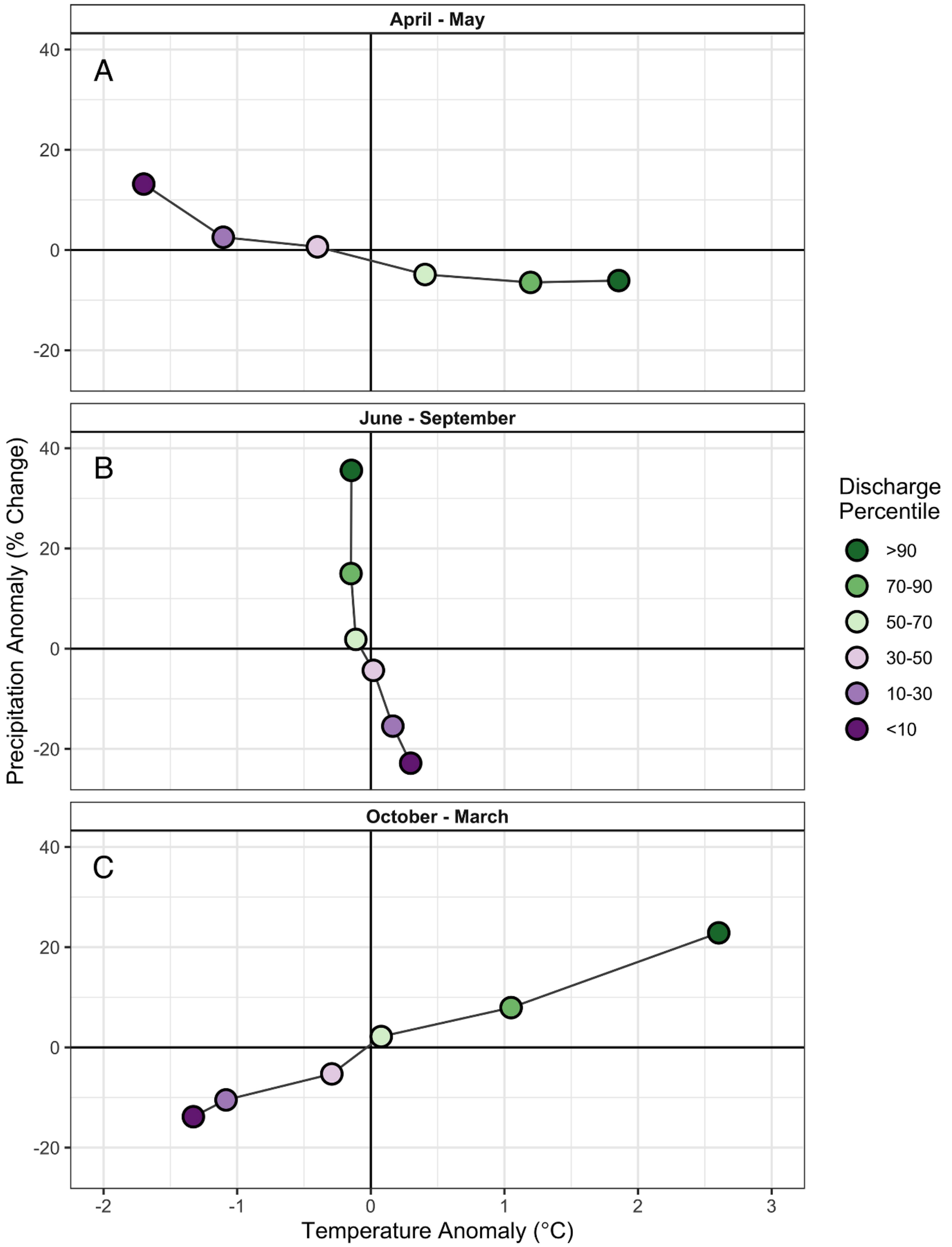

Figure 4. The percentile bin as a function of temperature and precipitation anomalies constructed by averaging discharge at each percentile bin for each year and each basin of the 60 year study period plotted versus temperature and precipitation difference from the historic mean (U.S. Geological Survey 2022).

in April has a strong positive correlation with discharge (0.68) up from a weak positive correlation (0.33) during the historic period (figure 5(A)), indicating that temperature is driving the earlier spring melt. Soil moisture also increases from a very weak (0.17) to a weak (0.3) correlation (figure 5(D)) in April indicating less frozen ground. April and October discharge were also correlated with average cold season (November–April) and warm season (May–October) hydroclimate variables respectively. However, these had less significance than monthly correlation values (figure S18).

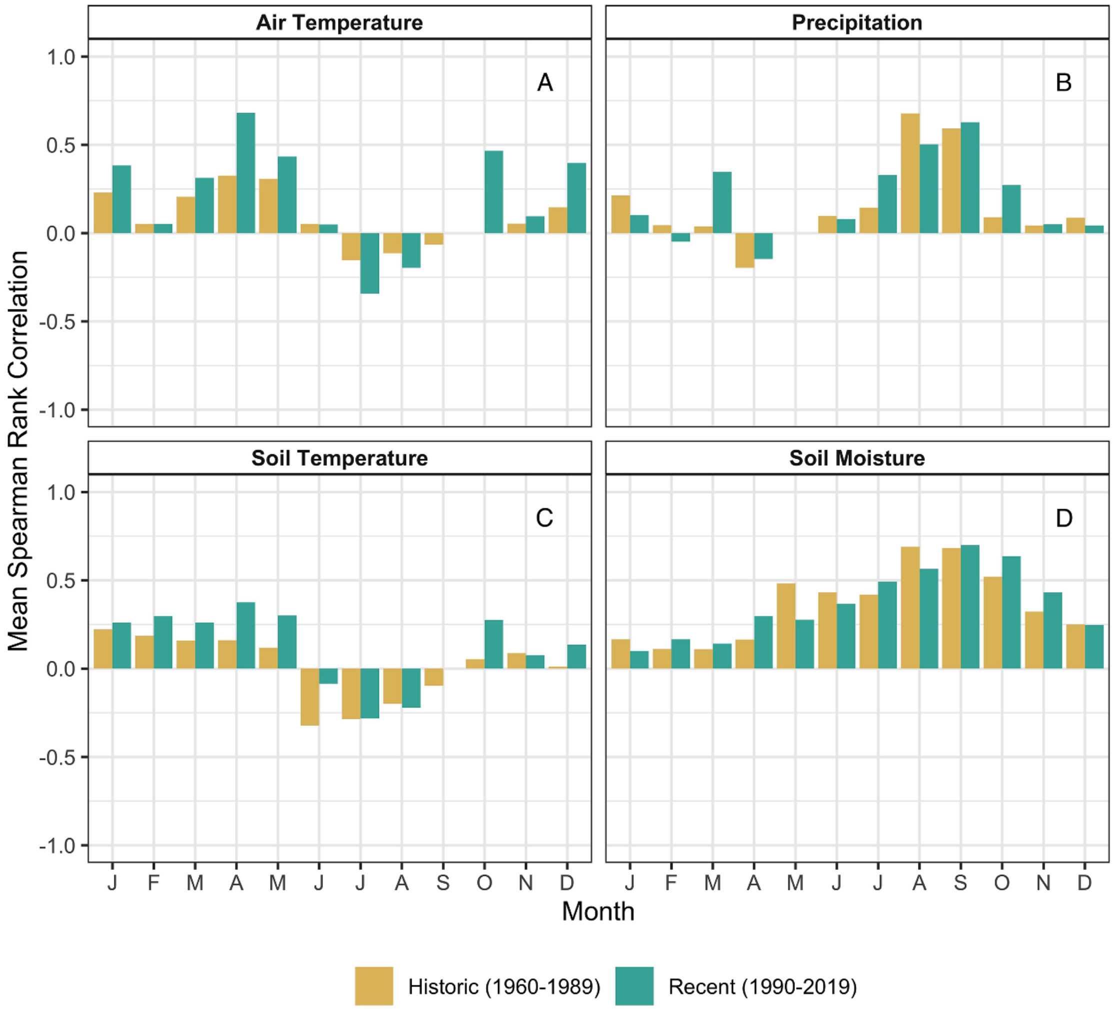

Figure 5. Mean Spearman Rank correlation between discharge and air temperature, precipitation, soil temperature and soil moisture for nine basins by month for the historic (1960–1989) and recent period (1990–2019). Only significant correlations ($p < 0.05$) are shown.

4. Discussion

4.1. Changing river discharge and its drivers

Cold season discharge (October–April) increased at all nine Alaskan basins we evaluated. In the months of river ice freeze-up (September–October) and break-up (April–May) discharge has rapidly increased. Discharge during the late winter also increased indicating more groundwater entering the rivers as baseflow. Conversely, there is little evidence of changing trends in peak discharge during the spring snowmelt period or other high discharge events consistent with previous studies (Bennett *et al* 2015). Annual discharge is also not exhibiting significant change. To account for the change in cold season but not annual discharge, high flows must have small, insignificant changes to offset the increased low flows during the cold months or increased winter discharge is not enough to increase annual discharge trends to a significant level. The trends do not have significant relationships to basin size, geographic location, or hydroclimate condition. Long-term regulation of discharge on the Ship Creek and the Kenai River may have impacted observed trends leading to fewer significant trends in winter compared to other basins in the region. Regulation on the Chena River is most likely the cause of the decrease in May discharge, but it should have no effect throughout the rest of the year when discharge is lower.

Climate indexes were only weakly correlated with monthly discharge indicating that other more local hydroclimatic conditions were responsible for these changes. Other studies have shown that PDO and AO are correlated with discharge during the cold season, however these were analyzed on a river-by-river basis (e.g. Brabets and Walvoord 2009, Bennett *et al* 2015), and do not include the North Slope of Alaska. We show that when river discharge is analyzed over the entire state, localized temperature and precipitation are more correlated with discharge than climate indexes are to discharge. L'Heureux *et al* (2004), found that precipitation on the North Slope was not influenced by any of the four climate indices studied here, interior Alaska was controlled by PNA and

PDO, and the south was influenced by ENSO. Additionally, these studies were completed before the last decade which has undergone rapid anthropogenic warming (Walsh and Brettschneider 2019). In the last 30 years, mean basin air temperature in April and October has become more correlated with discharge than the historic period (figure 5(A)). This indicates that climate change may now have a greater effect on river ice freeze-up and break-up and subsequent river discharge than low frequency climate variability.

Air temperatures have increased in every basin over the 60 year study period, which resulted in decreased SWE and increased snow ablation for much of the winter. This could be caused by multiple factors including rain-on-snow events (Serreze *et al* 2021), late summer rain, and permafrost degradation (Liu *et al* 2022). Increased temperatures are warming and thawing the permafrost, resulting in changing vegetation and soil moisture (Koch *et al* 2022), reduced ice thickness (Beltaos and Prowse 2008) and increased baseflow (Walvoord and Striegl 2007). Baseflow increased across all basins and the correlations between air and soil temperature have also increased during the cold months. When the rivers are most sensitive to small temperature changes during river ice freeze-up and break-up, increased temperatures resulted in more days with a mean daily temperature above the freezing point.

Higher air temperatures during the autumn and early winter prolongs the ice-free period in the rivers (Liu *et al* 2022), and have been shown to reduce the depth of frozen soils, which increases soil water storage and allows for more groundwater runoff during the winter (Streletskiy *et al* 2015), ultimately increasing discharge. Air and soil temperature and soil moisture in November and December in these basins increased in correlation between the two time periods. Additionally, increased temperatures can melt ice that forms in the river, almost all of which is converted to discharge (Makarieva *et al* 2019). Other studies have shown that early winter discharge is affected by precipitation falling as rain or snow melting on contact with the ground (Liu *et al* 2022), which is consistent with our result (figure 4(C)). April air temperatures are more correlated to discharge than cold season temperatures are to discharge (figure 4(A)). Lesack *et al* (2014) showed that higher air temperatures in early spring rather than winter cause a reduction in SWE and earlier spring melt.

4.2. Analysis uncertainty

There are two major sources of uncertainty in this study, measured discharge and reanalysis data. River discharge is calculated from rating curves, which relate stage and discharge. Calculated discharge contains errors from factors including individual stage and discharge measurements, sensor drift, and ice effects (Di Baldassarre and Montanari 2009). When ice is present in rivers, discharge is estimated based on gage height record, available winter discharge measurements, and other ancillary information (Turnipseed and Sauer 2010), so the overall uncertainty in ice-affected discharge is difficult to quantify. Ice cover was present on average eight days longer at the start of the study period leading to less uncertainty in modern measurements (Brown *et al* 2018). The major findings of this study are in April and October when rivers transition from ice cover to open water, but uncertainty is minimized by analyzing discharge on a monthly or seasonal scale due to the stochastic nature of river discharge and river ice freeze-up and breakup (Shiklomanov *et al* 2006).

Reanalysis data are physically based and spatially and temporally continuous, but are prone to biases compared to observations, problems resolving local effects, and issues with model physics (Hersbach *et al* 2020). A major source of uncertainty in trend analysis is the decreasing biases in times due to higher quality of assimilated data (Thorne and Vose 2010, Hersbach *et al* 2020). ERA5 is a new reanalysis product, so few studies have been conducted to validate these data locally, but ERA-Interim, a predecessor to ERA5, has proven reliable in Alaska (Bieniek *et al* 2016, Ladar *et al* 2016). ERA5 has been found to be the most reliable reanalysis product for its temporal consistency of biases (Wang *et al* 2021) and its minimal biases in solar radiation (Wang and Clow 2021) and other near surface processes in the Arctic (Betts *et al* 2019). There are minimal precipitation errors within ERA5, on average less than 0.5 mm per day, with the greatest bias occurring in the summer months (Lavers *et al* 2022). Precipitation biases in April and October are normally distributed with the mean bias near zero (Lavers *et al* 2022), ERA5 air and soil temperature have a slight warm bias of 1 °C in permafrost regions, but that is reduced to a bias of 0.2 °C when the data are limited to Alaska and Russia (Cao *et al* 2020). While these biases cause uncertainty within the trend and correlation analysis, they are much smaller than the trends determined by this study. Additionally, our results are consistent with studies showing increasing air temperature (Bieniek and Walsh 2017) and decreasing SWE (Liston and Hiemstra 2011) in Alaska.

4.3. Implications for biogeochemical cycles and aquatic ecosystems

River ecology is structured based on expected timing and magnitude of water, solute, and nutrient fluxes (Vannote *et al* 1980). Previous research has noted changing mean annual discharge, increased winter low discharge, earlier timing of peak discharge, and increasing recurrence intervals of floods and droughts in Arctic rivers (Shrestha *et al* 2021b). Our results show that the timing and distribution of water in Alaskan rivers has already been altered (described in section 4.1). Increased discharge during the cold season will thin river ice leading to a shortened ice cover season (Brown *et al* 2018). Late freeze-up allows more time for air-water interactions maintaining high dissolved oxygen levels late into the year (Prowse *et al* 2006). Reduced spring ice will limit the occurrence of ice jam floods altering the sediment transport in rivers, which affects fish habitat (Pavelsky and Zarnetske 2017). Baseflow increases resulting from permafrost degradation can decrease summer stream temperatures (Sjöberg *et al* 2021), contribute more salts and minerals to the rivers (Toohey *et al* 2016), and have a major impact on carbon cycling (Striegl *et al* 2005) which subsequently changes what fish are eating (O'Donnell *et al* 2020). Ultimately, altered seasonality of the river due to climate change affects Indigenous communities that rely on the natural cycles of the river (Jackson *et al* 2022). Improved understanding of changes in discharge may allow more effective preparation for future conditions.

5. Conclusions

This study used statistical methods to quantify historic Alaskan river discharge changes and the hydroclimatic mechanisms driving them. Nine river basins with long term gage data (1960–2019) spanning size, geography, and hydroclimatic conditions were analyzed for trend in hydroclimatic variables and river discharge. Cold season (October–April), discharge is increasing across Alaska with no changes in peak discharge or annual discharge. When averaged across the state, hydroclimatic factors (e.g. local temperature and precipitation) affect discharge more than internal climate variability such as decadal climate oscillations, The correlation between temperature and discharge increased between the historic (1960–1989) and current (1990–2019) period as temperatures across the basins increased. This indicates that temperature is becoming the dominate factor in streamflow during the cold season, especially during ice freeze up and thaw in October and April. The long-term dataset and wide range of climate and hydrologic inputs may allow for extrapolation across the Arctic and critically help to inform how rivers may continue to be altered by anthropogenic climate change.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/dblaskey/USGS_Stream_Data.

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