Regional-scale response of glacier speed to seasonal runoff variations on the Kenai Peninsula, Alaska

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Key Points:

- Glacier runoff can influence ice speed with considerable (multi-month) delays
- Ice speed is generally negatively correlated with runoff in preceding months or multi-month periods
- Winter speed is strongly inversely correlated with October/November runoff but weaker/uncorrelated with any of the summer months

Abstract

Subglacial hydrology directly impacts glacier motion, but few studies have investigated the connections between ice speed and water input on regional scales. Here, we analyze the correlation of glacier surface speed and runoff for 77 glaciers ≥3 km^2 (~3070 km^2) on the Kenai Peninsula, Alaska, within and between seasons from 2015-2019. Most correlations between monthly/seasonal mean ice speed and cumulative runoff in preceding months/multi-month periods are significant ($p<0.05$), while correlations for the same months or seasons are generally insignificant or weak indicating seasonally delayed responses of ice speed to runoff. In almost all cases lower-than-average monthly/seasonal ice speeds are associated with higher-than-average runoff in preceding months or multi-month periods. Overall, our results show that runoff can influence ice speed with considerable (multi-month) delays.

Plain language summary

Glacier flow is affected by melt and rainwater penetrating the glacier bed. Changes in meltwater supply due to climate change may affect how fast glaciers flow, which can affect their mass change. We compare monthly and seasonal mean satellite-derived ice speeds of 77 glaciers ≥3 km^2 on the Kenai Peninsula, Alaska, with modeled glacier runoff (glacier melt plus rain minus refreezing) during the same period and preceding months/seasons. We find no/weak connection between ice speed and runoff for the same months/seasons, but ice speed tends to depend on runoff in preceding months/multi-month periods. In almost all investigated cases ice speed is lower than average when runoff in preceding months/seasons is higher than average, and vice versa.

1 Introduction

Glacier flow directly impacts glacier mass and surface evolution, glacier thermodynamics, erosion and sediment transport, and glacial hazards. Glacier velocity is influenced by many factors, such as glacier geometry (e.g., ice thickness, surface and bed topography, crevasses, and debris cover), ice rheology, glacier melt, and terminus type, but most importantly, subglacial hydrology exerts a strong control on glacier motion (Iken & Bindschadler, 1986). Surface melt and rainwater drain to the bed through moulins and crevasses, where water can be stored or transported to the glacier terminus through diverse subglacial passageways, such as thin films (Weertman, 1964), distributed cavity networks (Kamb et al., 1985), or discrete channels (Fountain & Walder, 1998; Nye, 1965; Röthlisberger, 1972) . The type of drainage system and the amount of water reaching the bed subsequently control the effective water pressure and resulting variations in basal sliding (Iken, 1981; Iken & Bindschadler, 1986; Iken & Truffe, 1997). Numerous studies on mountain glaciers (e.g., Anderson et al., 2014; Bartholomaus et al., 2016; van Pelt et al., 2018) and the Greenland ice sheet (e.g., Davison et al., 2019; Howat et al., 2010; King et al., 2018; Moon et al., 2015; Sakakibara & Sugiyama, 2020; Sundal et al., 2013) highlight the complexity of the relationship between surface ice speed and water input to the subglacial drainage system and resulting subglacial water pressure.

These studies primarily focused on individual glaciers rather than regional scales. An exception is the study that mapped regional-scale winter velocities throughout Alaska and found that velocities were inversely correlated with cumulative positive degree-days (indicative of melt) during the preceding summer (Burgess et al., 2013). A more recent study measured the surface speeds of all glaciers (~3900 km^2) on the Kenai Peninsula (Yang et al., 2022). Largely synchronous seasonal and inter-annual speed variations indicated that meteorological factors play a crucial role in influencing the temporal variability. Annual mean speed was not correlated with summer precipitation but weakly and inversely correlated with summer air temperatures from nearby weather stations indicating possible slowdown with increased melt water. However, the combined effect of melt water and rain on glacier speed was not assessed.

Here we systematically investigate the relationship between satellite-derived ice speed variations and modeled glacier runoff (defined by glacier-wide melt plus rain minus refreezing) for glaciers on the Kenai Peninsula, south-central Alaska, during the period December 2014 – November 2019 (hence worth referred to as 2015-2019 for simplicity). Specifically, we correlate monthly and seasonal mean glacier-wide ice speed with glacier runoff during the same months/seasons as well as various preceding multi-month periods to investigate any time delays between ice speed variations and water input, and analyze the distinct relationship for tidewater, land-, and lake-terminating glaciers.

2 Study Area

Glaciers on the Kenai Peninsula of Alaska covered an area of ~3900 km^2 in 2016 (Yang et al., 2020) with elevations ranging from sea level to ~2000 m a.s.l.. Of the 1165 glaciers, 11 are tidewater (897 km^2, 23% of total glacierized area), 18 are lake-terminating (1326 km^2, 34 %) and 1136 are land-terminating (1677 km^2, 43%) (Yang et al., 2022). The glacierized area is dominated by four major ice complexes (Figure 1a). Regionally, glaciers on the east-south coast are strongly influenced by a maritime climate while further inland a more continental climate prevails. Widespread glacier recession has occurred since the Little Ice Age (Wiles & Calkin, 1992). Between 1986 and 2016 the glacier area shrunk by 543 ± 123 km^2 (12±3%) and the mean region-wide mass balance over the period 2005-2014 was strongly negative (-0.94±0.12 m w.e. a^{-1}) (Yang et al., 2020). The mean specific (i.e., per unit area) mass loss of the lake-terminating glaciers was also found to be more than three times greater than tidewater glaciers, and almost two times greater than land-terminating glaciers.

3 Data and Methods

Surface ice speed data are available for ~90% of the glacierized area on the Peninsula for the period 2015-2019 (Yang et al., 2022). These data include 92 sequential surface speed fields on a 90 m × 90 m grid derived from intensity offset tracking of 93 Sentinel-1 images (mostly with a 12 or 24-day repeat cycle).

The Python Glacier Evolution Model (PyGEM, Rounce et al., 2023; Rounce et al., 2020) estimated monthly glacier-wide glacier runoff for all glaciers on the Peninsula from 2005 to 2019. This period allowed us to calibrate the model with geodetic mass balances from 2005-2014 (Yang et al., 2020) and investigate the relationship between speed and runoff over 2015-2019. PyGEM estimates the climatic mass balance (the sum of accumulation, melt and refreezing) for each glacier using ~10 m elevation bins, the ice thickness (Farinotti et al., 2019), and a monthly time step forced with near-surface air temperature and precipitation data (Hersbach et al., 2020, see Text S1), and the model is validated by the in-situ data from US Geological Survey Benchmark Glaciers datasets (McNeil et al., 2016, Figure S7). We define glacier-wide glacier runoff as all water originating from the evolving glacier area, i.e. glacier melt plus rain (liquid precipitation) minus refreezing and consider this runoff to be a proxy of water input to the glacier bed. We calculate monthly mean glacier-wide ice speed by averaging speeds along each glacier´s main centerline (Figure 1c-d).

We focus on all glaciers connected to the four large icefields that have an area ≥3 km^2 (a size threshold to ensure confidence in the speed estimates). This subset includes 48 land-terminating glaciers, 18 lake-terminating glaciers, and 11 tidewater glaciers. These glaciers cover 79% (~3070 km^2) of all glacier areas on the Peninsula and have a wide range of topographic characteristics (area, slope, mean elevation; Figure S1).

4 Results

4.1 Modeled mass-balance and glacier runoff

The modeled annual mass balance of the 77 investigated glaciers is strongly negative (area-weighted mean = - 2.1 m w.e. a^{-1}) over 2015-2019 (Figure S2). The corresponding specific accumulation is 2.6 m w.e. a^{-1}, melt is -4.4 m w.e. a^{-1}, and frontal ablation is -0.32 m w.e. a^{-1}, while refreezing is negligible (0.01 m w.e. a^{-1}). The specific rainfall is 1.2 m a^{-1}. The specific runoff of all glaciers ranges from 3 to 12 m a^{-1} (Figure 1b). Glacier runoff is dominated by glacier melt with a relative contribution of 78 %, and the remainder coming from rain. The partitioning varies considerably amongst glaciers, with the melt portion ranging from 60% to 90%. Glaciers with the largest relative contributions from rain tend to be located near the coast (Figures S3). Differences between mass balance and runoff components of the 77 investigated glaciers and all 1165 glaciers on the Kenai Peninsula are very small (Table S1).

During the study period (2015-2019), the annual specific glacier runoff of the 77 investigated glaciers fluctuated by roughly ±17% around the period's median value (Figure S4). Inter-annual variations are largely synchronous across all terminus types, without any discernible trend although a notable increase (~1 m) compared to the period 2005-2014.

4.2 Seasonal ice speed and glacier runoff variations

The time series of monthly (Figures 1c-d) and seasonal (Figure S5) mean ice speed and cumulative glacier runoff demonstrate strong synchronicity in both ice speed and runoff among the 77 glaciers, irrespective of their terminus type. However, tidewater glaciers exhibit substantially higher ice speed and lower specific runoff than the land- and lake-terminating glaciers. Seasonal glacier runoff variations follow those of melt indicating that the runoff variations are largely driven by variations in glacier melt. More than 88% of annual glacier runoff and 92% of glacier melt (median of all glaciers) occurs between June and September, with the maximum in August and negligible amounts between November and March (Figure 1e-h). Rain steadily increases during spring and summer, reaching a peak in September before sharply declining. Therefore, decreasing melt rates in September are partially compensated by increased rainfall.

While the spring speed-up is a recurring feature in all years (Figure 1c), with peaks more than 50% above the annual mean (Yang et al., 2022) followed by a slowdown during summer, monthly variations in ice speed differ greatly from year to year. For example, in 2017 ice speed increased rapidly from its minimum in March to its maximum in May, whereas in 2016 the increase to peak speed occurred more gradually and over a period of four to five months. Speeds in winter 2017/2018 were considerably higher for all glacier types than in the other years, with February speeds reaching similar magnitudes as that year´s maxima.

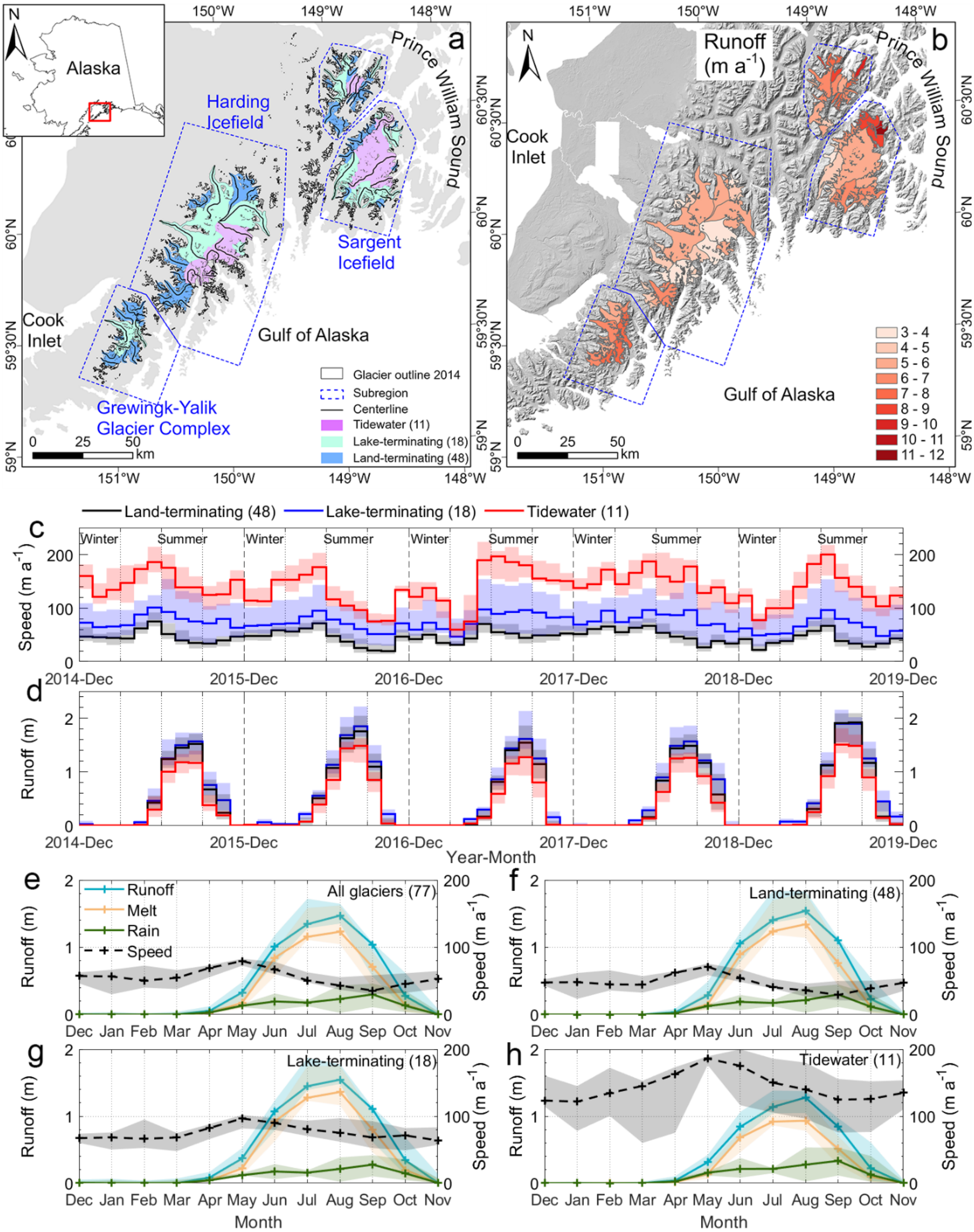

Figure 1. (a) Location of the investigated 77 glaciers on the Kenai Peninsula (b) modeled glacier-wide runoff over 2015-2019. The hillshade topography is derived from the IFSAR DEM. (c, d) Monthly time series of (c) ice speed averaged along the centerline and (d) modeled glacier runoff. Solid lines are the medians of all glaciers, and the shaded areas show the interquartile range (IQR). (e-h) Monthly distribution of median glacier-wide specific runoff, rain, and melt, as well as mean surface speed of glaciers with different terminus types over the 5-year period. Lines represent the medians over the five years, with shading

indicating the minimum and maximum values. Numbers in parentheses denote the number of glaciers.

4.3 Correlation of ice speed and glacier runoff

To analyze the impact of glacier runoff on ice speed and investigate potential time delays in the response of speed to runoff, we normalize ice speed and glacier runoff relative to the 5-year mean of each glacier and regress speed with runoff over various periods (see Figure 2i for the cases with the strongest correlation). Correlations with $p < 0.05$ are considered statistically significant.

We regress monthly ice speed and runoff in the same month and preceding months (Figure 2a-d), considering the months April to November since outside this period modeled runoff is negligible. In most cases there is no correlation between ice speed and runoff in the same month. A notable exception is a significant negative correlation ($r < -0.4$) in July (Figures 2a-c) and for the tidewater glaciers in August (Figure 2d). However, we find significant correlations with $|r| > 0.2$ between ice speed in the months between May and November and runoff in one or several preceding months in 68% of the 28 investigated cases (all glaciers, Figure 2a) pointing to a time delay in the dynamic response. All but one of these correlations are negative with the strongest correlation reaching $r = -0.65$ (Figure 2a), indicating that ice speed is lower than average when glacier runoff is higher. For all glacier types, correlations tend to be strongest between ice speed in August and runoff in May followed by June. Overall, May runoff appears to have the strongest impact on ice speed in the following months. Except for a strong negative correlation between ice speed in November and runoff in October, November ice speeds are not or only weakly (sometimes positively) correlated with runoff in any of the preceding months.

We also correlated seasonal (3-month) mean ice speeds with total glacier runoff during the same and all preceding seasons of the same year (Figure 2 e-h). Summer and fall ice speed correlate negatively with runoff in all investigated cases with the strongest correlations between summer ice speed and spring (or also winter) runoff. In contrast, correlations between winter or spring ice speed and corresponding runoff are either insignificant or weakly positive.

To investigate the delays in the response of ice speed to runoff in more detail, we also analyzed the correlations between monthly ice speed (as well as winter and spring means), and runoff across various one to six-month periods of the preceding year (Figure 3). We find significant correlations for almost all 168 combinations for each glacier type. Most of the correlations are negative indicating that higher-than-average summer and fall runoff leads to a subsequent lower-than-average speed during the following winter and spring, and vice versa. The strongest correlations are found between winter (especially January) ice speed and the preceding fall (especially October and November) runoff and between February-March ice speed and runoff in the preceding summer and fall (especially July). Correlations tend to be stronger for longer averaging periods of runoff. Correlations are insignificant or weak for ice speed in May (and June, not shown).

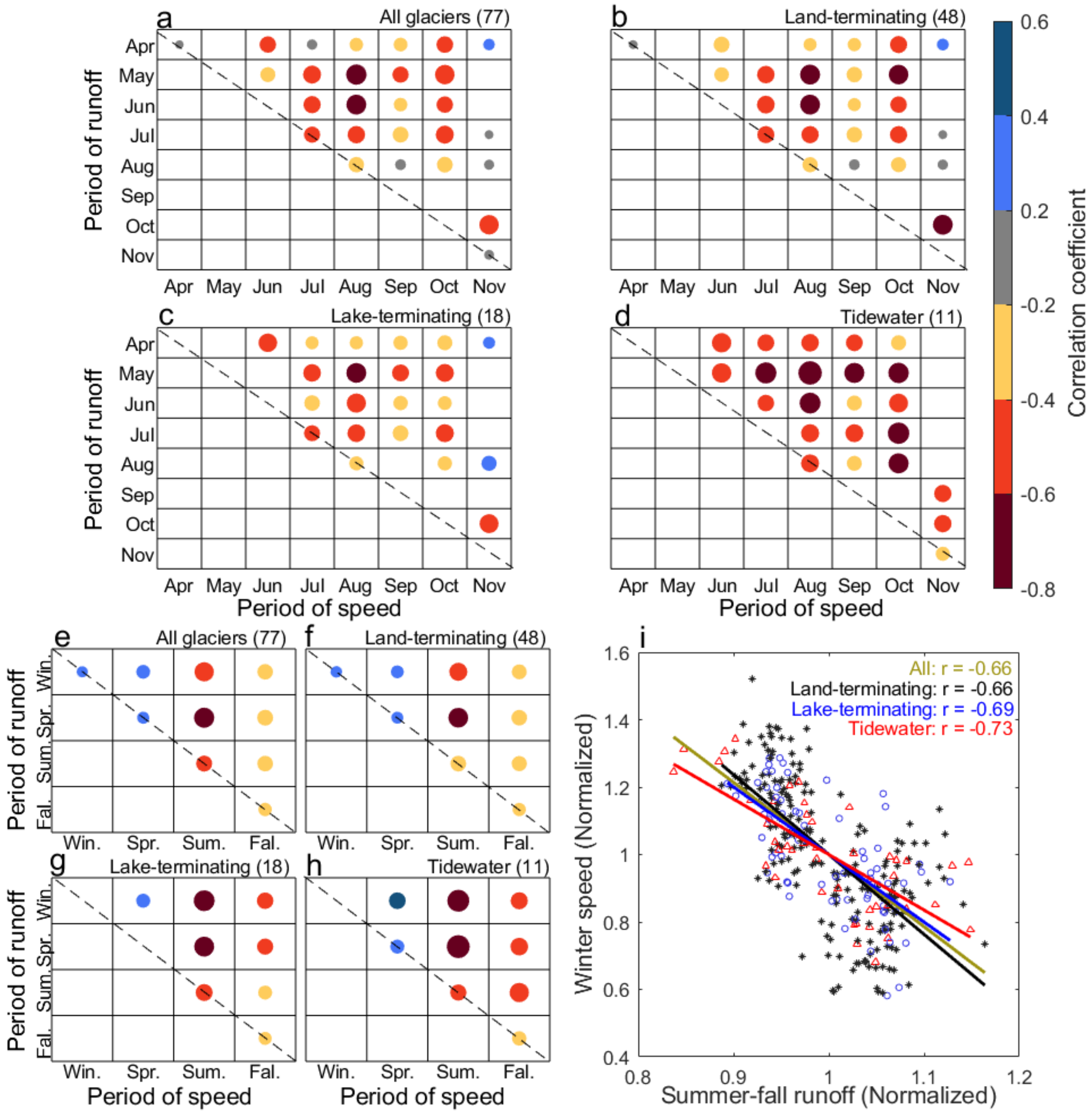

Figure 2. (a-d) Correlation coefficients (dots) between monthly surface ice speed (April-November) and modeled specific glacier runoff in the same and all preceding months in the same year for glaciers of different terminus type. (e-h) same as a-d, but seasonal mean speed and cumulative runoff. Both speed and runoff normalized by the 5-year means (2015-2019). Correlation coefficients are only shown when $p < 0.05$ with dot sizes proportional to their absolute value. Winter (Win.) refers to December to February, and summer (Sum.) from June to August. (i) Winter mean ice speed versus summer-fall cumulative runoff, and each marker (*/^/o) refers to one glacier in one year during 2015 – 2019 and solid lines represent the linear fits.

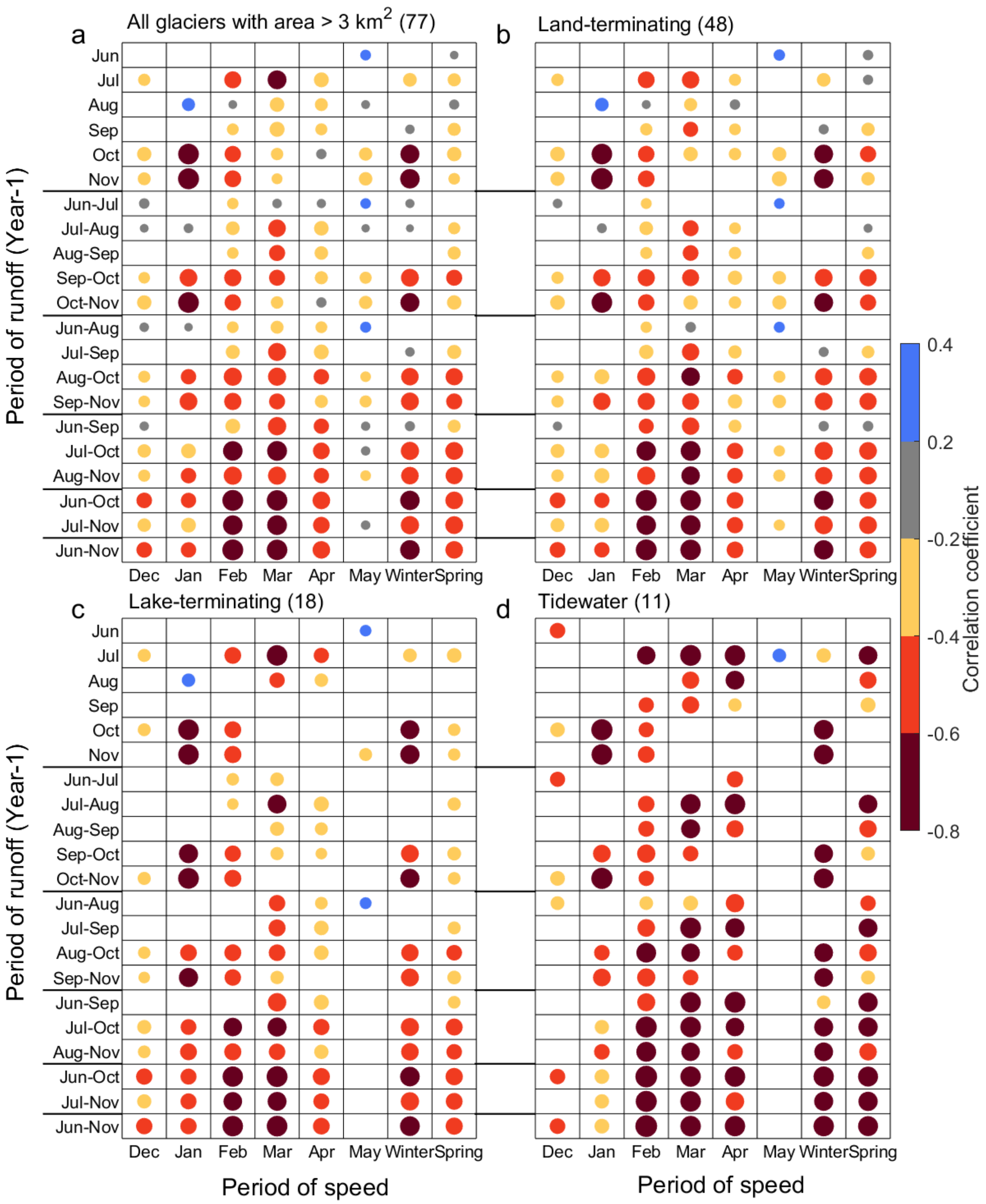

Figure 3. Correlation coefficients (dots) between monthly as well as winter/spring mean surface ice speed and modeled specific cumulative glacier runoff in various one-to-six-month periods between June and November of the preceding year (Year-1) for (a) all studied glaciers, (b) land-terminating, (c) lake-terminating, and (d) tidewater glaciers. December ice speed refers to the preceding year. Ice speed and runoff are normalized by the corresponding 5-year means during 2015-2019. The size of the dots is proportional to the absolute value of the correlation coefficients. Correlation coefficients are only visualized when the correlation is statistically significant ($p < 0.05$). Winter refers to December-February and spring to March-May. Solid short lines at the y-axis separate six clusters of cases with identical period length varying from one to six months.

5 Discussion

Our regional scale analyses based on both monthly and seasonal data enable a far more nuanced understanding of the ice speed-runoff relationship than previous studies which primarily relied on seasonal/annual means and were limited to single glaciers or point locations (e.g., Sole et al., 2013; Stevens et al., 2018; Tedstone et al., 2015; van Pelt et al., 2018). A majority of our investigated correlations between monthly/seasonal mean ice speed and runoff in various preceding months or longer periods are statistically significant while correlations for the same months or periods are generally insignificant or weak (Figures 2 and 3). This indicates a delayed and spatially uniform response of ice speed to water input across the Kenai Peninsula glaciers. Almost all significant correlations are negative indicating that higher-than-average glacier runoff leads to lower ice speed. Although the correlations between speed and runoff constitute purely statistical relationships, they point to a strong regionally uniform influence of runoff variability on seasonal ice speed. We note that tidewater glaciers show consistently stronger correlations for almost all investigated combinations. Since we relate runoff to surface speed rather than depth-integrated speed, this may reflect that basal sliding comprises a larger fraction of surface ice speed for the tidewater glaciers compared to the lake- and land-terminating glaciers.

5.1 Winter speed

Strong negative correlations between winter ice speed and runoff during various multi-month summer to fall periods across our study area regardless of terminus type are consistent with prior work on the Greenland ice sheet (Sole et al., 2013) and in Alaska (Burgess et al., 2013). The latter study found significant relationships between December-March ice speeds and cumulative positive degree-day from the previous summer, which was used as a proxy for melt. They attributed their findings to changes in the subglacial glacier-system caused by the amount of meltwater generated in the preceding summer. Our temporally finer resolved correlations allow us to pinpoint more precisely the timing of the delay between ice speed and water input. We find that winter speed is strongly negatively correlated with runoff in October and November but decisively weaker or uncorrelated with runoff in any of the preceding summer months (June to September) or multi-month averages (Figure 3). However, there is a weak correlation with July runoff largely driven by a stronger correlation between February speed and July runoff.

Stronger correlations of winter ice speed with multi-month summer-fall runoff ($r < -0.4$) are only found when runoff in October and/or November is included indicating that these correlations are driven by runoff variations in these two months. Thus, in contrast to Burgess et al. (2013), we find that summer runoff generally has little impact on mean winter ice speed, but winter speeds (especially in January) are significantly lower than average when runoff is higher than average in October and November. Hence our results highlight the important role of October to November (rather than summer) runoff in regulating mean ice speed in the following winter.

Several studies have demonstrated that channelized drainage systems, typically well-developed during the melt season, evacuate water more efficiently than poorly connected distributed drainage systems persisting in the accumulation season (Kamb, 1987; Schoof, 2010; Sundal et al., 2011). As glacier runoff decreases sharply in October and approaches zero in November the subglacial drainage system can be expected to start its transformation from an efficient channelized drainage system to the less efficient distributed winter configuration. We attribute the observed correlations between winter ice speed and October/November runoff to variations in the timing of this transition caused by interannual variations in rainfall. Roughly half of glacier runoff in October comes from rainfall (Figure 1e-h), and precipitation data from surrounding weather stations show that the most intense precipitation events in this region often occur around this time (see Figure 11 in Yang et al. (2022)). We hypothesize that short-term pressurization of the yet largely intact channelized system caused by heavy rain events delays the drainage system transformation. Hence, greater than average glacier runoff in this transition period leads to more efficient evacuation of subglacial water in the following winter months and thus a larger portion of the bed is prone to low water pressures which in turn promotes lower ice speeds. This interpretation is also consistent with a strong inverse relationship between November speeds and October runoff.

5.2 Spring speed

Significant ice speed-runoff correlations well into spring suggest that the influence of runoff in summer and early fall continues well beyond the end of the following winter although the decreasing strength of the correlations indicates that the impact tapers off during the following spring (Figure 3). In fact, in almost all cases May speeds are not (tidewater and lake-terminating glaciers) or only weakly correlated (land-terminating glaciers) with runoff in the investigated single or multi-month periods in the preceding year. Thus, with the onset of spring speed-up, ice speed is largely insensitive to runoff amounts in the previous year.

We find notable differences between different terminus types. For land-terminating glaciers mean spring speeds are correlated with fall runoff (September to November), but not or only weakly ($r < |0.2|$) with runoff in any of the summer months (Figure 3b). In contrast, for the tidewater glaciers October/November runoff appears to have no impact on spring speed (on average and for each individual month, Figure 3d). However, spring speed, more specifically March and April speeds, are strongly correlated with preceding summer (July to September) runoff instead. This finding contrasts with the results from a study on a tidewater glacier in Svalbard (van Pelt et al., 2018), where mean summer motion increases with summer ablation, fall motion decreases and spring speed is insensitive; thus, highlighting a short-lived impact of summer melt on ice motion during the cold season.

Spring ice speed is positively correlated with runoff in spring and the preceding winter, albeit weakly (Figure 2e-h). Increased glacier runoff in spring typically leads to pronounced flow acceleration (“spring speed-up") as the sudden increase in water input quickly exceeds the hydraulic capacity of the inefficient distributed system that prevails at the end of the winter. Hence, water is stored subglacial lubricating the ice-bed interface and lowering basal friction (Bartholomaus et al., 2008). With the inefficient subglacial drainage system, above-average spring/winter runoff leads to greater water storage and thus flow acceleration causing a positive correlation.

5.3 Summer/fall speed

Despite rapidly rising runoff following spring speedup (Figure 1e-h), on average, the glaciers on the Kenai Peninsula tend to decelerate over summer, although the monthly evolution exhibits large interannual variations (Figure 1c-d). This observation is consistent with the development of an interconnected channelized system (Röthlisberger, 1972), allowing efficient evacuation of the trapped water that initiated the preceding speed-up. The deceleration is thought to occur above a critical rate of water input (Schoof, 2010). On average, we observe annual speed maxima typically in May, when cumulative runoff reaches ~9% of its peak in August with deceleration thereafter (Figures 1e and S6).

The striking negative correlations between ice speed in each of the summer and fall months (June to October) with almost all corresponding preceding months starting in April suggest that ice speed is sensitive to runoff on a variety of scales (Figure 2a-d). We postulate that higher than average runoff in any end of spring or summer month triggers a more developed subglacial channel system characterized by larger and/or better-connected channels than would evolve during lower runoff thus causing lower ice speeds. The impact of variations in spring and summer runoff on speed into fall months (September/October) indicates a persistent and long-lived multi-month impact of runoff on speed. Stronger correlations show that runoff in May, and to a lesser degree in June, appear to matter most for ice speed in July and especially August. Our results differ distinctly from those by van Pelt et al. (2018) who found that summer speeds increased with higher summer ablation at several sites on Nordenskiøldbreen, Svalbard, which were attributed to a longer melt season and more intense rain events. Also, several studies in Greenland found higher ice speed with higher amounts of water (Sole et al., 2013; Stevens et al., 2016; Stevens et al., 2018; Zwally et al., 2002). While intense summer melt and rain events may trigger temporary short-lived flow acceleration of the glaciers, our results suggest that their effect on the relationship between runoff and ice speed on monthly scales is subdued on the Kenai Peninsula (Figure 2a-d).

6 Conclusion

Using satellite-derived regional-scale ice flow data and modeled glacier runoff of 77 glaciers on the Kenai Peninsula, Alaska, during the period 2015-2019, we document significant, mostly negative relationships between monthly/seasonal mean ice speed and cumulative runoff during preceding months or multi-month periods indicating considerable delays in the response of ice speed to water input. Correlations between ice speed and runoff during the same months or seasons are generally insignificant. Overall correlations are considerably stronger for tidewater glaciers than for land- or lake-terminating glaciers.

Correlations between ice speed and runoff several months earlier indicate a surprisingly long-lived impact of runoff on seasonal ice speed variability in all seasons. Contrary to previous studies we find no or only weak negative correlations between winter speed and summer runoff, but strong negative correlations with runoff in October and November, and multi-month periods (including October and/or November). We postulate that intense rain events, typical during this time of year, delay the transition of the efficient summertime to inefficient wintertime subglacial drainage system and thus precondition the bed-ice interface for slower ice motion. On average, rain contributed 22% of the total runoff, but up to 40% for individual glaciers, emphasizing the need to include rainwater in quantifying the dynamical response to water input. In contrast to several other studies (Sole et al., 2013; Zwally et al., 2002) we also find that ice speed in all summer/early fall months is inversely correlated with runoff during all corresponding preceding months from April on, which indicates that larger amounts of runoff facilitate a more developed subglacial drainage system.

Changes in meltwater supply caused by climate change can affect the speed of glacier flow, consequently impacting their mass change. Our results underline the complex interplay between seasonal ice speed variation and water input to the subglacial system and emphasize the need for further field observations and modeling studies to better understand the relevant mechanism behind the observed statistical relationships.

Acknowledgments

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R. Yang performed all data analyses and calculations and drafted all figures. RY and RH jointly developed the design, methodology and discussion, and wrote the paper. DR provided model support and information on the glacier runoff simulations and improved the clarity of the manuscript. SK provided initial funding and commented on the final draft.

Open Research

Data Availability Statement

Glacier outlines and speed map are available in Mendeley Data http://dx.doi.org/10.17632/g3s7m78zk9.1 (Yang, 2022). Geodetic mass balance dataset (DEMs) used in this study is available at PANGAEA https://doi.pangaea.de/10.1594/PANGAEA.965738 (Yang, 2024). PyGEM is an open-access model can be found at https://github.com/drounce/PyGEM. All data analysis for this project was undertaken using ArcGIS Pro or MATLAB software.

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