Compounding seasonal variations in outlet glacier dynamics revealed by high-resolution observations

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Key Points:

- Simple model can be used to attribute a portion of seasonal velocity variability caused by terminus position change.
- Seasonal velocity variability is complex and results from multiple compounding processes.
- Seasonal velocities are more sensitive to surface slope changes than uniform changes in elevation.

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Abstract

Understanding seasonality in outlet glacier dynamics reveals insight into long-term retreat and acceleration. Leveraging recent high-resolution satellite data, we examine changes in surface elevation, velocity, and terminus position for five glaciers in Central Western Greenland over the past ∼6 years. We employ an approach that examines the stress imbalance at the ice-ocean terminus and models the expected response in upstream velocity caused by the observed terminus changes. The model shows that some glaciers' seasonal velocity changes can be largely explained by terminus changes, while others can be compounded by multiple processes. Additionally, we test the sensitivity of the results by including seasonally varying and artificially modified surface topography. We find surface slope changes impact velocity response to terminus changes more than spatially uniform changes in along-flow elevation. Our approach provides a scalable framework to comprehend the compounded nature of glacier seasonal velocity variations across the Greenland Ice Sheet outlet glaciers.

Plain Language Summary

Understanding seasonal changes in glaciers is crucial for studying long-term trends. To capture glacier seasonality in detail, we combine detailed data on glacier speed and terminus movement at sub-weekly to daily intervals, along with seasonal surface topography data. We use a model that reveals how much glacier speed changes in response to terminus variations. For some glaciers, our model shows that seasonal glacier speed change is completely driven by terminus change. For other glaciers, we find that seasonal velocity changes can be influenced by runoff and seasonal changes in the drainage system beneath the glacier, in addition to terminus position change. Additional tests suggest that change in the surface slope of a glacier has a stronger impact on the sensitivity of seasonal speed changes to terminus changes than uniform changes in glacier surface topography; flattening of the glacier surface results in less sensitivity of the surface velocity to terminus changes. Our approach provides a framework to expand these observations to the entire Greenland to reveal the complexity of glacier seasonality.

1 Introduction

The Greenland Ice Sheet (GrIS) is currently the largest land ice contributor to present-day rising sea level (IPCC, 2022) with an acceleration in mass loss over the past few decades primarily attributed to ice discharge through outlet glaciers (Shepherd et al., 2012; Enderlin et al., 2014; van den Broeke et al., 2016). This acceleration underscores the importance of comprehending the intricate mechanisms that govern glacier dynamics. Despite the prevalence of glacier acceleration in Greenland, there exists notable spatio-temporal variability in glacier velocity change at a range of time scales (Moon et al., 2012, 2020), which is likely influenced by local conditions, like topography, and regionally by environmental factors. For example, runoff and ocean thermal forcing can influence velocity by changing basal friction (Ultee et al., 2022), subaqueous melt rates (Holland et al., 2008), and through terminus fluctuations (Howat et al., 2008; King et al., 2020; Wood et al., 2021). At the seasonal scale, many of these processes are synchronized, making it difficult to understand the cause and effect behind seasonal glacier acceleration. Despite this, recent advances in the temporal frequency of satellite measurements provide an opportunity to examine the factors that force glacier dynamic change over multiple epochs (Kehrl et al., 2017). Moreover, numerical simulations suggest that glacier seasonal changes can induce systematic bias in mass loss estimates at the multi-decadal time scale (Felikson et al., 2022). Thus, delving into the patterns of glacier seasonality is instrumental in unveiling and simulating the pivotal factors that control glacier dynamics at longer time scales and into the future.

Glaciers across Greenland exhibit discernible seasonal changes in terminus position (Goliber et al., 2022; Catania et al., 2018; Zhang et al., 2023) and surface velocity (Moon et al., 2015; Joughin et al., 2008), but the mechanisms behind such changes are varied. Studies have suggested that seasonal glacier retreat due to summertime air temperature increases causes reduced contact with bed and/or fjord walls, which along with increased net force at the calving cliff, leading to glacier acceleration (Howat et al., 2005; Joughin et al., 2012). Others have indicated that glacier acceleration can be due to seasonal changes in basal lubrication related to changes in the subglacial hydrological system (Davison et al., 2020; Stevens et al., 2022; Werder et al., 2013; Andrews et al., 2014), which can cause complex responses from glacier velocities. Subglacial hydrology can be influenced by seasonal input of surface meltwater, which generates changes in basal water pressure that evolve over the summer as subglacial conduits grow more efficient (Andrews et al., 2014; Vijay et al., 2019). However, subglacial hydrology can also be influenced by remnant summer meltwater (Iken & Truffe, 1997), water storage englacially (Abe & Furuya, 2015) and in basal crevasses (Harper et al., 2010), or exfiltrated groundwater (Robel et al., 2023), which can leak out of the subglacial system over time (Rennermalm et al., 2013).

Previous efforts have classified glacier seasonal velocity variations into types based on the observed timing of changes and correlation to runoff and terminus changes (Moon et al., 2014; Vijay et al., 2019, 2021). Three categories are generally described in the literature; 1) positive correlation of glacier velocity to glacier terminus retreat; 2) positive correlation of glacier velocity to seasonal summer runoff, and; 3) glacier velocity that slows in late summer and speeds up in winter. Recently, Solgaard et al. (2022) applied a machine learning approach to analyze velocity time series data across Greenland, revealing similar seasonal patterns as those first identified by Moon et al. (2014), however both studies used data with limited sampling frequency, resulting in possible aliasing of sub-seasonal velocity changes. Here, we re-examine glacier seasonality using high-frequency terminus (Zhang et al., 2023) and velocity (Gardner et al., 2023) observations, within an analytical model of velocity response to terminus position change (Joughin et al., 2012), to explore how compounding processes influence glacier seasonality. Additionally, we integrate a seasonally-varying elevation dataset into our analysis to assess the impact of elevation change on the seasonal velocity response of a glacier. By comparing model results with observed velocity time series, our results indicate that sub-seasonal glacier velocity change can be caused by the interplay of multiple processes.

2 Data, study regions, and method

We investigate five glaciers in central-west Greenland (Figure 1): Rink Isbrae (RNK), Sermeq Avannarleq (AVA), Sermeq Kujalleq (KUJ), Kangilernata Sermia (KAN), and Eqip Sermia (EQP) over the time period 2015-2021. This time span is specifically chosen to take advantage of the increased sample frequency available in both velocity and terminus position data due to the launch of Sentinel-1/2 in 2014. These five glaciers are selected because 1) they exhibit regular seasonal changes in both terminus and velocity changes (Catania et al., 2018; Fried et al., 2018) with minimal long-term variations over our study period and; 2) they exhibit a range of sub-seasonal behavior in both the terminus and velocity variability. For example, all glaciers advance in winter and retreat in summer and yet their seasonal velocity behavior differs over time and space. EQP and KUJ speed up during summertime terminus retreat while AVA and KAN slow down during summertime terminus retreat (Fried et al., 2018). AVA, KUJ, KAN, and EQP are located close to one another, suggesting that they likely experience the same regional climate forcing. We also examine RNK, which is further north than these four glaciers because it has a deep grounding line, in contrast to the shallower grounding lines of the other four glaciers to the south, and a partially floating terminus that permits large, buoyant flexure-style calving events driving glacier-wide step changes in the terminus position (Medrzycka et al., 2016; Fried et al., 2018).

We use dense velocity time series data generated using auto-RIFT (Gardner et al., 2018) and provided by the NASA MEaSUREs ITS_LIVE project (Gardner et al., 2023). ITS_LIVE combines velocity products derived from Landsat-8, Sentinel-1, and Sentinel-2 producing a near-daily temporal resolution since 2014. For each glacier, we identify multiple flowlines across the glacier from Felikson et al. (2021) and extract velocities at points that are situated roughly 1-2 kilometers upstream from the terminus along each flowline. We then average these velocities across all flowlines to produce a mean velocity time series for each glacier. RNK has eight flowlines because half of the terminus region of this glacier is floating and we want to examine the velocity variations of the floating and grounded ice separately. We identify floating ice based on the flattening of the surface elevation along flowlines towards the terminus and we take the mean of the velocities on floating ice and grounded ice separately (Figure S1). We refrain from employing bed elevation data to ascertain the floating condition for RNK because of the reliance of the bed data on mass conservation and the assumption that the glacier is grounded, as described below (Morlighem et al., 2017). Terminus position data come from AutoTerm (Zhang et al., 2023), a machine learning pipeline that automatically produces terminus traces with an average sampling frequency of 10 per month since 2014. We derive a time series of terminus changes by calculating sequential area changes between termini, accumulating these over time, and then normalizing this by the glacier width.

Surface elevation data come from a novel fusion of ICESat-2 data with DigitalGlobe high-resolution digital elevation models (DEM), termed "DG-IS2-DEM". Four DEMs per year are available since Fall 2018. We also use ArcticDEM (Porter et al., 2022) as supplementary elevation data in locations where the DG-IS2-DEM does not extend to the most advanced terminus position found in AutoTerm. To get ice thickness data, we subtract surface elevation data from bed elevation data from BedMachineV5 (Morlighem et al., 2022), which assimilates seafloor bathymetry and ice thickness data through a mass conservation approach (Morlighem et al., 2017). We extract the surface and bed elevation profiles along each flowline individually. We use GSFC-FDMv1.2.1 simulations of the surface mass balance (Medley et al., 2022) to produce a runoff time series with a five-day sampling frequency. We use runoff as a proxy for the start and end of the melt season.

We adopt the terminus-driven model described by Joughin et al. (2012) to predict the seasonal terminus velocity, which explicitly considers the influence of the dynamic changes at the glacier terminus on upstream velocity. For each flowline, we employ its associated geometry profile for velocity simulations. By using the terminus-driven model, we are able to isolate the contribution of sub-annual terminus variations to the observed variations in the velocity time series. The terminus-driven model focuses on the driving stress (τ_d) and an additional force due to the presence of the free calving face determined by the height above the fjord surface at the calving front and the density of seawater. The difference between these two forces at the terminus is expressed as

$$F = \frac{1}{2} \times \rho_i \; gH^2 - \frac{1}{2} \times \rho_w \; g(H-h)^2 \tag{1}$$

where g is the gravitational acceleration, H is ice thickness, h is ice surface elevation, ρ_w is the density of seawater ($1028 km \; m^{-3}$), and ρ_i is the density of ice ($910 km \; m^{-3}$). The force balance at the terminus requires the frontal force, F, to be balanced upstream by the longitudinal stress, which redistributes much of the frontal force to the margins and bed of the glacier upstream. The longitudinal stress that originates from the frontal force ($\tau_F(x)$) pulls the glacier and enhances the original driving stress (e.g., $\tau_d + \tau_F(x)$). The enhanced driving stress is considered to be balanced by resistance stress (e.g., basal drag and lateral shear stress). Based on the observation that the seasonal amplitude of velocity is strongest at the terminus and diminishes upstream, Joughin et al. (2012) made the assumption that $\tau_F(x)$ decreases linearly from the terminus to zero at the stress coupling length, and the integration of $\tau_F(x)$ along the flowline equals F.

By assuming a linear relationship between velocity and the cube of $\tau_d+\tau_F(x)$ (Van der Veen, 2013), the predicted velocity from terminus changes is thus given by:

$$\frac{V\left(x,t\right)}{V_0} = \left(\frac{\tau_d + \tau_F(x)}{\tau_d + \tau_{F_0}}\right)^3 \tag{2}$$

where V_0 is a reference velocity and $\tau_{F_0}$is the $\tau_F(x)$ for the reference velocity. The assumption holds when resistance increases with glacier speed due to factors like increased internal ice deformation (e.g., laminar flow) or larger basal friction over a rough and rigid bed (Van der Veen, 2013). For each year, we use the minimum velocity as the reference velocity and calculate τ_{F_0} based on the terminus position near the date of the reference velocity. We vary stress coupling lengths for each glacier and choose the one that produces the lowest mean difference between observations and simulated velocity (Table S1). The mean difference is determined by:

$$\frac{abs(model - observation)}{model} \times 100\% \tag{3}$$

Using Eqn. 2 we simulate a velocity time series at each observation point for each glacier (Figure 1) and average the simulated velocity across all flowlines in a manner consistent with observed velocity. Subsequently, we compare these averaged simulated velocities to observed velocity.

We make use of the new time-varying DG-IS2-DEM in order to determine if seasonal changes in surface elevation may also produce seasonal changes in velocity in addition to those driven by seasonal terminus change. To accomplish this, we produce a simulated velocity for all glaciers with and without time-varying surface elevation. For the fixed geometry simulations, we choose a time step from DG-IS2-DEM with an extent that aligns best with the position of the terminus when it is most advanced. This provides the most complete elevation profile across the terminus region. For EQP, KAN, and AVA we choose the October 2019 DG-IS2-DEM and for KUJ, we use the April 2019 DG-IS2-DEM time step. For RNK, we use additional elevation data from ArcticDEM (Porter et al., 2022) for the fixed geometry case, as the DG-IS2-DEM does not cover the most advanced terminus position for this glacier.

3 Results

We compare the simulated velocity time series with velocities from satellite observations to determine whether seasonal velocity variations are influenced primarily by terminus change, co-influenced by other factors, or entirely independent of terminus change. Overall, we find that the time-series velocity observations from 2015 are well-described by the terminus-driven model for RNK, KUJ, and EQP but not for KAN and AVA (Figure 2, S2–S6). For RNK, KUJ, and EQP, seasonal changes in glacier speed align well with terminus variations. This is supported by the coincident timing of the end of terminus retreat and the peak summertime velocity (vertical black lines in Figure 2), even in instances when retreat continues beyond the end of the melt season (Figure 2l). For these glaciers, the mean misfit between simulated and observed velocities over all years are 4.6% for KUJ, 6.2% for EQP, and 6.8% for RNK (Table S1), with correlations of 0.84, 0.67, and 0.56, respectively (Figure S7).

Although the terminus-driven model adequately resolves seasonal variability in velocity for RNK, KUJ, and EQP, there are observed sub-seasonal velocity changes that are not explained by the terminus-driven model. For all glaciers but KUJ, we observe additional pulses in velocity (acceleration and deceleration) in the middle of the melt season, a phenomenon not captured by the terminus-driven model (black dashed boxes in Figure 2l). While these are predominant, they do not occur consistently across all years for all glaciers. For example, melt-season pulses are visible for every year in the record for AVA (Figure S3) but they are only visible from 2015-2019 for KAN (Figure S5), from 2016-2019 for EQP (Figure S6), and in 2015, 2017, and 2019 for RNK (Figure S2).

In addition to melt-season velocity pulses, we find additional sub-seasonal pulses that coincide with large calving events. Such events are only visible on RNK, which experiences much larger calving events than the other glaciers and are associated with step changes in the terminus position. Calving-related pulses in velocity are only predicted to impact velocity noticeably for the grounded portion of RNK (Figure S2d), and while we observe sub-seasonal velocity pulses that are coincident with some of these predicted events (blue dashed box in Figures 2m and S2), they have a magnitude that is muted compared to those predicted by the terminus-driven model. Further, there are many more predicted velocity pulses from large calving events than are visible in the observed velocity.

While both KAN and AVA experience summertime terminus retreat and wintertime terminus advance similar to the other three glaciers, their velocity response is poorly predicted by the terminus-driven model. For these two glaciers, we observe accelerations during winter (during terminus advance) that plateau before the onset of the following year's melt season, and early melt season accelerations with the annual maximum velocity reached in the middle of the melt season (black dashed boxed in Figures 2n, S3, and S5). The terminus-driven model does not capture wintertime acceleration because the terminus at this time is advancing. For KAN, the model predicts slight deceleration in winter (Figure 2n and S5). For AVA, there is no significant seasonality in the simulated velocity likely because the scale of seasonal terminus advance and retreat for this glacier is small (Figure 2o and S3) and the frontal surface elevation is flat (Figure S8). The averaged seasonal terminus variation is 144 meters for AVA, while EQP is 224 meters, KAN is 390 meters, and KUJ is 417 meters.

We investigate the influence of changing surface topography by comparing the velocity simulated using a fixed geometry against velocity simulated using a seasonally varying surface elevation from 2018-2022. We find minimal differences between these results (blue versus red lines in Figure 2). To investigate this further, we consider only KUJ as an example and probe the terminus-driven model via two experiments; 1) we artificially shift the entire elevation profile vertically by $\pm$10-20 meters and; 2) we alter the slope of the surface elevation by $\pm 2\%$ within the 2 km-frontal region. The results suggest that terminus-driven velocities are relatively insensitive to spatially uniform, along-flow changes in surface elevation, but are highly sensitive to changes in surface slope (Figure S9). This result is important for providing context for interpreting the results for RNK, which has a flat, floating portion of the terminus. We find that the floating region of RNK exhibits seasonal variations in velocity of comparable magnitude to the observations in the grounded region (Figure S2e). However, the terminus-driven model simulates velocities that have no discernible seasonality for the floating region, nor is the magnitude of the simulated velocity comparable to what is observed for RNK (Figure S2e).

4 Discussion

Using high-temporal-resolution observations and a terminus-driven model to simulate velocity variations from terminus change, we investigate sub-seasonal velocity changes for GrIS outlet glaciers and find that glacier velocity responds to multiple compounding processes. The seasonal velocity changes of three glaciers (KUJ, EQP, and RNK) can largely be attributed to seasonal terminus variation, particularly for KUJ, which has a velocity that is almost entirely driven by the terminus fluctuations. However, 4 out of

5 study glaciers experience additional processes that drive changes in velocity. For example, EQP, RNK, AVA, and KAN all experience occasional sub-seasonal peaks in velocity that are coincident with the middle of the melt season, AVA and KAN exhibit wintertime speedup that occurs when their termini are advancing, and RNK experiences short-time pulses in velocity throughout the record (Figure 2).

The availability of seasonally-resolved elevation change allows us to investigate the degree to which velocity is sensitive to changing surface elevation. We find that seasonal elevation changes for EQP, KAN, KUJ, and AVA are overall uniform along flow (Figure S8), and as a result, they do not significantly alter terminus-driven velocity (blue lines in Figures 2, S3-S6). This aligns with our experimental results that suggest that overall vertical shifts in elevation have a limited contribution to velocity seasonality (Figure S9a). The experimental results also suggest steepening surface elevation will cause stronger velocity responses (Figure S9b), which agrees with our simulation results for RNK that seasonality is comparable with observations along the steep grounded flowlines but nearly absent on flat floating flowlines (Figure S2).

We hypothesize that the peaks in the middle of the melt season observed for EQP, RNK, AVA, and KAN (black dashed squares in Figure 2 and Supplementary Figures) result from runoff-driven acceleration and subsequent evolution of the subglacial drainage system (Moon et al., 2014; Vijay et al., 2019). Early in the melt season, the subglacial drainage system is inefficient (Andrews et al., 2014), thus as meltwater availability begins to increase (marked by increasing runoff in early summer), subglacial water pressures increase enhancing basal sliding by reducing friction between the ice and the bed (Bartholomew et al., 2010; Bartholomaus et al., 2008). As the melt season progresses, the drainage system channelizes becoming more efficient (Andrews et al., 2014; Schoof, 2010) and available meltwater decreases, producing a reduction in glacier speed. After the melt season, the impact of terminus retreat on seasonal velocities can become more pronounced. For example, EQP typically has a melt season that ends in October, but the terminus continues to retreat until December/January (Figure 2l). This produces a wintertime peak in velocity that is coincident with the most retreated terminus of EQP and is distinct from the melt-season peak.

To further explore the velocity variations that are not driven by terminus, we take a closer look at the velocity profiles for EQP, KAN, and AVA at particular times in our time series (Figure 3). To confirm that runoff drives summertime speed up for EQP, we compare the along-flow spatial pattern of velocity changes that occur in the summer melt season of 2017 (Apr 2017 - Sep 2017) and the subsequent time period after runoff has ceased, when the velocity is primarily influenced by terminus changes (Oct 2017 - Mar 2018). We quantify the range of upstream velocity at a distance of 8 km upstream of the terminus, 20 times the glacier's frontal thickness from the terminus to ensure we are several longitudinal coupling lengths upstream of the terminus. We find that runoff-driven acceleration is noticeable in the velocity further upstream than the terminus-driven velocity change. For example, when the runoff is large, EQP experiences a range in upstream velocity that is 80% of the velocity range observed at the terminus (Figure 3a). Conversely, in the winter when runoff is absent and the terminus alone is changing, EQP experiences a range in upstream velocity inland that is just 19% of what is observed at the terminus (Figure 3b). The rapid decline in speed with distance from the terminus is expected in the terminus-driven model because of the decline in terminus force with distance from the terminus (Joughin et al., 2012), while elevated inland velocities are typical for melt-driven acceleration (Sundal et al., 2011) because meltwater percolates throughout the ablation zone (Andrews et al., 2014), which extends about 700 km inland of the terminus for EQP (Noël et al., 2019).

AVA and KAN experience mid-summer velocity pulses similar to EQP, suggesting these pulses are also likely runoff-driven. However, these two glaciers do not exhibit any terminus-driven seasonal acceleration (Figures S3 and S5) and instead accelerate in winter. This suggests that seasonal velocity changes for these glaciers occur independent of terminus change. Similar to melt-driven summertime velocity pulses, we observe that wintertime speed up for AVA and KAN also extends far inland (Figure 3). For KAN, we observe that the range in upstream velocity during wintertime speed up is 72% of the range in frontal velocity. For AVA, we see a smaller range of velocities upstream, where they are 39% of the range of frontal velocity. However, the range in upstream velocity remains large compared to EQP and KAN (Figure 3d). We hypothesize that the elevated range of KAN and AVA's upstream velocities in winter suggests that winter acceleration is due to enhanced extensive basal slip, which can be caused by several different processes. During the onset of winter, refreezing of percolating meltwater (Boon & Sharp, 2003) and viscous deformation over subglacial conduits (Vieli et al., 2004; Bartholomaus et al., 2011) can obstruct the drainage system. Consequently, water becomes trapped within an inefficient drainage network, leading to increased water pressure and winter accelerations (Vijay et al., 2019). There are three possible sources of water at the ice–bed interface during winter: 1) remnants of summer meltwater (Iken & Truffe, 1997), englacial water stored by basal crevasses that do not reach the surface (Abe & Furuya, 2015; Harper et al., 2010), and sustained exfiltration of underground water caused by rapid unloading in melt season (Robel et al., 2023). The winter acceleration phase ends when the melt season begins to supply additional water to the subglacial system, which further increases basal water pressures causing summertime pulses in speed forcing the glacier to reach maximum speeds in summer.

RNK is a glacier that experiences three distinct modes of velocity variations including 1) seasonal terminus-driven velocity change; 2) occasional runoff-driven velocity change and; 3) frequent, small-magnitude velocity change that appears to be linked to large calving events. Large calving events have been documented to cause step-like acceleration for large calving events at Helheim Glacier (Nettles et al., 2008; de Juan et al., 2010) and, like Helheim, RNK experiences calving via buoyant flexure in which large tabular icebergs detach causing glacier-wide step retreats in the terminus position (Fried et al., 2018; Medrzycka et al., 2016). Calving-related velocity pulses at RNK are muted compared to those predicted by the terminus-driven model. In part, this may be due to the lower sampling frequency of terminus change. Prior to 2017, our terminus record contains just six termini per month. Indeed, we observe more velocity pulses related to calving events that are well predicted from the terminus-driven model after 2017, when there are up to fourteen termini per month. In addition to reduced sampling frequency, the floating portion of RNK with its flat surface topography likely produces a weaker response to calving events than would be seen on grounded ice, with its steeper surface topography. This may additionally explain the muted calving response.

For RNK, the velocity changes on the floating flowlines may be driven by lateral stresses originating on the adjacent grounded ice. The floating portion of the RNK terminus produces simulated velocities that exhibit only minimal change over time (Figure S2), indicating that velocity change is not driven by terminus variation. In contrast, the observed velocities in the floating portion of RNK show just as much variation over time as we observe in the grounded portion. We attribute this discrepancy to the fact that the terminus-driven model captures longitudinal stresses but not lateral stresses. Thus, the seasonal variations in the observed velocity over the floating region might be driven by the nearby velocities on the grounded ice through lateral stress, which is not captured by the terminus-driven model. The impact of flotation may also be observed on the grounded ice. For example, in 2017 and 2018 RNK underwent a large multi-year advance ($\sim$ 1000 meters), after which the seasonal variations in both simulated and observed velocity in the grounded ice are reduced in amplitude compared to other years. We speculate that as the glacier advanced, its original grounded front became floating and the surface flattened, which caused the velocity to be less sensitive to seasonal terminus variation.

5 Conclusion

We apply a terminus-driven model to elucidate the seasonal and sub-seasonal velocity changes for five glaciers in Central West Greenland. The comparison between simulated and observed velocity suggests that glacier velocity change is driven by the interplay of multiple processes: terminus variations, runoff changes, evolution of the subglacial drainage system, and calving. Notably, the observed seasonal elevation changes appear to have limited influence on velocity largely because the seasonal elevation signal is dominated by shifts in elevation and not changes in surface slope. While the terminus-driven model can effectively isolate the contribution of terminus changes on seasonal velocity variations, several unresolved issues remain. For instance, it is still unclear why some glaciers (RNK, KUJ, and EQP) display sensitivity to terminus changes, while others (KAN and AVA) apparently do not. Our study provides a framework that can be applied to all outlet glaciers around the Greenland Ice Sheet to reveal the compounded nature of each glacier's seasonality. Moreover, the same framework could be applied to investigate the long-term changes in glacier dynamics with adequate historical data. By systematically discerning the commonalities and disparities among glaciers with distinct glaciological settings, our approach has the potential to shed light on the controls on outlet glaciers.

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Open Research Section

Velocity data can be freely downloaded at `https://its-live.jpl.nasa.gov/` (Gardner et al., 2023). ArcticDEMs are available at `https://livingatlas2.arcgis.com/arcticdemexplorer/`. The code, terminus data, flowlines, and DG-IS2-DEMs can be downloaded at `https://zenodo.org/record/8428196`.

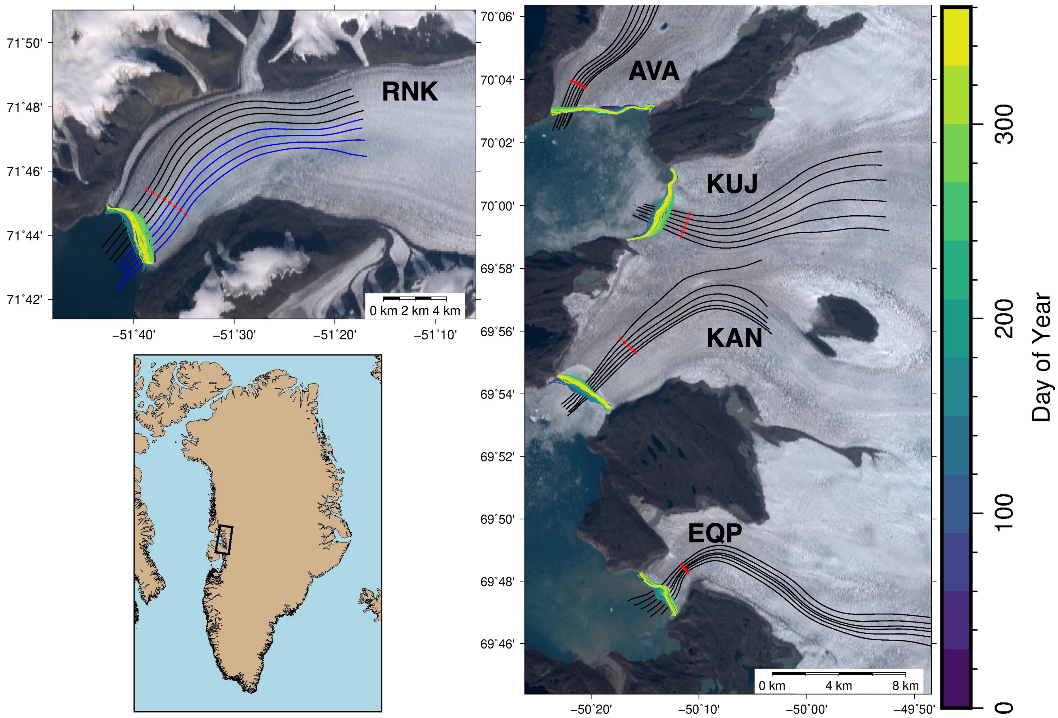

Figure 1. Glacier and data locations. Glaciers examined in this study include Rink Isbrae (RNK), Sermeq Avannarleq (AVA), Sermeq Kujalleq (KUJ), Kangilernata Sermia (KAN), and Eqip Sermia (EQP). Black flowlines represent grounded portions of the glaciers while blue flowlines represent floating portions of the glaciers. The terminus traces in 2018 from AutoTerm are colored by date. Red points on each flowline are the locations where we obtain velocity time series from ITS_LIVE.

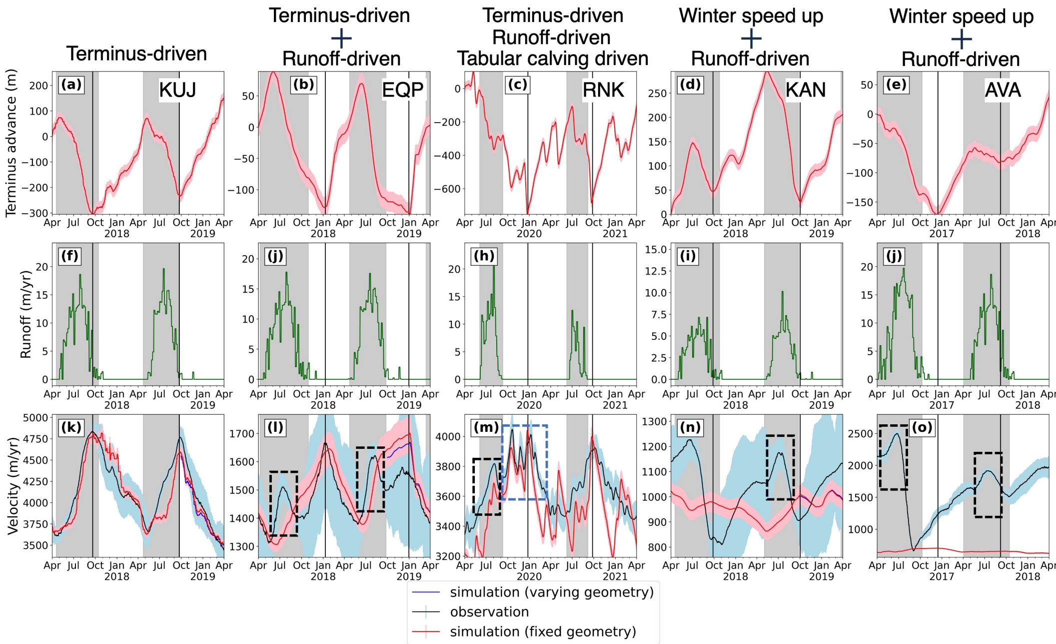

Figure 2. Comparison between velocity observations and simulations and examples of compounded seasonality. The left column is the results of KUJ, the middle column is for EQP, the third column is for RNK, the fourth column is for KAN, and the fifth column is for AVA. The black vertical lines indicate the end of retreating. The shaded areas indicated melt seasons. The blue-shaded areas indicate the uncertainty of the velocity observations, and the pink-shaded areas indicate the terminus uncertainty. The dashed boxes show the acceleration induced by runoff. The blue dashed box in (m) shows the acceleration caused by large calving events.

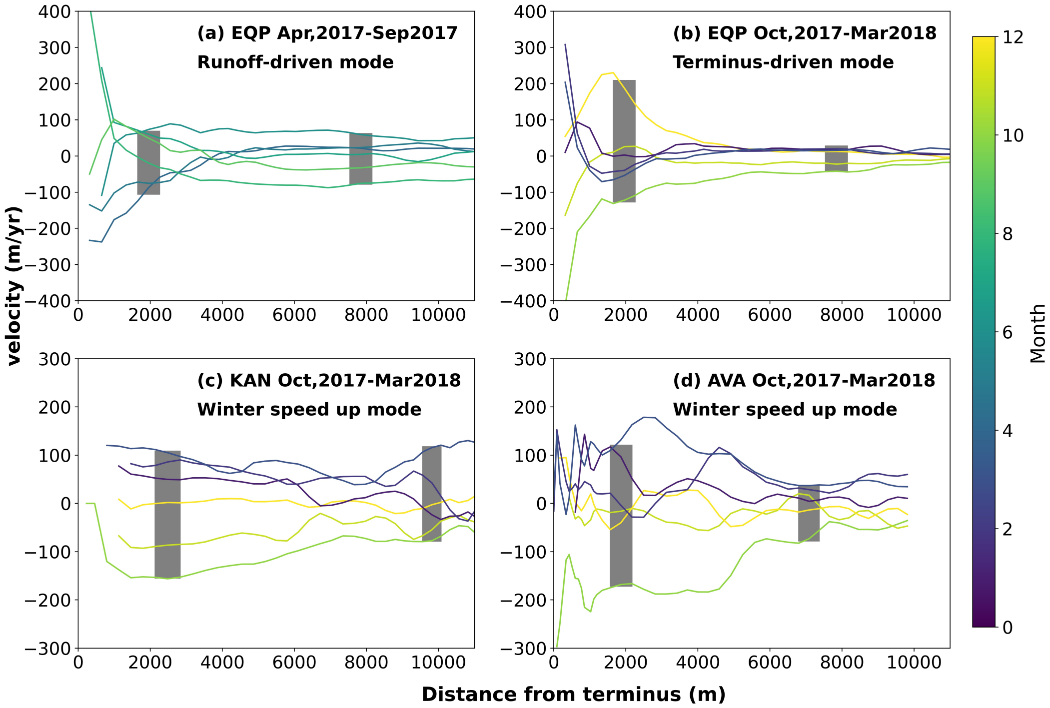

Figure 3. Velocity profiles over time for EQP, KAN, and AVA. The average velocity profile has been subtracted for a better display of changes over time. The original velocity profiles are shown in Figure S10. The shaded areas indicate regions where we obtain velocity variations in the frontal and upstream sections. (a) Velocity profiles of EQP during the melt season. (b) Velocity profiles of EQP after the melt season, during which velocity is primarily influenced by terminus changes. (c) Velocity profile of KAN during winter and early melt season. (d) Velocity profile of AVA during winter and early melt season.