Surface runoff impact on ice dynamics varies with altitude and location

Paul Halas[1], Basile de Fleurian[1], Jeremie Mouginot[2], and Petra Langebroek[3]

[1]University of Bergen
[2]Université Grenoble Alpes, CNRS
[3]NORCE Norwegian Research Centre

March 6, 2023

Abstract

Surface runoff over the Greenland Ice Sheet has been shown to have an impact on ice velocities, both at short as well as decadal timescales. While the short timescales are necessary to comprehend the physical processes connecting subglacial water pressure and ice motion, upscaling to longer timescales is paramount to assessing the future behavior of glaciers in a warming climate. In this study, we assess in a land-terminating part of Southwest Greenland over 2013-2021 the relationship between annual ice velocities derived from optical feature-tracking and surface runoff derived from the ERA5-MAR climate model. The recent time period, providing frequent satellite acquisition, allows for a precise selection of image pairs, while also covering summer melt seasons varying in both intensity and duration. We find that the exact link between runoff anomalies and ice velocity anomalies changes depending on the basin considered and that the relationship also changes with altitude. However, all basins do show a similar overall behavior: at low elevations, while a small increase in runoff leads to faster velocities, a large increase in runoff leads to a slowdown of the glacier ice, but years with even larger runoff would tend to make the ice faster again. As altitude increases, runoff anomalies variations seem to have less impact on ice velocities. We compute for each pixel a simple index to quantify this relationship, presenting here a map displaying how runoff anomalies affected the velocities in 2013-2021 and underlining the spatially varying impact of meltwater depending on altitude and location.

Surface runoff impact on ice dynamics varies with altitude and location

Paul Halas[1], Basile de Fleurian[1], Jérémie Mouginot[2], Petra M. Langebroek[3]

[1]University of Bergen, Bjerknes Centre for Climate Research, Bergen, Norway
[2]Institut des Géosciences de l'Environnement, Université Grenoble Alpes, CNRS, IRD, INP, Grenoble, France
[3]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

Key Points:

- We analyze the relationship between ice velocities and surface meltwater runoff for 5 Greenlandic basins over the last 9 years.
- Surface meltwater and ice velocity are not linearly correlated, and their relationship varies with altitude and basin.
- A large part of the velocity, runoff relationship can be explained by considering the efficiency of the subglacial drainage system.

Corresponding author: Paul Halas, `paul.halas@uib.no`

Abstract

Surface runoff over the Greenland Ice Sheet has been shown to have an impact on ice velocities, both at short as well as decadal timescales. While the short timescales are necessary to comprehend the physical processes connecting subglacial water pressure and ice motion, upscaling to longer timescales is paramount to assessing the future behavior of glaciers in a warming climate. In this study, we assess in a land-terminating part of Southwest Greenland over 2013-2021 the relationship between annual ice velocities derived from optical feature-tracking and surface runoff derived from the ERA5-MAR climate model. The recent time period, providing frequent satellite acquisition, allows for a precise selection of image pairs, while also covering summer melt seasons varying in both intensity and duration. We find that the exact link between runoff anomalies and ice velocity anomalies changes depending on the basin considered and that the relationship also changes with altitude. However, all basins do show a similar overall behavior: at low elevations, while a small increase in runoff leads to faster velocities, a large increase in runoff leads to a slowdown of the glacier ice, but years with even larger runoff would tend to make the ice faster again. As altitude increases, runoff anomalies variations seem to have less impact on ice velocities. We compute for each pixel a simple index to quantify this relationship, presenting here a map displaying how runoff anomalies affected the velocities in 2013-2021 and underlining the spatially varying impact of meltwater depending on altitude and location.

Plain Language Summary

During summer, meltwater is produced at the surface of glaciers. This water can enter the glaciers through crevasses or moulins, and affect how the ice slides on its bedrock. Here, we assess in the southwest of the Greenland Ice Sheet, the relationship between runoff and ice velocities on a yearly timescale, at different altitudes, and for 5 different basins, for the period 2013-2021. We find that the meltwater will have a different impact on the ice velocities depending on altitude and location. Previous studies expected our study area to be resilient to warmer summers, as a slowdown was observed in conjunction with increased melt. We find here that at low altitudes, a small increase will lead to faster velocities, a larger increase will indeed lead to a deceleration, but also that a much larger increase of runoff could lead to an acceleration of the ice. As altitude increases, our observations indicate that meltwater anomalies have less impact on the ice velocities. We derived an index to quantify the impact of meltwater and observe a clear effect of altitude and variations of runoff effect by basins all along the study area.

1 Introduction

Dramatic increases in surface meltwater on the Greenland Ice Sheet (GrIS) have been observed for more than three decades now (e.g., Van Den Broeke et al., 2009; Velicogna, 2009; Rignot et al., 2011; Mouginot et al., 2019). The importance of surface meltwater to glacial systems has long been recognized, and numerous studies have investigated its role in the dynamics of the ice (e.g., Zwally et al., 2002; Joughin et al., 2008; Shepherd et al., 2009; Hoffman et al., 2011). Yet meltwater impact on ice velocities on decadal timescales remains not fully understood (Davison et al., 2019).

Understanding the impact of meltwater on ice dynamics is paramount to improving the predictions of future ice discharge to the ocean or glacier geometry changes under expected warmer summers (Van De Wal et al., 2008; Nienow et al., 2017; Koziol & Arnold, 2018). The relationship between ice velocities, meltwater, and subglacial water pressure has for example been observed in Van De Wal et al. (2015), where a sudden runoff event induced a clear ice speedup but sustained high runoff throughout summer eventually lead to a deceleration of the ice. They show that runoff influences the subglacial water pressure, and this pressure in return affects the sliding of the ice, which affects surface ice velocities. Variations of subglacial pressure throughout the summer were observed and interpreted as a switch from an inefficient subglacial drainage system to a more efficient one, induced by sustained high runoff.

It is however unclear whether the same pattern can be observed everywhere, for example where ice is thicker and runoff smaller (e.g., Doyle et al., 2014; de Fleurian et al., 2016). Doyle et al. (2014) did not observe a deceleration in the late melt season far from the ice sheet margin, indicating that the subglacial drainage system does not systematically evolve towards an efficient system, so the slowdown of the ice after summer may be confined to low elevations. Yet previous studies implementing the impact of runoff on ice velocities for future projections did not always consider altitude variations, mostly because the availability of observations was not sufficient (Shannon et al., 2013; Fürst et al., 2015). While seasonal studies of the relation between meltwater input and ice velocity bring a better understanding of the local physical processes at play, the necessary high-temporal resolution velocity data is not often available for long periods of time, and even less so on a large spatial scale (Davison et al., 2019).

At a decadal timescale, Tedstone et al. (2015) and Williams et al. (2020) found that a land-terminating sector of the ice sheet has been slowing down, and at the same time an increase in surface meltwater was observed. As the rate of the slowdown was only 1.5 m/yr^2, a long period such as 2000-2012 was necessary in order to identify the trend. More recently, a re-acceleration of the ice was found by Williams et al. (2020) in Southwest Greenland and was attributed to a reduction of meltwater production, although we found in Halas et al. (2023) that the observed trend was spatially heterogeneous with significant trends mostly confined to low-lying ice tongues. The variability in runoff produced every year in this period is indeed high, varying by up to 40% compared to an average over the same time period, rendering the understanding of the relationship between runoff and ice velocities at the decadal timescale difficult. In addition, ice velocity trends in this land-terminating area of the Greenland Ice Sheet are relatively small compared to the signal. In this context of alternating intense and less intense melt seasons, we want to step back from decadal trends to assess the impact of surface melting at a yearly timescale, in order to understand how a given melt season impacts the velocities until the next melt season. How this relationship varies with altitude and location is also required for improving the assessment of the future behavior of the ice sheet in a warming climate.

We therefore assess here how surface meltwater and velocities are related, using yearly feature-tracked ice velocities in conjunction with runoff derived from climate reanalysis over 2013-2021.

2 Data and Methods

2.1 Study area

Our study area is located in Southwest Greenland and is displayed in Figure 1. We focused the first part of our study on 5 land-terminating basins, but extend our work to the whole region for the second part. This land-terminating area is a perfect study area for such work as it is an ocean-free setting, and it is assumed that variations in ice velocity are mostly controlled by changes in basal conditions (Tedstone et al. (2015); Maier et al. (2019); Derkacheva et al. (2020)).

For our 5 basins, we focused naturally on Russell Gletscher and Isunnguata Sermia close to the town of Kangerlussuaq, since they have been the subject of in-situ geophysical investigations such as mechanical properties of sediment bed underlying the glaciers and their influence on the ice flow (Dow et al., 2013; Wright et al., 2016; Harper et al., 2017; Kulessa et al., 2017; Maier et al., 2019), as well as numerical investigations (Bougamont et al., 2014; de Fleurian et al., 2016; Koziol & Arnold, 2017, 2018; Brinkerhoff et al., 2021).

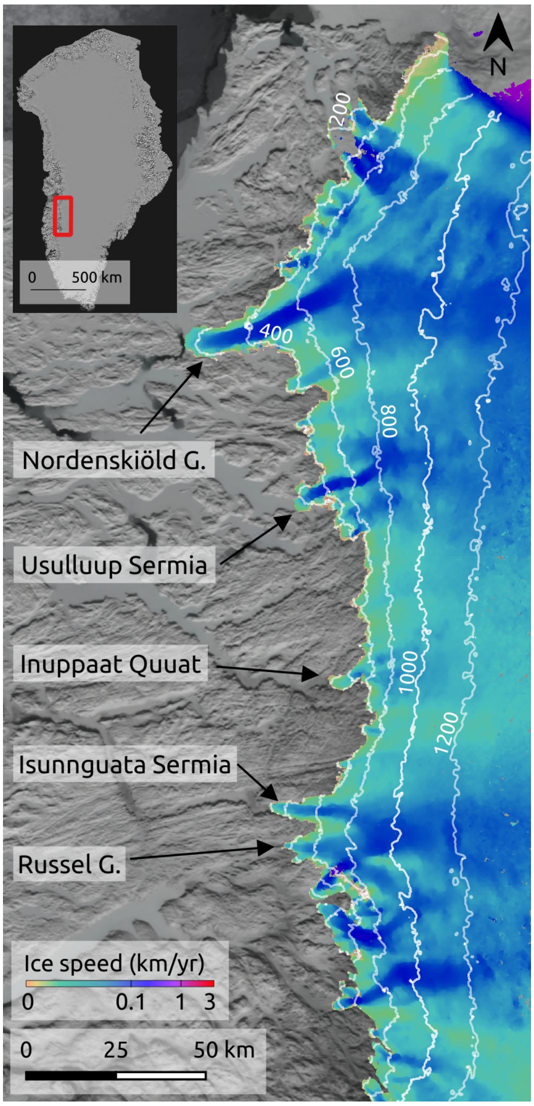

Figure 1. Map of the study area. Ice velocities displayed are derived by combining all velocity fields computed in this study from image pairs of Landsat 8 and Sentinel-2 for the years 2019-2020. The ice velocities are overlaying a 2015 MODIS Mosaic of Greenland (MOG) at 100 m resolution (Haran et al., 2018). White lines represent the 200 m isolines extracted from MEaSUREs Greenland Ice Mapping Project (GIMP) Digital Elevation Model.

These two basins, spatially close, also offer an interesting comparison to see whether runoff effect on ice velocities can differ for neighboring glaciers. North of these two glaciers, we focus on Nordenskiöld Gletscher and Usulluup Sermia, both displaying similar orders of magnitude for their ice velocity and altitude ranges. Being central between our four other sites, our 5th site is Inuppaat Quuat. It also offers an interesting comparison as this glacier is displaying slower velocities than the rest, while having a reasonably large tongue.

2.2 Velocities from satellite observations

In order to understand how surface meltwater correlates to ice dynamics, we used observations of ice velocities, derived from feature-tracking over the period 2013-2021.

While being an ocean-free setting, land-terminating glaciers are also displaying slower velocities, potentially leading to smaller - i.e. less easily detectable - variations in velocity (Halas et al., 2023). Studying such ice velocities, therefore, requires a combination of accurate velocity estimations and good spatial coverage that yearly feature-tracking can provide (Millan et al., 2019). The period 2013-2021 was selected since the launch of Landsat 8 in 2013 greatly increased the number of image pairs for feature-tracking, allowing for a much more aggressive selection of the data. We used the same velocity products derived by feature-tracking produced for Halas et al. 2023, publicly available on open repositories (Halas et al., 2022, released 9 December 2022). We selected pairs with images separated by about one year, since it allows for a much greater level of precision compared to shorter baselines, as demonstrated with the same correlation algorithm in Mouginot et al. (2017) and Millan et al. (2019). Following the recommendations of Halas et al. (2023) on the selection of image pairs, we only used velocity data derived from pairs with the starting date before summer, so that every single annual velocity is sampled over one melt season and the following winter. While this precise selection reduces the spatial coverage, it avoids sampling two summers, allowing us to compare the same period every year.

The complete methodology regarding the processing of satellite images to obtain velocity maps is detailed in Halas et al. (2023).

From the selected image pairs, we computed a per-pixel average to produce a regional velocity map for every single year. We also computed the average velocity over our 9 years and derived yearly velocity anomalies over this time interval. Only the data points where data was available for all 9 years were kept. These velocity anomalies maps are displayed in supplemental material Figure S1.

2.3 Runoff reanalysis from MAR

We use daily outputs of the polar regional climate model MAR forced by the ERA5 reanalysis over our region, downscaled to 1 km. The model MAR (version 3.12.1) has been run at a resolution of 10 km forced every 6 hours by ERA5 at its lateral boundaries. It is one of the best surface mass balance products currently available over the Greenland ice sheet (Fettweis et al., 2020). From these products, we extracted the daily runoff signal and used it to compute cumulative yearly runoff, the average cumulative runoff over our 9 years, and yearly cumulative runoff anomalies. During summer, meltwater is generated, but part of this water can refreeze or be trapped in the snow. The remaining water is defined as runoff and can be routed to the base of the glacier. As most of the area where we have data is located in the ablation zone, the surface meltwater signal is equal to the runoff signal. At higher altitudes, however, the runoff signal is smaller than the melt signal since the snowpack is able to retain a large part of the meltwater (Noël et al., 2019). We, therefore, use the runoff from MAR, although it is equal to the melt for most of our data points located in the ablation zone. Figure S2 gives an example of the daily runoff signal near the terminus of Nordenskiöld glacier. The signal is typical for the 5 basins studied in the region at similar altitudes. In large parts of the dataset, the runoff signal at low and higher altitudes evolves together, with the higher altitude signal being of lesser amplitude. In order to give an idea, we plot in Figure S2 over the low altitude signal a black line representing the runoff signal at 1000 m, and representative for our 5 basins.

2.4 Trend analysis

We plotted velocity anomalies against runoff anomalies for the 5 land-terminating basins in Southwest Greenland, with data separated by altitude bins of 25 m, 50 m, 100 m, and 200 m. We chose to display here in Figure 2 the 100 m altitude bin plots for Russel. This 100 m bin is a compromise, as this size of altitude bins was found to be sufficiently separating pixels by 9 different altitude bins while keeping a higher number of pixels compared to smaller altitude bins. We found no significant signal difference from 100 m bins to smaller bins. A 200 m bin seems however to stack too much data and we observe differences, especially at low altitudes. These additional bins are available in supplementary materials as Figures S4a-S4b (25 m), S5 (50 m), and S6 (200 m) for Russel Gletscher. In order to facilitate the reading of trends, we computed locally weighted scatterplot smoothing (LOWESS), which is a non-parametric regression fitting a moving regression model on neighboring data (Cleveland, 1979). We specifically chose this algorithm since we want to avoid having prior assumptions regarding the relationship between runoff anomalies and velocity anomalies. The algorithm computes locally weighted linear regressions such that closer data points will have greater weight. The curve displayed over our scatterplots is a combination of all local regressions. Three iterations of LOWESS are computed to adjust the weights while seeking to reduce root-mean-square deviation so that outliers are less likely to affect the final local regression. We display LOWESS estimations for velocity anomalies versus runoff anomalies for every altitude bin for Russel Gletscher over the scatterplot that was used for these estimations in Figure 2. We also plot for all 5 basins studied here, all 100 m bin LOWESS estimations on a single graph for easier comparison (Figure 3). With this approach, we disregard the temporal evolution of runoff and velocities, but rather aggregate all years to identify the relationship between the two, assuming the system has no memory of previous years' runoff input.

Since the resolution of our velocity map is 150 m compared to the 1 km resolution for reanalysis products, we located for every velocity map pixel the closest reanalysis pixel and used this value, assuming that the runoff is not varying drastically over a 1 km^2 area.

In addition to the trends, we assessed how strongly the ice velocity is undergoing variations over our 9 years, by calculating for each pixel the root mean square to 0 of the velocity anomalies over the 9 years, indicating how much on average the velocity differs from the average. We present a map of this index in Figure 5. Since we consider that the velocity changes in this region are mostly controlled by surface runoff, we argue that this index can be interpreted as the impact of runoff on ice velocity, with a higher index showing a stronger relationship between runoff and ice velocity whereas a lower index shows that changes in runoff do not lead to large changes in ice velocity.

3 Results and discussion

3.1 Runoff and velocity linked through the efficiency of subglacial drainage

As we see in Figure 2 for Russel Gletscher, but also for other basins in supplemental materials (Figures S7, S8, S9, and S10), both runoff and ice velocities are varying each year. When we combine all the years on the same plot as done in Figure 2, we see patterns giving insights into glacier behavior. We can observe strong ice velocity variations for low altitudes for different runoff quantities, but also that the relationship describing velocity evolution with respect to runoff anomalies is evolving with altitude. We will first focus on the behavior at low altitudes and will discuss the higher altitudes' behavior in a the next section.

The pattern emerging for Russel Gletscher up to 900 m is the following: we first observe maximum velocity anomalies for the years with the lowest runoff. When the runoff is higher than the average (around +5% to +15%), velocities are slower, which is especially visible at low altitudes. Finally, when runoff is even higher, as in 2019 when the runoff was 20% above average, velocities tend to be faster than when there is just slightly more runoff than on average.

This maximal velocity obtained for low runoff years must have been driven by fast summer velocities or fast post-melt season velocities. The explanation in terms of basal hydrology could be that the drainage system would develop into an efficient system but

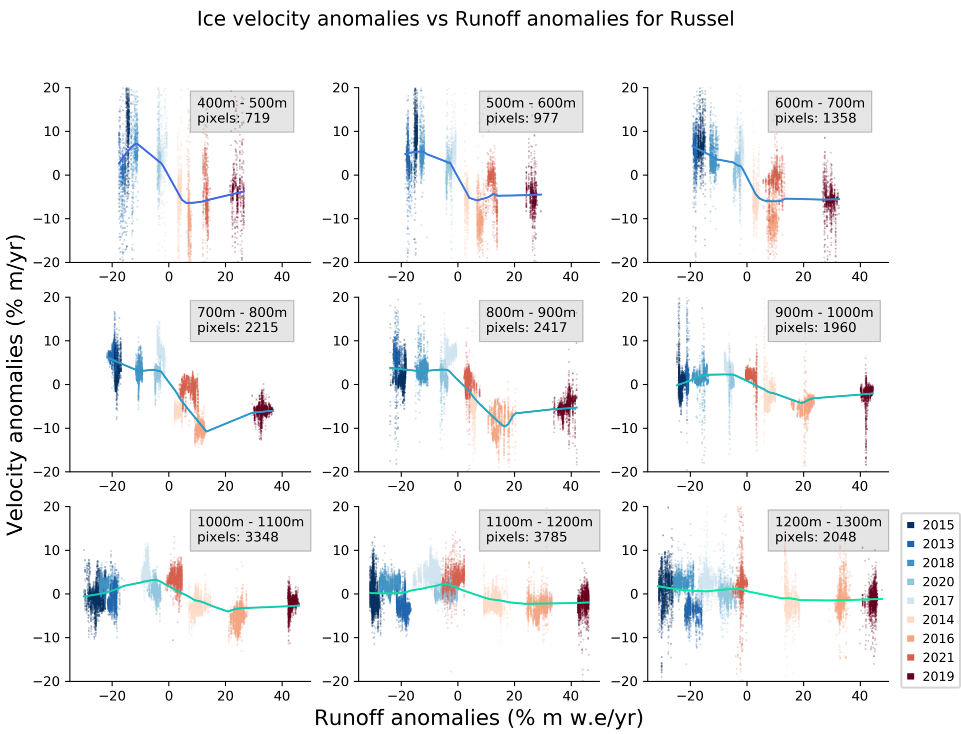

Figure 2. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Russel Gletscher. The colors indicate the year corresponding to the data, where blue dots represent low runoff years (minimum in 2015) and red dots high runoff years (maximum in 2019). Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS). Other basins are available in the supplemental material in Figures S7 to S10.

is not sustained due to less water input to the system, resulting in relatively fast velocities during late summer due to a switch back to a pressurized but inefficient system at this time, and leading potentially also to faster velocities during the winter season. When the runoff is slightly above average, it could be high enough to activate and sustain an efficient drainage system, resulting into slower summer velocities on average and an efficient drainage system still opened during the late melt season that could lead to slower winter velocities, as observed in Van De Wal et al. (2015). Finally, for years with high positive runoff anomalies like 2019, the efficient drainage system is at its limit, and although it develops, we still have sustained high water pressure driving fast ice flow during summer, but still slower velocities during winter than usual, as the velocity observed for such high melt years are still slower than average.

Figure 3 shows all runoff and velocity data per studied basin. To emphasize the various behaviour per altitude, the coloured lines indicate the smoothed trends per altitude bin (using the LOWESS calculation, see Sect. 2.4). Isunguata Sermia and Nordenskiöld Gletscher both display at low altitudes (blue lines) slower velocities than the average for the minimum runoff anomalies, down to around -10% in velocities. This behavior is different from Russel Gletscher where the lowest runoff anomalies generally lead to faster than average velocities. For Isunguata Sermia and Nordenskiöld Gletscher at low altitudes, we then observe a slight increase in velocities for years with runoff just under the average, then a slowdown if runoff is slightly above average, and clear faster velocities (around +10%) for years with even higher runoff anomalies. Nordenskiöld Gletscher seems to display again slightly slower velocities for 2019 (the year with the highest runoff anomaly), which is a behavior that we do not find in Isunguata Sermia, but the runoff anomalies in that basin do not reach as high values as in the first, so this behavior could potentially be observed if runoff anomalies were higher.

When we observe the behavior for other basins in Figure 3, Usulluup Sermia and Russel Gletscher seem to share common behavior at low altitudes, namely slightly faster velocities if the runoff was below average, negative velocity anomalies for years with runoff slightly above average, and a tendency towards faster velocities again for years when runoff is even higher. This time, however, high runoff anomalies still translate to slower velocities in opposition with Nordenskiöld Gletscher and Isunguata Sermia where such runoff anomalies lead to positive velocity anomalies.

Finally, Inuppaat Quuat appears to have a clear trend towards slower velocities as runoff anomalies are increasing, and this behavior is found for altitudes up to 1000 m.

The difference between Isunguata Sermia and Russel Gletscher is striking, as these two glaciers are lying next to each other but display different behaviors both at low and high altitudes under similar runoff inputs. This underlines that even for glaciers that are spatially close, we cannot assume a similar behavior in relation to hydrology, as other parameters such as the ice thickness, the hydraulic gradient, or the substrate could impact the development of the subglacial drainage system.

For all basins, we recognize a sawtooth pattern developing with an increase in velocity as runoff increases which is followed by a velocity drop with further runoff increase, and again faster velocities with even higher runoff, as summarized in Figure 4. Our interpretation is that the drainage system pressurization is rising with an increase in runoff leading to faster glaciers. However, at a given runoff value, the system reaches a threshold and becomes more efficient leading to lower water pressure and velocities, but the pressurization of this new system can also rise in case of an even higher runoff, leading again to faster velocities. The threshold where a new efficient system develops seems to depend on glacier characteristics, inducing different positioning of the velocity break point and seemingly different responses for each glacier. It is especially visible for Nordenskiöld Gletscher and Isunnguata Sermia at low altitudes and can be explained by different meltwater inputs to the system. If for a given year the water input is sufficient but without

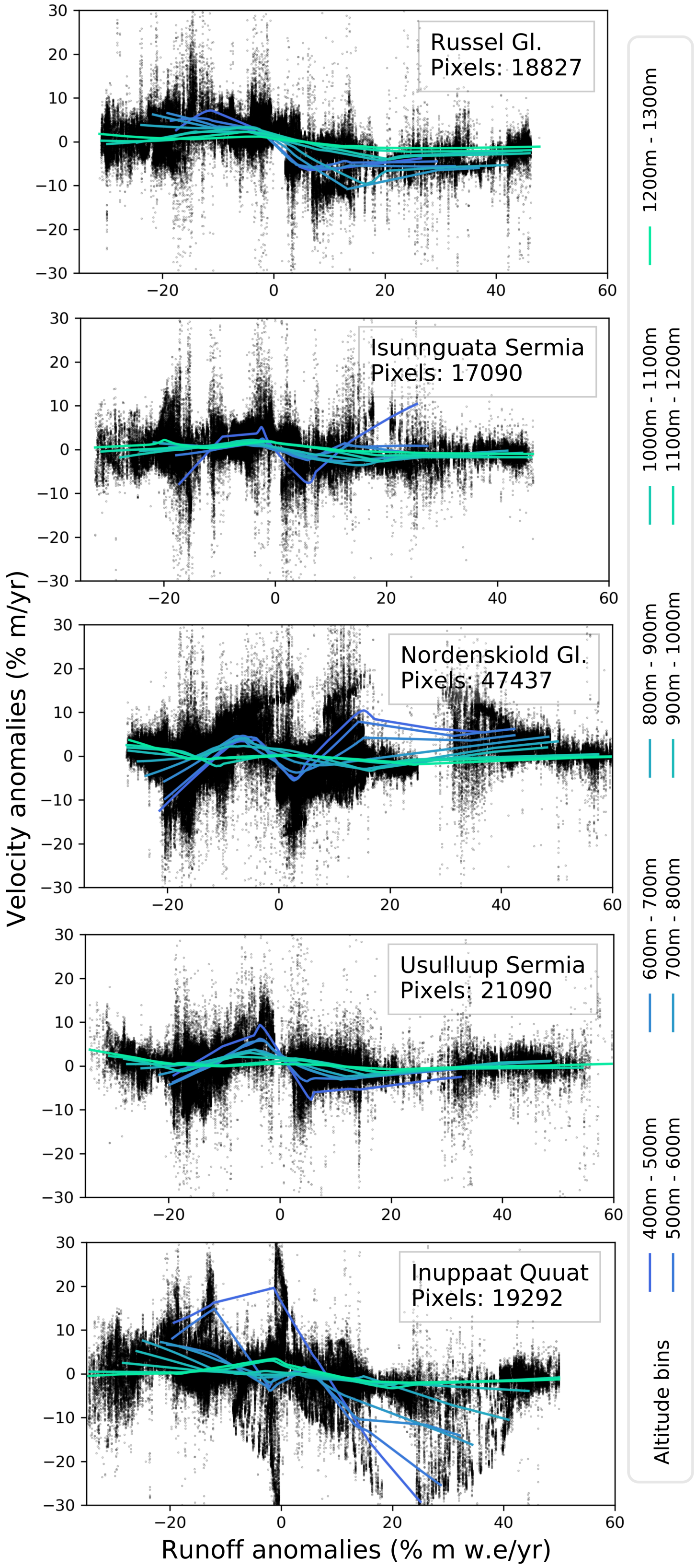

Figure 3. All data (velocity anomalies against runoff anomalies) in black dots for the 5 basins studied. The smoothing per altitude bin is in solid blue to green curves (LOWESS), the bluest curve being the lowest altitude bin, and the greenest the highest altitude bin. The number of pixels is the total number of individual data points used for the basin. For Isunnguata Sermia, Nordenskiöld Gletscher, Usulluup Sermia and Inuppaat Quaat, individual altitudes bins are available in supplemental materials Figures S7 to S10.

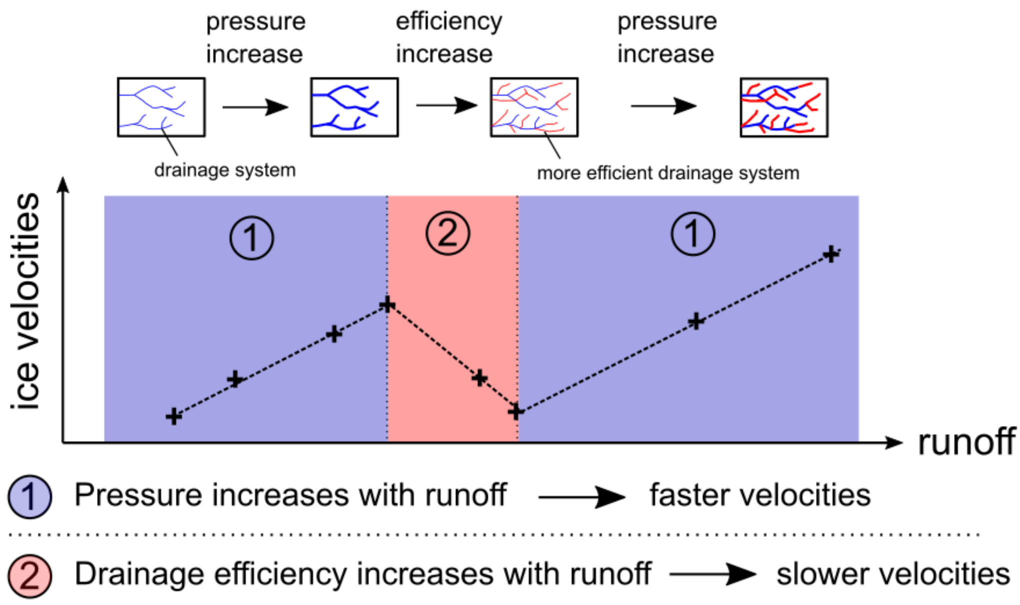

Figure 4. The sawtooth pattern, as observed in the basins such as Isunnguata Sermia and Nordenskiöld Gletscher. The points on the pattern are based on the observations of Isunnguata Sermia. We also observe the sawtooth pattern for Russel Gletscher and Usulluup Sermia, but the velocities anomalies obtained for the highest runoff are not as high as in the two first basins.

crossing a threshold like in 2017 or 2020, the velocities increase can be explained by the saturation of the drainage system, leading to faster velocities than if the system is less saturated (as in 2015). If it increases slightly, just enough to cross a threshold like in 2014 or 2016, the system will adapt into a more efficient one for these years and lead to slower velocities. If a year produces sufficient meltwater to saturate this efficient system, ice velocities will reaccelerate as in 2021. But if the water input is even higher (2019), a probably even more efficient drainage system will develop, leading to a slowdown in ice velocities, and this new system could also be saturated in the future leading once again to faster velocities before the cycle repeats. This idea, therefore, challenges the assumption that warmer summers would not increase annual ice displacement as they would likely be followed by reduced winter ice flow as found in Sole et al. (2013). We propose instead the idea that the system could potentially face an increasing runoff input that would constantly force the subglacial drainage system to adapt, even when a drainage system that we would consider efficient is already established during the first part of the melt season. Whether the runoff input would result in a slowdown or an acceleration would therefore be regulated by thresholds, and depending on the amount of runoff produced, lead to either a saturated water drainage system or to the development of a more efficient drainage system.

This sawtooth behavior could potentially happen on all the glaciers of our study, but it is likely that it would be conditioned by basin characteristics, leading to specific thresholds for each basin. Thus, it is possible that a similar pattern is observed everywhere, but that quantities of runoff required for displaying the sawtooth pattern are different for each basin, and that the amplitude of runoff anomalies over 2013-2021 would not be sufficient for some basins to display the full behavior. Another explanation could also be that the intrinsic characteristics of each glacier would simply produce a different behavior for ice velocities. Here from the data, we can only confirm that for similar runoff anomalies, the different basins have ice velocities that react differently.

In the Inuppaat Quuat case, we would interpret the behavior as the development of an efficient drainage system, leading to a slowdown of ice, although the amount of runoff produced may not be sufficient for this specific basin to lead to a reacceleration and display a sawtooth pattern as observed in Isunnguata Sermia and Nordenskiöld Gletscher. Additional years with different runoff signals would help in confirming this hypothesis.

A common point for all basins can nevertheless be observed: even though the shape of the relationship observed at low altitude still tend to appear at higher altitudes, it is strongly diminished and this reduction does not appear at the same altitude for all basin studied, which we will address in the next section.

3.2 Impact of runoff on velocities depends on altitude

Common to all our basins is how altitude is affecting the response to the runoff signal: all 5 basins display a relationship that is flattening when altitude increases as observed in Figure 3. We observe for Russel Gletscher in Figure 2 that for altitudes between 400 m and 900 m, the observed ice velocity varies with runoff, loosely following the sawtooth pattern as described in Figure 4. But at higher altitudes, ice velocities vary less, even with higher runoff variability. This could be explained by both the glacier characteristics that evolve with altitude, such as a different subglacial drainage system which could be caused by ice thickness or also different water input to the system. Indeed, while the runoff variability over these 9 years at high altitudes displays variations from -30% to up to 45%, we do not expect as much meltwater produced as at lower altitudes, and less runoff reaching the bottom with thicker ice. Higher altitudes display generally here what we can consider an inefficient drainage system, showing really small velocity variation, with considerable differences in the runoff between the years, but the altitude at which the efficient drainage system ceases to exist is probably driven by the specific characteristics of each glacier and the quantity of meltwater produced locally. However, even if velocity anomalies are small, they exist and tend to go hand-in-hand with the behavior observed at lower altitudes. Bartholomew et al. (2011) observed at higher altitudes a delay between the onset of the melt season and ice acceleration, requiring an accumulation of meltwater to penetrate through thicker ice, and this delay would be responsible for the limited velocity variations that they observed. They also found a linear relationship between rates of annual ablation and ice velocity variations that could explain here why we observe this attenuation of the signal at higher altitudes.

We cannot infer from this how the system would react with similar meltwater inputs as happening at lower altitudes, but the results presented here show that with the current production of runoff water, considerable runoff variations do not translate into much ice velocity differences at high altitudes. We cannot decipher whether the meltwater produced at high altitudes contributes to ice velocity at lower altitudes. In addition, we do not observe a clear cut at a specific altitude that could help to uncover a change in the subglacial water drainage system, but rather a progressive flattening of the ice velocity for higher altitudes.

A similar behavior, strong velocity variations at low altitudes that tend to disappear at higher altitudes, is observed for all 5 basins studied. However, the altitude at which it occurs also varies with the basin. For Nordenskiöld Gletscher and Isunguata Sermia higher in altitudes, the pattern is indeed similar to the one at lower altitudes but attenuated, especially for Isunguata Sermia, where absolute velocity anomalies are smaller and do not reach 5% above 500 m. However, for Nordenskiöld Gletscher, velocity variations are observed at higher altitudes, with a pronounced sawtooth pattern up to 1000 m. Russel Gletscher displays a strong reaction of ice velocities to runoff up to 900 m, whereas Usulluup Sermia does not display velocity variations above 5% for ice higher than 700 m. Finally, Inuppaat Quuat displays also almost no variations in ice velocities above 1000 m.

In summary, our data shows that above 500-1000 m ice velocities are not varying much from year to year, even when meltwater runoff displays strong intensity variations. The exact cutoff altitude depends on the glacier system and region.

3.3 Mapping the area

To further highlight regional and altitude variations, we present a map depicting the interannual variability of the ice velocities during our 9-year period of data (Fig. 5). This is an interesting tool to visualize spatially how strong are the variations of velocities at one point. Considering that surface meltwater is the main driver of velocity variations in the area, this map allows us to observe how ice velocities can vary with different melt inputs.

The map suggests a gradual evolution of interannual variability of ice velocities, from high values to low values from low to high altitudes, and extending to our entire study area. At low altitudes, high values indicate a strong response to runoff anomalies over the 9 years, while at high altitudes ice velocities do not vary much over the 9 years. We can clearly see that the velocity variations are following closely the basins. We also observe that, as observed on the smoothing curves, Isunnguata Sermia and Russel Gletscher, although spatially neighboring, have different patterns. We find again on the map the low ice velocity variations of Isunnguata Sermia observed earlier: while Russel Gletscher has an average interannual variability of around 5% up to 800 m, Isunnguata Sermia has already values below 5% at 500 m, indicating much lower velocity variations during 2013-2021 at the same altitudes. This fast decrease could be associated with a change in the drainage system that we do not observe at that altitude for Russel Gletscher. The values observed in that area are still relatively small compared to Inuppaat Quuat and Nordenskiöld Gletscher which have an average velocity anomaly of over 10%. The entire Inuppaat Quuat basin seems to have strong variations up to 900 m, while Nordenskiöld Gletscher, although displaying high values at low altitudes, has a much more gradual signal weakening as altitude increases. As seen earlier, this weaker response to runoff anomalies at higher altitudes could be due to the characteristics of the system at higher altitudes, such as thicker ice, different subglacial drainage system, or the smaller amounts of meltwater produced at that altitude. It is interesting to note that the areas around Nordenskiöld Gletscher's main tongue display relatively small average velocity anomalies compared to the trunk of the glacier.

3.4 Discussion regarding the method

Regarding our interpretation of the results, we observe conjointly the runoff anomalies and the velocity anomalies and try to assess correlations. Although these are not causation relationships, we believe that the behavior in our area and at the altitudes considered is mainly driven by the basal sliding, as observed in the Russel area in Maier et al. (2019). Therefore, we argue that we give here an idea of the impact of melt on the ice dynamics through subglacial water systems, although many other processes can affect the development of such drainage systems and lead to the differences by basins that we observed here.

Following the previous comment, it is assumed that there is no lag in the system, so that runoff for a given year will act on ice velocities the same year. The melt season produces meltwater during summer, and previous literature found a direct response of the system during the summer and during the following winter (e.g., Palmer et al., 2011; Bartholomew et al., 2012; Fitzpatrick et al., 2013; Tedesco et al., 2013). We made sure to sample yearly velocities based on image pairs taken before summer, so that the yearly velocity measured encompasses the respective summer to which we associate the melt season, and the following winter, without taking into account velocities from the following summer.

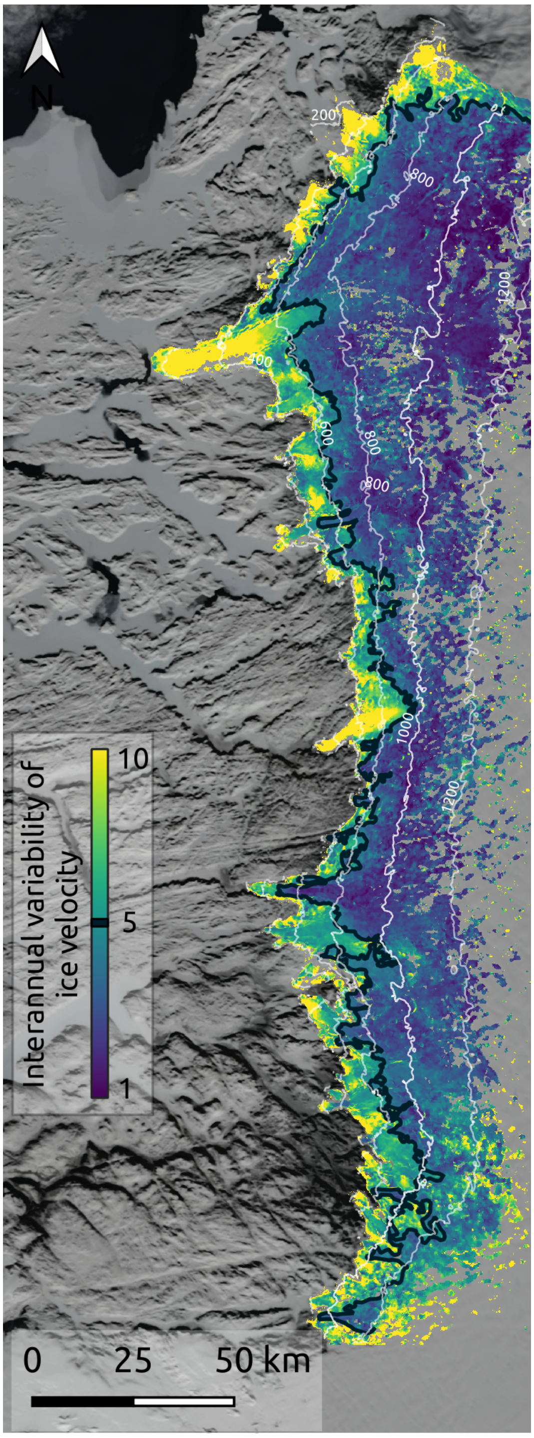

Figure 5. Interannual variability of ice velocity, computed with the root mean square over the 9 years for velocity anomalies for each pixel. Values at the glaciers' tongues are over 10, indicating high ice velocity variations over the period, while at high altitudes, the variability of ice velocity is much smaller. The black line is the isoline for a root mean square of 5.

Regarding the way we analyzed surface runoff and velocities, we used the same value from the reanalysis product that was available at 1km, for our velocity data which is 150 m in resolution. The opposite could have been done, averaging the velocity to resample at 1km resolution, but we do not expect both the velocity to change drastically over this 1km^2, as well as we do not expect the surface meltwater signal to vary within a 1km^2. Therefore this does not impact our results since we do not compute any statistical significance index that would have been prone to bias with a higher number of points.

4 Conclusions

We investigate runoff anomalies from ERA5-MAR and velocity anomalies from satellite observations over Southwest Greenland for the years 2013-2021. These data gave insights into glacier response to meltwater input. We found that ice reacts differently to similar runoff anomalies depending on basin and altitude, and found an interesting sawtooth pattern. We explain it by the subglacial drainage system getting more and more pressurized due to higher water input until a certain point where the whole drainage system is modified with a more developed efficient drainage system, leading to a drop in pressure and velocities, but this new drainage system could also be saturated and even more efficient drainage systems may have to develop to accommodate higher runoff quantities. This finding challenges the idea of the resilience of this land-terminating part of the Greenland Ice Sheet to warmer summers, as we find that high runoff years can result in faster velocities even at low altitudes. At higher altitudes, however, we find that the velocity variations are largely attenuated compared to low altitudes and that large variability in runoff does not result in large ice velocity variations. The altitude at which the velocities signal is attenuated depends on the basin. Our studied glaciers show a breakpoint at different runoff anomalies which are probably driven by basin-specific characteristics giving the seemingly different responses observed on these closely spaced basins. Therefore, the sawtooth pattern is not exactly the same in all basins, but understanding whether regional differences occur due to intrinsic glacier characteristics or due to a lack of sufficient water input variations in our data will require a few more years of observation. Future modeling work should take special care into making sure a proper hydrological model is implemented as the ice dynamics in this part of Greenland is highly non-linear and it seems that the impact of meltwater lubrication feedback can not be investigated through a simplified runoff-velocity relationship.

Open Research Section

The data supporting our conclusions is publicly available.

- Velocity data is available at : https://doi.org/10.5281/zenodo.7418361
- MAR output are available at : ftp://climato.be/fettweis/MARv3.12/Greenland/ERA5_6.5km/

Acknowledgments
This work is part of the SWItchDyn project funded by the Research Council of Norway (NFR-287206). Thanks to Xavier Fettweis for providing the downscaled MAR output. Computing was performed on the resources provided by UNINETT Sigma2 – the National Infrastructure for High-Performance Computing and Data Storage in Norway (NN9635K and NS9635K). A warm thanks to Bjerknes colleagues for their support.

References

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T., & King, M. A. (2012, sep). Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. *Journal of Geophysical Research: Earth Surface*, *117*, n/a–n/a. Retrieved from `http://doi.wiley.com/10.1029/2011JF002220` doi: 10.1029/2011JF002220

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T., Palmer, S., & Wadham, J. (2011, apr). Supraglacial forcing of subglacial drainage in the ablation zone of the Greenland ice sheet. *Geophysical Research Letters*, *38*(8), n/a–n/a. Retrieved from `http://doi.wiley.com/10.1029/2011GL047063` doi: 10.1029/2011GL047063

Bougamont, M., Christoffersen, P., Hubbard, A. L., Fitzpatrick, A. A., Doyle, S. H., & Carter, S. P. (2014, sep). Sensitive response of the Greenland Ice Sheet to surface melt drainage over a soft bed. *Nature Communications*, *5*(1), 1–9. Retrieved from `www.nature.com/naturecommunications` doi: 10.1038/ncomms6052

Brinkerhoff, D., Aschwanden, A., & Fahnestock, M. (2021, jun). Constraining subglacial processes from surface velocity observations using surrogate-based Bayesian inference. *Journal of Glaciology*, *67*(263), 385–403. Retrieved from `https://www.cambridge.org/core.` doi: 10.1017/jog.2020.112

Cleveland, W. S. (1979). Robust locally weighted regression and smoothing scatterplots. *Journal of the American Statistical Association*, *74*(368), 829–836. doi: 10.1080/01621459.1979.10481038

Davison, B. J., Sole, A. J., Livingstone, S. J., Cowton, T. R., & Nienow, P. W. (2019, feb). *The influence of hydrology on the dynamics of land-terminating sectors of the Greenland ice sheet* (Vol. 7). Frontiers Media S.A. doi: 10.3389/feart.2019.00010

de Fleurian, B., Morlighem, M., Seroussi, H., Rignot, E., van den Broeke, M. R., Kuipers Munneke, P., … Tedstone, A. J. (2016, oct). A modeling study of the effect of runoff variability on the effective pressure beneath Russell Glacier, West Greenland. *Journal of Geophysical Research: Earth Surface*, *121*(10), 1834–1848. Retrieved from `https://onlinelibrary.wiley.com/doi/10.1002/2016JF003842` doi: 10.1002/2016JF003842

Derkacheva, A., Mouginot, J., Millan, R., Maier, N., & Gillet-Chaulet, F. (2020, jun). Data Reduction Using Statistical and Regression Approaches for Ice Velocity Derived by Landsat-8, Sentinel-1 and Sentinel-2. *Remote Sensing*, *12*(12), 1935. Retrieved from `https://www.mdpi.com/2072-4292/12/12/1935` doi: 10.3390/rs12121935

Dow, C. F., Hubbard, A., Booth, A. D., Doyle, S. H., Gusmeroli, A., & Kulessa, B. (2013, sep). Seismic evidence of mechanically weak sediments underlying Russell Glacier, West Greenland. *Annals of Glaciology*, *54*(64), 135–141. Retrieved from `https://www.cambridge.org/core.` doi: 10.3189/2013AoG64A032

Doyle, S. H., Hubbard, A., Fitzpatrick, A. A., Van As, D., Mikkelsen, A. B., Pettersson, R., & Hubbard, B. (2014, feb). Persistent flow acceleration within the interior of the Greenland ice sheet. *Geophysical Research Letters*, *41*(3), 899–905. doi: 10.1002/2013GL058933

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., … Zolles, T. (2020, nov). GrSMBMIP: Intercomparison of the modelled 1980-2012 surface mass balance over the Greenland Ice Sheet. *Cryosphere*, *14*(11), 3935–3958. doi: 10.5194/tc-14-3935-2020

Fitzpatrick, A. A., Hubbard, A., Joughin, I., Quincey, D. J., Van As, D., Mikkelsen, A. P., … Jones, G. A. (2013, aug). Ice flow dynamics and surface meltwater flux at a land-terminating sector of the Greenland ice sheet. *Journal of Glaciology*, *59*(216), 687–696. Retrieved from `https://doi.org/10.3189/2013JoG12J143` doi: 10.3189/2013JoG12J143

Fürst, J. J., Goelzer, H., & Huybrechts, P. (2015, may). Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming.

Cryosphere, *9*(3), 1039–1062. doi: 10.5194/tc-9-1039-2015

Halas, P., Mouginot, J., de Fleurian, B., & Langebroek, P. (2022, dec). *Southwest Greenland Ice Sheet Yearly Ice Velocities dataset from 1984 to 2020.* Retrieved from `https://zenodo.org/record/7418361` doi: 10.5281/ZENODO.7418361

Halas, P., Mouginot, J., de Fleurian, B., & Langebroek, P. M. (2023, feb). Impact of seasonal fluctuations of ice velocity on decadal trends observed in Southwest Greenland. *Remote Sensing of Environment*, *285*, 113419. doi: 10.1016/j.rse.2022.113419

Haran, T., Bohlander, J., Scambos, T., Painter, T., & Fahnestock, M. (2018). *Measures modis mosaic of greenland (mog) 2005, 2010, and 2015 image maps, version 2 — national snow and ice data center.* Retrieved 2022-04-12, from `https://nsidc.org/data/NSIDC-0547/versions/2`

Harper, J. T., Humphrey, N. F., Meierbachtol, T. W., Graly, J. A., & Fischer, U. H. (2017, sep). Borehole measurements indicate hard bed conditions, Kangerlussuaq sector, western Greenland Ice Sheet. *Journal of Geophysical Research: Earth Surface*, *122*(9), 1605–1618. Retrieved from `http://doi.wiley.com/10.1002/2017JF004201` doi: 10.1002/2017JF004201

Hoffman, M. J., Catania, G. A., Neumann, T. A., Andrews, L. C., & Rumrill, J. A. (2011, dec). Links between acceleration, melting, and supraglacial lake drainage of the western Greenland Ice Sheet. *Journal of Geophysical Research*, *116*(F4), F04035. Retrieved from `http://doi.wiley.com/10.1029/2010JF001934` doi: 10.1029/2010JF001934

Joughin, I., Das, S. B., King, M. A., Smith, B. E., Howat, I. M., & Moon, T. (2008, may). Seasonal speedup along the western flank of the Greenland ice sheet. *Science*, *320*(5877), 781–783. Retrieved from `www.sciencemag.org/cgi/content/full/1153360/DC1` doi: 10.1126/science.1153288

Koziol, C. P., & Arnold, N. (2017, dec). Incorporating modelled subglacial hydrology into inversions for basal drag. *Cryosphere*, *11*(6), 2783–2797. doi: 10.5194/tc-11-2783-2017

Koziol, C. P., & Arnold, N. (2018, mar). Modelling seasonal meltwater forcing of the velocity of land-terminating margins of the Greenland Ice Sheet. *Cryosphere*, *12*(3), 971–991. doi: 10.5194/tc-12-971-2018

Kulessa, B., Hubbard, A. L., Booth, A. D., Bougamont, M., Dow, C. F., Doyle, S. H., ... Jones, G. A. (2017, aug). Seismic evidence for complex sedimentary control of Greenland Ice Sheet flow. *Science Advances*, *3*(8). Retrieved from `https://www.science.org` doi: 10.1126/sciadv.1603071

Maier, N., Humphrey, N., Harper, J., & Meierbachtol, T. (2019). Sliding dominates slow-flowing margin regions, Greenland Ice Sheet. *Science Advances*, *5*(7). Retrieved from `https://www.science.org` doi: 10.1126/sciadv.aaw5406

Millan, R., Mouginot, J., Rabatel, A., Jeong, S., Cusicanqui, D., Derkacheva, A., & Chekki, M. (2019, oct). Mapping Surface Flow Velocity of Glaciers at Regional Scale Using a Multiple Sensors Approach. *Remote Sensing*, *11*(21), 2498. Retrieved from `https://www.mdpi.com/2072-4292/11/21/2498` doi: 10.3390/rs11212498

Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., ... Wood, M. (2019, may). *Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018* (Vol. 116) (No. 19). National Academy of Sciences. Retrieved from `https://www.pnas.org/doi/abs/10.1073/pnas.1904242116` doi: 10.1073/pnas.1904242116

Mouginot, J., Rignot, E., Scheuchl, B., & Millan, R. (2017). Comprehensive annual ice sheet velocity mapping using Landsat-8, Sentinel-1, and RADARSAT-2 data. *Remote Sensing*, *9*(4), 1–20. doi: 10.3390/rs9040364

Nienow, P. W., Sole, A. J., Slater, D. A., & Cowton, T. R. (2017, dec). *Recent Advances in Our Understanding of the Role of Meltwater in the*

Greenland Ice Sheet System (Vol. 3) (No. 4). Springer. Retrieved from https://link.springer.com/article/10.1007/s40641-017-0083-9 doi: 10.1007/s40641-017-0083-9

Noël, B., van de Berg, W. J., Lhermitte, S., & van den Broeke, M. R. (2019, sep). Rapid ablation zone expansion amplifies north Greenland mass loss. *Science Advances*, *5*(9). Retrieved from https://www.science.org doi: 10.1126/sciadv.aaw0123

Palmer, S., Shepherd, A., Nienow, P., & Joughin, I. (2011, feb). Seasonal speedup of the Greenland Ice Sheet linked to routing of surface water. *Earth and Planetary Science Letters*, *302*(3-4), 423–428. doi: 10.1016/j.epsl.2010.12.037

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., & Lenaerts, J. T. M. (2011, mar). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, *38*(5), n/a–n/a. Retrieved from http://doi.wiley.com/10.1029/2011GL046583 doi: 10.1029/2011GL046583

Shannon, S. R., Payne, A. J., Bartholomew, I. D., Van Den Broeke, M. R., Edwards, T. L., Fettweis, X., … Zwinger, T. (2013, aug). Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(35), 14156–14161. Retrieved from https://www.pnas.org/doi/abs/10.1073/pnas.1212647110 doi: 10.1073/pnas.1212647110

Shepherd, A., Hubbard, A., Nienow, P., King, M., McMillan, M., & Joughin, I. (2009, jan). Greenland ice sheet motion coupled with daily melting in late summer. *Geophysical Research Letters*, *36*(1), L01501. Retrieved from http://doi.wiley.com/10.1029/2008GL035758 doi: 10.1029/2008GL035758

Sole, A., Nienow, P., Bartholomew, I., Mair, D., Cowton, T., Tedstone, A., & King, M. A. (2013, aug). Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters*, *40*(15), 3940–3944. Retrieved from http://doi.wiley.com/10.1002/grl.50764 doi: 10.1002/grl.50764

Tedesco, M., Willis, I. C., Hoffman, M. J., Banwell, A. F., Alexander, P., & Arnold, N. S. (2013, jul). Ice dynamic response to two modes of surface lake drainage on the Greenland ice sheet. *Environmental Research Letters*, *8*(3), 034007. Retrieved from http://asterweb.jpl.nasa.gov/ doi: 10.1088/1748-9326/8/3/034007

Tedstone, A. J., Nienow, P. W., Gourmelen, N., Dehecq, A., Goldberg, D., & Hanna, E. (2015, oct). Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming. *Nature*, *526*(7575), 692–695. Retrieved from http://www.nature.com/articles/nature15722 doi: 10.1038/nature15722

Van De Wal, R. S., Boot, W., Van Den Broeke, M. R., Smeets, C. J., Reijmer, C. H., Donker, J. J., & Oerlemans, J. (2008, jul). Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. *Science*, *321*(5885), 111–113. Retrieved from www.sciencemag.org/cgi/content/full/321/5885/108/DC1 doi: 10.1126/science.1158540

Van De Wal, R. S., Smeets, C. J., Boot, W., Stoffelen, M., Van Kampen, R., Doyle, S. H., … Hubbard, A. (2015, apr). Self-regulation of ice flow varies across the ablation area in south-west Greenland. *Cryosphere*, *9*(2), 603–611. doi: 10.5194/tc-9-603-2015

Van Den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Van Berg, W. J. D., … Wouters, B. (2009, nov). Partitioning recent Greenland mass loss. *Science*, *326*(5955), 984–986. Retrieved from www.sciencemag.org/cgi/content/full/326/5955/980/DC1 doi: 10.1126/science.1178176

Velicogna, I. (2009, oct). Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Let-*

ters, *36*(19), L19503. Retrieved from http://doi.wiley.com/10.1029/2009GL040222 doi: 10.1029/2009GL040222

Williams, J. J., Gourmelen, N., & Nienow, P. (2020). Dynamic response of the Greenland ice sheet to recent cooling. *Scientific Reports*, *10*(1), 1–11. Retrieved from http://dx.doi.org/10.1038/s41598-020-58355-2 doi: 10.1038/s41598-020-58355-2

Wright, P. J., Harper, J. T., Humphrey, N. F., & Meierbachtol, T. W. (2016, jun). Measured basal water pressure variability of the western Greenland Ice Sheet: Implications for hydraulic potential. *Journal of Geophysical Research: Earth Surface*, *121*(6), 1134–1147. Retrieved from http://doi.wiley.com/10.1002/2016JF003819 doi: 10.1002/2016JF003819

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., & Steffen, K. (2002, jul). Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, *297*(5579), 218–222. Retrieved from www.sciencemag.org/cgi/content/full/1071795/DC1 doi: 10.1126/science.1072708

Surface runoff impact on ice dynamics varies with altitude and location

Paul Halas[1], Basile de Fleurian[1], Jérémie Mouginot[2], Petra M. Langebroek[3]

[1]University of Bergen, Bjerknes Centre for Climate Research, Bergen, Norway
[2]Institut des Géosciences de l'Environnement, Université Grenoble Alpes, CNRS, IRD, INP, Grenoble, France
[3]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

Key Points:

- We analyze the relationship between ice velocities and surface meltwater runoff for 5 Greenlandic basins over the last 9 years.
- Surface meltwater and ice velocity are not linearly correlated, and their relationship varies with altitude and basin.
- A large part of the velocity, runoff relationship can be explained by considering the efficiency of the subglacial drainage system.

Corresponding author: Paul Halas, paul.halas@uib.no

Abstract

Surface runoff over the Greenland Ice Sheet has been shown to have an impact on ice velocities, both at short as well as decadal timescales. While the short timescales are necessary to comprehend the physical processes connecting subglacial water pressure and ice motion, upscaling to longer timescales is paramount to assessing the future behavior of glaciers in a warming climate. In this study, we assess in a land-terminating part of Southwest Greenland over 2013-2021 the relationship between annual ice velocities derived from optical feature-tracking and surface runoff derived from the ERA5-MAR climate model. The recent time period, providing frequent satellite acquisition, allows for a precise selection of image pairs, while also covering summer melt seasons varying in both intensity and duration. We find that the exact link between runoff anomalies and ice velocity anomalies changes depending on the basin considered and that the relationship also changes with altitude. However, all basins do show a similar overall behavior: at low elevations, while a small increase in runoff leads to faster velocities, a large increase in runoff leads to a slowdown of the glacier ice, but years with even larger runoff would tend to make the ice faster again. As altitude increases, runoff anomalies variations seem to have less impact on ice velocities. We compute for each pixel a simple index to quantify this relationship, presenting here a map displaying how runoff anomalies affected the velocities in 2013-2021 and underlining the spatially varying impact of meltwater depending on altitude and location.

Plain Language Summary

During summer, meltwater is produced at the surface of glaciers. This water can enter the glaciers through crevasses or moulins, and affect how the ice slides on its bedrock. Here, we assess in the southwest of the Greenland Ice Sheet, the relationship between runoff and ice velocities on a yearly timescale, at different altitudes, and for 5 different basins, for the period 2013-2021. We find that the meltwater will have a different impact on the ice velocities depending on altitude and location. Previous studies expected our study area to be resilient to warmer summers, as a slowdown was observed in conjunction with increased melt. We find here that at low altitudes, a small increase will lead to faster velocities, a larger increase will indeed lead to a deceleration, but also that a much larger increase of runoff could lead to an acceleration of the ice. As altitude increases, our observations indicate that meltwater anomalies have less impact on the ice velocities. We derived an index to quantify the impact of meltwater and observe a clear effect of altitude and variations of runoff effect by basins all along the study area.

1 Introduction

Dramatic increases in surface meltwater on the Greenland Ice Sheet (GrIS) have been observed for more than three decades now (e.g., Van Den Broeke et al., 2009; Velicogna, 2009; Rignot et al., 2011; Mouginot et al., 2019). The importance of surface meltwater to glacial systems has long been recognized, and numerous studies have investigated its role in the dynamics of the ice (e.g., Zwally et al., 2002; Joughin et al., 2008; Shepherd et al., 2009; Hoffman et al., 2011). Yet meltwater impact on ice velocities on decadal timescales remains not fully understood (Davison et al., 2019).

Understanding the impact of meltwater on ice dynamics is paramount to improving the predictions of future ice discharge to the ocean or glacier geometry changes under expected warmer summers (Van De Wal et al., 2008; Nienow et al., 2017; Koziol & Arnold, 2018). The relationship between ice velocities, meltwater, and subglacial water pressure has for example been observed in Van De Wal et al. (2015), where a sudden runoff event induced a clear ice speedup but sustained high runoff throughout summer eventually lead to a deceleration of the ice. They show that runoff influences the subglacial water pressure, and this pressure in return affects the sliding of the ice, which affects surface ice velocities. Variations of subglacial pressure throughout the summer were observed and interpreted as a switch from an inefficient subglacial drainage system to a more efficient one, induced by sustained high runoff.

It is however unclear whether the same pattern can be observed everywhere, for example where ice is thicker and runoff smaller (e.g., Doyle et al., 2014; de Fleurian et al., 2016). Doyle et al. (2014) did not observe a deceleration in the late melt season far from the ice sheet margin, indicating that the subglacial drainage system does not systematically evolve towards an efficient system, so the slowdown of the ice after summer may be confined to low elevations. Yet previous studies implementing the impact of runoff on ice velocities for future projections did not always consider altitude variations, mostly because the availability of observations was not sufficient (Shannon et al., 2013; Fürst et al., 2015). While seasonal studies of the relation between meltwater input and ice velocity bring a better understanding of the local physical processes at play, the necessary high-temporal resolution velocity data is not often available for long periods of time, and even less so on a large spatial scale (Davison et al., 2019).

At a decadal timescale, Tedstone et al. (2015) and Williams et al. (2020) found that a land-terminating sector of the ice sheet has been slowing down, and at the same time an increase in surface meltwater was observed. As the rate of the slowdown was only 1.5 m/yr^2, a long period such as 2000-2012 was necessary in order to identify the trend. More recently, a re-acceleration of the ice was found by Williams et al. (2020) in Southwest Greenland and was attributed to a reduction of meltwater production, although we found in Halas et al. (2023) that the observed trend was spatially heterogeneous with significant trends mostly confined to low-lying ice tongues. The variability in runoff produced every year in this period is indeed high, varying by up to 40% compared to an average over the same time period, rendering the understanding of the relationship between runoff and ice velocities at the decadal timescale difficult. In addition, ice velocity trends in this land-terminating area of the Greenland Ice Sheet are relatively small compared to the signal. In this context of alternating intense and less intense melt seasons, we want to step back from decadal trends to assess the impact of surface melting at a yearly timescale, in order to understand how a given melt season impacts the velocities until the next melt season. How this relationship varies with altitude and location is also required for improving the assessment of the future behavior of the ice sheet in a warming climate.

We therefore assess here how surface meltwater and velocities are related, using yearly feature-tracked ice velocities in conjunction with runoff derived from climate reanalysis over 2013-2021.

2 Data and Methods

2.1 Study area

Our study area is located in Southwest Greenland and is displayed in Figure 1. We focused the first part of our study on 5 land-terminating basins, but extend our work to the whole region for the second part. This land-terminating area is a perfect study area for such work as it is an ocean-free setting, and it is assumed that variations in ice velocity are mostly controlled by changes in basal conditions (Tedstone et al. (2015); Maier et al. (2019); Derkacheva et al. (2020)).

For our 5 basins, we focused naturally on Russell Gletscher and Isunnguata Sermia close to the town of Kangerlussuaq, since they have been the subject of in-situ geophysical investigations such as mechanical properties of sediment bed underlying the glaciers and their influence on the ice flow (Dow et al., 2013; Wright et al., 2016; Harper et al., 2017; Kulessa et al., 2017; Maier et al., 2019), as well as numerical investigations (Bougamont et al., 2014; de Fleurian et al., 2016; Koziol & Arnold, 2017, 2018; Brinkerhoff et al., 2021).

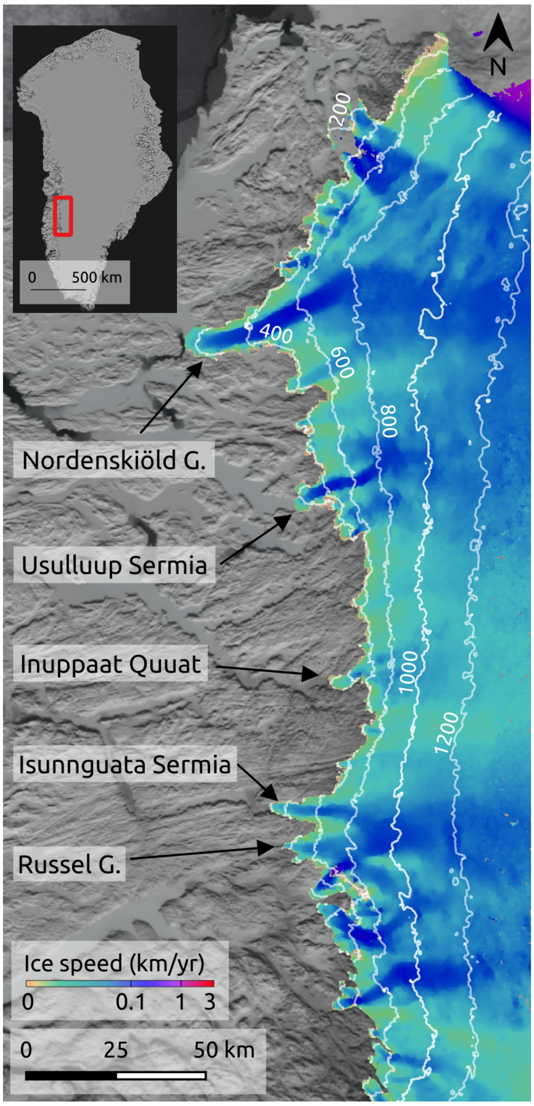

Figure 1. Map of the study area. Ice velocities displayed are derived by combining all velocity fields computed in this study from image pairs of Landsat 8 and Sentinel-2 for the years 2019-2020. The ice velocities are overlaying a 2015 MODIS Mosaic of Greenland (MOG) at 100 m resolution (Haran et al., 2018). White lines represent the 200 m isolines extracted from MEaSUREs Greenland Ice Mapping Project (GIMP) Digital Elevation Model.

These two basins, spatially close, also offer an interesting comparison to see whether runoff effect on ice velocities can differ for neighboring glaciers. North of these two glaciers, we focus on Nordenskiöld Gletscher and Usulluup Sermia, both displaying similar orders of magnitude for their ice velocity and altitude ranges. Being central between our four other sites, our 5th site is Inuppaat Quuat. It also offers an interesting comparison as this glacier is displaying slower velocities than the rest, while having a reasonably large tongue.

2.2 Velocities from satellite observations

In order to understand how surface meltwater correlates to ice dynamics, we used observations of ice velocities, derived from feature-tracking over the period 2013-2021.

While being an ocean-free setting, land-terminating glaciers are also displaying slower velocities, potentially leading to smaller - i.e. less easily detectable - variations in velocity (Halas et al., 2023). Studying such ice velocities, therefore, requires a combination of accurate velocity estimations and good spatial coverage that yearly feature-tracking can provide (Millan et al., 2019). The period 2013-2021 was selected since the launch of Landsat 8 in 2013 greatly increased the number of image pairs for feature-tracking, allowing for a much more aggressive selection of the data. We used the same velocity products derived by feature-tracking produced for Halas et al. 2023, publicly available on open repositories (Halas et al., 2022, released 9 December 2022). We selected pairs with images separated by about one year, since it allows for a much greater level of precision compared to shorter baselines, as demonstrated with the same correlation algorithm in Mouginot et al. (2017) and Millan et al. (2019). Following the recommendations of Halas et al. (2023) on the selection of image pairs, we only used velocity data derived from pairs with the starting date before summer, so that every single annual velocity is sampled over one melt season and the following winter. While this precise selection reduces the spatial coverage, it avoids sampling two summers, allowing us to compare the same period every year.

The complete methodology regarding the processing of satellite images to obtain velocity maps is detailed in Halas et al. (2023).

From the selected image pairs, we computed a per-pixel average to produce a regional velocity map for every single year. We also computed the average velocity over our 9 years and derived yearly velocity anomalies over this time interval. Only the data points where data was available for all 9 years were kept. These velocity anomalies maps are displayed in supplemental material Figure S1.

2.3 Runoff reanalysis from MAR

We use daily outputs of the polar regional climate model MAR forced by the ERA5 reanalysis over our region, downscaled to 1 km. The model MAR (version 3.12.1) has been run at a resolution of 10 km forced every 6 hours by ERA5 at its lateral boundaries. It is one of the best surface mass balance products currently available over the Greenland ice sheet (Fettweis et al., 2020). From these products, we extracted the daily runoff signal and used it to compute cumulative yearly runoff, the average cumulative runoff over our 9 years, and yearly cumulative runoff anomalies. During summer, meltwater is generated, but part of this water can refreeze or be trapped in the snow. The remaining water is defined as runoff and can be routed to the base of the glacier. As most of the area where we have data is located in the ablation zone, the surface meltwater signal is equal to the runoff signal. At higher altitudes, however, the runoff signal is smaller than the melt signal since the snowpack is able to retain a large part of the meltwater (Noël et al., 2019). We, therefore, use the runoff from MAR, although it is equal to the melt for most of our data points located in the ablation zone. Figure S2 gives an example of the daily runoff signal near the terminus of Nordenskiöld glacier. The signal is typical for the 5 basins studied in the region at similar altitudes. In large parts of the dataset, the runoff signal at low and higher altitudes evolves together, with the higher altitude signal being of lesser amplitude. In order to give an idea, we plot in Figure S2 over the low altitude signal a black line representing the runoff signal at 1000 m, and representative for our 5 basins.

2.4 Trend analysis

We plotted velocity anomalies against runoff anomalies for the 5 land-terminating basins in Southwest Greenland, with data separated by altitude bins of 25 m, 50 m, 100 m, and 200 m. We chose to display here in Figure 2 the 100 m altitude bin plots for Russel. This 100 m bin is a compromise, as this size of altitude bins was found to be sufficiently separating pixels by 9 different altitude bins while keeping a higher number of pixels compared to smaller altitude bins. We found no significant signal difference from 100 m bins to smaller bins. A 200 m bin seems however to stack too much data and we observe differences, especially at low altitudes. These additional bins are available in supplementary materials as Figures S4a-S4b (25 m), S5 (50 m), and S6 (200 m) for Russel Gletscher. In order to facilitate the reading of trends, we computed locally weighted scatterplot smoothing (LOWESS), which is a non-parametric regression fitting a moving regression model on neighboring data (Cleveland, 1979). We specifically chose this algorithm since we want to avoid having prior assumptions regarding the relationship between runoff anomalies and velocity anomalies. The algorithm computes locally weighted linear regressions such that closer data points will have greater weight. The curve displayed over our scatterplots is a combination of all local regressions. Three iterations of LOWESS are computed to adjust the weights while seeking to reduce root-mean-square deviation so that outliers are less likely to affect the final local regression. We display LOWESS estimations for velocity anomalies versus runoff anomalies for every altitude bin for Russel Gletscher over the scatterplot that was used for these estimations in Figure 2. We also plot for all 5 basins studied here, all 100 m bin LOWESS estimations on a single graph for easier comparison (Figure 3). With this approach, we disregard the temporal evolution of runoff and velocities, but rather aggregate all years to identify the relationship between the two, assuming the system has no memory of previous years' runoff input.

Since the resolution of our velocity map is 150 m compared to the 1 km resolution for reanalysis products, we located for every velocity map pixel the closest reanalysis pixel and used this value, assuming that the runoff is not varying drastically over a 1 km^2 area.

In addition to the trends, we assessed how strongly the ice velocity is undergoing variations over our 9 years, by calculating for each pixel the root mean square to 0 of the velocity anomalies over the 9 years, indicating how much on average the velocity differs from the average. We present a map of this index in Figure 5. Since we consider that the velocity changes in this region are mostly controlled by surface runoff, we argue that this index can be interpreted as the impact of runoff on ice velocity, with a higher index showing a stronger relationship between runoff and ice velocity whereas a lower index shows that changes in runoff do not lead to large changes in ice velocity.

3 Results and discussion

3.1 Runoff and velocity linked through the efficiency of subglacial drainage

As we see in Figure 2 for Russel Gletscher, but also for other basins in supplemental materials (Figures S7, S8, S9, and S10), both runoff and ice velocities are varying each year. When we combine all the years on the same plot as done in Figure 2, we see patterns giving insights into glacier behavior. We can observe strong ice velocity variations for low altitudes for different runoff quantities, but also that the relationship describing velocity evolution with respect to runoff anomalies is evolving with altitude. We will first focus on the behavior at low altitudes and will discuss the higher altitudes' behavior in a the next section.

The pattern emerging for Russel Gletscher up to 900 m is the following: we first observe maximum velocity anomalies for the years with the lowest runoff. When the runoff is higher than the average (around +5% to +15%), velocities are slower, which is especially visible at low altitudes. Finally, when runoff is even higher, as in 2019 when the runoff was 20% above average, velocities tend to be faster than when there is just slightly more runoff than on average.

This maximal velocity obtained for low runoff years must have been driven by fast summer velocities or fast post-melt season velocities. The explanation in terms of basal hydrology could be that the drainage system would develop into an efficient system but

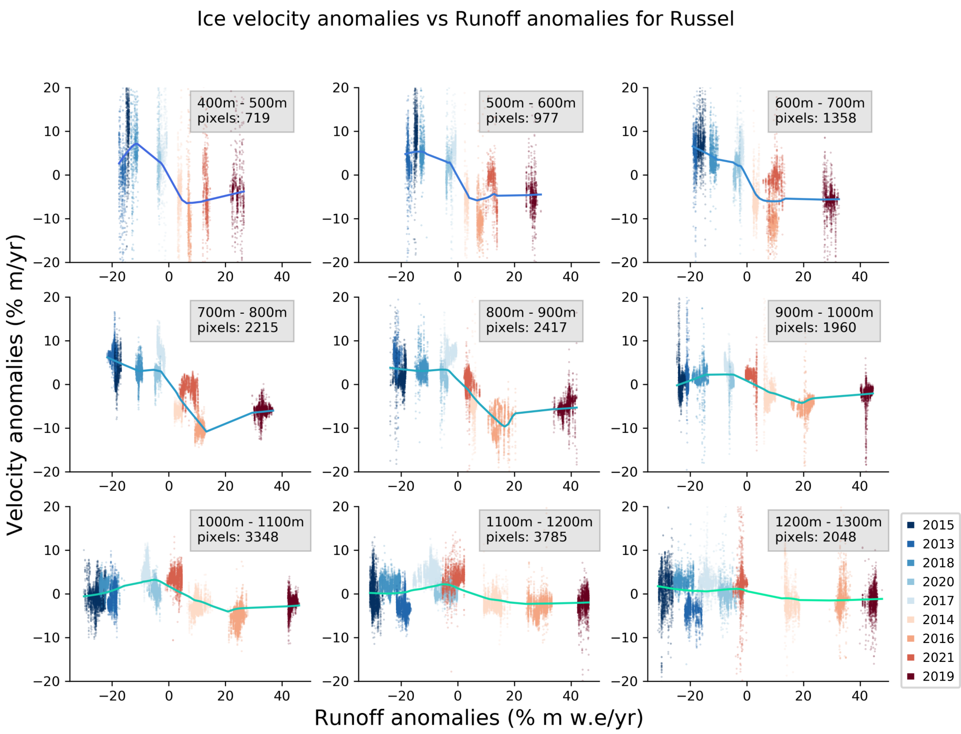

Figure 2. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Russel Gletscher. The colors indicate the year corresponding to the data, where blue dots represent low runoff years (minimum in 2015) and red dots high runoff years (maximum in 2019). Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS). Other basins are available in the supplemental material in Figures S7 to S10.

is not sustained due to less water input to the system, resulting in relatively fast velocities during late summer due to a switch back to a pressurized but inefficient system at this time, and leading potentially also to faster velocities during the winter season. When the runoff is slightly above average, it could be high enough to activate and sustain an efficient drainage system, resulting into slower summer velocities on average and an efficient drainage system still opened during the late melt season that could lead to slower winter velocities, as observed in Van De Wal et al. (2015). Finally, for years with high positive runoff anomalies like 2019, the efficient drainage system is at its limit, and although it develops, we still have sustained high water pressure driving fast ice flow during summer, but still slower velocities during winter than usual, as the velocity observed for such high melt years are still slower than average.

Figure 3 shows all runoff and velocity data per studied basin. To emphasize the various behaviour per altitude, the coloured lines indicate the smoothed trends per altitude bin (using the LOWESS calculation, see Sect. 2.4). Isunguata Sermia and Nordenskiöld Gletscher both display at low altitudes (blue lines) slower velocities than the average for the minimum runoff anomalies, down to around -10% in velocities. This behavior is different from Russel Gletscher where the lowest runoff anomalies generally lead to faster than average velocities. For Isunguata Sermia and Nordenskiöld Gletscher at low altitudes, we then observe a slight increase in velocities for years with runoff just under the average, then a slowdown if runoff is slightly above average, and clear faster velocities (around +10%) for years with even higher runoff anomalies. Nordenskiöld Gletscher seems to display again slightly slower velocities for 2019 (the year with the highest runoff anomaly), which is a behavior that we do not find in Isunguata Sermia, but the runoff anomalies in that basin do not reach as high values as in the first, so this behavior could potentially be observed if runoff anomalies were higher.

When we observe the behavior for other basins in Figure 3, Usulluup Sermia and Russel Gletscher seem to share common behavior at low altitudes, namely slightly faster velocities if the runoff was below average, negative velocity anomalies for years with runoff slightly above average, and a tendency towards faster velocities again for years when runoff is even higher. This time, however, high runoff anomalies still translate to slower velocities in opposition with Nordenskiöld Gletscher and Isunguata Sermia where such runoff anomalies lead to positive velocity anomalies.

Finally, Inuppaat Quuat appears to have a clear trend towards slower velocities as runoff anomalies are increasing, and this behavior is found for altitudes up to 1000 m.

The difference between Isunguata Sermia and Russel Gletscher is striking, as these two glaciers are lying next to each other but display different behaviors both at low and high altitudes under similar runoff inputs. This underlines that even for glaciers that are spatially close, we cannot assume a similar behavior in relation to hydrology, as other parameters such as the ice thickness, the hydraulic gradient, or the substrate could impact the development of the subglacial drainage system.

For all basins, we recognize a sawtooth pattern developing with an increase in velocity as runoff increases which is followed by a velocity drop with further runoff increase, and again faster velocities with even higher runoff, as summarized in Figure 4. Our interpretation is that the drainage system pressurization is rising with an increase in runoff leading to faster glaciers. However, at a given runoff value, the system reaches a threshold and becomes more efficient leading to lower water pressure and velocities, but the pressurization of this new system can also rise in case of an even higher runoff, leading again to faster velocities. The threshold where a new efficient system develops seems to depend on glacier characteristics, inducing different positioning of the velocity break point and seemingly different responses for each glacier. It is especially visible for Nordenskiöld Gletscher and Isunnguata Sermia at low altitudes and can be explained by different meltwater inputs to the system. If for a given year the water input is sufficient but without

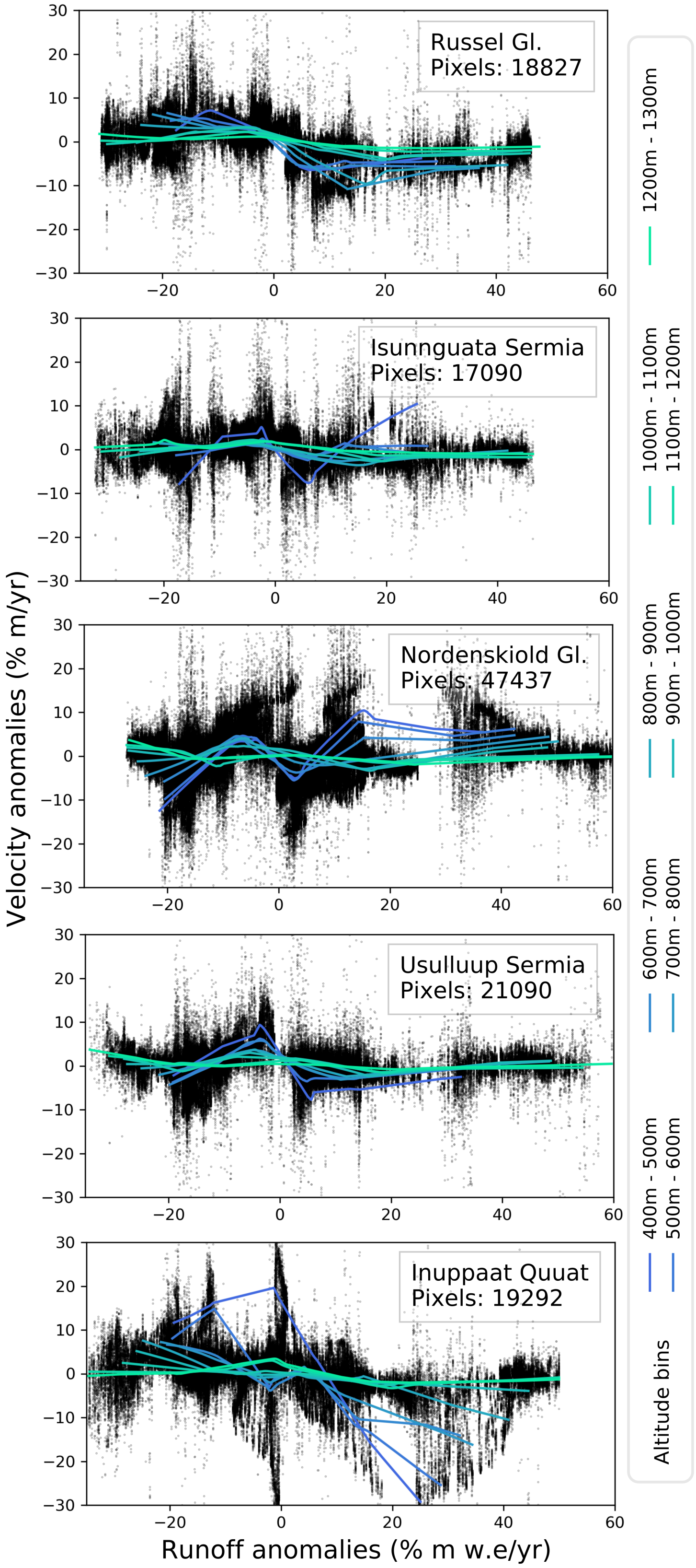

Figure 3. All data (velocity anomalies against runoff anomalies) in black dots for the 5 basins studied. The smoothing per altitude bin is in solid blue to green curves (LOWESS), the bluest curve being the lowest altitude bin, and the greenest the highest altitude bin. The number of pixels is the total number of individual data points used for the basin. For Isunnguata Sermia, Nordenskiöld Gletscher, Usulluup Sermia and Inuppaat Quuat, individual altitudes bins are available in supplemental materials Figures S7 to S10.

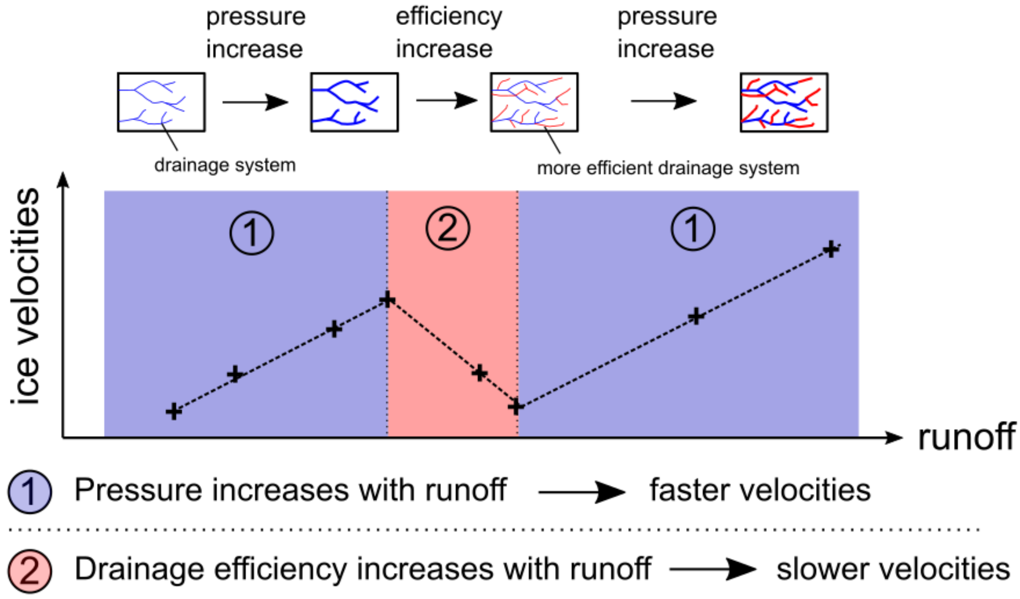

Figure 4. The sawtooth pattern, as observed in the basins such as Isunnguata Sermia and Nordenskiöld Gletscher. The points on the pattern are based on the observations of Isunnguata Sermia. We also observe the sawtooth pattern for Russel Gletscher and Usulluup Sermia, but the velocities anomalies obtained for the highest runoff are not as high as in the two first basins.

crossing a threshold like in 2017 or 2020, the velocities increase can be explained by the saturation of the drainage system, leading to faster velocities than if the system is less saturated (as in 2015). If it increases slightly, just enough to cross a threshold like in 2014 or 2016, the system will adapt into a more efficient one for these years and lead to slower velocities. If a year produces sufficient meltwater to saturate this efficient system, ice velocities will reaccelerate as in 2021. But if the water input is even higher (2019), a probably even more efficient drainage system will develop, leading to a slowdown in ice velocities, and this new system could also be saturated in the future leading once again to faster velocities before the cycle repeats. This idea, therefore, challenges the assumption that warmer summers would not increase annual ice displacement as they would likely be followed by reduced winter ice flow as found in Sole et al. (2013). We propose instead the idea that the system could potentially face an increasing runoff input that would constantly force the subglacial drainage system to adapt, even when a drainage system that we would consider efficient is already established during the first part of the melt season. Whether the runoff input would result in a slowdown or an acceleration would therefore be regulated by thresholds, and depending on the amount of runoff produced, lead to either a saturated water drainage system or to the development of a more efficient drainage system.

This sawtooth behavior could potentially happen on all the glaciers of our study, but it is likely that it would be conditioned by basin characteristics, leading to specific thresholds for each basin. Thus, it is possible that a similar pattern is observed everywhere, but that quantities of runoff required for displaying the sawtooth pattern are different for each basin, and that the amplitude of runoff anomalies over 2013-2021 would not be sufficient for some basins to display the full behavior. Another explanation could also be that the intrinsic characteristics of each glacier would simply produce a different behavior for ice velocities. Here from the data, we can only confirm that for similar runoff anomalies, the different basins have ice velocities that react differently.

In the Inuppaat Quuat case, we would interpret the behavior as the development of an efficient drainage system, leading to a slowdown of ice, although the amount of runoff produced may not be sufficient for this specific basin to lead to a reacceleration and display a sawtooth pattern as observed in Isunnguata Sermia and Nordenskiöld Gletscher. Additional years with different runoff signals would help in confirming this hypothesis.

A common point for all basins can nevertheless be observed: even though the shape of the relationship observed at low altitude still tend to appear at higher altitudes, it is strongly diminished and this reduction does not appear at the same altitude for all basin studied, which we will address in the next section.

3.2 Impact of runoff on velocities depends on altitude

Common to all our basins is how altitude is affecting the response to the runoff signal: all 5 basins display a relationship that is flattening when altitude increases as observed in Figure 3. We observe for Russel Gletscher in Figure 2 that for altitudes between 400 m and 900 m, the observed ice velocity varies with runoff, loosely following the sawtooth pattern as described in Figure 4. But at higher altitudes, ice velocities vary less, even with higher runoff variability. This could be explained by both the glacier characteristics that evolve with altitude, such as a different subglacial drainage system which could be caused by ice thickness or also different water input to the system. Indeed, while the runoff variability over these 9 years at high altitudes displays variations from -30% to up to 45%, we do not expect as much meltwater produced as at lower altitudes, and less runoff reaching the bottom with thicker ice. Higher altitudes display generally here what we can consider an inefficient drainage system, showing really small velocity variation, with considerable differences in the runoff between the years, but the altitude at which the efficient drainage system ceases to exist is probably driven by the specific characteristics of each glacier and the quantity of meltwater produced locally. However, even if velocity anomalies are small, they exist and tend to go hand-in-hand with the behavior observed at lower altitudes. Bartholomew et al. (2011) observed at higher altitudes a delay between the onset of the melt season and ice acceleration, requiring an accumulation of meltwater to penetrate through thicker ice, and this delay would be responsible for the limited velocity variations that they observed. They also found a linear relationship between rates of annual ablation and ice velocity variations that could explain here why we observe this attenuation of the signal at higher altitudes.

We cannot infer from this how the system would react with similar meltwater inputs as happening at lower altitudes, but the results presented here show that with the current production of runoff water, considerable runoff variations do not translate into much ice velocity differences at high altitudes. We cannot decipher whether the meltwater produced at high altitudes contributes to ice velocity at lower altitudes. In addition, we do not observe a clear cut at a specific altitude that could help to uncover a change in the subglacial water drainage system, but rather a progressive flattening of the ice velocity for higher altitudes.

A similar behavior, strong velocity variations at low altitudes that tend to disappear at higher altitudes, is observed for all 5 basins studied. However, the altitude at which it occurs also varies with the basin. For Nordenskiöld Gletscher and Isunguata Sermia higher in altitudes, the pattern is indeed similar to the one at lower altitudes but attenuated, especially for Isunguata Sermia, where absolute velocity anomalies are smaller and do not reach 5% above 500 m. However, for Nordenskiöld Gletscher, velocity variations are observed at higher altitudes, with a pronounced sawtooth pattern up to 1000 m. Russel Gletscher displays a strong reaction of ice velocities to runoff up to 900 m, whereas Usulluup Sermia does not display velocity variations above 5% for ice higher than 700 m. Finally, Inuppaat Quuat displays also almost no variations in ice velocities above 1000 m.

In summary, our data shows that above 500-1000 m ice velocities are not varying much from year to year, even when meltwater runoff displays strong intensity variations. The exact cutoff altitude depends on the glacier system and region.

3.3 Mapping the area

To further highlight regional and altitude variations, we present a map depicting the interannual variability of the ice velocities during our 9-year period of data (Fig. 5). This is an interesting tool to visualize spatially how strong are the variations of velocities at one point. Considering that surface meltwater is the main driver of velocity variations in the area, this map allows us to observe how ice velocities can vary with different melt inputs.

The map suggests a gradual evolution of interannual variability of ice velocities, from high values to low values from low to high altitudes, and extending to our entire study area. At low altitudes, high values indicate a strong response to runoff anomalies over the 9 years, while at high altitudes ice velocities do not vary much over the 9 years. We can clearly see that the velocity variations are following closely the basins. We also observe that, as observed on the smoothing curves, Isunnguata Sermia and Russel Gletscher, although spatially neighboring, have different patterns. We find again on the map the low ice velocity variations of Isunnguata Sermia observed earlier: while Russel Gletscher has an average interannual variability of around 5% up to 800 m, Isunnguata Sermia has already values below 5% at 500 m, indicating much lower velocity variations during 2013-2021 at the same altitudes. This fast decrease could be associated with a change in the drainage system that we do not observe at that altitude for Russel Gletscher. The values observed in that area are still relatively small compared to Inuppaat Quuat and Nordenskiöld Gletscher which have an average velocity anomaly of over 10%. The entire Inuppaat Quuat basin seems to have strong variations up to 900 m, while Nordenskiöld Gletscher, although displaying high values at low altitudes, has a much more gradual signal weakening as altitude increases. As seen earlier, this weaker response to runoff anomalies at higher altitudes could be due to the characteristics of the system at higher altitudes, such as thicker ice, different subglacial drainage system, or the smaller amounts of meltwater produced at that altitude. It is interesting to note that the areas around Nordenskiöld Gletscher's main tongue display relatively small average velocity anomalies compared to the trunk of the glacier.

3.4 Discussion regarding the method

Regarding our interpretation of the results, we observe conjointly the runoff anomalies and the velocity anomalies and try to assess correlations. Although these are not causation relationships, we believe that the behavior in our area and at the altitudes considered is mainly driven by the basal sliding, as observed in the Russel area in Maier et al. (2019). Therefore, we argue that we give here an idea of the impact of melt on the ice dynamics through subglacial water systems, although many other processes can affect the development of such drainage systems and lead to the differences by basins that we observed here.

Following the previous comment, it is assumed that there is no lag in the system, so that runoff for a given year will act on ice velocities the same year. The melt season produces meltwater during summer, and previous literature found a direct response of the system during the summer and during the following winter (e.g., Palmer et al., 2011; Bartholomew et al., 2012; Fitzpatrick et al., 2013; Tedesco et al., 2013). We made sure to sample yearly velocities based on image pairs taken before summer, so that the yearly velocity measured encompasses the respective summer to which we associate the melt season, and the following winter, without taking into account velocities from the following summer.

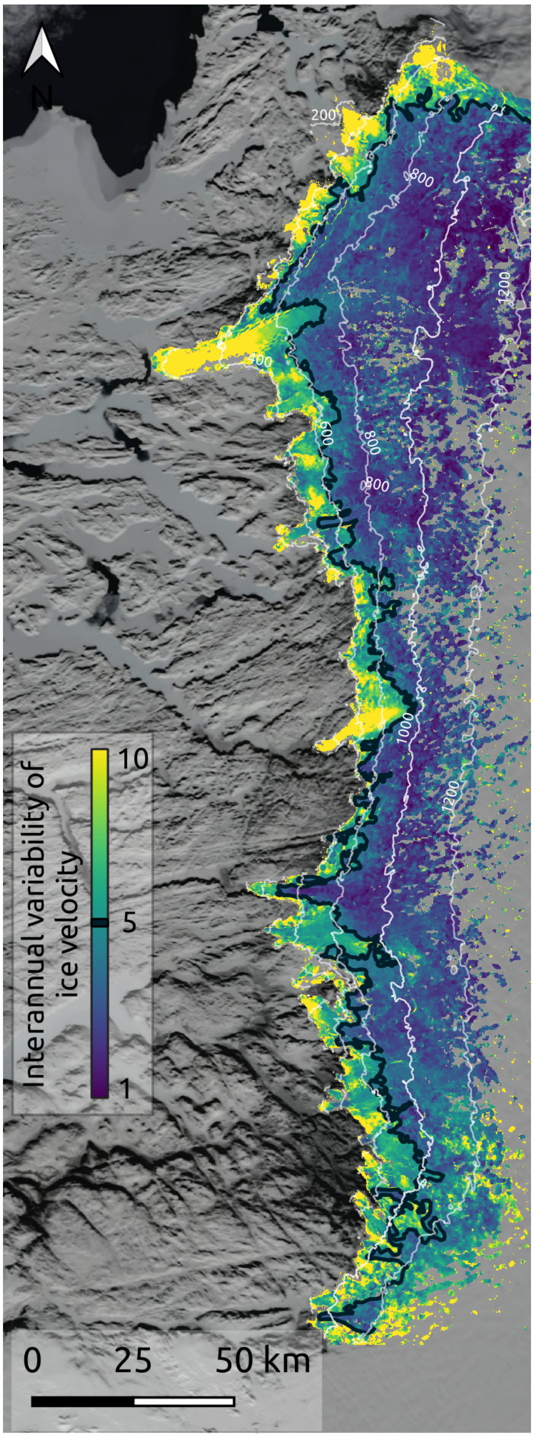

Figure 5. Interannual variability of ice velocity, computed with the root mean square over the 9 years for velocity anomalies for each pixel. Values at the glaciers' tongues are over 10, indicating high ice velocity variations over the period, while at high altitudes, the variability of ice velocity is much smaller. The black line is the isoline for a root mean square of 5.

Regarding the way we analyzed surface runoff and velocities, we used the same value from the reanalysis product that was available at 1km, for our velocity data which is 150 m in resolution. The opposite could have been done, averaging the velocity to resample at 1km resolution, but we do not expect both the velocity to change drastically over this 1km^2, as well as we do not expect the surface meltwater signal to vary within a 1km^2. Therefore this does not impact our results since we do not compute any statistical significance index that would have been prone to bias with a higher number of points.

4 Conclusions

We investigate runoff anomalies from ERA5-MAR and velocity anomalies from satellite observations over Southwest Greenland for the years 2013-2021. These data gave insights into glacier response to meltwater input. We found that ice reacts differently to similar runoff anomalies depending on basin and altitude, and found an interesting sawtooth pattern. We explain it by the subglacial drainage system getting more and more pressurized due to higher water input until a certain point where the whole drainage system is modified with a more developed efficient drainage system, leading to a drop in pressure and velocities, but this new drainage system could also be saturated and even more efficient drainage systems may have to develop to accommodate higher runoff quantities. This finding challenges the idea of the resilience of this land-terminating part of the Greenland Ice Sheet to warmer summers, as we find that high runoff years can result in faster velocities even at low altitudes. At higher altitudes, however, we find that the velocity variations are largely attenuated compared to low altitudes and that large variability in runoff does not result in large ice velocity variations. The altitude at which the velocities signal is attenuated depends on the basin. Our studied glaciers show a breakpoint at different runoff anomalies which are probably driven by basin-specific characteristics giving the seemingly different responses observed on these closely spaced basins. Therefore, the sawtooth pattern is not exactly the same in all basins, but understanding whether regional differences occur due to intrinsic glacier characteristics or due to a lack of sufficient water input variations in our data will require a few more years of observation. Future modeling work should take special care into making sure a proper hydrological model is implemented as the ice dynamics in this part of Greenland is highly non-linear and it seems that the impact of meltwater lubrication feedback can not be investigated through a simplified runoff-velocity relationship.

Open Research Section

The data supporting our conclusions is publicly available.

- Velocity data is available at : https://doi.org/10.5281/zenodo.7418361
- MAR output are available at : ftp://climato.be/fettweis/MARv3.12/Greenland/ERA5_6.5km/

Acknowledgments
This work is part of the SWItchDyn project funded by the Research Council of Norway (NFR-287206). Thanks to Xavier Fettweis for providing the downscaled MAR output. Computing was performed on the resources provided by UNINETT Sigma2 – the National Infrastructure for High-Performance Computing and Data Storage in Norway (NN9635K and NS9635K). A warm thanks to Bjerknes colleagues for their support.

References

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T., & King, M. A. (2012, sep). Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. *Journal of Geophysical Research: Earth Surface*, *117*, n/a–n/a. Retrieved from http://doi.wiley.com/10.1029/2011JF002220 doi: 10.1029/2011JF002220

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton, T., Palmer, S., & Wadham, J. (2011, apr). Supraglacial forcing of subglacial drainage in the ablation zone of the Greenland ice sheet. *Geophysical Research Letters*, *38*(8), n/a–n/a. Retrieved from http://doi.wiley.com/10.1029/2011GL047063 doi: 10.1029/2011GL047063

Bougamont, M., Christoffersen, P., Hubbard, A. L., Fitzpatrick, A. A., Doyle, S. H., & Carter, S. P. (2014, sep). Sensitive response of the Greenland Ice Sheet to surface melt drainage over a soft bed. *Nature Communications*, *5*(1), 1–9. Retrieved from www.nature.com/naturecommunications doi: 10.1038/ncomms6052

Brinkerhoff, D., Aschwanden, A., & Fahnestock, M. (2021, jun). Constraining subglacial processes from surface velocity observations using surrogate-based Bayesian inference. *Journal of Glaciology*, *67*(263), 385–403. Retrieved from https://www.cambridge.org/core. doi: 10.1017/jog.2020.112

Cleveland, W. S. (1979). Robust locally weighted regression and smoothing scatterplots. *Journal of the American Statistical Association*, *74*(368), 829–836. doi: 10.1080/01621459.1979.10481038

Davison, B. J., Sole, A. J., Livingstone, S. J., Cowton, T. R., & Nienow, P. W. (2019, feb). *The influence of hydrology on the dynamics of land-terminating sectors of the Greenland ice sheet* (Vol. 7). Frontiers Media S.A. doi: 10.3389/feart.2019.00010

de Fleurian, B., Morlighem, M., Seroussi, H., Rignot, E., van den Broeke, M. R., Kuipers Munneke, P., … Tedstone, A. J. (2016, oct). A modeling study of the effect of runoff variability on the effective pressure beneath Russell Glacier, West Greenland. *Journal of Geophysical Research: Earth Surface*, *121*(10), 1834–1848. Retrieved from https://onlinelibrary.wiley.com/doi/10.1002/2016JF003842 doi: 10.1002/2016JF003842

Derkacheva, A., Mouginot, J., Millan, R., Maier, N., & Gillet-Chaulet, F. (2020, jun). Data Reduction Using Statistical and Regression Approaches for Ice Velocity Derived by Landsat-8, Sentinel-1 and Sentinel-2. *Remote Sensing*, *12*(12), 1935. Retrieved from https://www.mdpi.com/2072-4292/12/12/1935 doi: 10.3390/rs12121935

Dow, C. F., Hubbard, A., Booth, A. D., Doyle, S. H., Gusmeroli, A., & Kulessa, B. (2013, sep). Seismic evidence of mechanically weak sediments underlying Russell Glacier, West Greenland. *Annals of Glaciology*, *54*(64), 135–141. Retrieved from https://www.cambridge.org/core. doi: 10.3189/2013AoG64A032

Doyle, S. H., Hubbard, A., Fitzpatrick, A. A., Van As, D., Mikkelsen, A. B., Pettersson, R., & Hubbard, B. (2014, feb). Persistent flow acceleration within the interior of the Greenland ice sheet. *Geophysical Research Letters*, *41*(3), 899–905. doi: 10.1002/2013GL058933

Fettweis, X., Hofer, S., Krebs-Kanzow, U., Amory, C., Aoki, T., Berends, C. J., … Zolles, T. (2020, nov). GrSMBMIP: Intercomparison of the modelled 1980-2012 surface mass balance over the Greenland Ice Sheet. *Cryosphere*, *14*(11), 3935–3958. doi: 10.5194/tc-14-3935-2020

Fitzpatrick, A. A., Hubbard, A., Joughin, I., Quincey, D. J., Van As, D., Mikkelsen, A. P., … Jones, G. A. (2013, aug). Ice flow dynamics and surface meltwater flux at a land-terminating sector of the Greenland ice sheet. *Journal of Glaciology*, *59*(216), 687–696. Retrieved from https://doi.org/10.3189/2013JoG12J143 doi: 10.3189/2013JoG12J143

Fürst, J. J., Goelzer, H., & Huybrechts, P. (2015, may). Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming.

Cryosphere, *9*(3), 1039–1062. doi: 10.5194/tc-9-1039-2015

Halas, P., Mouginot, J., de Fleurian, B., & Langebroek, P. (2022, dec). *Southwest Greenland Ice Sheet Yearly Ice Velocities dataset from 1984 to 2020.* Retrieved from `https://zenodo.org/record/7418361` doi: 10.5281/ZENODO.7418361

Halas, P., Mouginot, J., de Fleurian, B., & Langebroek, P. M. (2023, feb). Impact of seasonal fluctuations of ice velocity on decadal trends observed in Southwest Greenland. *Remote Sensing of Environment*, *285*, 113419. doi: 10.1016/j.rse.2022.113419

Haran, T., Bohlander, J., Scambos, T., Painter, T., & Fahnestock, M. (2018). *Measures modis mosaic of greenland (mog) 2005, 2010, and 2015 image maps, version 2 — national snow and ice data center.* Retrieved 2022-04-12, from `https://nsidc.org/data/NSIDC-0547/versions/2`

Harper, J. T., Humphrey, N. F., Meierbachtol, T. W., Graly, J. A., & Fischer, U. H. (2017, sep). Borehole measurements indicate hard bed conditions, Kangerlussuaq sector, western Greenland Ice Sheet. *Journal of Geophysical Research: Earth Surface*, *122*(9), 1605–1618. Retrieved from `http://doi.wiley.com/10.1002/2017JF004201` doi: 10.1002/2017JF004201

Hoffman, M. J., Catania, G. A., Neumann, T. A., Andrews, L. C., & Rumrill, J. A. (2011, dec). Links between acceleration, melting, and supraglacial lake drainage of the western Greenland Ice Sheet. *Journal of Geophysical Research*, *116*(F4), F04035. Retrieved from `http://doi.wiley.com/10.1029/2010JF001934` doi: 10.1029/2010JF001934

Joughin, I., Das, S. B., King, M. A., Smith, B. E., Howat, I. M., & Moon, T. (2008, may). Seasonal speedup along the western flank of the Greenland ice sheet. *Science*, *320*(5877), 781–783. Retrieved from `www.sciencemag.org/cgi/content/full/1153360/DC1` doi: 10.1126/science.1153288

Koziol, C. P., & Arnold, N. (2017, dec). Incorporating modelled subglacial hydrology into inversions for basal drag. *Cryosphere*, *11*(6), 2783–2797. doi: 10.5194/tc-11-2783-2017

Koziol, C. P., & Arnold, N. (2018, mar). Modelling seasonal meltwater forcing of the velocity of land-terminating margins of the Greenland Ice Sheet. *Cryosphere*, *12*(3), 971–991. doi: 10.5194/tc-12-971-2018

Kulessa, B., Hubbard, A. L., Booth, A. D., Bougamont, M., Dow, C. F., Doyle, S. H., … Jones, G. A. (2017, aug). Seismic evidence for complex sedimentary control of Greenland Ice Sheet flow. *Science Advances*, *3*(8). Retrieved from `https://www.science.org` doi: 10.1126/sciadv.1603071

Maier, N., Humphrey, N., Harper, J., & Meierbachtol, T. (2019). Sliding dominates slow-flowing margin regions, Greenland Ice Sheet. *Science Advances*, *5*(7). Retrieved from `https://www.science.org` doi: 10.1126/sciadv.aaw5406

Millan, R., Mouginot, J., Rabatel, A., Jeong, S., Cusicanqui, D., Derkacheva, A., & Chekki, M. (2019, oct). Mapping Surface Flow Velocity of Glaciers at Regional Scale Using a Multiple Sensors Approach. *Remote Sensing*, *11*(21), 2498. Retrieved from `https://www.mdpi.com/2072-4292/11/21/2498` doi: 10.3390/rs11212498

Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., … Wood, M. (2019, may). *Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018* (Vol. 116) (No. 19). National Academy of Sciences. Retrieved from `https://www.pnas.org/doi/abs/10.1073/pnas.1904242116` doi: 10.1073/pnas.1904242116

Mouginot, J., Rignot, E., Scheuchl, B., & Millan, R. (2017). Comprehensive annual ice sheet velocity mapping using Landsat-8, Sentinel-1, and RADARSAT-2 data. *Remote Sensing*, *9*(4), 1–20. doi: 10.3390/rs9040364

Nienow, P. W., Sole, A. J., Slater, D. A., & Cowton, T. R. (2017, dec). *Recent Advances in Our Understanding of the Role of Meltwater in the*

Greenland Ice Sheet System (Vol. 3) (No. 4). Springer. Retrieved from https://link.springer.com/article/10.1007/s40641-017-0083-9 doi: 10.1007/s40641-017-0083-9

Noël, B., van de Berg, W. J., Lhermitte, S., & van den Broeke, M. R. (2019, sep). Rapid ablation zone expansion amplifies north Greenland mass loss. *Science Advances*, *5*(9). Retrieved from https://www.science.org doi: 10.1126/sciadv.aaw0123

Palmer, S., Shepherd, A., Nienow, P., & Joughin, I. (2011, feb). Seasonal speedup of the Greenland Ice Sheet linked to routing of surface water. *Earth and Planetary Science Letters*, *302*(3-4), 423–428. doi: 10.1016/j.epsl.2010.12.037

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., & Lenaerts, J. T. M. (2011, mar). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, *38*(5), n/a–n/a. Retrieved from http://doi.wiley.com/10.1029/2011GL046583 doi: 10.1029/2011GL046583

Shannon, S. R., Payne, A. J., Bartholomew, I. D., Van Den Broeke, M. R., Edwards, T. L., Fettweis, X., ... Zwinger, T. (2013, aug). Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(35), 14156–14161. Retrieved from https://www.pnas.org/doi/abs/10.1073/pnas.1212647110 doi: 10.1073/pnas.1212647110

Shepherd, A., Hubbard, A., Nienow, P., King, M., McMillan, M., & Joughin, I. (2009, jan). Greenland ice sheet motion coupled with daily melting in late summer. *Geophysical Research Letters*, *36*(1), L01501. Retrieved from http://doi.wiley.com/10.1029/2008GL035758 doi: 10.1029/2008GL035758

Sole, A., Nienow, P., Bartholomew, I., Mair, D., Cowton, T., Tedstone, A., & King, M. A. (2013, aug). Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers. *Geophysical Research Letters*, *40*(15), 3940–3944. Retrieved from http://doi.wiley.com/10.1002/grl.50764 doi: 10.1002/grl.50764

Tedesco, M., Willis, I. C., Hoffman, M. J., Banwell, A. F., Alexander, P., & Arnold, N. S. (2013, jul). Ice dynamic response to two modes of surface lake drainage on the Greenland ice sheet. *Environmental Research Letters*, *8*(3), 034007. Retrieved from http://asterweb.jpl.nasa.gov/ doi: 10.1088/1748-9326/8/3/034007

Tedstone, A. J., Nienow, P. W., Gourmelen, N., Dehecq, A., Goldberg, D., & Hanna, E. (2015, oct). Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming. *Nature*, *526*(7575), 692–695. Retrieved from http://www.nature.com/articles/nature15722 doi: 10.1038/nature15722

Van De Wal, R. S., Boot, W., Van Den Broeke, M. R., Smeets, C. J., Reijmer, C. H., Donker, J. J., & Oerlemans, J. (2008, jul). Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. *Science*, *321*(5885), 111–113. Retrieved from www.sciencemag.org/cgi/content/full/321/5885/108/DC1 doi: 10.1126/science.1158540

Van De Wal, R. S., Smeets, C. J., Boot, W., Stoffelen, M., Van Kampen, R., Doyle, S. H., ... Hubbard, A. (2015, apr). Self-regulation of ice flow varies across the ablation area in south-west Greenland. *Cryosphere*, *9*(2), 603–611. doi: 10.5194/tc-9-603-2015

Van Den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Van Berg, W. J. D., ... Wouters, B. (2009, nov). Partitioning recent Greenland mass loss. *Science*, *326*(5955), 984–986. Retrieved from www.sciencemag.org/cgi/content/full/326/5955/980/DC1 doi: 10.1126/science.1178176

Velicogna, I. (2009, oct). Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Let-*

ters, *36*(19), L19503. Retrieved from http://doi.wiley.com/10.1029/2009GL040222 doi: 10.1029/2009GL040222

Williams, J. J., Gourmelen, N., & Nienow, P. (2020). Dynamic response of the Greenland ice sheet to recent cooling. *Scientific Reports*, *10*(1), 1–11. Retrieved from http://dx.doi.org/10.1038/s41598-020-58355-2 doi: 10.1038/s41598-020-58355-2

Wright, P. J., Harper, J. T., Humphrey, N. F., & Meierbachtol, T. W. (2016, jun). Measured basal water pressure variability of the western Greenland Ice Sheet: Implications for hydraulic potential. *Journal of Geophysical Research: Earth Surface*, *121*(6), 1134–1147. Retrieved from http://doi.wiley.com/10.1002/2016JF003819 doi: 10.1002/2016JF003819

Zwally, H. J., Abdalati, W., Herring, T., Larson, K., Saba, J., & Steffen, K. (2002, jul). Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, *297*(5579), 218–222. Retrieved from www.sciencemag.org/cgi/content/full/1071795/DC1 doi: 10.1126/science.1072708

Supporting Information for "Surface runoff impact on ice dynamics varies with altitude and location"

Paul Halas[1], Basile de Fleurian[1], Jérémie Mouginot[2], Petra M. Langebroek[3]

[1]University of Bergen, Bjerknes Centre for Climate Research, Bergen, Norway

[2]Institut des Géosciences de l'Environnement, Université Grenoble Alpes, CNRS, IRD, INP, Grenoble, France

[3]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, Bergen, Norway

Contents of this file

1. Figures S1 to S10

Introduction

The supporting information contains 11 figures that support the findings of the associated paper. We display information that is not paramount for the understanding of the results, but that provides information for the reader that wants more detail about the data used such as the velocity anomalies maps used in Figure S1, and the typical runoff signal in Figure S2 and S3 for all 9 years of the study. We also display in the main manuscript smoothed curves for all altitudes with varying altitude bins and chose to display bins of 100 m in the main manuscript as it is a compromise between not too many bins but without aggregating too much data. We display here in Figures S4a and S4b the smoothing curves for altitude bins of 25 m (requiring two separate figures), in Figure S5 altitude bins of 50 m, and in Figure S6 altitude bins of 200 m. Finally, we display in the main manuscript all altitudes bins combined on the same plot for all basins but display smoothed curves separated by altitude only for Russel Gletscher. We display the other separated smoothed curves for 100 m altitude bins for the other 4 basins in Figures S7, S8, S9, and S10.

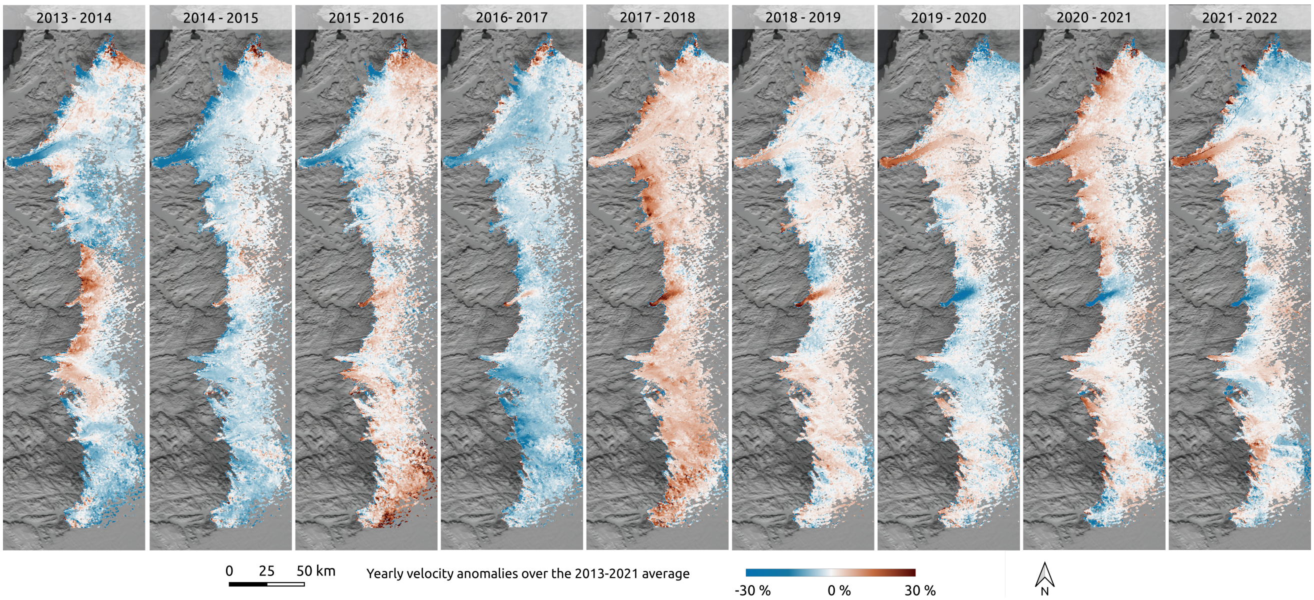

Figure S1. Yearly ice velocity anomalies map compared to the average over the 9 years.

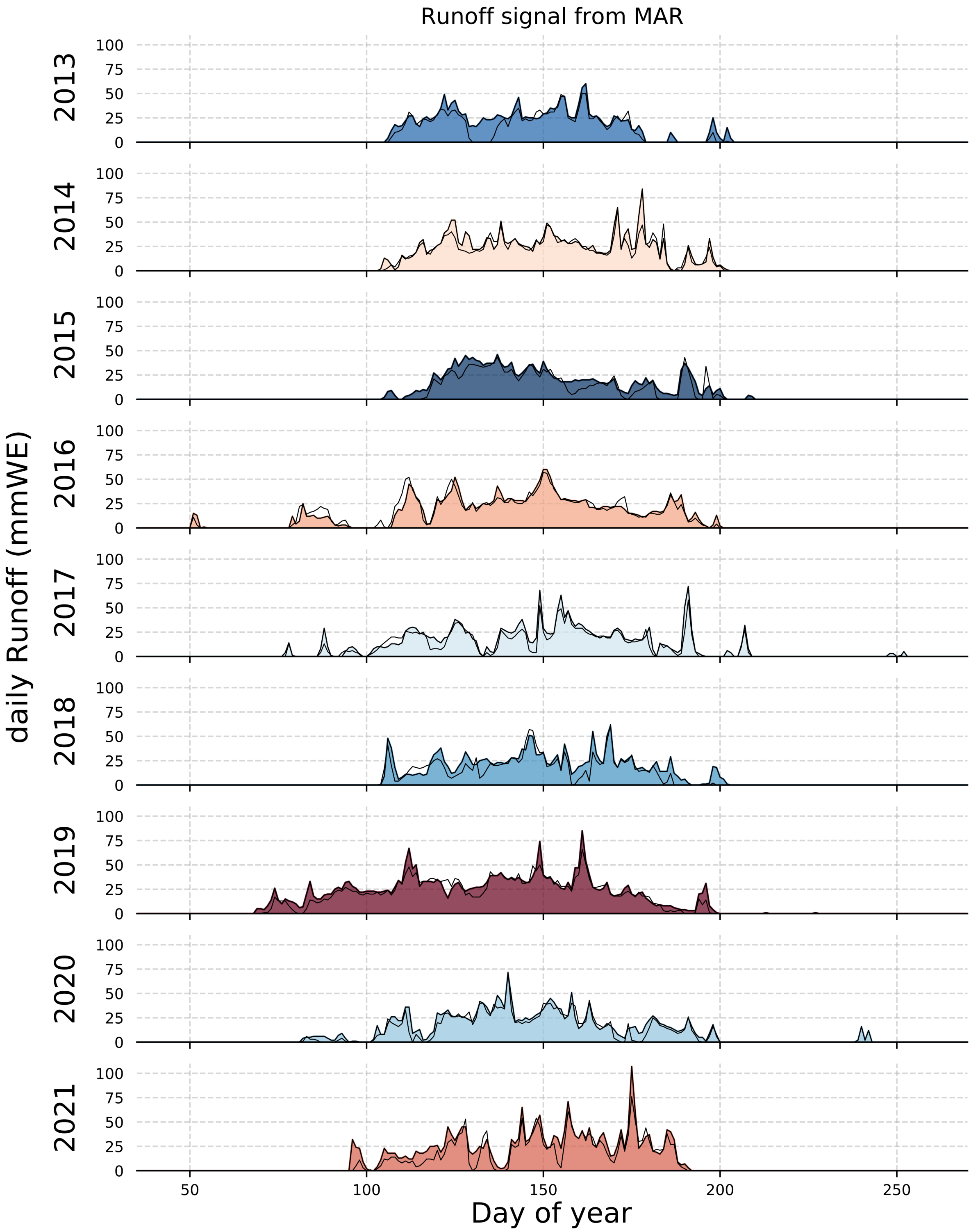

Figure S2. Daily runoff signal from MAR for all 9 years, representative of our area. We color each year of the daily runoff signal depending on how much the integrated melt on the given year is compared to the average over the 9 years. The thin black line is the signal at 1000 m.

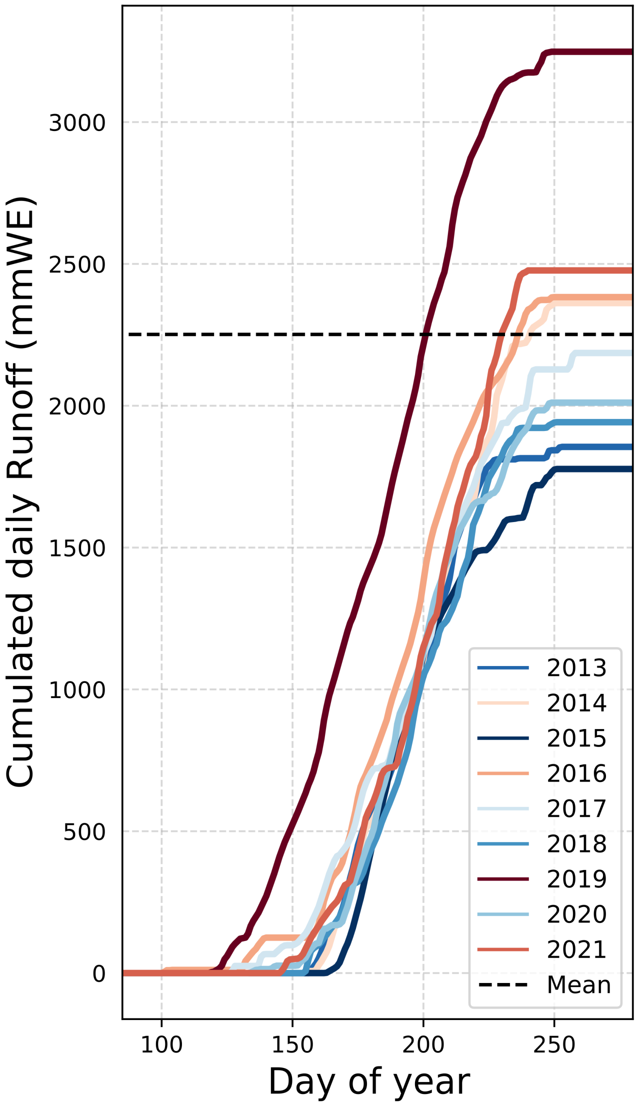

Figure S3. Daily cumulated runoff from MAR for all 9 years. We color each year of the daily runoff signal depending on how much the integrated melt on the given year is compared to the average over the 9 years.

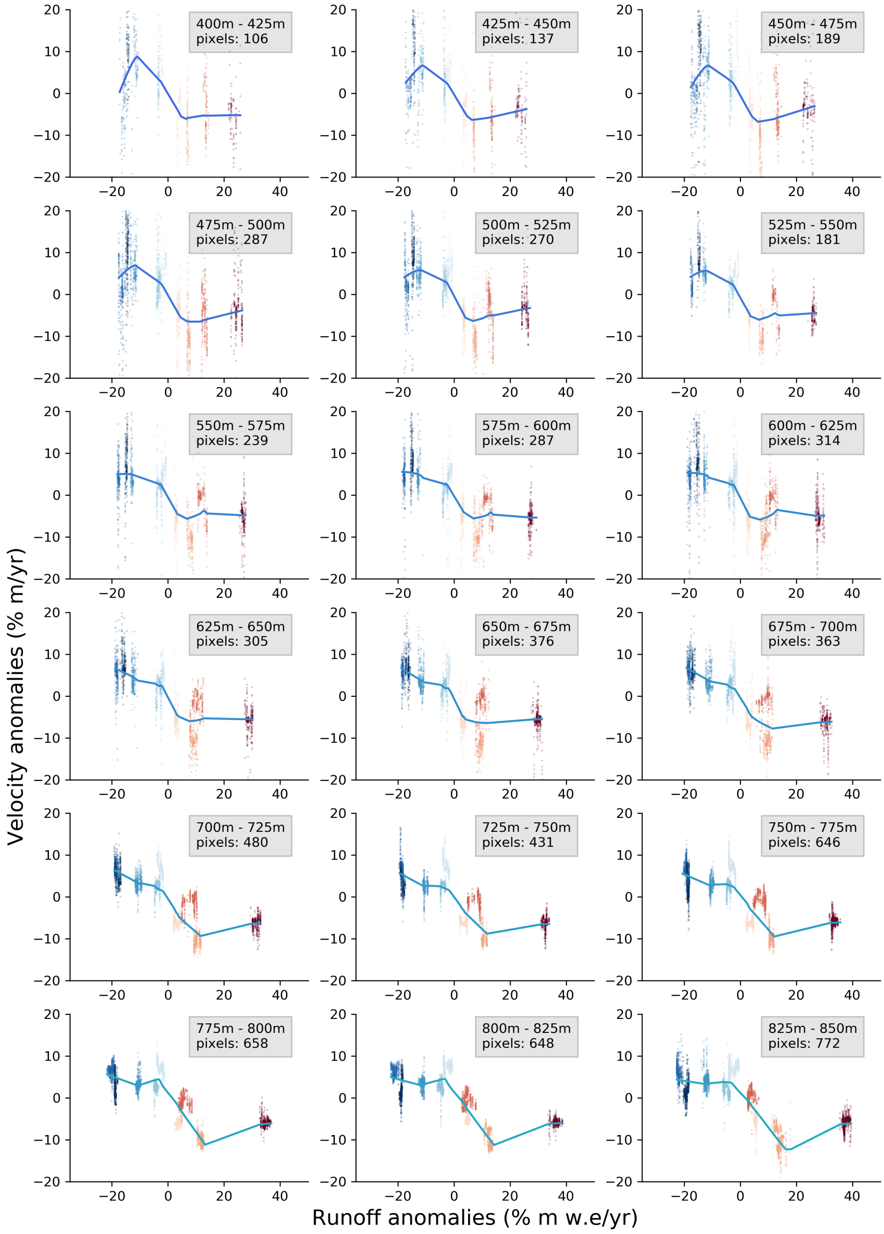

Figure S4a. Velocity anomalies against runoff anomalies over 2013-2021 for 25 m altitude bins for Russel Gletscher for altitudes between 400 m and 850 m. The colors indicate the year corresponding to the data. The color gradient is defined depending on the total runoff anomalies over the given year; negative anomalies are in shades of blue and positive anomalies are in shades of red. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

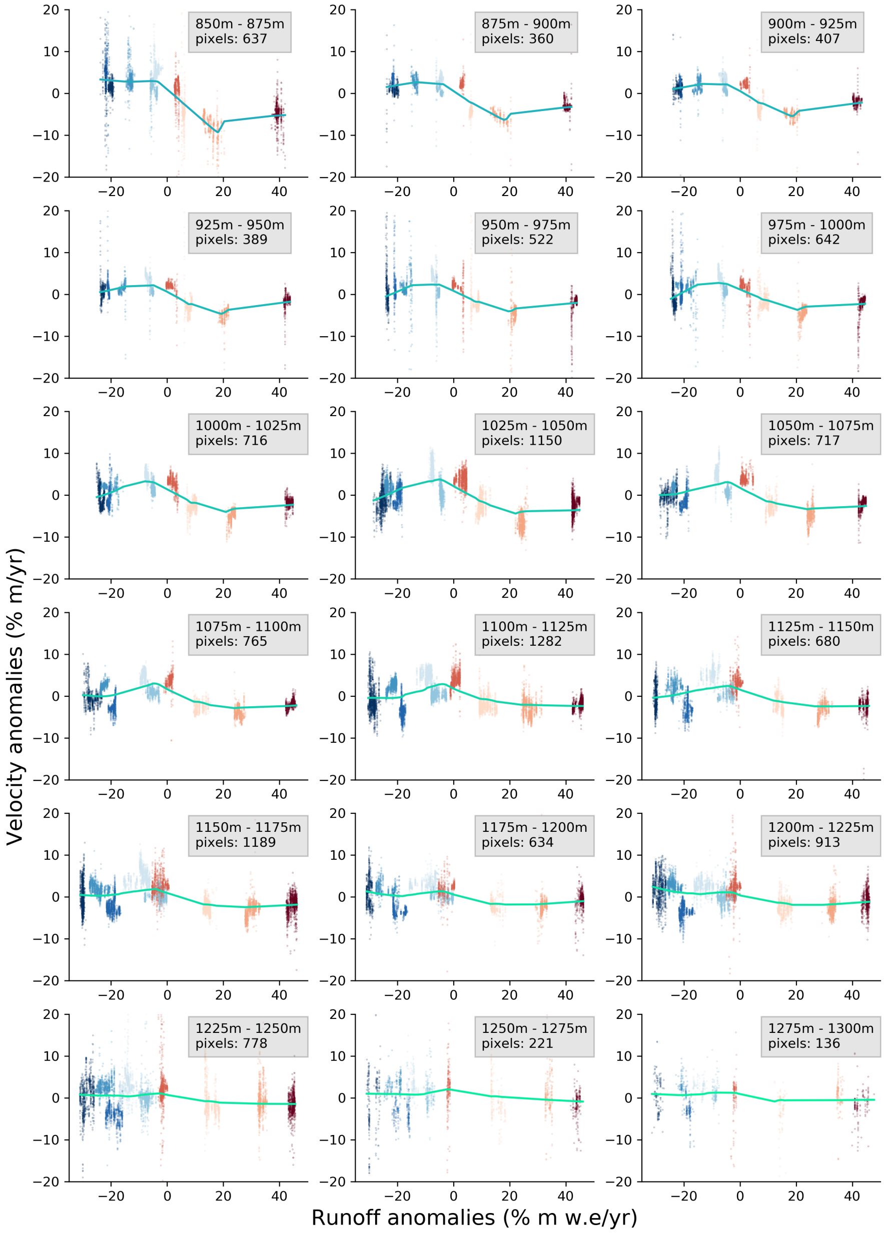

Figure S4b. Velocity anomalies against runoff anomalies over 2013-2021 for 25 m altitude bins for Russel Gletscher for altitudes between 850 m and 1300 m. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

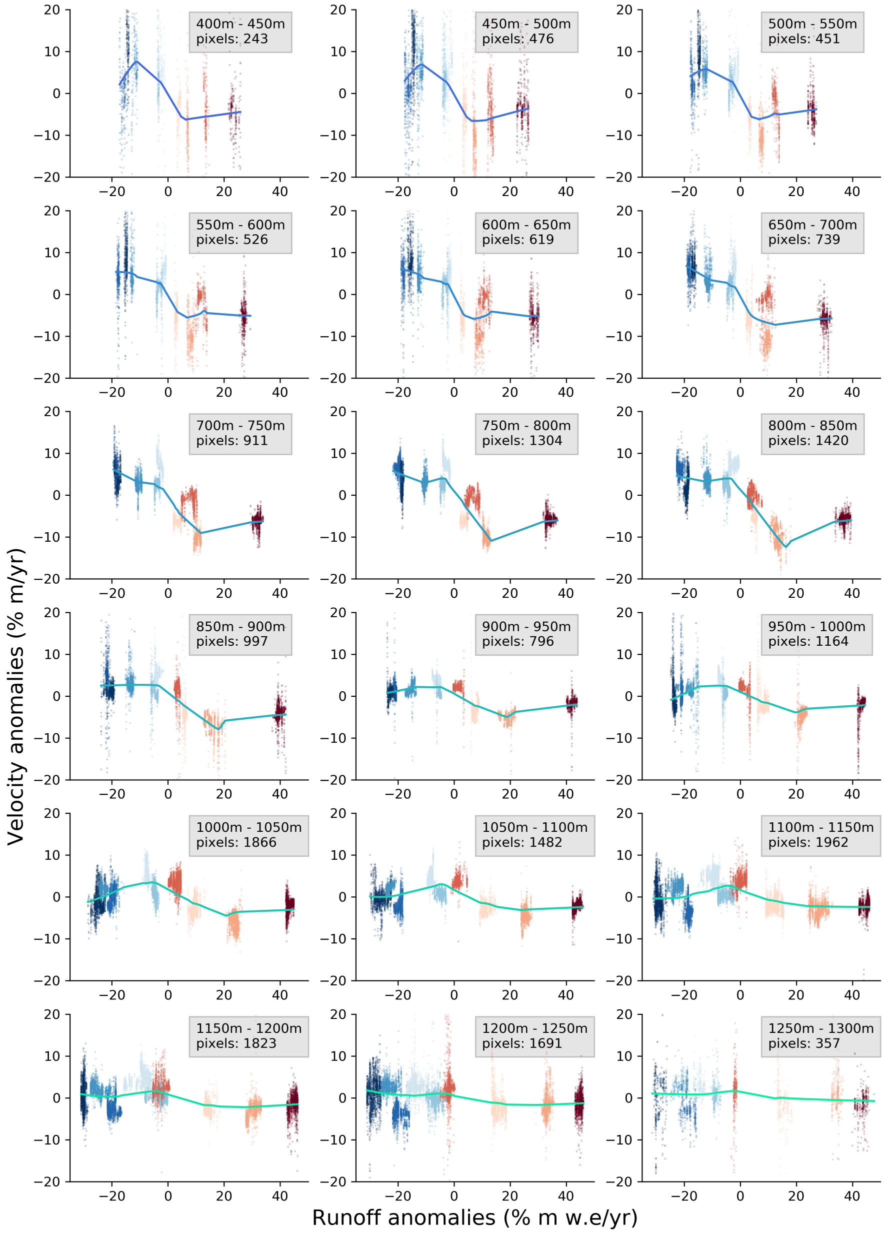

Figure S5. Velocity anomalies against runoff anomalies over 2013-2021 for 50 m altitude bins for Russel Gletscher. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

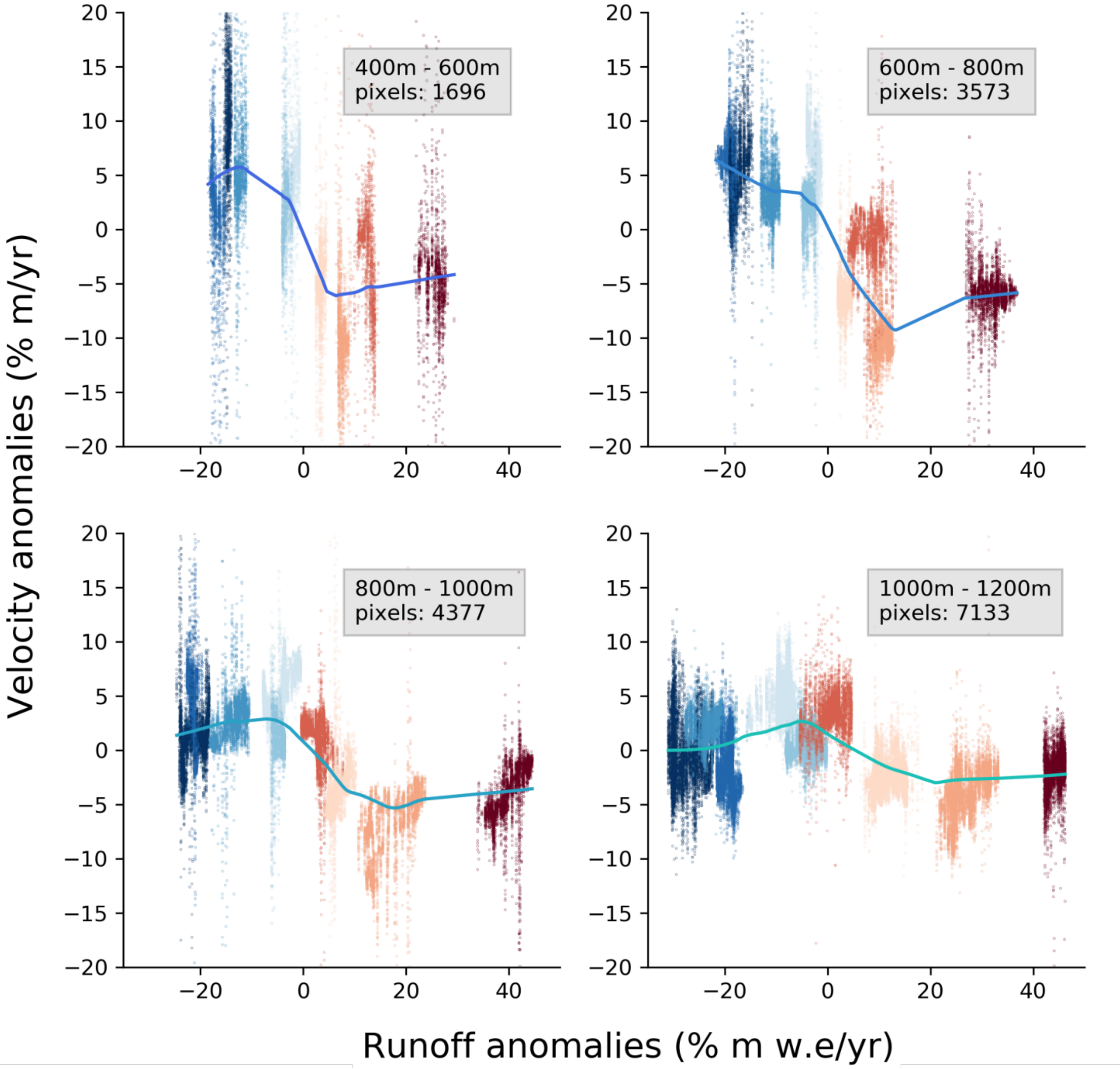

Figure S6. Velocity anomalies against runoff anomalies over 2013-2021 for 200 m altitude bins for Russel Gletscher. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

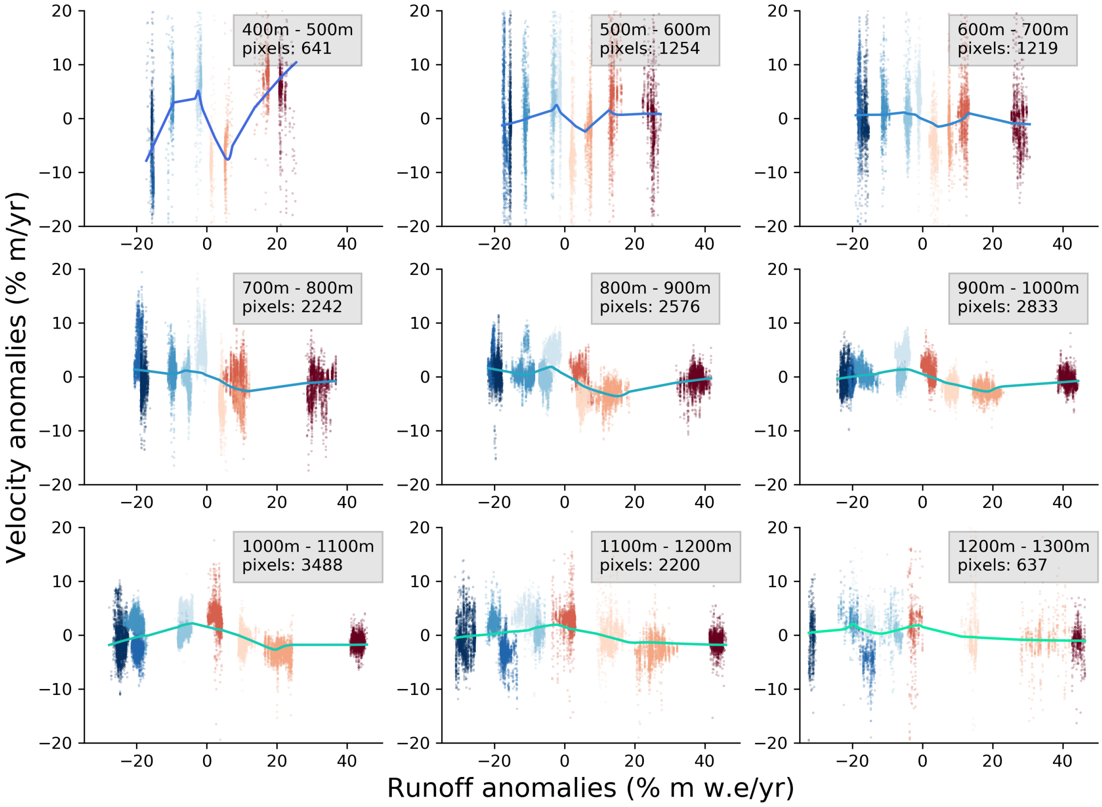

Figure S7. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Isunnguata Sermia. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

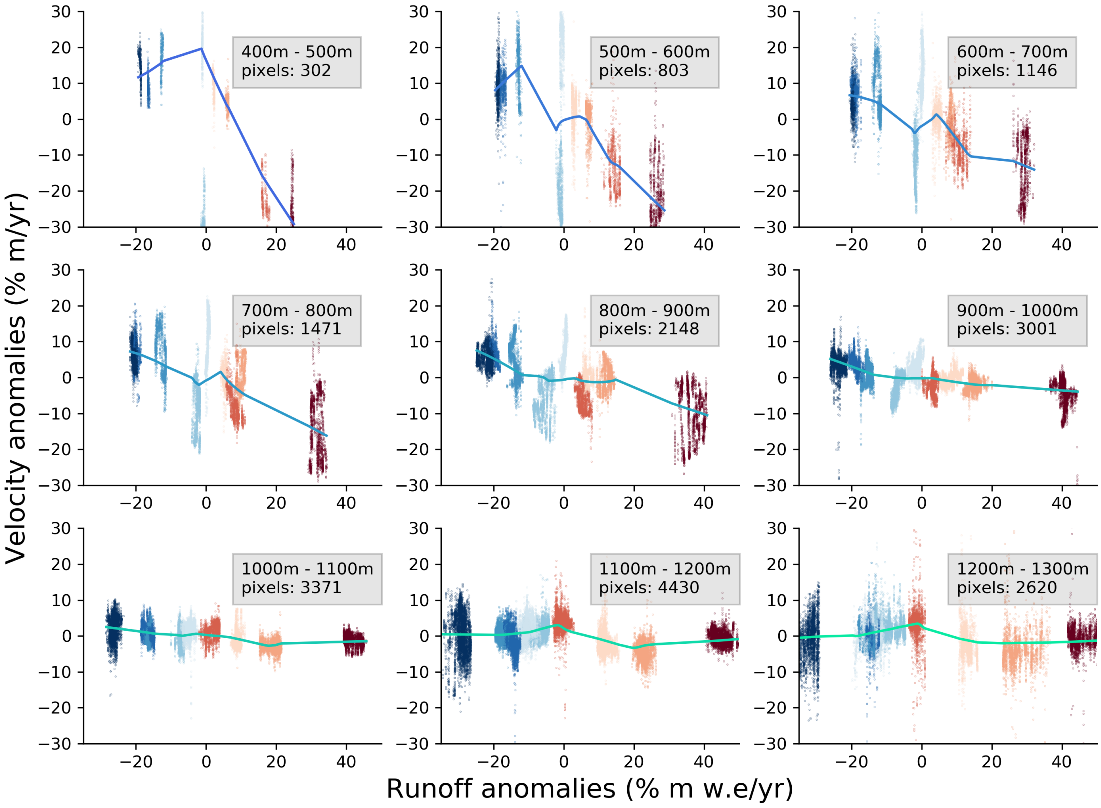

Figure S8. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Inuppaat Quuat. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

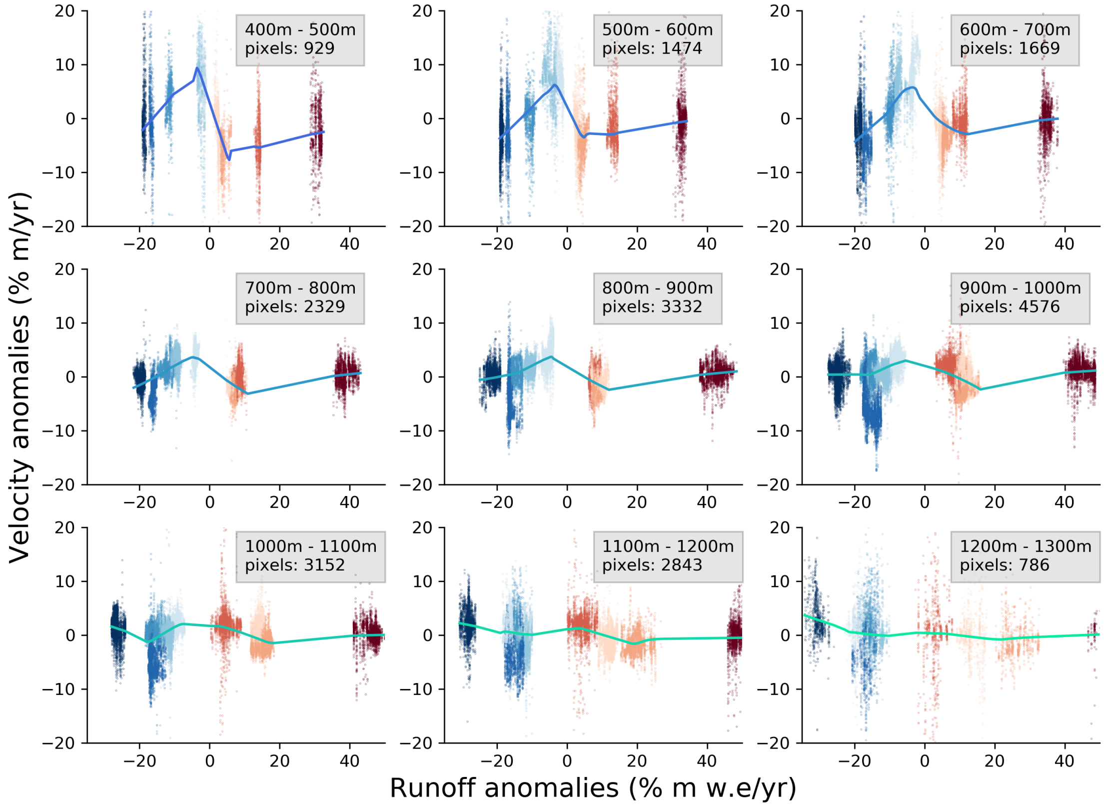

Figure S9. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Usulluup Sermia. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).

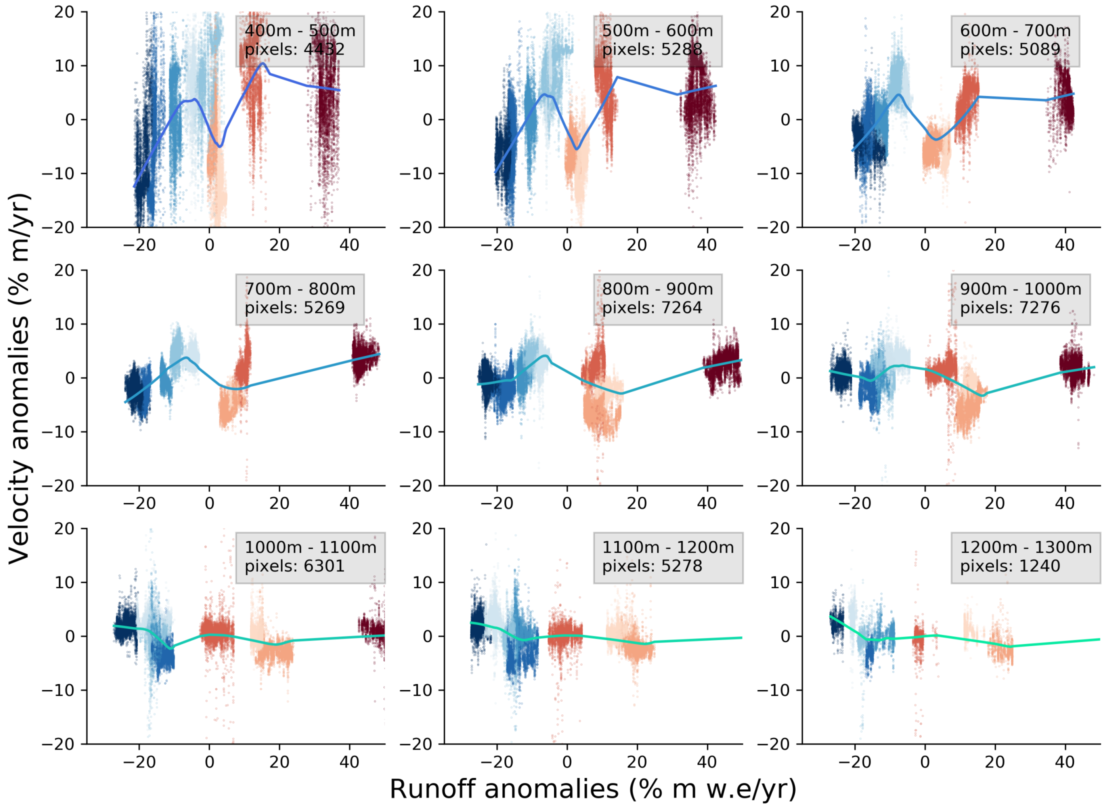

Figure S10. Velocity anomalies against runoff anomalies over 2013-2021 for 100 m altitude bins for Nordenskiöld Gletscher. Solid lines indicate the statistical relationship between runoff and velocity anomalies (calculated using LOWESS).