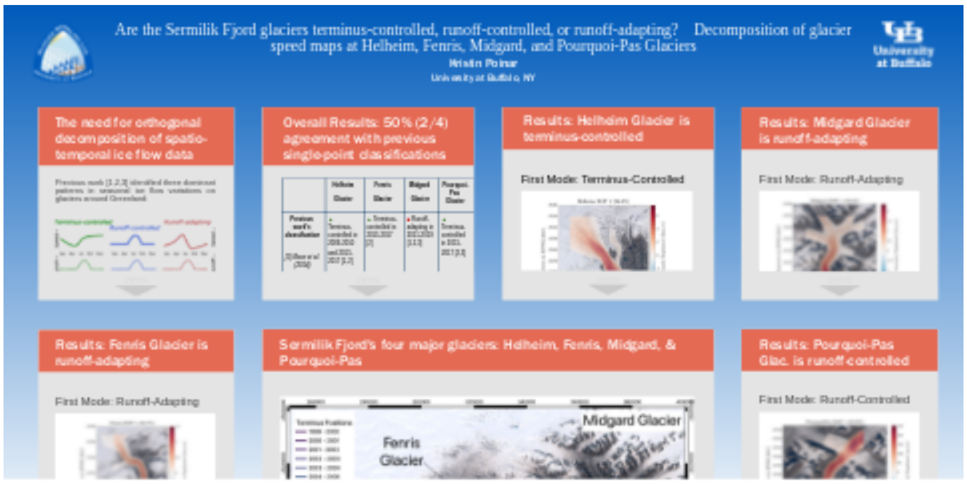
Are the Sermilik Fjord glaciers terminus-controlled, runoff-controlled, or runoff-adapting? Decomposition of glacier speed maps at Helheim, Fenris, Midgard, and Pourquoi-Pas Glaciers



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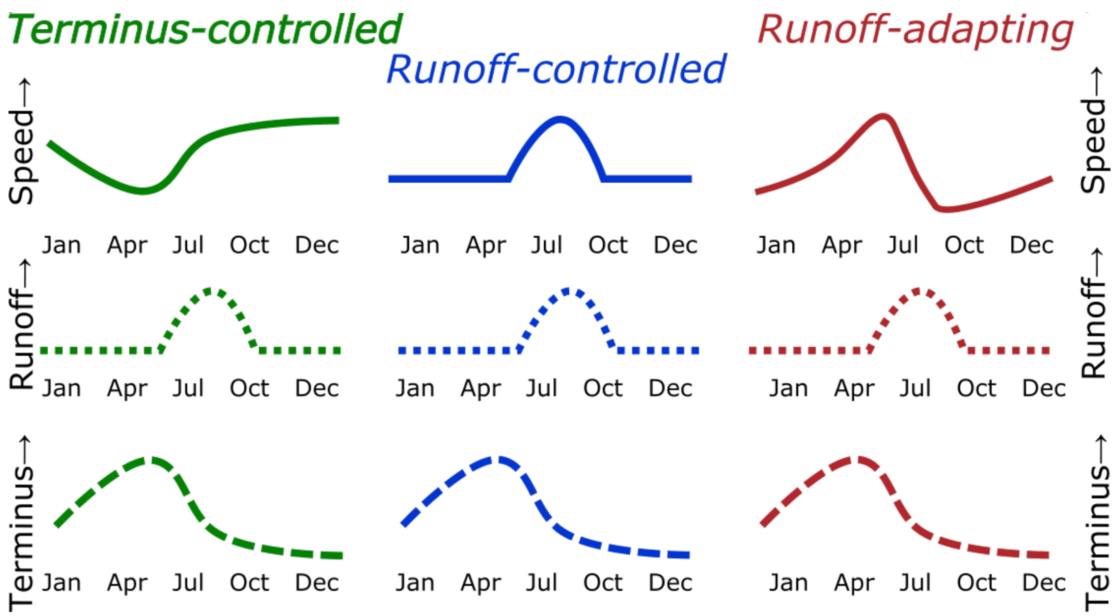
PRESENTED AT:

THE NEED FOR ORTHOGONAL DECOMPOSITION OF SPATIO-TEMPORAL ICE FLOW DATA

Previous work [1,2,3] identified three dominant patterns in seasonal ice flow variations on glaciers around Greenland:



Termins-controlled glaciers: Fluctuations in speed respond primarily to the position of the terminus. When the terminus position is extended, this provides additional sidewall friction that slows ice flow. Speeds generally decline steadily through the winter.

Runoff-controlled glaciers: Fluctuations in speed correlate to the volume of meltwater runoff in the glacier catchment. Annual maximum speeds thus occur near the peak of the melt season (roughly July). The simplest conceptual model, that basal water reduces friction and increases ice speed, applies.

Runoff-adapting glaciers: Fluctuations in speed relate to runoff volumes, but speeds reach their maxima in the early melt season (roughly May), decline by the peak of the melt season (roughly July), and rise again over the winter. The Iken [4] or Schoof [5] model, that the subglacial hydrologic system adapts to accommodate high runoff, is applicable.

Analysis across the entire glacier, not just at one point

Previous analyses classified glacier type by observing ice flow at a single point within a few kilometers of the terminus [1,2,3]. Our analysis allows that glacier flow may be more complex than what is observable at a single point, with the lower glacier and upper glacier potentially behaving differently and responding to distinct forcings. Our analysis thus analyzes coherent variability across the entire domain of the glacier.

Here, we explore the hypothesis that seasonal flow type inferred across an entire glacier trunk may differ from type inferred from a single point. We use principal component (PC) / empirical orthogonal function (EOF) analysis to extract temporal patterns that are coherent in space across the trunks of four glaciers that terminate in Sermilik Fjord, Southeast Greenland. We infer glacier type from these temporal patterns.

EOF/PC Analysis Methods

We analyze velocity data in overlapping 3-year chunks for four glaciers separately. We remove the trend at each pixel (the Helheim scene, for example, has p = 251 x 381 = 99,000 pixels) and then normalize each pixel by its mean speed over that time interval. We decompose the stack of velocity scenes using MATLAB's *pca* function with alternating least squares (ALS) to fill gaps. Finally, we add back in the mean velocity magnitudes to the EOFs (spatial patterns), and plot the time-varying EOFs along with their corresponding PCs (temporal patterns).

References

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2. Vijay, Khan, Kusk, Solgaard, Moon, & Bjørk (2019). **Resolving Seasonal Ice Velocity of 45 Greenlandic Glaciers With Very High Temporal Details**. *Geophysical Research Letters*, doi:10.1029/2018gl081503 (http://10.1029/2018gl081503).
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4. Iken & Bindschadler (1986). **Combined measurements of Subglacial Water Pressure and Surface Velocity of Findelengletscher, Switzerland: Conclusions about Drainage System and Sliding Mechanism**. *Journal of Glaciology*, doi:10.3189/s0022143000006936 (https://doi.org/10.3189/s0022143000006936).
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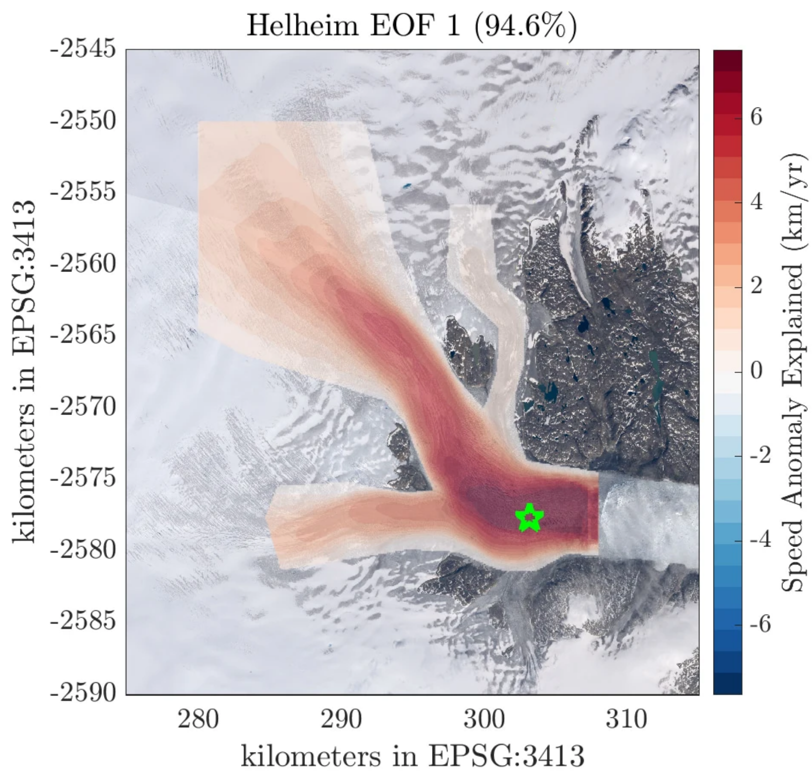
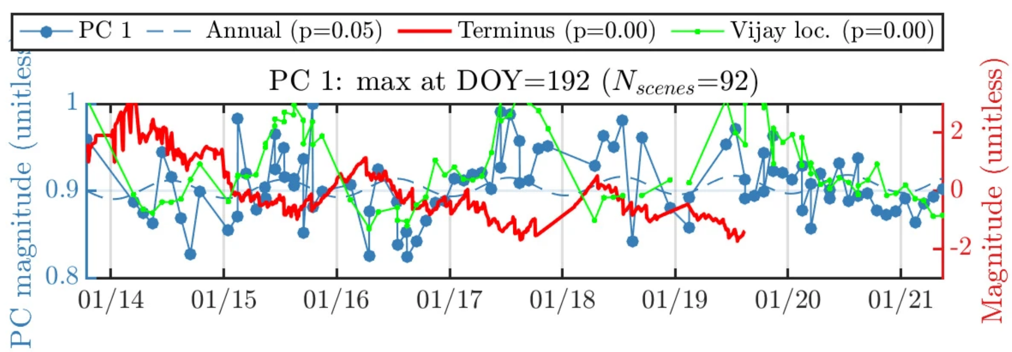
OVERALL RESULTS: 50% (2/4) AGREEMENT WITH PREVIOUS SINGLE-POINT CLASSIFICATIONS

	Helheim Glacier	**Fenris Glacier**	**Midgard Glacier**	**Pourquoi-Pas Glacier**
Previous work's classification *[1] Moon et al. (2014)* *[2] Vijay et al. (2019)* *[3] Vijay et al. (2021)*	▲ Terminus-controlled in 2009-2010 and 2015-2017 [1,2] ✚ Runoff-controlled in 2013 [1] and 2009-2017 [2]	▲ Terminus-controlled in 2015-2017 [2]	■ Runoff-adapting in 2011-2019 [1,2,3]	▲ Terminus-controlled in 2015-2017 [2,3]
This work's classification	▲ Primarily terminus-controlled 2014-2021 ($p=0.003$) ✚ Secondarily runoff-controlled in 2014-2021 ($p=0.05$)	■ Runoff-adapting in 2016-2021 ($p=0.004$)	■ Runoff-adapting in 2016-2021 ($p < 10^{-4}$)	✚ Runoff-controlled 2015-2021 ($p < 10^{-5}$)
Agreement?	✓	–	✓	–
Correlation between PC and single- point speed	$R^2 = 0.3$, $N = 68$, $p < 10^{-4}$ Significant ✓ ⇒ This glacier can be analyzed using speeds at one point.	$R^2 = 0.3$, $N = 56$, $p = 0.09$ Insignificant ✘ ⇒ This glacier's flow contains spatio- temporal patterns that one point alone cannot capture.	$R^2 = 0.5$, $N = 49$, $p < 10^{-5}$ Significant ✓ ⇒ This glacier can be analyzed using speeds at one point.	$R^2 = 0.5$, $N = 52$, $p < 10^{-5}$ Significant ✓ ⇒ This glacier can be analyzed using speeds at one point.

RESULTS: HELHEIM GLACIER IS TERMINUS-CONTROLLED

First Mode: Terminus-Controlled





↑ The leading PC correlates with both the terminus position (p=0.003) and a seasonal cycle with maximum in mid-July (p=0.05) consistent with runoff-control. The terminus position itself correlates to this annual cycle (R=-0.11, p=0.1). Examining p-values and considering some commonality of the forcings, we classify Helheim Glacier as terminus-controlled over 2014-2021.

This agrees with previous classifications of Helheim Glacier as usually terminus-controlled (2009, 2010, 2015, 2016, 2017) [1,2,3] and sometimes runoff-controlled (2013) [1]. It agrees less with a study that found Helheim was runoff-controlled over 2009-2017 [4].

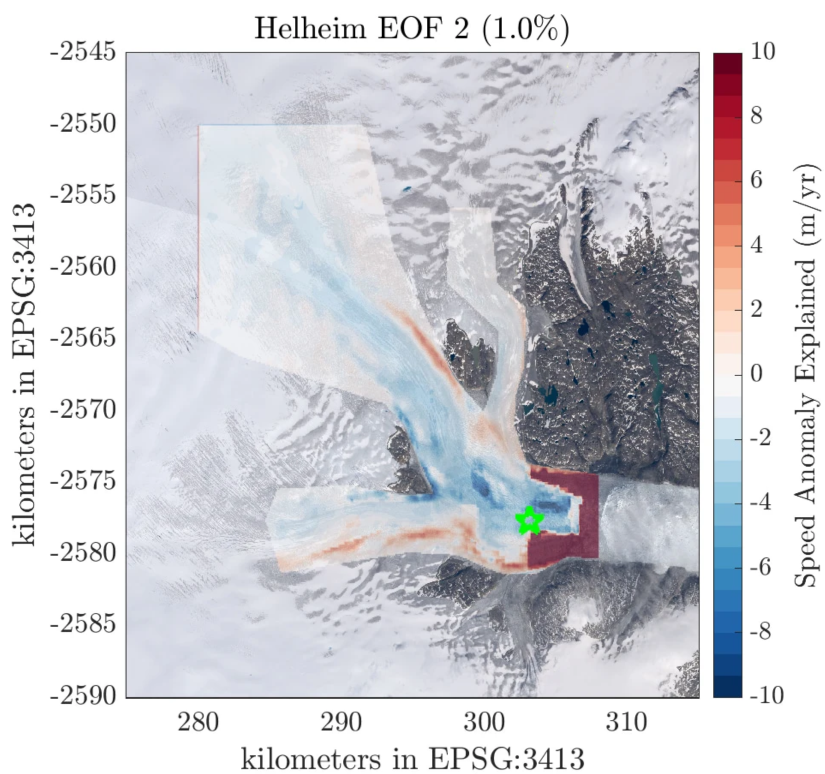
The top panel shows the spatial pattern. The effect of runoff on ice flow is strongest within ~10 km of the terminus (dark red), where it reaches ~7 km/yr. The effect decays upflow but is still important in all three tributaries (pink). Compare this to the mean annual flow speed at the green star, ~8 km/yr, and annual and interannual variability of ~3 km/yr there. Finally, the well-known basal ridge on the lower trunk of the glacier does not appear in the first EOF.

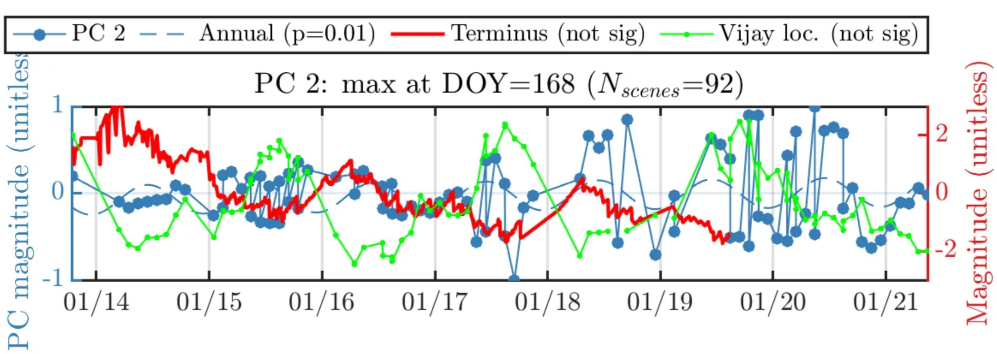
The time series (lower panel) visually supports our conclusion that the first PC (blue dots) is significantly correlated to the terminus position (red) (R=-0.30, R^2=0.09, p=0.003). Correlation between the first PC and a fitted annual cycle (blue dashed line) is less (R=0.18, R^2=0.03, p=0.05), and the amplitude of variations in the fitted cycle is much less than that of the first PC.

The first mode explains 95% of the variance in flow speed, which is substantially greater than for the other three glaciers we analyzed (66%, 79%, 75%). The very high score of the first mode suggests that Helheim is a "simple" glacier, which would sound extremely wrong to anyone who has previously studied Helheim.

The first PC correlates significantly with flow at the point studied by Vijay et al. (2019) [2], the green star (R^2 = 0.20, $p < 10^{-4}$). This indicates that EOF/PC analysis was not really needed for Helheim Glacier: single-point analysis would capture sufficient variability.

Second Mode: Runoff-Controlled

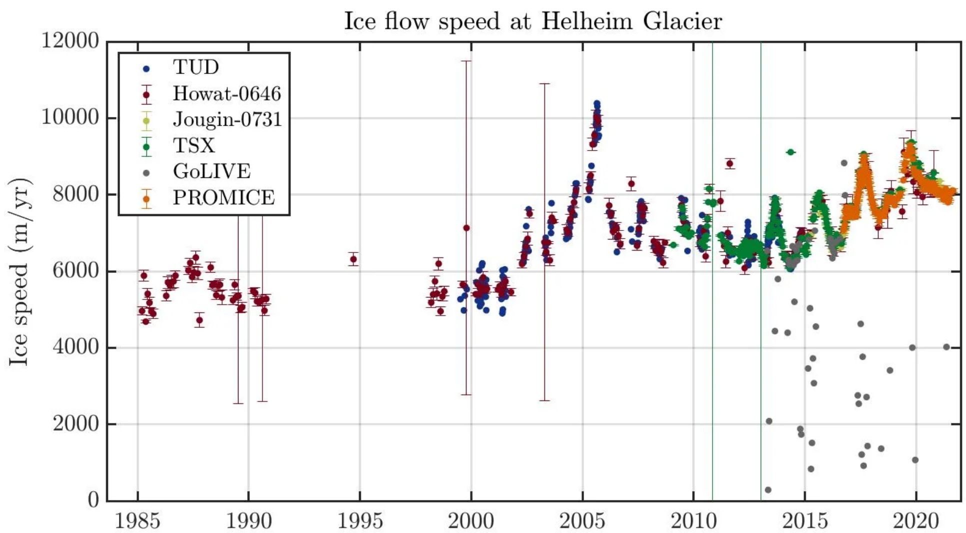




↑ The second mode (shown below) explains 1% of the variance. Its EOF is a dipole that separates the lowest 2 km of the glacier (dark red near the terminus) and the glacier margins (ligher red) from the rest of the domain (light blue). The last 2 km represent the range of terminus fluctuation over our period of study, 2014-2021 and explain ~100 m/yr of variability. The dark blue patches on the main trunk are roughly co-located with Helheim's well-known basal ridge. However, these patches explain only ~15 m/yr of variability.

The second PC (blue dots) peaks in mid-July and is consistent with a Type 2 (runoff-controlled) glacier (p=0.006). However, we believe that the first PC (95% of the overall variance) provides more evidence of runoff control than the second PC (1% of the overall variance).

Ice flow speed at a single point



↑ Ice flow speed at the point on Helheim Glacier studied by Vijay et al. (2019) [2], shown on other maps as a green star.

Terminus positions

We compared the PCs to three different terminus datasets. We found significant correlation between the first PC and two of the three datasets.

- Ultee et al. (2020) [7]: R = -0.30, p=0.003. The Ultee terminus position data are shown on all Helheim figures.
- TermPicks [8]: R = -0.27, p=0.006
- CALFIN [9]: R = 0.13, p=0.11 (not significant)

The CALFIN dataset is substantially coarser in time than the other two (TermPicks: 3.5 days; Ultee: 3.0 days; CALFIN: 25 days), which may cause its lack of significant correlation.

Velocity datasets used in the Helheim Glacier EOF/PC analysis

- MEaSUREs selected glacier site velocity maps from optical images (Howat, NSIDC-0646) [12]
- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]

No other datasets had adequate spatial coverage (obserations over >90% of the glacier) and/or produced coherent EOF/PC patterns.

Datasets available and tested on Helheim Glacier, and used in the raw ice flow speed figure above:

- Technical University of Dresden Landsat-based velocity maps [11]
- MEaSUREs selected glacier site velocity maps from optical images (Howat, NSIDC-0646) [12]
- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]
- MEaSUREs selected glacier site velocity maps from InSAR (Joughin, NSIDC-0481) [14]
- GoLIVE Global Land Ice Velocity Extraction from Landsat 8 (NSIDC-0710) [15]
- PROMICE Greenland Ice Velocity from Sentinel-1 [16]

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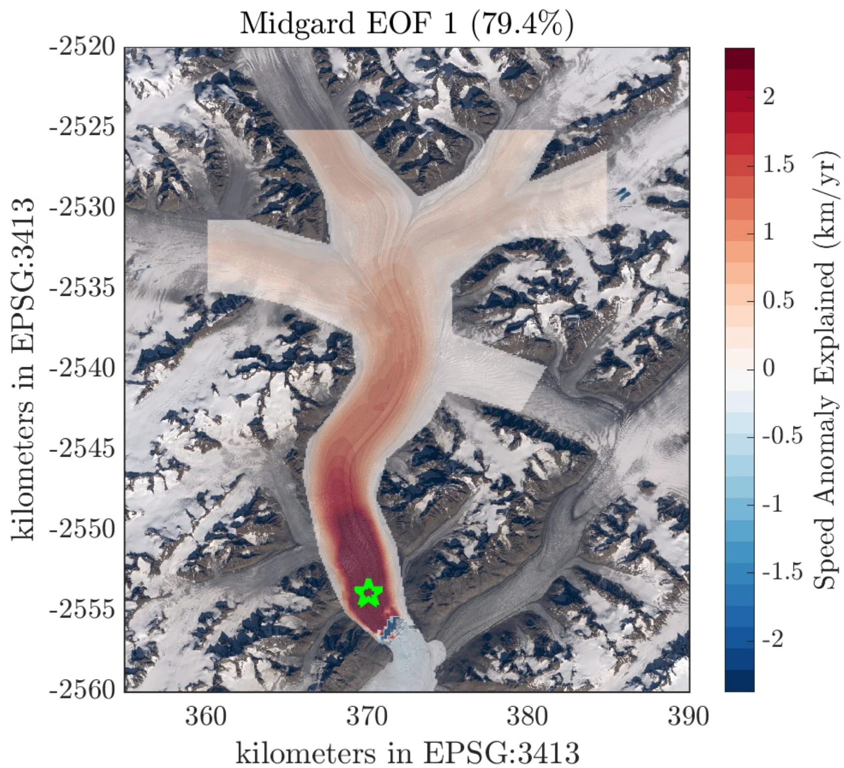
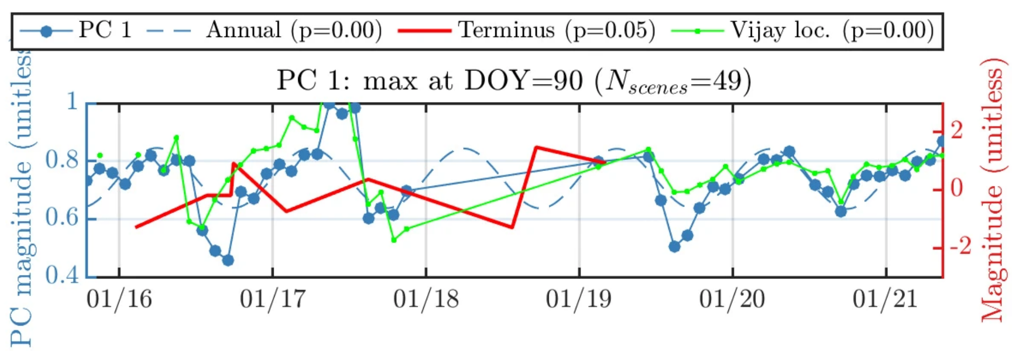
17. Korsgaard (2021). **Greenland Ice Sheet outlet glacier terminus positions 1978-1987 from aero-photogrammetric map data**, Version 1, GEUS Dataverse, doi:10.22008/FK2/B2JYVC (https://doi.org/10.22008/FK2/B2JYVC).

RESULTS: MIDGARD GLACIER IS RUNOFF-ADAPTING

First Mode: Runoff-Adapting





↑ The leading PC peaks in April and declines quickly, consistent with a runoff-adapting glacier, over 2016-2021. This agrees with previous classifications of Midgard Glacier as runoff-adapting over 2011-2019 [1,2,3].

The top panel shows the spatial pattern. The effect of runoff on ice flow is strongest within ~10 km of the terminus (dark red), where it reaches ~1.5 km/yr. The effect decays upflow but is still important in the upper tributaries (pink). Compare this to the mean annual flow speed at the green star, ~3.5 km/yr, and annual and interannual variability ~2 km/yr there.

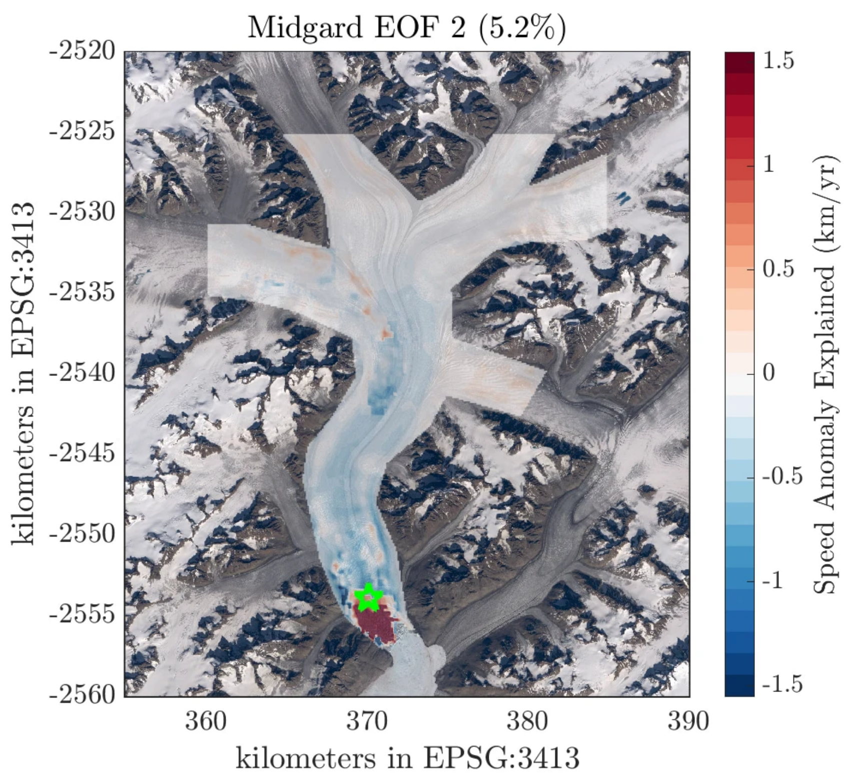
The bottom panel shows the temporal pattern. The first PC correlates significantly with an annual cycle (R^2 = 0.43, $p < 10^{-4}$). Its seasonal evolution has a steady rise in speed over autumn and winter, then a peak in April. This points to runoff-adapting behavior.

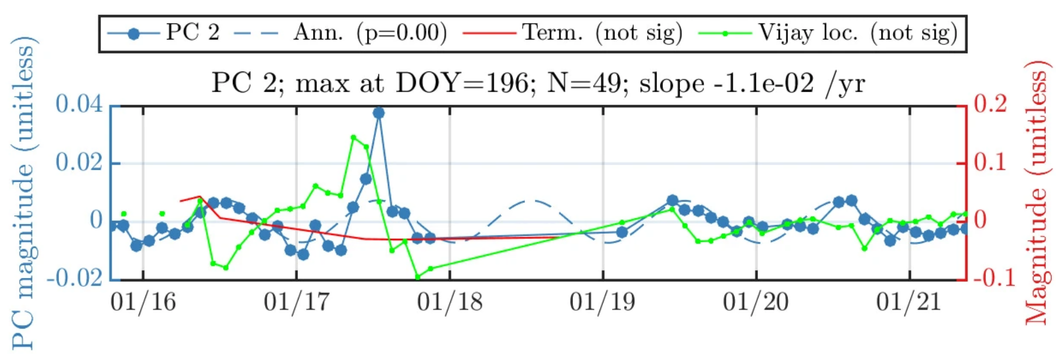
The first mode explains 79% of the variance in flow speed. The first PC correlates significantly with flow at the point studied by Vijay et al. (2019) [2], the green star (R^2 = 0.51, $p < 10^{-5}$). This indicates that EOF/PC analysis was not really needed for Midgard Glacier: single-point analysis would capture sufficient variability.

Second Mode: Runoff-Controlled

The second mode (shown below) explains 5% of the variance. Its EOF is a dipole that separates the lowest 4 km of the glacier (dark red near the terminus) from the rest of the domain. The terminus location was steady and always extended beyond this area over the entire analysis period.

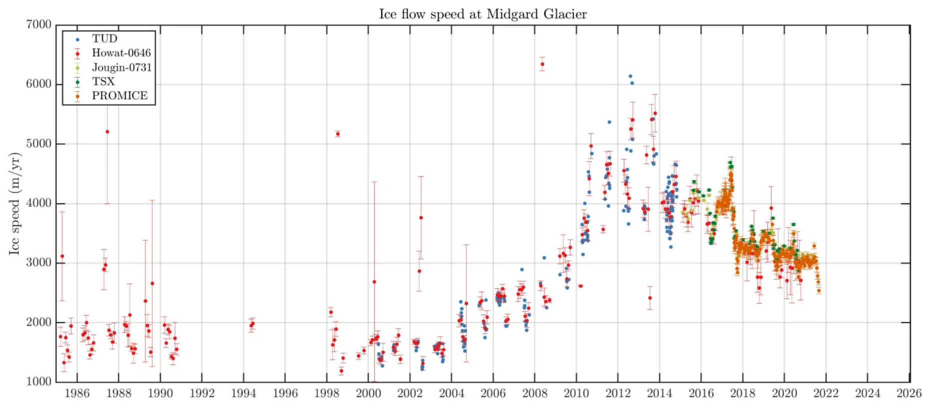
The near-terminus area contains the majority of the variance of Mode 2; its speed magnitude reaches 1.2 km/yr there. Elsewhere on the glacier, Mode 2 explains only order ~100 m/yr variability (light blue and pink). Its PC (blue dots) peaks in mid-July and is consistent with a Type 2 (runoff-controlled) glacier.





↑ The second-order mode suggests that the 4 km closest to the terminus is more runoff-controlled (p< 10-4) than the rest of the glacier, which is runoff-adapting (leading-order mode, also p< 10-4). This is unexpected and counterintuitive, as the glacier drainage system should be most well developed in the lower glacier. One possibility is that the second-order mode is in fact terminus control (p=0.04), which is also significantly correlated to the second PC.

Ice flow speed at a single point



↑ Ice flow speed at the point on Midgard Glacier studied by Vijay et al. (2019) [2], shown on other maps as a green star.

Terminus positions

We compared the PCs to two different terminus datasets.

- TermPicks [8]: First mode R = 0.26, p=0.047 (significant). Second mode R = 0.25, p=0.04 (significant). Average spacing 140 days. The TermPicks data are shown on all Midgard figures.
- CALFIN [9]: First mode R = 0.006, p=0.5 (not significant). Second mode R = -0.17, p = 0.1 (not significant). Average spacing 180 days.

Velocity datasets used in the Midgard Glacier EOF/PC analysis

- Technical University of Dresden Landsat-based velocity maps [11]
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Note on nomenclature

Vijay et al. (2019, 2021) [2,3] refer to this glacier as Franche Comté Glacier.

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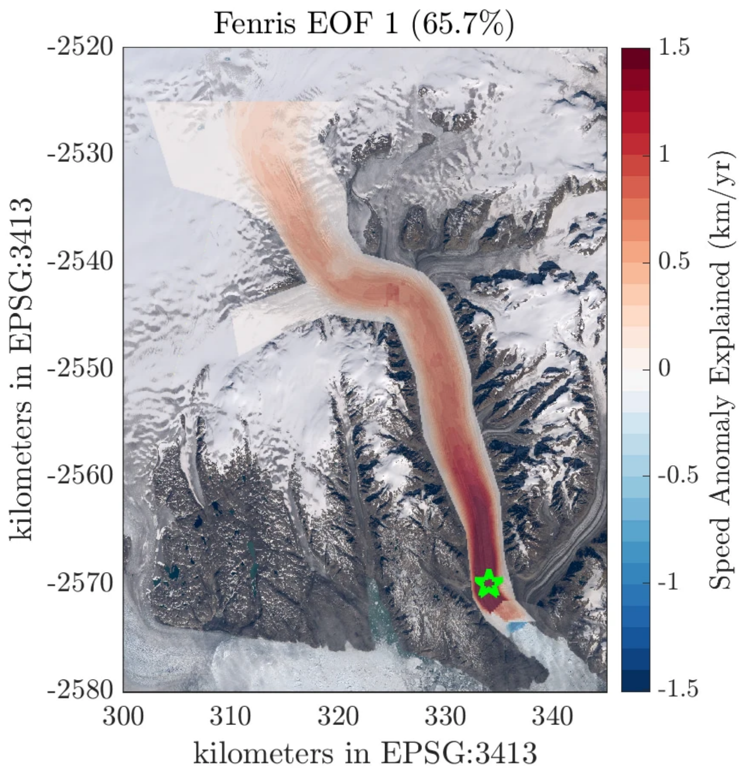
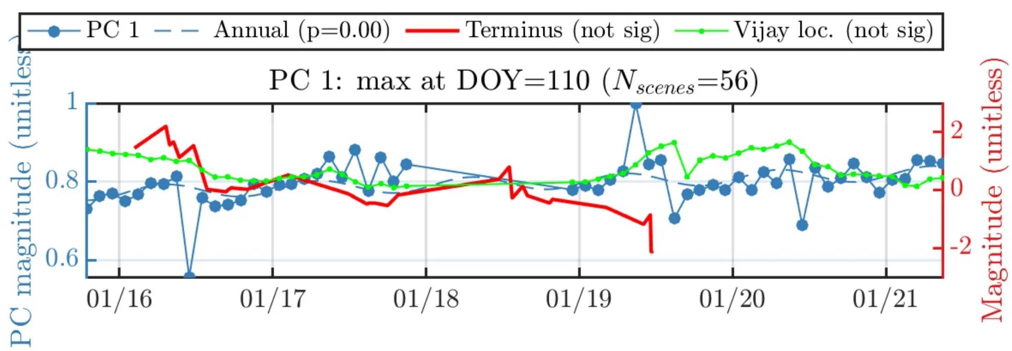
RESULTS: FENRIS GLACIER IS RUNOFF-ADAPTING

First Mode: Runoff-Adapting





↑ The first PC peaks in March and declines quickly, consistent with a runoff-adapting glacier over 2016-2021.

This is at odds with a previous classification of Fenris Glacier as terminus-controlled over 2015-2017 [2].

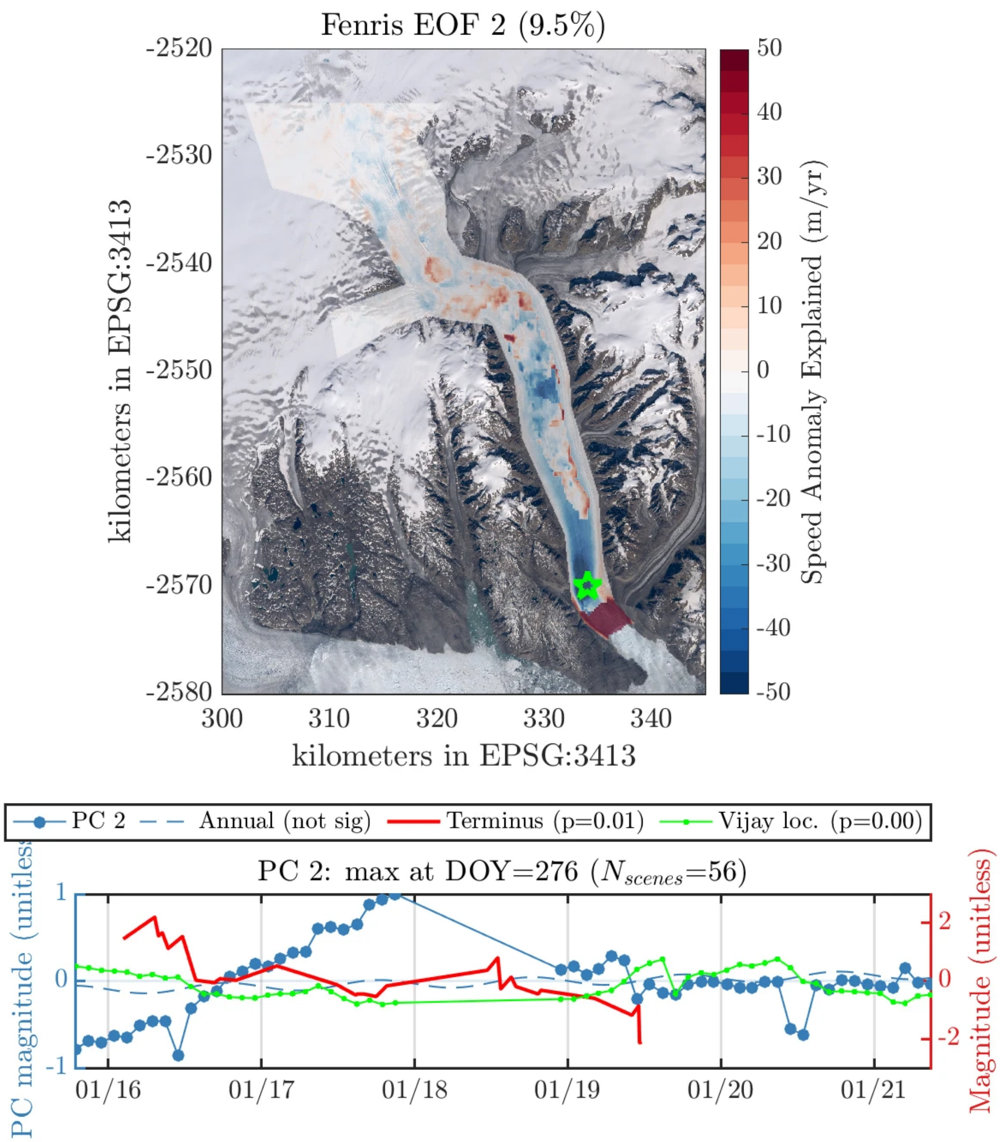
The top panel shows the spatial patterns. Near the green star 5 kilometers inland from the terminus, the magnitude of the first EOF reaches 2.5 km/yr. Compare this to the mean annual flow speed there, ~5 km/year, and annual and interannual variability ~3 km/year.

The bottom panel shows the temporal patterns. The first PC correlates significantly with an annual cycle that peaks in March (R^2=0.15, p=0.004) and declines quickly. This is consistent with a runoff-adapting glacier. We find no significant correlation between the first PC and terminus position

(R^2=0.03, p=0.096), although three previous studies classified Fenris as terminus-controlled.

The first mode explains 66% of the variance in flow speed. This is substantially less than for two of the other glaciers we analyzed (95%, 79%), but similar to Pourquoi Pas (67%). The first PC also does not significantly correlate with the time series at the point studied by Vijay et al. (2019) [2], shown in green above (R^2=0.03, p=0.093). This indicates that the first mode includes significant variability at places unrelated to the green star.

Second Mode: Interannual change

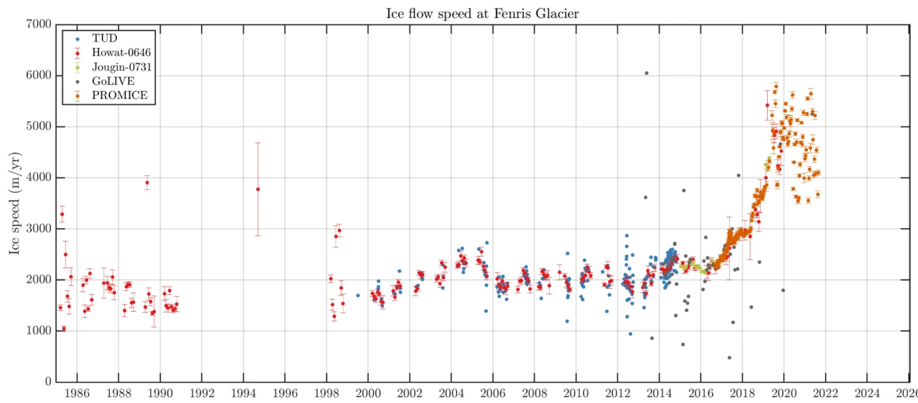


↑ The second EOF (red/blue map) contains a near-terminus dipole (the dark red southernmost 2 km of the glacier) and noise (splotches in the upper glacier). The dipole coincides with the retreat of the terminus (red line) in 2018. The PC shows no significant annual patterns (p=0.13) or correlation with terminus position (p=0.26). Intead, it shows a steady change over 2016-2017, then no change over 2019-2021.

At the terminus, the magnitude of the second EOF reaches 140 m/yr; near the green star 5 kilometers inland from the terminus, the magnitude is 40 m/yr. This is a small fraction of the mean annual flow speed (~5 km/year) and its annual and interannual variability (~3 km/year).

The second mode explains 10% of the variance in flow speed. The second mode appears to capture the acceleration of Fenris Glacier that occurred over 2016-2020 (see figure below).

Ice flow speed at a single point



↑ Ice flow speed at the point on Fenris Glacier studied by Vijay et al. (2019) [2], shown on other maps as a green star.

Terminus positions

We compared the PCs to two different terminus datasets. We found no significant correlation between the first PC and either dataset. We found significant correlation between the second PC and one of the terminus datasets.

- TermPicks [8]: First mode R = -0.20, p=0.08 (not significant). Second mode R = +0.35, p=0.007 (significant). The TermPicks data are shown on all Fenris figures.
- CALFIN [9]: First mode R = -0.18, p=0.1 (not significant). Second mode R = -0.09, p = 0.3 (not significant).

Velocity datasets used in the Fenris Glacier EOF/PC analysis

- Technical University of Dresden Landsat-based velocity maps [11]
- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]
- GoLIVE Global Land Ice Velocity Extraction from Landsat 8 [15]

No other datasets had adequate spatial coverage (observations over >50% of the glacier) and/or produced coherent EOF/PC patterns.

Datasets available and tested on Fenris Glacier, and used in the raw ice flow speed figure above:

- Technical University of Dresden Landsat-based velocity maps [11]
- MEaSUREs selected glacier site velocity maps from optical images (Howat, NSIDC-0646) [12]
- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]
- MEaSUREs selected glacier site velocity maps from InSAR (Joughin, NSIDC-0481) [14]
- GoLIVE Global Land Ice Velocity Extraction from Landsat 8 (NSIDC-0710) [15]
- PROMICE Greenland Ice Velocity from Sentinel-1 [16]

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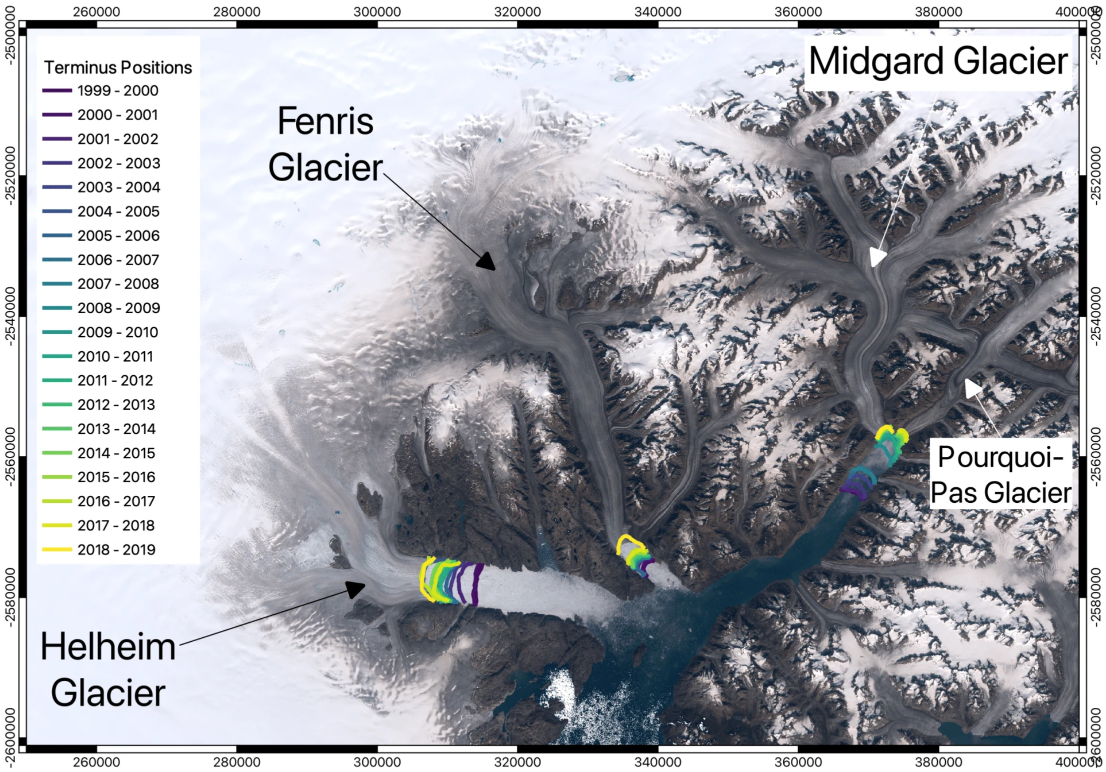
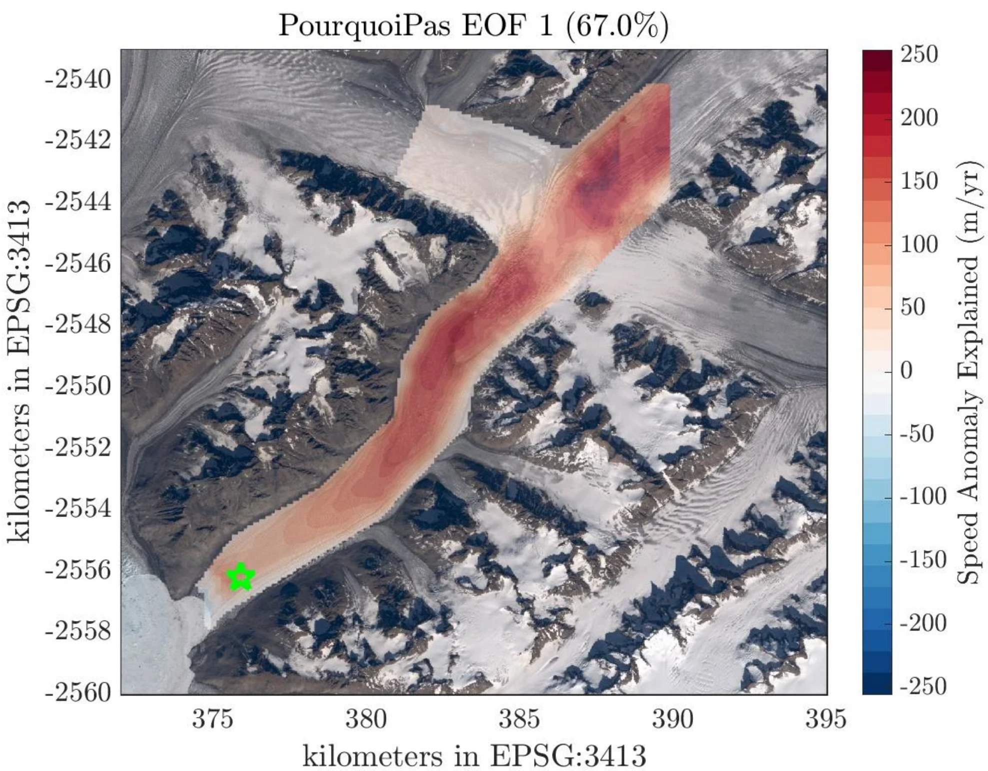
SERMILIK FJORD'S FOUR MAJOR GLACIERS: HELHEIM, FENRIS, MIDGARD, & POURQUOI-PAS

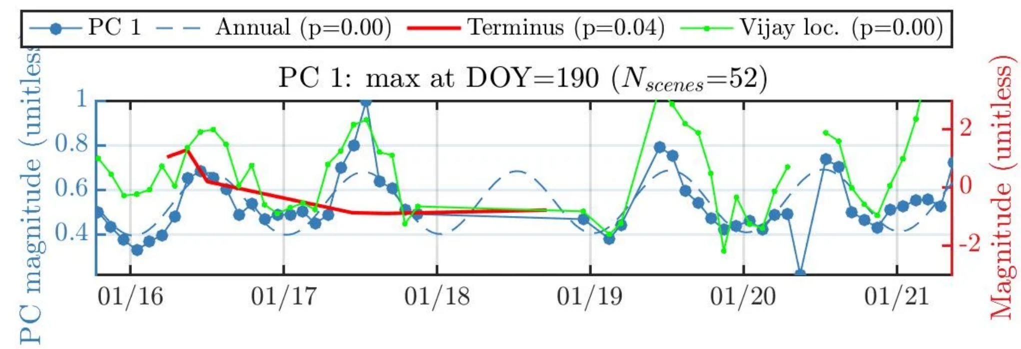


↑ Sermilik Fjord, eastern Greenland, contains four major outlet glaciers. Helheim Glacier (westernmost) is the largest. The base map is a mosaic of Sentinel-2 images from summer 2019, by MacGregor et al. (2020) [10]. The wintertime terminus positions are from PROMICE [17].

RESULTS: POURQUOI-PAS GLAC. IS RUNOFF-CONTROLLED

First Mode: Runoff-Controlled



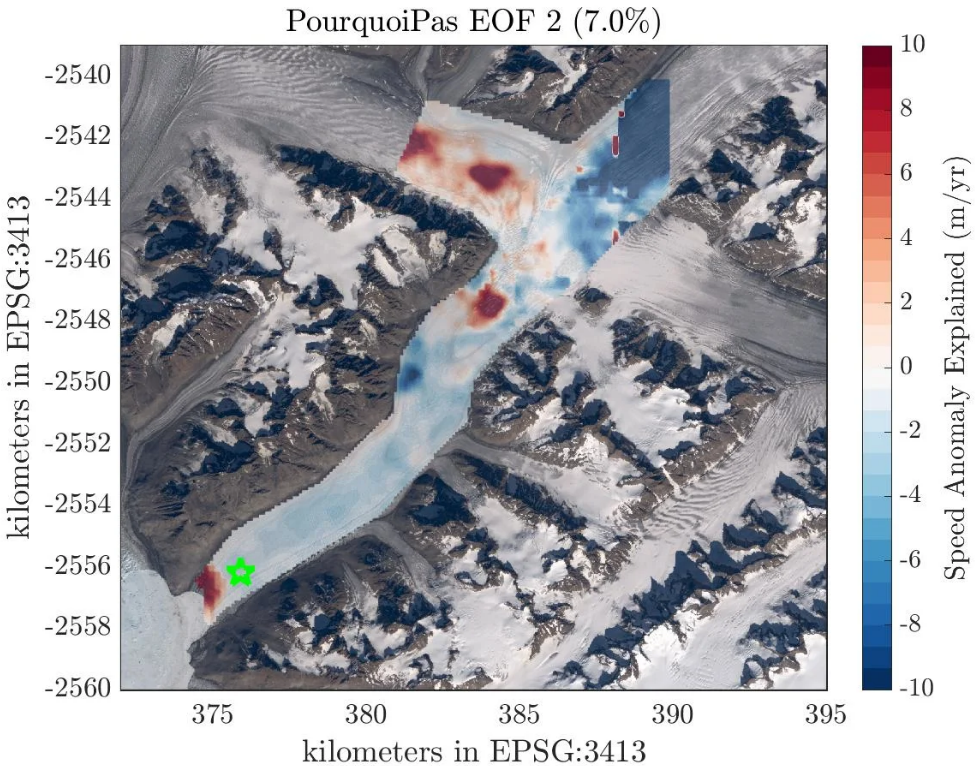


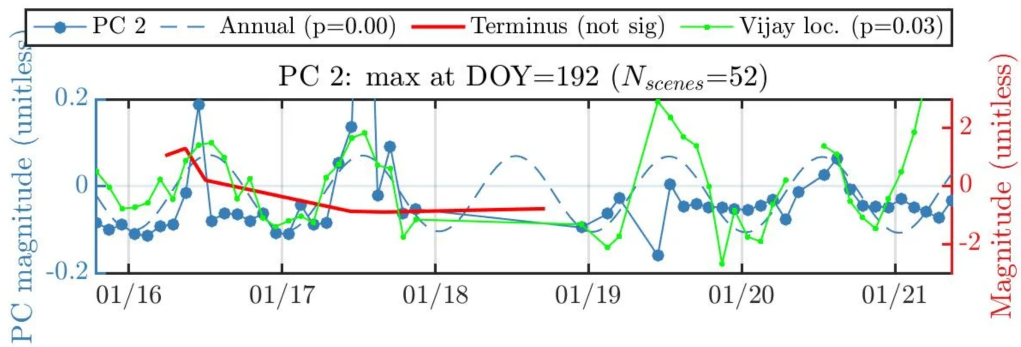
↑ The leading PC has symmetric seasonal variability and a peak in July, consistent with a runoff-controlled glacier, over 2016-2021. It also correlates significantly with terminus position, but the correlation is not as strong.

Our classification as runoff-controlled is at odds with a previous classification as terminus-controlled over 2015-2017 [2,3].

The first mode explains 67% of the variance in flow speed. This is substantially less than for two of the other glaciers we analyzed (95%, 79%), but similar to Fenris Glacier (66%).

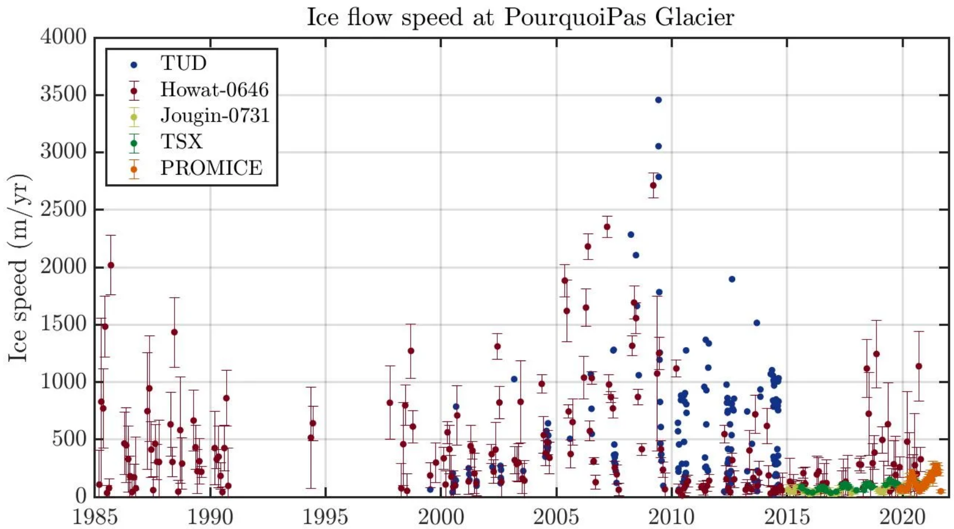
Second Mode: Spatial heterogeneity **and noise**





↑ The second mode explains 7% of the variance. Its PC peaks in early July and is also consistent with a runoff-controlled glacier. The pattern is a dipole, with the closest 1 km to the terminus showing runoff-controlled behavior that only explains ~10 m/yr of ice flow. The rest of the second EOF captures velocity artifacts in the upper glacier.

Ice flow speed at a single point



↑ Ice flow speed at the point on Pourquoi-Pas Glacier studied by Vijay et al. (2019) [2], shown on other maps as a green star.

Velocity datasets used in the Pourquoi-Pas Glacier EOF/PC analysis

- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]

No other datasets had adequate spatial coverage (observations over >50% of the glacier) and/or produced coherent EOF/PC patterns.

Datasets available and tested on Fenris Glacier, and used in the raw ice flow speed figure above:

- Technical University of Dresden Landsat-based velocity maps [11]
- MEaSUREs selected glacier site velocity maps from optical images (Howat, NSIDC-0646) [12]
- MEaSUREs monthly Greenland Ice Sheet velocity mosaic (Joughin, NSIDC-0731) [13]
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- PROMICE Greenland Ice Velocity from Sentinel-1 [16]

Note on nomenclature

Vijay et al. (2019, 2021) [2,3] refer to this glacier as Midgard Glacier. This glacier and the larger one to the west (which is called Midgard Glacier on this poster) have been in retreat since the early 2000s and separated in 2011-2012. I refer to this smaller, eastern glacier as Pourquoi Pas Glacier, following a UK Alpine Club expedition to peaks bordering its upper reaches in 1994 [6].

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ABSTRACT

Are the Sermilik Fjord glaciers terminus-controlled, runoff-controlled, or runoff-adapting? Decomposition of glacier speed maps at Helheim, Fenris, Midgard, and Pourquoi-Pas Glaciers

Previous research has identified three common seasonal patterns ("types") of ice flow at Greenland glaciers (Moon et al., 2014; Vijay et al., 2019). Some glaciers have a consistent type, while others change from year to year. Neighboring glaciers may have the same or different type. Previously, types were identified by examining flow at a single point. This limitation may affect the inferred variability. We use principal component (PC) / empirical orthogonal function (EOF) analysis to decompose maps of ice speed (Joughin et al., 2018; Joughin, 2021; Howat, 2020; Scambos et al., 206; Rosenau et al., 2015; Solgaard & Kusk, 2021) at four glaciers feeding Sermilik Fjord over 2014-2021. This improves on the previous single-point method by yielding temporal patterns (PCs), which allow types to be identified, plus their associated spatial patterns (EOFs).

Helheim Glacier shows the most spatial and temporal heterogeneity of the four glaciers. PC #1 (95% of the variance in 2014-2021 speed) suggests primarily terminus control ($p=0.003$) but also some runoff control ($p=0.05$). PC #2 (1% of the variance in 2014-2021 speed) shows only runoff control ($p=0.006$). Previous work found that Helheim can be either terminus- or runoff-controlled.

Fenris Glacier is runoff-adapting (PC #1, 66% of the variance in 2014-2021 speed). This disagrees with previous work that classified it as terminus-controlled.

On Midgard Glacier, PC #1 (79% of the variance in 2014-2021 speed) is consistent with runoff-adapting behavior ($p<0.0001$). EOF #2 shows that the lowest 4 km is more runoff-controlled ($p<0.00001$) or terminus-controlled ($p=0.04$) than the upstream area. Our conclusion agrees with previous work that classified Midgard as runoff-adapting.

Since separating from Midgard in 2009, Pourquoi Pas Glacier has slowed near the terminus while accelerating upstream. EOF #1 shows this pattern (67% of the variance in 2014-2021 speed); its PC shows runoff control. Previous work classified Pourquoi Pas as terminus-controlled.

Overall, these results agree moderately with previous, simpler analyses. Thus, application of EOF/PC analysis to the popular "glacier type" problem holds some promise in the quest to discover what controls the seasonal flow patterns of Greenland glaciers.

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