Episodic Subglacial Drainage Cascades Below the Northeast Greenland Ice Stream

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Published in:
Geophysical Research Letters

DOI:
10.1029/2023GL103240

Publication date:
2023

Document version
Publisher's PDF, also known as Version of record

Document license:
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Citation for published version (APA):
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Abstract Subglacial hydrology can exert an important control on ice flow by affecting friction at the ice-bedrock interface. Here, we report on a series of subglacial drainage events along the Northeast Greenland Ice Stream (NEGIS), initiating as far inland as 500 km from the margin of Zachariae Isstrøm. The drainage events exhibit local transient uplift, followed by prolonged subsidence, measured by differential satellite synthetic aperture radar interferometry (DInSAR). In downstream regions, drainage events are associated with temporary acceleration in ice flow. The high spatiotemporal resolution of the DInSAR measurements allows for a detailed mapping of the drainage propagation pathway. We show that multiple drainage cascades have occurred along the same pathway over the years 2020–2022. Finally, the propagation speed of subglacial water flow is found to vary greatly along NEGIS, suggesting that fundamental differences could exist in the subglacial environment.

Key Points:
- Episodic subglacial drainage of water over a ~500 km extent along the Northeast Greenland Ice Stream is revealed by radar interferometry
- The drainage events cause transient uplift and ice flow speed-up in downstream regions, and multiple drainage cascades are observed
- Propagation speed of the drainage cascade varies widely along the ice stream

Supporting Information: Supporting Information may be found in the online version of this article.

1. Introduction

The presence of water flowing beneath the Greenland Ice Sheet impacts the friction exerted on ice flowing from inland to marginal regions, potentially affecting the rate of sea level rise by increasing ice discharge. Direct observations of the hydrological system beneath glaciers are, however, limited due to inaccessibility. Here, we present satellite observations of localized ice uplift and subsidence, which indicate water propagating below the Northeast Greenland Ice Stream, from far inland to a major marine-terminating glacier, Zachariae Isstrøm. In downstream regions, ice flow speeds up as the subglacial water passes. The measurements could suggest variations in the local subglacial environment, which provide important constraints for understanding the flow and stability of the ice stream.
separating subglacial water bodies from saturated sediments at the uniformly thawed bed under NEGIS (Bowling et al., 2019; MacGregor et al., 2022).

In this study, we document a series of episodic local subglacial drainage events occurring in a cascading manner ~500 km along the NEGIS. Using interferometric Synthetic Aperture Radar (SAR) measurements of high spatio-temporal resolution, we observe centimetric, transient vertical displacements caused by each drainage event, in the form of uplift followed by subsidence, as water propagates through the upstream parts of the ice stream (>200 km from the margin). Furthermore, we show that passing of the drainage cascade in downstream regions (<200 km from the margin) is associated with increasing ice flow speed. Finally, we demonstrate that similar drainage cascades have occurred multiple times over the past few years and argue that interferometric SAR measurements provide a valuable tool for monitoring the dynamic ice response to transient subglacial hydrological activity, which, in combination with other observations, may ultimately provide constraints on basal properties and the subglacial drainage system.

2. Data and Methods

2.1. Sentinel-1 DInSAR Motion Measurements

The EU Copernicus Sentinel-1 satellites have recorded an extensive archive of SAR images over most of Greenland, including NEGIS, since the launch of the two satellites, Sentinel-1A and Sentinel-1B, in 2014 and 2016, respectively. Most outlet glaciers have been consistently imaged with the lowest possible repeat-pass period (6-days with both satellites operational), allowing for frequent acquisitions of ice motion. Here, we use Differential SAR Interferometry (DInSAR) to retrieve ice motion measurements of high accuracy. DInSAR measures motion in the radar line-of-sight (LoS) direction between two acquisitions. As the LoS is slanted toward ground, DInSAR retrievals are sensitive to vertical as well as horizontal motion. We produced two Sentinel-1D InSAR velocity time series consisting of all available image pairs with a 6-day temporal baseline during 2016–2021 for ascending track 74 and descending track 112. Interferometric processing is carried out as described in Andersen et al. (2020) and Kusk et al. (2022) (see also Text S1 in Supporting Information S1). In order to reveal transient changes, we subtract a reference LoS velocity field, taken as the pixel-wise median of the full time series, from the velocity retrievals of each track. Assuming a constant ice flow direction, the resulting velocity anomaly maps contain, in general, both horizontal flow speed change and vertical motion components (projected onto the radar LoS).

To investigate ice flow in fast-flowing downstream regions (where DInSAR is not applicable) we use Sentinel-1 amplitude-based velocity mosaics from NASA MEaSUREs (Joughin, 2021). These mosaics are generated through range and azimuth offset tracking of 6- and 12-day image pairs and are scaled to provide 6-day horizontal velocity estimates. The estimated standard error of the velocity magnitude is 10 m/y (Joughin, 2021), substantially higher than that expected of DInSAR measurements (~0.5 m/y in radar LoS, see Figure S1 in Supporting Information S1), but low enough to detect flow speed changes of 2%–3% in downstream NEGIS where flow speeds exceed 400 m/y.

2.2. Identifying Dynamic Response of Individual Drainage Events

For a given point on the ice surface, fully decomposing the 3D displacement field requires three temporally coincident DInSAR acquisitions with linearly independent LoS directions. In the present case, only two different LoS directions are available with a temporal overlap of 3.5 days between 6-day pairs from each acquisition geometry. This makes an exact quantitative decomposition impractical. However, since the ground-projections of the ascending and descending LoS vectors differ by ~140°, sensitivity to horizontal motion varies widely between the two tracks, whereas the similar vertical incidence angles (varying between 30° and 45° for both tracks) lead to similar sensitivities to vertical motion (Figure S2 in Supporting Information S1). Assuming a constant ice flow direction, the exact sensitivity to a change in horizontal flow speed and vertical displacement can be computed, respectively, for each satellite track (Figure S3 in Supporting Information S1). In some cases, this allows us to qualitatively distinguish between these two signals (Section 3.2). In other cases, the horizontal component may be assumed negligible (Section 3.1).

If a measured LoS velocity anomaly, $v_{\text{LoS}}$, is assumed to arise purely from vertical displacement (over the 6-day temporal baseline, $T$), the vertical displacement is computed as:

$$d_{\text{vert}} = \frac{v_{\text{LoS}}}{\cos \theta_i} \cdot T$$

where $\theta_i$ is the local incidence angle.
In most of the upstream NEGIS region where subglacial drainage events are observed, we interpret all LoS motion anomalies as vertical displacements (see Section 3.1). For each of the local uplift events observed in this region, we estimate the subglacial water volume, \( V_{sub} \), consistent with such uplift, simply as:

\[
V_{sub} = \sum_{n=1}^{N} d_{vert,n} \cdot dx \cdot dy
\]

where \( dx = dy = 50 \) m is the pixel spacing of the DInSAR measurements. The sum is over all pixels affected by uplift, which are defined as pixels with \( d_{vert} > 2.5 \) cm (well above the estimated noise floor of 1 cm, see Figure S1 in Supporting Information S1). Although calibration errors and other noise sources may bias individual volume estimates, the subglacial water volume time series provides a first order magnitude estimate of the amount of water transported by the drainage cascade. We explored how imposed elastic displacements of the subglacial interface transfer to the surface in an idealized finite-element model, finding that although the displaced surface volume does not perfectly equal the subglacial water volume, the effect of changing ice thickness and basal roughness scale on inferred water volumes is small (<10%) in comparison to inferred volume differences (Text S2 in Supporting Information S1).

3. Results

3.1. Tracking Subglacial Water Propagation

Figure 1 shows an overview of the study region and observations. Figure 2a shows uplift/subsidence measurements inferred from DInSAR in the upstream parts of the study site (blue rectangle in Figure 1). In these upstream regions, observed DInSAR LoS velocity anomalies generally consist of small-scale, contiguous regions, which are not consistent with a change in horizontal flow speed. This is supported by comparing measurements from the descending track (112) to measurements from an additional ascending track (89), suggesting that the observed anomalies are indeed consistent with vertical displacements (see Figure S4 in Supporting Information S1). For individual events in upstream NEGIS, uplift magnitudes are generally about 5–15 cm (over the 6-day temporal baseline), but for events during 25th July through 12th August, uplift magnitudes exceeding 30 cm (per 6 days) are measured. Note that some areas exhibit uplift through multiple 6-day acquisition cycles. Subsequent uplift events are observed to form a bead-and-thread structure, with uplift concentrated in contiguous regions with lengths on the order of 5–25 km, suggesting a cascading downstream transport of subglacial water similar to observations from recent studies (Maier et al., 2023; Neckel et al., 2021). Within most of the identified regions of uplift, subsidence of a relatively low magnitude is observed during weeks or months following the original uplift signal, with cumulated subsidence generally equal to cumulated uplift (Figure S5 in Supporting Information S1). From July 25th, the drainage cascade (indicated by the wave of uplift signals) branches out in two components: one propagating further downstream toward the ZI margin, and one propagating eastward, ultimately ending up in the eastern-most section of ZI. Polygons in Figure 1a indicate the extent and timing of uplift events occurring in part of the upstream regions.

Figure 3 shows an overview of location, timing, and estimated water volume for uplift events observed along 220 km of the upstream study site. For events further downstream, vertical displacement cannot be quantitatively separated from horizontal flow acceleration (Section 3.2), and for events further upstream, the uplift signals tend to fall below the selected signal threshold (Figure S6 in Supporting Information S1). For the first ~150 km, individual events generally show water volumes of a few million m\(^3\), whereas events in the last 50 km of the transect, occurring during summertime, show substantially higher volumes >15 million m\(^3\). Figure 3 also shows estimates of the propagation speed of uplift events (with uncertainties, see Text S3 in Supporting Information S1), taken as a proxy for the speed at which subglacial water is transported downstream, for three arbitrarily selected sectors. We observe that the propagation speed is highly variable. In the first sector of the transect (0–50 km), the speed is 0.009 ± 0.004 m/s (23.3 km/month), twice as high as in the second sector (~50–80 km), where uplift is continuously observed in the same area for 2 months. From ~80 km onwards, the estimated propagation speed is nearly four times higher than in the second sector.

3.2. Downstream Dynamic Response

Figure 2b shows ascending and descending DInSAR LoS velocity anomaly measurements in downstream NEGIS (within ~200 km of the ZI front, see red rectangle in Figure 1). The measurements suggest that together with the wave of vertical displacements, concentrated in a localized bead-and-thread pattern (indicated by positive
anomalies in the LoS velocity for both tracks), a spatially smooth, large-scale wave of LoS velocity anomalies also propagates downstream during early September to early October. The signal is most clear for the ascending track, which has a higher sensitivity to flow-directed motion. Considering the LoS vectors, this smooth anomaly field is consistent with a speed-up in horizontal ice flow within this part of the ice stream (and the signal magnitude, ∼10 m/y, is far above the estimated noise floor). Indeed, an increase in flow speed is also observed with Sentinel-1 offset tracking measurements. We assembled a time series of MEaSUREs Sentinel-1 6-day horizontal velocity mosaics from July–November for the years 2018–2021. Interpolating the measurements to a transect along the downstream region reveals that flow speed during 1st–24th September 2020 is ∼5% higher than the average speed during October–November; this is not the case in 2018 or 2019, where September flow speed is lower than, or comparable to, October–November values (Figure 4, Figure S8 in Supporting Information S1). Figure S9 in Supporting Information S1 illustrates that, in 2020, the time of maximum velocity (during July–August) coincides with the September drainage cascade for the final ∼200 km of ZI (excluding the ∼20 km before the margin, where peak velocity consistently occurs during July–August). The same region does not show a clear peak velocity time in 2018 or 2019.

As DInSAR coverage is lost about 50 km before the ZI margin, uplift events could not be traced in this final stretch. Although range offset tracking measurements are also sensitive to vertical motion, we found that individual 6-day retrievals did not allow the propagating drainage cascade to be tracked in this region (assuming it...
Figure 2.
exists). However, the MEaSUREs mosaics do indicate an increase in flow speed beyond the DInSAR coverage, suggesting that the drainage cascade impacted ice dynamics far downstream.

### 3.3. Derived Drainage Propagation Pathways

By manually delineating a path intersecting identified uplift events, a subglacial drainage pathway is inferred. We delineate the pathway such that it intersects the central parts of the observed uplift events. In many cases, the spatial extent of subsequent uplift events overlap. When this is not the case, subsequent events are connected by the shortest possible straight path. In Figure 1b, the inferred drainage path (white/purple lines) is compared to paths expected from following the negative hydro-potential gradient (black lines; estimated using surface and bed topography from BedMachine v4 (Morlighem, 2021)). Specifically, hydro-potential-derived paths are plotted by calculating, and subsequently thresholding, the flow accumulation map (Text S4 in Supporting Information S1). The DInSAR and hydro-potential-derived pathways closely align in most areas, except for the downstream basal trough, where the paths diverge.

### 3.4. Recurrence of Drainage Cascades

Investigating the full DInSAR time series revealed that the 2020 drainage cascade described above is not unique. Throughout the time series, other localized incidents of transient uplift and subsidence are observed, both inside and outside of NEGIS, but do not appear to be associated with changes in ice flow, nor do they propagate hundreds of kilometers. However, two additional instances of a propagating uplift wave (interpreted as a drainage path) are observed.
cascade) within NEGIS are observed during 2021 and 2022. Figure S10 in Supporting Information S1 shows derived uplift/subsidence maps covering these events, plotted alongside the propagation pathway observed for the 2020 drainage cascade. Both the 2021 and 2022 drainage cascades appear to closely follow the 2020 pathway. Note, however, that the earliest uplift events in 2021 occur outside of this pathway, before subsequent events coalesce into the previous year's propagation path downstream. The 2021 cascade even repeats the split into two branches at exactly the same location as in 2020 (Figure S10 in Supporting Information S1, middle row) and the accompanying horizontal flow speed-up (Figure 4d, Figure S11 in Supporting Information S1). For 2022, DInSAR coverage is severely degraded due to the loss of Sentinel-1B in December 2021.

4. Discussion

4.1. Subglacial Water Budget

We interpret the observed uplift wave as arising from an episodic transport of water through the subglacial environment, where water pressure is locally increased to a point above ice overburden pressure as water is siphoned.
downstream. Contrary to previous observations of supraglacial lake drainage cascades, where the collapse of a surface lake triggers a sudden evacuation of water through the subglacial system (potentially causing the drainage of more lakes) and a resulting large-scale dynamic response (Andrews et al., 2018; Christoffersen et al., 2018; Dow et al., 2015; Maier et al., 2023), we interpret our observations as arising from a gradual build-up of subglacial water along the NEGIS, with no clear singular trigger event (Figure S6 in Supporting Information S1), similar to observations made in vastly different glacial settings (Neckel et al., 2021; Schoof et al., 2014). The earliest uplift signals are observed far inland (elevation above 1,800 m) and outside surface melt season, suggesting that the subglacial water in these inland regions originates from basal melt, likely caused by some combination of geothermal and frictional heat. Indeed, NEGIS has been suggested to be initiated by a geothermal heat flux anomaly (Fahnestock et al., 2001; Smith-Johnsen et al., 2020). Frictional heat from basal sliding provides an increasing source of meltwater along NEGIS as ice velocity increases (Karlsson et al., 2021). According to our estimates (Text S5 in Supporting Information S1), melt by frictional heating could alone explain the observed water volume increases.

Another potential water source arises from the drainage cascade picking up existing subglacial water bodies as it propagates. Previous studies have suggested the presence of water bodies below NEGIS (Livingstone et al., 2013; Oswald et al., 2018) and the observed event propagation pathway closely follows the hydro-potential-derived basal flow pathway (except for the final ~110 km). We found evidence suggesting an existing water body being picked up at about 100 km along the Figure 3 transect, where the observed cumulated subsidence greatly exceeds the initial uplift (Figure S5 in Supporting Information S1). The location of this observation coincides with an increase in both water volume and propagation speed estimates (label P3 in Figure 3). It is possible that additional water bodies are drained in a similar fashion but are obscured by data gaps.

Finally, supraglacial lakes formed in the NEGIS region up to 1,600 m elevation in the warm summer of 2019 (Turton et al., 2021). The 2020 drainage cascade reaches these elevations during summer (170 km along the Figure 3 transect), meaning that surface melt may have infiltrated the hydrological system through crevasses or supraglacial lake drainages, contributing further to the total subglacial water budget (although we did not observe evidence of supraglacial drainages).

Our observations alone do not allow a decomposition of the subglacial water budget between the components described above, however, our findings suggest that they all may contribute to the observed increase in water volume along the propagation pathway.

4.2. Subglacial Water Propagation
Basal hydrology is closely linked to sliding and friction at the basal interface (Nienow et al., 2017). The characteristics of the observed drainage cascade suggest that the basal interface between ice, water, and subglacial till evolves in a stick-slip motion, where water is drained by burst-like dynamics. Since upstream NEGIS likely rests on water-saturated till near its onset (Christianson et al., 2014; Franke et al., 2021; Keisling et al., 2014), it is possible that the burst-like drainage results from varying permeability of the till. The varying subglacial propagation speeds (Figure 3) could indicate differences in the subglacial environment along the ice stream. The variation is, however, also likely explained in part by the surface/bed topography and hence the hydro-potential gradient along NEGIS (Figure S12a in Supporting Information S1)—the first two sectors of the Figure 3 transect follow a relatively rough upward-sloping bed, while the last sector (featuring the highest propagation speed) transitions into a smooth downward-sloping bed where the hydro-potential gradient is greatly increased. A similar pattern is observed for the secondary branch of the inferred flow pathway (Figure S12b in Supporting Information S1).

The inferred drainage events indicate an active subglacial system at high elevations, outside of the melt season, which has implications for how the system will respond to seasonal surface melt inputs and for our understanding of Greenland hydrology. Our observations could guide future surveys seeking to constrain different sliding regimes and hence sliding physics in this region.

4.3. Dynamic Response
In the downstream part (200 km from the margin), NEGIS flows into a wide and deep basal trough at more than 500 m below sea level, in which flow speeds are also substantially higher (>400 m/y). In this region, passing of
the drainage cascade is associated with widespread flow acceleration (Figures 2b and 4, Figure S9 in Supporting Information S1), which could suggest a distributed subglacial water flow. At the same time, the DlnSAR measurements indicate localized uplift in a bead-and-thread structure, similar to that observed upstream (Figure 2a), through central parts of this sector. Maier et al. (2023) observed a similar superposition of wide scale flow acceleration and localized uplift signals resulting from the drainage of a series of supraglacial lakes in western Greenland. They found that most high-magnitude uplift signals occurred over hydro-potential sinks—a pattern which is not apparent in the present case (Figure S13 in Supporting Information S1). Neckel et al. (2021) documented localized uplift/subsidence associated with episodic subglacial drainage in a slow-moving region of Antarctica. While possibly limited by sensor geometry, they observed no signs of flow acceleration following the propagating drainage cascade, similar to our observations from upstream NEGIS (Figure 2a). The fact that flow acceleration is restricted to the downstream NEGIS sector might be explained by the apparent increase in water volume along the drainage propagation pathway, meaning that water is able to overwhelm the topographic/hydro-potential lows in this region and propagate outwards, lubricating the bed under the ice stream. Note that bed topography is substantially smoother in this downstream region compared to the upstream (Figure 1, Figure S12a in Supporting Information S1). The ice stream shear margins could be acting as gutters limiting subglacial water, and hence flow acceleration, to the ice stream width, as indicated by our observations (Figure 2b, Figure S9 in Supporting Information S1) (Hvidberg et al., 2020). After the drainage cascade has passed, velocity decreases to the pre-event level, but no further slow-down is observed, indicating a net increase in annual ice motion is caused by the subglacial drainage event (Figure S8 in Supporting Information S1) and highlighting the importance of understanding hydrology-dynamic effects beneath NEGIS and other ice streams.

**Conflict of Interest**

The authors declare no conflicts of interest relevant to this study.

**Data Availability Statement**

All data used to generate this manuscript is publicly available. Sentinel data: https://scihub.copernicus.eu/, BedMachine bed and surface elevation: https://doi.org/10.5067/VLJ5YXKCNGXO, TanDEM-X elevation model: https://download.geoservice.dlr.de/TDM90/, PROMICE ice velocity products: https://dataverse.geus.dk/dataverse/Ice_velocity, NASA MEaSUREs ice velocity mosaics: https://doi.org/10.5067/1AMEDB6VJ1NZ. Line-of-sight anomaly measurements for local uplift events and inferred drainage propagation pathways (indicated by polygons and dashed lines in Figure 1a, respectively) are available at the online repository: https://doi.org/10.11583/DTU.22060061. All Figures were produced with Matplotlib version 3.5.0.

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**Acknowledgments**

This work was funded by DTU Space (Technical University of Denmark) and the Independent Research Fund Denmark (DFF), Grant 2032-00364B. The authors thank Stephen Livingstone and two anonymous reviewers for insightful reviews.


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