Tracking glacier surge evolution using interferometric SAR coherence — examples from Svalbard

Journal:	*Journal of Glaciology*
Manuscript ID	JOG-2024-0133
Manuscript Type:	Letter
Date Submitted by the Author:	10-Oct-2024
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Keywords:	Glacier surges, Remote sensing, Ice dynamics
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Journal of Glaciology, Vol. 00, No. 0, 0000 1

Tracking glacier surge evolution using interferometric SAR coherence — examples from Svalbard

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ABSTRACT. We present a practically simple methodology for tracking glacier surge onset and evolution using interferometric Synthetic Aperture Radar (InSAR) coherence. Detecting surges early and monitoring their build-up is interesting for a multitude of scientific and safety-related aspects. We show that InSAR coherence maps allow the detection of surge-related instability on Svalbard many years before being detectable by, for instance, feature tracking or crevasse detection. Furthermore, we present derived data for two types of surges; downstream- and upstream-propagating, with interestingly consistent surge propagation and post-surge relaxation rates. The method works well on Svalbard glaciers, and the data and core principle suggest a global applicability.

INTRODUCTION

Glacier surges are sudden temporary glacier speed-ups, sometimes by one or many orders of magnitudes. They pose local safety hazards by damming lakes that subsequently outburst (Post and Mayo, 1971; Bazai and others, 2021), or for travel across glaciers, and reveal problems in our understanding of general glacier dynamics due to our inability to properly predict them beforehand. Work has been done on glaciers that are on the brink of surging (e.g. Clarke, 1976; Bouchayer and others, 2024), but the lack of indications before surges means they are generally not known before it is too late to study their evolution in situ. Here, we present a new tool for detecting glacier surges years before they become detectable by established methods, and present statistics on the rates of surge progression for glaciers on Svalbard.

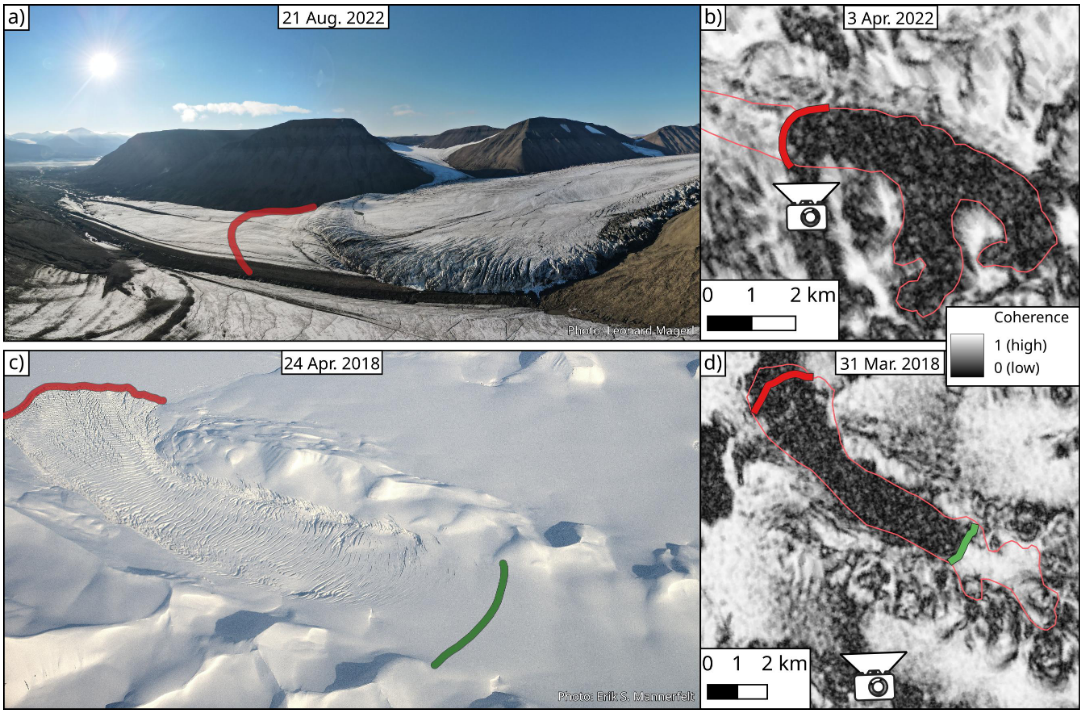

Fig. 1. In-situ photographs compared to coherence maps in the same year. **a)** Bulge-initiated surge of Vallåkrabreen, showing a surge bulge with splaying crevasses and a less pronounced forebulge ahead of it. The red line shows the approximate location of the low-coherence boundary from earlier that year (shown in **b**, together with the photo location); roughly coincident with the forebulge. **c)** terminus initiated surge of Arnesenbreen, showing the lower surge boundary in red and the upper low-coherence boundary in green (c.f. panel **d**). We presume that the discrepancy between the green line in **c)** and the region of substantial crevassing is due to coherence being sensitive to smaller disturbances than what can be seen in a winter photograph. The largest surge extent (so far) is shown in pink outlines for panels **b)** and **d)**.

Previous methods of surge detection involve identifying sudden changes in geometry, texture or surface velocity of a glacier. Elevation change maps reveal large mass displacement events (e.g. Paul and others, 2022). If the surface velocity is high enough, i.e. when a surge has accelerated sufficiently, it can also be autonomously detected using feature tracking (surface velocity) time series (Koch and others, 2023). Drastic increases in crevassing is finally a robust method of identifying an ongoing surge through subtracting SAR backscatter intensity images over time (Kääb and others, 2023). While all of these methods work well on their own, they mostly function when the glacier is already fully surging; characterising the build-up is much more difficult. High-accuracy elevation data can technically be used over long time periods to reveal unstable mass redistribution associated with future surging (Sund and others, 2009). Acquiring these elevation data at high accuracy and temporal frequency requires thorough processing and error assessment, however (c.f. Hugonnet and others, 2022); finding an easier and less resource-intensive method would clearly be advantageous.

Repeated Synthetic Aperture Radar (SAR) acquisitions of terrain can be used to asses changes in signal phase, affected by terrain motion and changes in reflective characteristics. Interferometric SAR (InSAR), the process of describing these phase changes, is commonly used in cryospheric sciences, e.g for ground subsidence (Rouyet and others, 2021), glacier velocity (Eldhuset and others, 2003) and classification of debris covered glaciers (Thomas and others, 2023). While normal InSAR workflows generally involve heavy post-processing to obtain displacement products, a simpler and useful by-product is the normalized cross-correlation of two single-look complex (SLC) SAR scenes, usually denoted as coherence. InSAR coherence varies in the range of 0 (no phase correlation between two acquisitions) to 1 (the phase between acquisitions is identical), and is normally used for quality assessment of the co-registration (Eldhuset and others, 2003), masking out low-coherence areas within phase unwrapping, and terrain classification (Shi and others, 2019), including mapping of debris-covered parts of glaciers that are difficult to do using optical methods (Atwood and others, 2010; Frey and others, 2012). Coherence is normally lost either if terrain displacement or nonlinear motion components (shear, rotation, etc.) become too large, or if terrain reflective characteristics change, for example during a rainfall event or during ice- or snowmelt (Weydahl, 2001). Thus, in intervals featuring stable cold weather, the presence or absence of significant glacier motion, motion gradients, and deformation can be assessed visually or computationally using InSAR coherence maps.

Many or most glaciers on Svalbard have a recent past of surging (Sevestre and Benn, 2015; Farnsworth and others, 2016), meaning most currently non-surging glaciers can be described as being in quiescence. Quiescent glacier surface velocities are usually low, measuring 5–18 m / yr on Svalbard (Nuttall and others, 1997; Sund and Eiken, 2004; Sund and others, 2014). Surges dramatically increase this speed to a few or tens of metres per day instead, and this order-of-magnitude change can be used for detection. Two types of surge propagation directions have been shown to exist on Svalbard; downstream propagating, characterised by a surface bulge (e.g. Murray and others, 1998), or upstream propagating, i.e. in a terminus initiated surge (Sevestre and others, 2018). In Alaska, synchronous up- and downstream propagation of a surge that initiates in the central body has been shown (Altena and others, 2019), but this has not yet been described on Svalbard. Improved monitoring of surge propagation would thus certainly contribute to better characterising and understanding of the (potentially different) types of surge evolution and its direction with respect to the direction of glacier flow.

We demonstrate the usefulness InSAR coherence maps on Svalbard for tracking down- or upstream

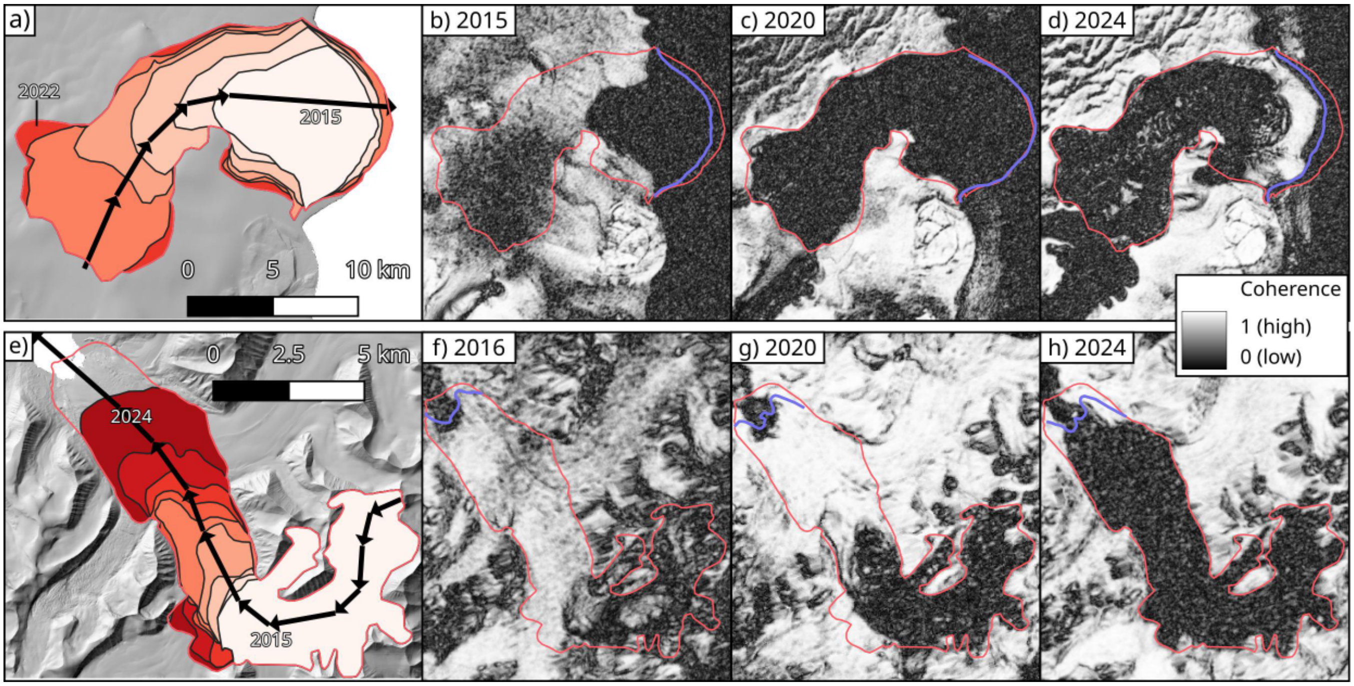

Fig. 2. Examples of coherence changes during the progression of two surges. **Top (a–d):** Terminus-initiated surge of Stonebreen. Note the onset of stagnation in 2024 (**d**) shown by the terminus regaining coherence. **Bottom (e–h):** Surge bulge propagation of Paulabreen. The pink outlines in all panels represent the maximum attained extent of the surges so far, and the blue lines represent the concomitant front positions. Basemap hillshade from 2010 of panels a) and e) courtesy of the Norwegian Polar Institute.

propagating surges by mapping out zones of low coherence (disturbed flow) and measuring temporal changes in their extent. Our resultant patterns show that the technique opens new doors to ways of quantifying surging, and allows for rough empirical predictions of the timing of surge acceleration. While our study focuses on Svalbard only, the data and techniques can be used for global assessments of surge propagation rates and patterns in regions with similarly low quiescent baseline flow.

DATA AND METHODS

We obtain processed Sentinel-1 inSAR coherence maps from the Alaska Satellite Facility (ASF) Vertex tool (`https://search.asf.alaska.edu`). We order the processing of every 12-day acquisition pair since the beginning of the Sentinel-1 record on Svalbard (January 2015) in the winter months of 1 November to 30 April. We choose this interval as spring or summer melt strongly reduces the phase coherence and renders the data unusable for our purposes. Qualitative assessments of 6-day returns using the Sentinel-1A and -B satellites revealed much cleaner coherence maps, but we stayed consistent with 12-day baselines as the 6-day availability period lasted only a subset of the study period (Oct. 2016 to Dec. 2021) due to the failure of Sentinel-1B. A total of 797 scenes were successfully processed, with some failures due to co-registration errors not converging below the pre-set threshold. Most 12-day pairs show very low coherence throughout the scene due to weather effects (Weydahl, 2001). We sift through the entire catalogue manually for each glacier, and extract at least one suitable coherence map per year. For each good scene, we manually delineate any encountered low-coherence front with an upper and/or lower boundary line. A detailed investigation of the influence and the spatio-temporal variations of factors that contribute to coherence loss at the surge fronts (in particular likely motion magnitude, motion gradients, surface deformation, and surface changes by crevasse formation) is out of scope for this brief communication and remains to be done. However, comparison of our coherence-derived surge fronts to in-situ photographs (Figure 1) and DEM differences between occasional individual ArcticDEM products shows that our coherence-derived surge fronts coincide with topographic bulges, thus indicating a change in glacier mass transport. To obtain terminus positions, we download Sentinel-1 backscatter intensity and Sentinel-2 L1C true colour scenes for manual terminus delineation. We assess length and length change along a manually drawn glacier centreline, measuring the glacier terminus, the lower and upper low-coherence front. We measure lengths of buffered centrelines within ±200 m of the discrete centreline to obtain a spread and to reduce uncertainty in the exact placement of the centreline. The chosen buffer width of ±200 m is open to discussion, but not critical for this method demonstration study.

In order to derive further statistics of the mapped surges, we divide them in three stages (if observed); pre-surge, surge, and post-surge, based on our available data. The surge date is defined differently for down- and upstream propagating surges. For downstream propagating surges, we simply assign the date when the low-coherence front (surge bulge) reaches the terminus. For upstream propagating surges, we choose a low-coherence expanse threshold whereafter the glacier typically starts to advance. As tidewater glaciers often naturally advance in winter due to sea ice lowering the calving rate, we could not use a simple advance rate threshold. We observe that all mapped upstream-propagated surging glaciers advanced, regardless of season, when 40% or more of the glacier had lost coherence (Supplementary Figure S1). Thus, we use this 40% coverage threshold to define the start of an upstream propagating surge. An exception is made at the glacier Etonbreen as it is part of an ice cap and therefore has an undefined upper bound. Instead, we used the date when the glacier first advanced without the help of a sea-ice buffer (November 2023). The surge termination is defined the same for both types of surges; when the terminus regains coherence and thus shows a near or total stagnation at the front. We want to highlight that the exact definition of

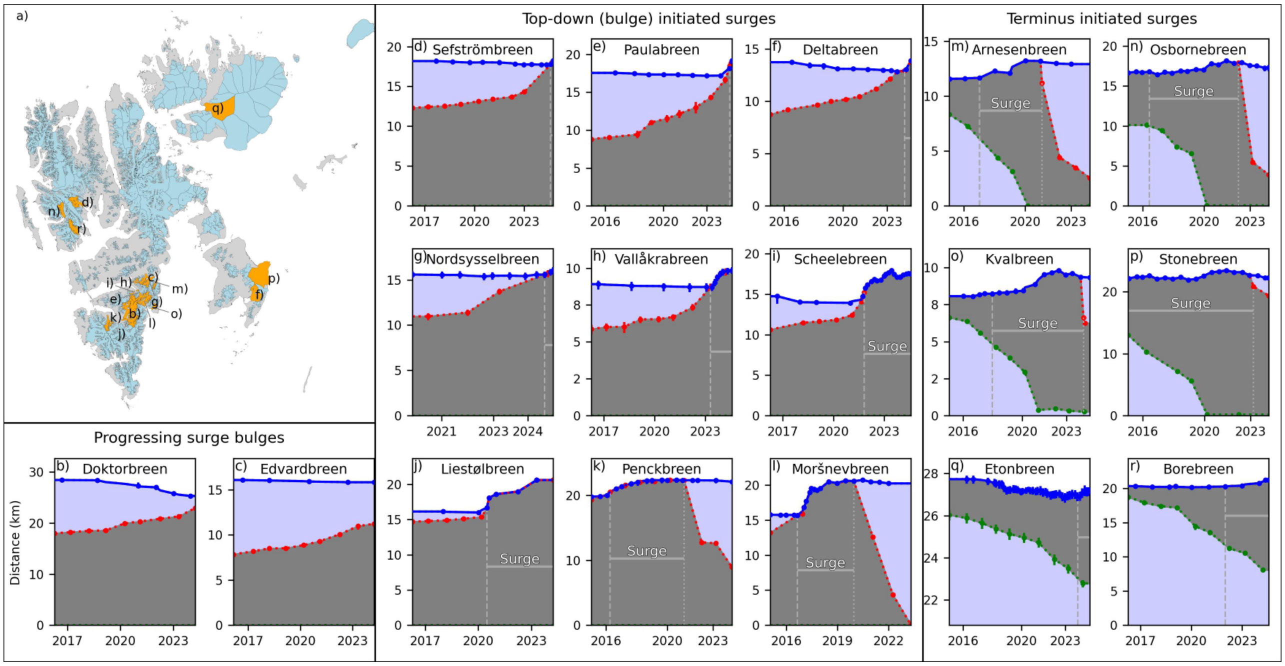

Fig. 3. Digitised low-coherence (surge) front progressions for surges on Svalbard. **a)** Overview map showing all glaciers (blue) and the location of the presented glaciers (orange plus letters). Glacier front outlines are from Nuth and others (2013). **b–c)** Low-coherence front progressions that indicate a future advance. **d–l)** Top-down (bulge) propagating surge examples. **m–r)** Bottom-up (terminus initiated) surge examples. High-coherence parts of the glacier are shaded light blue, low-coherence parts are shaded grey, front positions are shown in blue, the lower boundary of the low-coherence front in red, and the upper boundary in green. Points (with 25th to 75th percentile spreads) represent measured values, and the parts in between are interpolated. For reference, **c)** is lake-terminating, **h)**, **i)** (before 2022) and **k)** are land-terminating, and the rest are tidewater glaciers.

when a surge starts and ends, where it does so, and which indicators are used to define them are all up to discussion; we rather see our dates as common "milestone" events along the continuum of surge behaviour.

RESULTS

We present statistics from 18 recently terminated or still ongoing surging glaciers on Svalbard. Out of these, 12 initiated by propagating downstream and 6 by propagating upstream. We focus on aggregate statistics here; individual glacier information is found in the Supplementary Table S1. Unless otherwise specified, the presented numbers show the median±standard deviation. We find that downstream propagating surges generally lead to significantly faster terminus advance rates (4.69±6.00 m/d) compared to the upstream propagating counterparts (0.51±0.44 m/d). However, the instability propagation itself generally shows an opposite tendency, with upstream propagation rates of 4.23±1.83 m/d and downstream propagation rates of 2.24±2.30 m/d. We qualitatively note an accelerating tendency of both up- and downstream propagation rates near the beginning of the phase when the terminus advances (Figure 3). There is only a weak correlation between instability propagation rates and subsequent advance rates in our data, showing Pearson correlation coefficients of 0.45 and -0.30 for down- and upstream propagating surges, respectively. In other words, there seems to be no simple way to predict the magnitude of a surge before it accelerates from these data alone.

The most consistent measured rate is the gradual return to coherence after a surge. Figure 2d demonstrates the ongoing stagnation of the recent Stonebreen surge, shown by regained high coherence at the terminus. All stagnating glaciers in this study show the same pattern of starting at the terminus and gradually continuing up-glacier. This occurs at a rate of 12.21±3.98 m/d, with little to no variability between down- and upstream propagated surges.

DISCUSSION

The identified and described surges in this study display a perhaps surprising similarity in rates and patterns of propagation, advance and subsequent stagnation. Most downstream propagating surges have a well-defined boundary between low and high coherence, with only a few edge cases where shear margins (stripes of low coherence) are seen instead (Figure 2). But the similarities should not instil overconfidence in the method, as we abandoned the characterisation of the recent surges of Monacobreen (Banerjee and others, 2022) and Tunabreen (Vallot and others, 2019); both glaciers are fast-flowing even during quiescence, featuring low glacier-wide coherence, and surge propagation monitoring is therefore not possible with our method alone.

An outstanding question in this work is how the initial formation of a downstream propagating instability looks like. In other words, how far back in time can we detect a future downstream propagating surge? We only have vague indications of initial bulge formation; low-coherence lines associated with shear margins gradually lose coherence and subsequently start progressing down-glacier. This is exemplified at the surge of Paulabreen in Figure 2, where the 2016 scene displays only partial loss of coherence in the surge front, while the latter scenes show a total loss. This type of proto-bulge can be seen in other examples throughout Svalbard (Supplementary Figure S2), and might represent the earliest detectable stage of unstable flow through this method. While interpretations turn vague too far back in time, we still see that many surges can be seen up to (and maybe longer than) eight years before they reach the front. Thus, mapping the progression of low-coherence zones on glaciers can be used as an early warning system for many surges.

We do not mean to convey that all cases of lost coherence mean that a surge is about to happen. Persistent low-coherence zones that could be misclassified as surge bulges are found all over Svalbard, and are most easily explained through uneven variations in subglacial topography leading to disturbed flow. In addition, all tidewater glaciers seem to feature a low-coherence zone near their termini, easily explainable by tidal effects at their calving bays. What sets out a potential surge from both of these cases in the coherence is the temporal progression; an expanding disturbance or an accelerating large terminal low-coherence zone indicates a state change in the glacier's local flow characteristics. Therefore, we are confident that all our presented examples represent actual surges, but we may have missed smaller instability progressions that got lost between all other more natural zones of low to no coherence.

CONCLUSION

Here, we present InSAR coherence maps as a new tool to track glacier surge evolution from its buildup phase to stagnation. While the method is only proven to work on glaciers with low baseline quiescent velocities, the ones we study show clear similarities in surge evolution rates. There is a strong case for future automation of the tool to detect surge-like glacier flow instabilities, as the ones mapped in this study are clearly visible in the coherence data with the naked eye. We could infer glacier surges many years (in one case up to eight) before they reached the front, supporting the potential use of the method for safety-related or scientific forecasting of surge-like behaviour. We believe that the method can provide new insights into the physics and evolution of glacier surges, for instance regarding the spatio-temporal patterns of initial ice-flow change. For example, our (limited) study for Svalbard suggests that the instability propagation during the build-up phase has no direct correlation with the magnitude of a later surge, meaning the physics that drive them might be different. As another potentially important result, we want to highlight that the instability propagation that eventually led to surging started many years before accelerating and advancing. This has implications for studies that investigate connections between meteorological or climatic conditions and glacier surging, as a substantial time delay between build-up conditions and the subsequent surge might have to be considered. We thus suggest that this simple method is implemented in the toolbox for detecting, mapping, classifying and tracking surges and other surge-like glacier flow instabilities.

DATA AVAILABILITY

The source code for InSAR post-processing and figures are found at `https://github.com/erikmannerfelt/IncoherentSurges`. Before the potential acceptance and publication of this manuscript, an associated Zenodo publication will be made and linked here with supporting output data.

ACKNOWLEDGEMENTS

TS was financed by the Research Council of Norway ("Researcher Project for Scientific Renewal", MASSIVE, Project 315971)

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