https://doi.org/10.5194/egusphere-2026-3849
Preprint. Discussion started: 29 September 2026

Review article: Glacier surges observed by Synthetic Aperture Radar

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Abstract. Glacier surges are episodes of strongly accelerated glacier flow. The phenomenon is important to study not only for the advancement of geosciences, but also for risk management and human safety. Unfortunately, surge events remain difficult to observe and predict due to their short duration relative to the entire surge cycle, as well as to their spatial heterogeneity and diverse manifestations. Over the past decades, satellite remote sensing has become the primary source of information for monitoring surge activity, with synthetic aperture radar (SAR) offering unique advantages in terms of temporal coverage and independence from illumination and weather conditions. This article provides an overview of SAR-based methods applied to the study of glacier surges, including interferometry, offset tracking, altimetry, backscatter and coherence map analysis. We discuss how individual SAR products detect complementary aspects of surge dynamics, such as velocity increase, elevation change, terminus fluctuations, surface crevassing and the propagation of instability front. Based on the reviewed literature, we identify current research trends ranging from surge detection and glacier classification to long-term monitoring of individual glaciers, and we point to the main challenges that arise from the characteristics of surge behavior. Finally, we discuss directions for future research, including the integration of multi-aspect SAR observations, the use of machine learning techniques, and the potential role of new SAR methods in early detection and prediction of surge events.

1 Introduction

According to the most commonly accepted definition, glacier surges are periodic or quasiperiodic episodes of rapid ice flow (Jiskoot, 2011). During the surge, surface velocity increases by up to several orders of magnitude compared to the normal, i.e. quiescent state. Although surges are relatively rare, they are worth investigating, as they provide valuable information about the dynamics of glaciers and the functioning of the entire cryosphere (Cuffey and Paterson, 2010). They may also provide information about long-term response of glaciers to climate change (Strozzi et al., 2026). Moreover, they have significant short-term effects on local ecosystems. Surges directly cause various types of disasters, such as floods, avalanches, or changes in fjords and forest ecosystems (Harrison et al., 2015).

Scientific reports on glacier surging began to be published in the early 20th century, but some descriptions of what was most likely a glacier surge date back to as early as the 16th century (Jiskoot, 2011). Similar phenomena were known to some extent first from oral accounts and then from expedition reports (e.g., Tarr and Martin, 1914). Initially, they were called “rapid advances” (Moffit, 1942) or ”exceptional advances” (Desio, 1954). The term “glacier surges” has been used since the 1960s.

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The entire concept was described in detail by Maier and Post (1969) on the basis of a series of observations of glaciers located in Alaska and Yukon. Over the years, various techniques and methods have been used to monitor surges. Early analyses were based on the documentation acquired directly in the area of interest and referenced against available materials, such as analogue maps, ground and aerial photographs (e.g., Harrison, 1964; Post, 1969). This approach was later expanded by introducing manual surveys and close-range sensing methods (theodolites, total stations, drones, laser scanning, photogrammetry), as well as satellite positioning systems, for example GPS (e.g., Jania et al., 2002; Hubbard and Glasser, 2005; Błaszczyk et al., 2024; Harcourt et al., 2024). Glacier movement has been also studied in a geophysical context, with the use of seismographs or ground-penetrating radars (GPR) (e.g., Woodward et al., 2003; Gajek et al., 2017). However, all these methods exhibited significant temporal and spatial limitations, and therefore in the majority of cases they were replaced by satellite remote sensing (Watson and Quincey, 2015; Harcourt et al., 2025). Satellite imagery significantly transformed geosciences, and it has been widely used in glaciological research for several decades. Currently, extensive access to high-quality images allows the monitoring of large glaciated areas at short time intervals, with satisfactory resolution and extensive spatial coverage (Dirscherl et al., 2020).

Data on the behavior of surge-type glaciers can be obtained from both optical and radar imagery. Although optical data facilitates the interpretation of ground events, its availability is limited by the need to acquire images during the day and without significant cloud cover. On the other hand, satellites equipped with a synthetic aperture radar (SAR) are able to collect data of the same quality regardless of the time of day or weather conditions. Owing to the diversity of algorithms and techniques for the processing of radar images, they have a wide range of applications, and they have enabled many advances in glaciology (Joughin et al., 2010b).

Here we present an overview of the use of SAR data and methods in studying glacier surges. We examine which properties of different methods allow the identification of particular aspects and manifestations of the surge. We also present approaches aimed at identifying and long-term monitoring of surge cycles, so as to define current and potential future directions for research in the field. This article is intended to demonstrate the potential of SAR in developing effective tools for glaciology, and thus to address the research gap related to the phenomenon of surges.

2 Glacier surges characteristics

2.1. Global distribution

According to current estimates, only about 1% of glaciers worldwide can be classified as surge-type glaciers (Jiskoot et al., 1998). Interestingly, their geographical distribution is not even – they form clusters, and their vast majority is located in a few specific glaciated regions. The most extensively documented clusters of surge-type glaciers are: the Norwegian archipelago of Svalbard, the western and eastern coasts of Greenland, Alaska along with the Canadian territory of Yukon, as well as High Mountain Asia (HMA – Karakoram, Tian Shan and Pamir Mountains). Some documentation also exists for surge-type glaciers in Iceland, the Canadian and Russian High Arctic (e.g., Ellesmere Island, Novaya Zemlya, Severnaya Zemlya), some parts of

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the Tibetan Plateau, and the Central Andes (Jiskoot, 2011; Sun and Qiao, 2021). Rare or historical cases of surges have been reported for Caucasus Mountains (Evans et al., 2009), Kamchatka Peninsula (Muraviev et al., 2012), the Alps (Hoinkes, 1969) and New Zealand (Sutherland et al., 2019). No surge events have been reported for the Antarctic continent so far. However, not all glaciers classified as surge-type were directly observed during a surge. According to the most recent data from Randolph Glacier Inventory (RGI 7.0), some glaciers are described as "probable" or "possible" (RGI Consortium, 2023). A global distribution of surge-type glaciers, highlighting the main clusters, is shown in Figure 1.

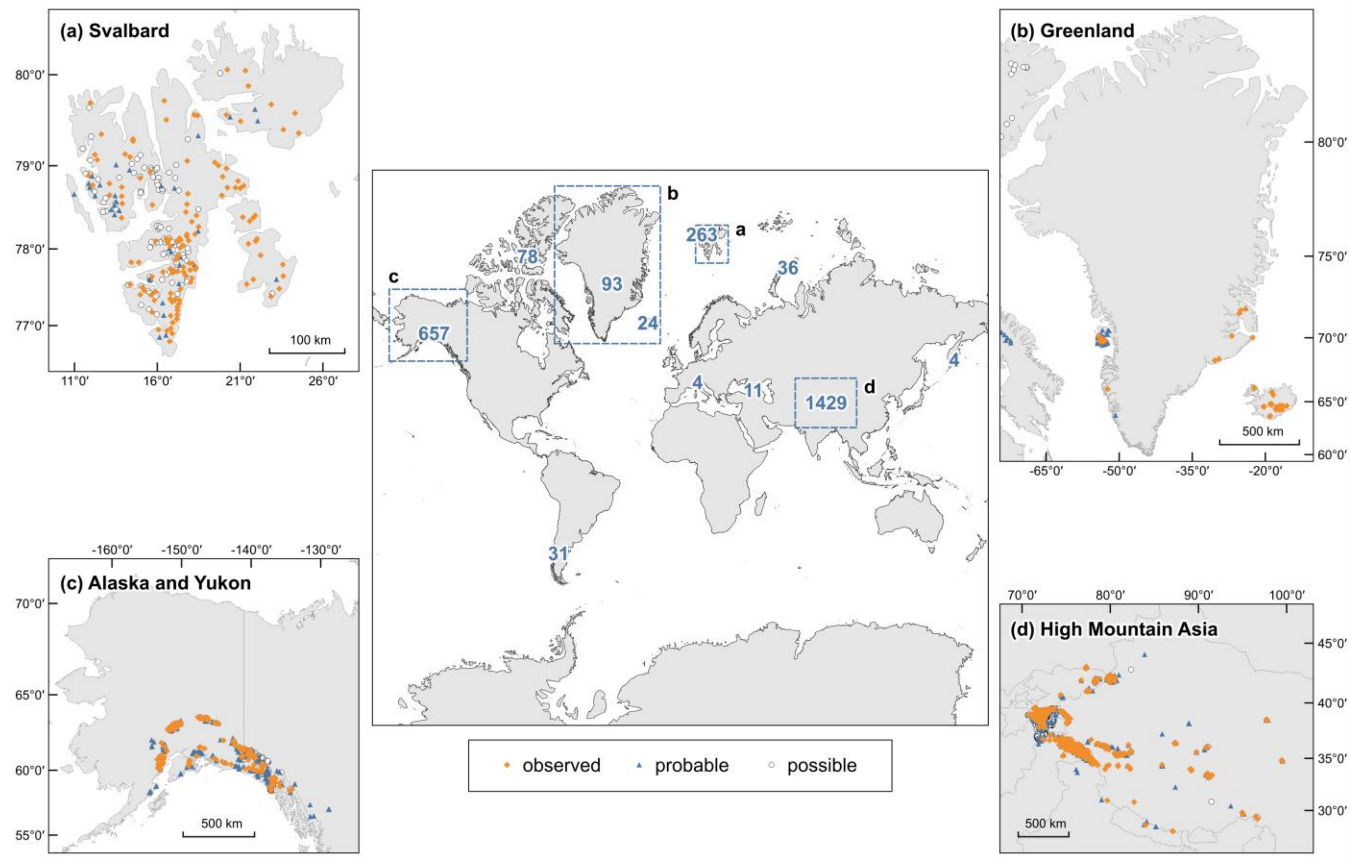

Figure 1: A global distribution of surge-type glaciers based on RGI 7.0. The central map shows the locations of the four main clusters presented in detail: (a) Svalbard, (b) Greenland, (c) Alaska and Yukon, and (d) HMA. Numbers indicate the number of surge-type glaciers within each region. Symbols represent the surge classification in RGI (observed, probable, possible). Base map derived from Natural Earth vector data.

The clustering mainly in specific regions of the northern hemisphere suggests some connection between local conditions and the probability of surge events. Several studies which focused on this relationship analyzed the impact of such parameters as climate, or geological and topographic conditions (Post, 1969; Hamilton and Dowdeswell, 1996; Jiskoot et al., 1998; Sevestre and Benn, 2015). It seems that surges usually occur for glaciers which have soft, erodible beds (Clarke et al., 1983). In some cases, the winter months with particularly cold and dry conditions facilitated surges, as they resulted in a more rapid flow than

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in the previous cycle (Harrison and Post, 2003). The impact of climatic factors is more difficult to define. For example, there is a noticeable difference in the behavior of the subpolar glaciers in Svalbard and of the temperate glaciers in North America (Dowdeswell et al., 1991). Some glaciers, however, do not seem to follow this pattern because, for example, they change their cycle. Some glaciers, on the other hand, ceased to surge, because the extent of ice cover in a given area has decreased (Hoinkes, 1969). The global distribution of surge-type glaciers may be therefore assumed to be a function of time and to change as a result of long-term climate trends (Harrison and Post, 2003).

2.2. Surge cycle

Glaciers have two commonly identified areas: the accumulation area, located in their upper part, where snowfall exceeds mass loss, and the ablation area at their lower parts, where ice is removed by melting, sublimation or calving. Ice transport can be expressed by the balance flux, which enables the glacial system to maintain a steady-state profile (Clarke, 1987). Surge-type glaciers may be also classified by the presence of reservoir and receiving zones that do not necessarily coincide with the accumulation and ablation areas and may partially overlap with them. These zones reflect the dynamics of ice transport during surge events. While non-surging glaciers typically have an ice flux close to the balance flux, surge-type glaciers undergo long periods of slow flow alternating with relatively short periods of rapid flow. Ice thickness increases in the reservoir zone due to insufficient downstream transport, whereas during short surge events large volumes of ice are rapidly transferred into the receiving zone. Each surging glacier has its own individual surge cycle. Nevertheless, it has been possible to distinguish particular phases of this cycle so as to describe what happens between two surges (Jiskoot, 2011).

Surging glaciers are in a quiescent phase most of the time. In quiescence, their behavior may appear similar to that of glaciers with stable flow. However, the ice flux is low, so the rate at which mass is removed from the glacier is not equal to the rate of accumulation. As a result, albeit relatively slowly, new ice masses, finding no outflow, remain in the upper parts for a long period. At this stage, there are no visible sudden changes caused by an imbalance in mass distribution and internal instability. The quiescent phase can last for tens or even hundreds of years, depending on the case (Jiskoot, 2011).

Quiescence is followed by the buildup phase. At this stage, the volume of ice accumulated in the reservoir zone is sufficient for the glacier profile to be easily divided into upper and lower areas. A distinct bulge may form between the two zones (Meier and Post, 1969). Due to mass imbalance, basal shear stress is high and the entire system is gradually losing stability. During the buildup phase there may also occur episodes of temporary flow acceleration, known as "mini-surges", which signal the beginning of the main surge (Raymond and Malone, 1986).

Once a certain critical point is exceeded, the active phase begins, also known as the surge. The ice flux increases significantly, causing rapid transfer down the glacier (Jiskoot, 2011). The glacier does not surge immediately along its entire length. The boundary between the fast-flowing ice and slower ice masses in front of it is called the "surge front". In the case of glaciers terminating on land, the surge front has been found to often form in the upper parts and then, as a visible bulge, propagate down. On the other hand, in the case of tidewater glaciers, the surge may be initiated by the terminus and then propagated upward (Sevestre et al., 2018; Koch et al., 2023). At the point of the fastest flow, the glacier surface is usually crevassed and

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deformed (Meier and Post, 1969). The intensity of surge symptoms may vary depending on the specific case. The transition from low to high velocities may be sudden, but it may also be gradual, and the same applies also to the deceleration at the end of the surge. The active phase can last 1–10 years (Dowdeswell et al., 1991).

The next stage of the surge cycle is the stagnation phase. After losing its previous flow velocity, the glacier remains virtually motionless for some time. The changes that occurred during the active phase are gradually eliminated. The deformed glacier surface slowly returns to its previous state, the glacier profile becomes even, and the advanced terminus retreats as a result of increased ablation. The stagnation phase may last several years or several dozen years. It is followed by another quiescent phase and the cycle starts again (Jiskoot, 2011).

2.3. Glacier types

Surge behavior (or the lack thereof) is not an officially recognized category in the classification of glaciers. Surge activity was observed for land-terminating and marine-terminating glaciers, temperate and polythermal glaciers, valley and cirque glaciers, large and small glaciers, as well as for other types. In addition, as mentioned in the previous section, the behavior of a glacier during the surge is an individual process (Murray et al., 2003b). Even glaciers sharing accumulation areas do not always surge simultaneously (Cuffey and Paterson, 2010). However, there has been developed a classification based exclusively on criteria related to the surge. It identifies two groups, named after two large global clusters: the Svalbard type and the Alaska type. Glaciers located in these regions show similar patterns of behavior. The differences between these two types relate in particular to the duration of individual phases and to the possible mechanisms regulating this phenomenon (Dowdeswell et al., 1991).

Svalbard-type glaciers have a relatively long surge cycle. The active phase may last 2–10 years, while the quiescence may last from several decades to even hundreds of years. Any changes related to their surge activity are more extended in time. At the beginning of the active phase, the flow velocity increases slowly. Similarly, at the end of the surge, the glacier decelerates gradually. As their name suggests, the vast majority of such glaciers are located in the Svalbard archipelago (Dowdeswell et al., 1991; Jiskoot et al., 2000).

The surge cycle of Alaska-type glaciers is short compared to that of Svalbard-type glaciers. The active phase usually lasts 1–3 years, whereas the quiescent phase lasts 20–40 years. As a result, the surge is more intensive and the resulting changes are more evident. Rapid changes of ice velocity are also observed at the beginning and end of the surge (Kamb et al., 1985; Dowdeswell et al., 1991).

Glaciers in other regions do not fit in this classification. It is claimed that Greenland and Central Asia have both Svalbard-type and Alaska-type glaciers. Moreover, some glaciers may show both types of behavior simultaneously (Chudley and Willis, 2019; Solgaard et al., 2020).

2.4. Surge mechanisms

Some theories indicated natural disasters such as earthquakes or landslides as surge triggers (Gardner and Hewitt, 1990). There is currently agreement, however, that surges do not directly depend on external factors, but result from internal instability

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within the glacial system (Kotlyakov, 1996). The causes most frequently mentioned in this context include thermal and hydrological mechanisms, which largely correspond to the classification of surge-type glaciers into Svalbard and Alaska types (Sun and Qiao, 2021). Most theories agree that subglacial water conditions and soft, deformable beds influence the probability of surging (Jiskoot, 2011). They also agree, however, that no universal mechanism can be applied to all surge-type glaciers (Cuffey and Paterson, 2010). Nevertheless, researchers continue attempts at developing a general model of glacier surging (Thøgersen et al., 2019; Terleth et al., 2021). A notable recent example is the enthalpy-based general theory proposed by (Benn et al., 2019).

Flow instability has been suggested to result from changes in ice temperature at the base of the glacier (Robin, 1955). During quiescence, the basal layers of temperate ice are covered with cold ice. As new ice masses accumulate in the reservoir zone, increasing thickness and friction generate heat. As a result, cold ice is replaced by temperate ice, which melts at the base, causing the glacier to become unstable and slide down the slope. During the active phase, the ice slowly thins, the basal temperature decreases, and the rapid flow eventually stops (Clarke et al., 1983; Fowler et al., 2001). The thermal mechanism occurs in polythermal, Svalbard-type glaciers (Murray et al., 2003b).

Surges may also be triggered by increased water pressure due to changes in basal drainage (Kamb et al., 1985). In the quiescent phase, water flows out of the glacier through an efficient, channelized system. In temperate glaciers the drainage system periodically changes and forms a system of linked cavities, in which water spreads less efficiently and is partly retained at the base. In consequence, the basal water pressure increases, causing the ice to detach from the ground and slide down. Over time, the cavities are rearranged into channels, and reduced water pressure results in decreased flow velocity. This kind of behavior is typical of Alaska-type glaciers (Kamb, 1987; Murray et al., 2002).

Benn et al. (2019) proposed a general surge model, which describes the behavior of both temperate and polythermal glaciers. The authors describe a glacier as a thermodynamic system with a specific total amount of energy, defined as enthalpy. Surge-type glaciers are unable to dissipate heat effectively either through thermal conduction, as in colder and drier regions, or through the loss of meltwater, as in warmer and more humid regions. As a result, the energy generated by geothermal heat and basal friction gradually accumulates in the bed of the glacier, eventually causing detachment and rapid flow. This theory also explains why surging glaciers are clustered mostly in specific regions. The climate in the “Arctic Ring”, which extends through the Arctic and sub-Arctic from Alaska to Novaya Zemlya, is intermediate, with particular combinations of such factors as of temperature and precipitation, which promote long-term imbalance of glacier enthalpy (Benn et al., 2019).

2.5. Surge manifestations

2.5.1. Ice velocity changes

Although surge manifestations do not need to occur simultaneously or with equal intensity (Murray et al., 2003b), they most typically take the form of ice velocity changes. During quiescence, surge-type glaciers typically flow at velocities comparable to those of non-surging glaciers, i.e. below several hundred meters per year in the case of valley glaciers and up to several

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kilometers per year in the case of outlet glaciers. Some velocity fluctuations may result, for example, from seasonal melting (Cuffey and Paterson, 2010). The first surge-related velocity anomalies (mini-surges) appear in the buildup phase (Raymond and Malone, 1986). A significant, gradual or rapid increase occurs at the beginning of the active phase, when ice velocity may reach several dozen or, occasionally, several hundred meters per day (Jiskoot, 2011). Initial acceleration may occur in the upper or lower parts of the glacier, depending on the type of surge initiation (Mannerfelt et al., 2025). The highest surge velocity of 125 meters per day was recorded in Iceland (Thorarinsson, 1969). At the end of the active phase, velocity decreases significantly to approach zero in the stagnation phase (Jiskoot, 2011).

Being the main manifestation of glacier surges, this rapid velocity increase is investigated in the majority of studies, which view the changing distribution of internal forces and the resulting rapid movement of ice masses as the primary factor influencing all other phenomena (Sun and Qiao, 2021). In order to simplify the reconstruction of horizontal velocity components, many SAR-based approaches assume that ice motion is predominantly horizontal and approximately parallel to the glacier surface (Kwok and Fahnestock, 1996).

2.5.2. Elevation changes

The irregular distribution and variable transfer of ice masses are visible in the changing longitudinal profile of a surging glacier. During quiescence, ice mass gradually accumulates in the reservoir area, but cannot be effectively transported to the ablation area due to low balance flux (Clarke, 1987). Consequently, the lower part of the glacier becomes thinner, while the upper part thickens and rises. During the buildup phase, the elevation difference between the upper and lower parts noticeably increases, and short before the surge the lower boundary of the reservoir area becomes steep (Meier and Post, 1969). The process may lead to the formation of a characteristic, bulge-shaped ramp having a height from several meters to tens of meters (Murray et al., 1998). When land-terminating glaciers enter active phase, their surge front can be observed to progress down the slope, in the form of a bulge (Thøgersen et al., 2019). This phenomenon is accompanied by elevation changes ranging from tens to over a hundred meters. Over time, the glacier surface becomes even and returns to its previous state (Jiskoot, 2011). The characteristic bulge is not observed in marine-terminating glaciers with an upward propagation of the surge. Instead, the gradual steepening of the glacier may occur before the active phase (Sevestre et al., 2018).

2.5.3. Terminus fluctuations

During the active phase of a surge, the ice mass moves rapidly down the slope towards the glacier terminus. At that stage, the rate of mass accumulation in the lower part exceeds the rate of ablation (Clarke, 1987). When the surge front reaches the terminus, the length of the glacier increases gradually. This process is known as terminus advance or glacier advance (Meier and Post, 1969). As in the case of other surge manifestations presented in this section, the rate of terminus advance and the change in glacier length vary between individual surge events. For example, the majority of surges in High Mountain Asia never reach the terminus, which therefore does not advance (Guillet et al., 2022). In contrast, the largest terminus advance due to a surge was recorded in Svalbard and reached about 21 km (Schytt, 1969), while average advances range from 0 to 10 km

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(Jiskoot, 2011). Importantly, surges do not necessarily increase the glacier length over several consecutive cycles, as this can be compensated by ablation (Meier and Post, 1969). In the stagnation phase, glacier motion becomes negligible and ablation accelerates. As a result, the glacier tongue thins and retreats. Often, the terminus eventually returns to its previous location, as mass balance is restored in the glacier (Yde and Knudsen, 2007). Unlike land-terminating glaciers, increased ice flux in marine-terminating glaciers typically increases calving, which partially offsets terminus advance (Mansell et al., 2012). In such cases as well, even long before a surge event, the terminus may thin and retreat from the pinning point, as has been observed for numerous glaciers in Svalbard (e.g., Sevestre et al., 2018).

2.5.4. Surface crevassing

Various forces acting on a surging glacier change its structure and surface (Jennings and Hambrey, 2021). The glacier is divided into two parts which move dynamically as the surge front advances (Koch et al., 2023). The ice above the front moves very quickly, causing the glacier to stretch in the flow direction. When extensional stresses exceed the strength of the ice, cracks and crevasses form transversely to the centerline of the glacier. In contrast, the ice below the surge front moves more slowly and is subjected to compressive stresses, which may cause deformations such as folds or uplifts (Meier and Post, 1969). As the surge front propagates, the zone of deformation or intense crevassing moves up or down the glacier and crevasses allow more water to penetrate deep into the glacier (Sevestre et al., 2018). The water, in turn, increases basal pressure and, as a result, the glacier slides faster down the slope and undergoes further crevassing (Nanni et al., 2025). In the active phase, crevasses and deformation often form on the entire surface of the glacier. During the stagnation phase, crevasses slowly close and deformations become level (Jiskoot, 2011).

2.5.5. Other

Glacier surges affect not only the glacier itself but also the entire local ecosystem, including adjacent glaciers. Numerous observations have helped identify the glaciological and geomorphological features that can be attributed to surges. Some of them are transient, while others may be traces of past surges. Because surges are quasicyclical phenomena, the vast majority of glaciers with recorded surge activity have certainly surged repeatedly in the past. Each successive surge cycle leaves characteristic terrain features that form the so-called surging-glacier landsystem. It helps identify surge-type glaciers, even when no surge has been directly observed (Harcourt et al., 2025). Glaciological features include, among others, looped moraines, shear margins, splayed terminus, strandlines of ice, and surface potholes (Copland et al., 2003; Grant et al., 2009). Remnants of past surges are typically identified with the use of geomorphological criteria, including characteristic features such as crevasse-squeeze ridges and zigzag eskers. Other features may also result from general glacial activity, including non-surge glaciers. Therefore, surge activity is not identified from any single feature, but rather from the entire landsystem, by analyzing the number, size, and distribution of all features in a given area. Remnants of surges are typically more apparent, irregular, and chaotically distributed, and their formation does not seem correlated with any climatic variations (Evans and Rea, 1999, 2003; Grant et al., 2009).

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3. SAR methods

3.1. Background

For several decades researchers have been able to use technological advances to perform satellite observations of glaciers. With large spatial coverage and short revisit times, satellites allow researchers to trace glacier changes both visually and through raster-data analysis. The first data used for glacier mapping came from passive optical satellites, which are still widely used in Earth sciences (Racoviteanu et al., 2008). However, the data obtained with this method is high-quality only if acquired in daylight and with low cloud cover. This limitation was overcome by satellites equipped with radar sensors. Being an active instrument, SAR emits a signal that is scattered from the Earth's surface and then recorded back. Therefore, it does not require a separate light source for the targeted areas (Agrawal and Khairnar, 2019). The ability to acquire data at any time of day is very important in the context of glaciological research, as some areas are located in the Arctic Circle, where polar night occurs. In addition, electromagnetic waves in the microwave range penetrate clouds, so the quality of the images is independent of weather conditions (Dirscherl et al., 2020).

This independence is not the only advantage of SAR over optical systems in glaciological research. The two types of sensors provide different information about the observed surface. Optical images primarily show the biochemical and biophysical properties of the terrain. The sensor divides the reflected signal into beams of different wavelengths, each sensitive to specific surface properties. Therefore, optical data is widely used in land-use and land-cover classification (Joshi et al., 2016). In contrast, SAR sensors record how terrain scatters an electromagnetic wave of known length and polarization. The scattered signal reveals many physical and dielectric properties of the terrain, including roughness, water content, grain size, temperature, and degree of contamination. Also, microwaves penetrate below the glacier surface and show their internal structure (Winsvold et al., 2018). Importantly, SAR data also contain information about the position of a given fragment of terrain at the time of acquisition, and therefore land movement and displacement can be identified by compiling a series of SAR images. For the above reasons, SAR data are widely used in glaciology to map the movement of glaciers, as well as dynamic changes in their surface and internal structure (Joughin et al., 2010b).

From 1978 to the end of 2025, approximately 200 SAR satellites were launched into orbit (D'Errico, 2025). About 20 of them are currently operational as part of such missions as Sentinel-1A/C/D, ALOS PALSAR 2, RADARSAT-2, NISAR, ICEYE. Further satellites, such as ROSE-L-A/B and Harmony, are going to be launched in the future. Their sensors operate at frequencies ranging from 0.3 GHz (P band) to 12.5 GHz (X band). Some instruments allow spatial resolution under one meter and revisit times as short as one day (Drinkwater, 2025).

3.2. Methods

3.2.1. InSAR

Satellite radar interferometry (InSAR) is one of the main methods used to identify ground motion, deformation, and displacement from SAR data. Its most important product is the interferogram, which is obtained by matching and multiplying

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two single look complex (SLC) images of the same area, acquired at a certain time interval and from a slightly different satellite position. The resulting image shows the phase difference between the reference and the repeat image signals. These differences take the form of characteristic fringes. The interferometric phase depends on many factors that affect signal propagation between acquisitions. These factors include Earth curvature, terrain topography, surface deformations, and ionospheric and tropospheric delays, (Sandwell et al., 2025).

An interferogram provides detailed measurements of surface deformations and displacements over a time interval. These changes can be estimated visually from the interferometric phase, as each color cycle, or fringe, represents a phase change of 2π. However, such an estimation requires phase-noise filtering, which does not always produce reliable results (Sandwell et al., 2025). This limitation is addressed with differential interferometric SAR (DInSAR). In the preparation process, digital elevation models (DEM), atmospheric models, or orbital data are used to isolate the phase component associated with surface deformations from other components. In the next step, the interferogram phase, wrapped in the range from $-\pi$ to π, is unwrapped into a form representing actual displacements in metric units (Kwok and Fahnestock, 1996). Optionally, ground control points from an external DEM are used to aid phase unwrapping, improve the baseline, and enable the generation of an accurate displacement map (Murray et al., 2003a).

The main goal of research into glacier movement is to generate flow velocity fields and represent them as velocity maps (Watson and Quincey, 2015). These may provide not only scalar values but also vectors. A single interferogram shows displacement only in the range direction, i.e. radar line-of-sight (LOS). The remaining components of the vector can be calculated under certain geometric assumptions, for example that the flow is parallel to the glacier surface and consistent with the direction of the greatest slope. In this case, the surface velocity can be determined from a single pair of SAR images combined with topography information. The topographic data may be sourced from an external DEM or from a separate topography-only interferogram generated from a pair of long-baseline images (Joughin et al., 1996a; Kwok and Fahnestock, 1996). Joughin et al. (1998) obtained flow velocities by combining two interferograms acquired from ascending and descending paths. This dual-azimuth approach has been widely used to measure the three-dimensional velocity vector under the assumption that the ice flow is parallel to the glacier surface (Mattar et al., 1998; Mohr et al., 1998; Reeh et al., 2003). Reeh et al. (1999) estimated a three-dimensional velocity vector by taking into account the continuity equation, after they had demonstrated that local mass balance and changes in glacier thickness contribute to vertical velocity. Yet another technique is the Multiple-Aperture Interferometry (MAI), in which split-beam technique is used to produce forward- and backward-looking interferograms, and to determine the velocity component in the azimuth direction (Bechor and Zebker, 2006). In several studies, MAI is combined with DInSAR (Gourmelen et al., 2011; Merryman Boncori et al., 2018). Currently, with advances in satellite systems, researchers are able to produce full three-dimensional ice-flow velocity fields from three or more interferograms acquired with different viewing angles (Joughin et al., 2010b).

Phase-based interferometric methods have been used to analyze ice dynamics since their introduction to cryosphere research (Goldstein et al., 1993). InSAR was the first satellite radar method used to track glacier movement (Sandwell et al., 2025). Glacier velocity is identified from time series of repetitive SAR images which show the area of interest at specific intervals.

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These time series allow the monitoring of seasonal or multi-year changes in glacier dynamics (Wen and Wang, 2025). InSAR techniques have been used to study glaciers in polar regions, including Antarctica (Goldstein et al., 1993; Joughin, 2002; Rott et al., 2002, Zhou et al., 2014), Greenland (e.g., Joughin et al., 1996a; Kwok and Fahnestock, 1996; Reeh et al., 2003; Andersen et al., 2020), and Svalbard (e.g., Perski et al., 2003; Wangensteen et al., 2005; Nela et al., 2022), as well as in mountainous regions, including the Andes (e.g., Michel and Rignot, 1999), the Alps (e.g., Mattar et al., 1998) and the Himalayas (e.g., Luckman et al., 2007). Observations of velocity changes in surging glaciers follow the same principles and therefore frequently employ InSAR methods, for example in Svalbard (e.g., Dowdeswell et al., 1999; Luckman et al., 2002; Murray et al., 2003a; Murray et al., 2003b; McMillan et al., 2014; Strozzi et al., 2017b), in Alaska (e.g., Fatland and Lingle, 1998), and in Greenland (e.g., Joughin et al., 1996b, 1999, 2010a; Mohr et al., 1998; Murray et al., 2002). Although most of the studies produce velocity maps, some rely only on wrapped interferograms (e.g., Murray et al., 2002) or displacement maps produced without generating velocity fields (e.g., Schneevoigt et al., 2012).

Another important application of InSAR is in generating high-quality DEMs from two SAR images acquired from different positions (Zebker and Goldstein, 1986; Hanssen, 2001). These models provide information about the topography of the analyzed area and are widely used in differential interferometry. By comparing compatible DEMs of the same area but acquired at different times, it is possible to determine elevation changes directly for any point in space (Neckel et al., 2013). Studies of glacier dynamics often involve vertical displacements, particularly in the case of active surge phases, when the upper part of the glacier lowers significantly, while the lower part rises (Meier and Post, 1969). DEMs generated specifically for a particular study, e.g., from TanDEM-X SAR images, can be used to track the height of surging glaciers (e.g., Wendt et al., 2017; Guo et al., 2020). Studies of glacier surges also employ various local and global models, including data from Shuttle Radar Topography Mission (SRTM), which are produced by interferometric processing of C-band images (Farr et al., 2007). Although SRTM is not available for polar regions, it is an important source of data for Central Asia (e.g., Yan et al., 2019; Paul et al., 2021; Zhou et al., 2024). Sometimes, DEMs provide information about changes of ice volume in specific glacier regions and surge phases, or about total mass transfer (e.g., Muskett et al., 2008; Gardelle et al., 2013, Neckel et al., 2013; Kienholz et al., 2016, Steiner et al., 2018). In some cases, subsidence and thickness changes during a surge can be derived directly from the unwrapped interferogram (e.g., Sigmundsson et al., 2005).

3.2.2. Offset tracking

The idea that ice velocity can be measured from the displacement of surface features over time predates satellite imaging missions. For example, Harrison (1964) estimated the velocities of a surging glacier by comparing the positions of debris patterns identified on the glacier surface from maps and photographs. Repeated measurements of the position of a marked terrain object are basic to both classical geodetic methods and those relying on satellite positioning systems (e.g., Jania et al., 2002; Flowers et al., 2016; Gajek et al., 2025). They were improved with the advent of satellite imagery. Lucchitta and Ferguson (1986) used successive Landsat mission optical images to determine the velocity of a glacier in Antarctica. They co-registered the images by manually identifying characteristic surface features, such as rifts, depressions, tidal cracks, and

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crevasses (Lucchitta and Ferguson, 1986). This feature-tracking process was further improved by adding automatic or semi-automatic cross-correlation (Bindschadler and Scambos, 1991). The algorithm divides the reference image into chips and searches for corresponding features in the repeat image (Scambos et al., 1992). The user determines the optimal size of a single chip, which should be small enough to avoid excessive internal variation, but also large enough to obtain maximum correlation. Measurements that do not meet the specified correlation threshold are rejected, and the repeat image is resampled to obtain an accurate matching (Werner et al., 2005). The peak of the local correlation function indicates the displacement value (Haug et al., 2010). Image-matching methods differ in domain or normalization. They include normalized cross-correlation in the spatial domain as well as cross-correlations and phase correlations in the frequency domain, based on the fast Fourier transform (Heid and Kääb, 2012). The latter group includes the algorithm implemented in the COSI-Corr software (Leprince et al., 2007).

Feature tracking in optical images has been widely used in cryosphere research (e.g., Haug et al., 2010; Redpath et al., 2013; Dehecq et al., 2015; Chen et al., 2016; Kääb et al., 2016; Gardner et al., 2018; Miles et al., 2018; Wood et al., 2025), as well as in studies of surge-type glaciers (Denby et al., 1997; Kääb et al., 2005; Błaszczyk et al., 2009; Mayer et al., 2011; Turrin et al., 2013; Quincey et al., 2015; Chudley and Willis, 2019; Li et al., 2024). The method has been relatively quickly adapted to radar images (e.g., Fahnestock et al., 1993; Gray et al., 1998). It also led to the development of the offset-tracking method, which is a SAR-data equivalent of feature tracking. The difference between the two concepts is that optical imagery tracks the displacement of visible terrain objects, while radar imagery tracks the displacement of patterns or signal scattering derivatives (Leinss et al., 2022). Offset tracking measures displacements in both range and azimuth directions, so it can be used to create two-dimensional velocity maps. The third dimension of the vector space can be obtained from the slope in the DEM, under the assumption of surface-parallel flow (e.g., Rignot and Mouginot, 2012; Strozzi et al., 2017a). Alternatively, a full three-dimensional vector can be obtained by combining the results of offset tracking from the ascending and descending orbits, as they provide displacements in a total of four directions (e.g., Nagler et al., 2012; Guo et al., 2020).

Offset tracking is a set of several techniques based on the same principles but using different types of input data for correlation (Dirscherl et al., 2020). One of such techniques is coherence tracking, introduced by Derauw (1999) as a support to InSAR-based glacier velocity studies. In this technique, an interferogram is first obtained from SLC images and then divided into small fragments. In the next step, coherence is estimated between each of the image fragments, and correlation windows are shifted until the maximum possible coherence is achieved. In this method, maximizing coherence is equivalent to finding the peak of cross-correlation. Coherence decrease between repeated images is assumed to result from pixel mismatch caused mainly by glacier movement (Derauw, 1999; Strozzi et al., 2002).

Natural surfaces without coherent scatterers produce unstable radar-wave scatter. Each pixel in an SLC image is a complex sum of phase and amplitude. Its value is recorded with a certain degree of randomness, and the variance of a single measurement is comparable to its expected value. Therefore, SAR images contain granular structures, called radar speckles or speckle noise (Oliver and Quegan, 1998). Although excessive noise generally interferes with analysis, it can often help determine horizontal displacements, and based on this observation Gray et al. (1998) introduced the so-called speckle tracking method. In SAR intensity or amplitude images, correlation is achieved by matching similar speckle patterns. As in the case of

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coherence tracking, displacements can be detected with sub-pixel accuracy. On the other hand, speckle tracking may produce a sharper correlation peak, if intensity (the square of amplitude) is used (Gray et al., 1998; Leinss et al., 2022).

Intensity tracking, yet another offset-tracking technique, is the most similar to optical feature tracking, as both of them track specific physical features of the terrain (Leinss et al., 2022). It performs well also when two SAR images signals are weakly correlated. Therefore, some studies refer to it as incoherent offset tracking, in contrast to speckle pattern correlation, which is sometimes referred to as coherent offset tracking (e.g., Merryman Boncori et al., 2018). However, intensity tracking requires larger correlation windows to provide more spatial context for identifying surface features (crevices, rocks, cracks, etc.) and to average speckle noise (Strozzi et al., 2002). It is also less accurate than coherence tracking and speckle tracking and it has limited accuracy, because the window size increases its computational demand, but this problem can be solved by performing cross-correlation in the frequency domain using the fast Fourier transform (Leinss et al., 2022). Another improvement, proposed by Erten et al. (2009), consists in replacing cross-correlation with a maximum likelihood statistical approach, so as to increase the accuracy of displacement estimation, especially under low-coherence conditions.

SAR offset tracking is a common method in cryosphere research. It has been used to determine the velocities of glaciers in the Arctic (e.g., Luckman et al., 2003; Gourmelen et al., 2011; Nagler et al., 2012; Rignot and Mouginot, 2012; Paul et al., 2015; Milczarek et al., 2022), in Antarctica (e.g., Gray et al., 1998, 2001; Joughin, 2002; Pattyn and Derauw, 2002; Zhou et al., 2014) and in high mountain regions (e.g., Michel and Rignot, 1999; Luckman et al., 2007). It is also widely used in monitoring glacier surges in Svalbard (e.g., Strozzi et al., 2002; Murray et al., 2003b; Mansell et al., 2012; Strozzi et al., 2017a; Sevestre et al., 2018; Koch et al., 2023; Kavan et al., 2024), in Greenland (e.g., Murray et al., 2002; Pritchard et al., 2005; Joughin et al., 2010a; Hill et al., 2017; Mouginot et al., 2018), in Central Asia (e.g., Quincey et al., 2011; Yasuda and Furuya, 2015; Round et al., 2017; Wendt et al., 2017; Yan et al., 2019; Yao et al., 2019; Guo et al., 2020; Paul et al., 2021) and in other glaciated regions (e.g., Strozzi et al., 2008, 2017b; Burgess et al., 2012; Burgess et al., 2013). While the majority of studies employ intensity or speckle tracking, some rely on a combination of different techniques (e.g., Strozzi et al., 2002; Merryman Boncori et al., 2018). Offset tracking is an important method in ice cover mapping missions. It is used in various programs and initiatives to provide data on glacier velocities in both global (e.g., Gardner et al., 2025) and regional scale (e.g., Jezek et al., 2003; Friedl et al., 2021; Solgaard et al., 2021). Its output data aid research on glaciers, including on glacier surges (e.g., Hill et al., 2018; Solgaard et al., 2020; Guillet et al., 2022, 2025).

3.2.3. Altimetry

Satellite altimetry involves measuring the distance from the satellite to the Earth's surface on the basis of the return time of a pulse emitted by an instrument aboard a satellite. This measurement is then converted to surface elevation, by allowing for the position of the satellite relative to a reference ellipsoid (Fu and Cazenave, 2001). Elevations are determined for points along the flight path of a satellite. Both laser and radar altimetry have long been used in environmental monitoring. Radar altimeters are less accurate than laser altimeters. However, like radar imaging instruments, they emit microwave waves, and therefore they can acquire data regardless of the time of day and cloud cover. They can also penetrate snow and firn. The first devices

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of this type were installed on the ERS-1 and ERS-2 satellites. They were conventional instruments originally designed for use in oceanography and they performed poorly in cryosphere studies (Rémy and Parouty, 2009). Significant progress was made with the introduction of delay radar altimetry (SAR altimetry). This technique uses the Doppler effect to compensate for signal propagation delays resulting from complex terrain topography, in a manner similar to how SAR instruments correct for the curvature of the Earth (Raney, 1998). As a result, SAR altimetry can be successfully applied in areas with different surface relief. Currently, glaciological research relies mainly on data from the CryoSat-2 mission, designed specifically to monitor continental and marine ice. The satellite is equipped with SIRAL, an instrument which operates in three modes: LRM (low-resolution mode – designed for flat interior ice sheets), SAR (synthetic aperture mode – designed for sea-ice and coastal zones), and SARIn (interferometric mode – designed for steep ice sheet margins and high-slope mountain glaciers) (Drinkwater et al., 2004, Wingham et al., 2006).

Radar altimeters have been used to generate large-scale DEMs and to analyze changes in the thickness of ice sheets e.g. in like Antarctica and Greenland (e.g., Bamber et al., 2001; Helm et al., 2014; Slater et al., 2018; Byrne et al., 2024). In such applications, accurate interpolation requires elevation measurements from as many points as possible, i.e. the study area should be densely covered by satellite flight paths. Both conventional and SAR instruments are effective for such tasks, because ice sheets typically have small slopes, i.e. the ratio of the elevation difference to the satellite footprint length is small (Rémy and Parouty, 2009). However, glacier studies, especially in areas with complicated topography, require a different approach and benefit from employing SAR instruments with interferometric mode (Dehecq et al., 2013). SAR enables advanced swath altimetry processing, in which the height of the ice surface is measured not only at the nadir point, but also in the swath on both sides of the satellite's flight path (Gourmelen et al., 2018). With the sufficient spatial density of the satellite footprints on the glacier surface, researchers can reconstruct longitudinal profiles for different periods and use them to analyze elevation changes between these periods. SAR altimetry has already been successfully used to monitor glaciers undergoing rapid mass redistribution associated with surging, and to quantify surface elevation changes during different phases of the surge cycle (e.g., Trantow and Herzfeld, 2016; Foresta et al., 2018; Morris et al. , 2020; Trantow et al., 2021).

3.2.4. Backscatter

SAR instruments emit pulses of energy which are, after interacting with the Earth, partially reflected from surface objects and partially backscattered by them. The backscattered part of the signal returns to the instrument and is recorded by the sensor. Its strength is manifested as the amplitude value in pixels of the target image (Curlander and McDonough, 1991). Interactions with flat and smooth surfaces reduce the signal strength. As a result, pixels representing such surfaces store lower values and are dark. In contrast, rough surfaces produce more backscatter, and because more signal returns to the instrument, such surfaces appear brighter. Backscatter strength depends not only on the roughness of the surface, but also on other properties such as water content, grain size, conductivity, temperature, and internal structure. These properties have been used repeatedly in glaciological research, for example to identify individual glacial facies (e.g., Fahnestock et al., 1993; Hall et al., 2000; Winsvold et al., 2018).

Leclercq et al. (2021) were the first to use SAR backscatter data as the primary indicator of surface changes in surging glaciers. Because during the active surge phase the glacier surface deforms extensively, the resulting crevasses have rough surfaces and the signal that interacts with them is stronger than after interaction with other parts of the glacier, such as wet snow. The authors used winter SAR images from the Sentinel-1 mission in the C band to generate aggregated rasters of maximum backscatter for different periods. In the next step, they calculated normalized seasonal differences and identified global surge activity by assuming that the unnaturally rapid increase of backscatter values in the time series results from the rapid formation of crevasses (Leclercq et al., 2021). The same method was used by Kaab et al. (2023), who additionally generated minimum and maximum backscatter rasters for the entire analyzed period to obtain a broader temporal context. Strozzi et al. (2026) combined backscatter data from current and past missions to detect surges in Svalbard. Guillet et al. (2025), in turn, adapted backscatter anomalies as one of the criteria for global-scale surge detection, alongside surface velocities and elevation changes.

3.2.5. Coherence maps

Interferometric coherence indicates similarity between SLC images. When the phase and amplitude of the radar beams are consistent between acquisitions, the data for a given area are well correlated and are represented in bright pixels. Low coherence, which appears as dark spots on the image, typically indicates temporal decorrelation between reference and repeat images. This results from various environmental processes, such as displacements or vegetation growth, which change terrain properties and, consequently, the scattering pattern of radar waves. In glaciological studies, decorrelation may result from changes in water content due to seasonal melting, heavy precipitation, or rapid glacier movement (Zebker and Villasenor, 1992; Sandwell et al., 2025).

Loss of coherence is an obstacle in conventional InSAR studies, as it significantly complicates or even prevents phase unwrapping. However, it can also indicate upcoming glacier activity. Early SAR studies of surging glaciers demonstrated spatial and temporal relationships between decreased coherence and increased ice velocities during the active phase. Strozzi et al. (2002) used a phase raster to show that a fast-flowing glacier is visible as noise-like structures rather than as regular interferometric stripes. Murray et al. (2002) visually interpreted and described the differences between interferograms produced from data acquired during and after the surge.

Mannerfelt et al. (2025) published the first study in which glacier surge monitoring is based entirely on interferometric coherence analysis. The authors treated coherence loss as the main indicator of surge activity, and attributed it to changes in radar wave scattering properties caused by changes in the glacier surface and structure during the buildup phase. Using time series of coherence maps from Sentinel-1 data, they identified spatial and temporal patterns in the propagation of low coherence areas along surge-type glaciers in Svalbard. They demonstrated that a low coherence front can be interpreted as a surge front, whose migration precedes or accompanies the active phase. Their approach enables retrospective determination of the surge duration, as well as predictions about future glacier activity. The authors emphasize that coherence analysis can be used to detect early changes which occur during the buildup phase but often remain undetected by other methods (Mannerfelt et al., 2025).

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4. Discussion

4.1. Challenges in glacier surges research

Research into glacier surges is complicated by various obstacles. For example, in situ observations are logistically challenging, because they require the presence of a crew directly on the glacier, which is often located far from permanent settlements. Manually marking measurement points and collecting data is a time-consuming process, which often fails to produce a sufficiently large and representative data set. In addition, field work on glaciers involves increased risk due to rapid ice movement and extensive crevassing. Satellite imaging missions have largely overcome these problems by providing effective remote monitoring tools. With satellite imagery, glacier changes can be now monitored with unprecedented accuracy owing to large-scale spatial coverage and high-frequency repeat acquisitions (Watson and Quincey, 2015). The increase in the number of satellites and in the availability of data from different orbit tracks also enables a more accurate simulation of glacier flow patterns and reduce the need to simplify assumptions (Joughin et al., 2010b).

However, a number of other challenges cannot be overcome by improving observation technologies, because they result from the complexity and unpredictability of glacier surges, especially those of the Svalbard type, whose cycle is very long and whose quiescent phase may last several hundred years, minimizing the chances for direct observations of several complete cycles of the same glacier. Reconstructing surge histories requires the integration of different data sets. The process is laborious, and it is rarely possible to obtain a complete and continuous time series (e.g., Devaux-Chopin et al., 2025). Another problem results from the diversity of surge-type glaciers, both between regions and between adjacent glaciers (Cuffey and Paterson, 2010). As a result, each glacier often requires individual analysis informed by its surge history, if such information is available. The definition of a surge and its identification criteria also remain subject to debate, and as a result many local and global inventories classify surge-type glaciers differently (Hareid and Truffer 2015). Subtle or slowly evolving surge-related features inevitably introduce some degree of uncertainty to the identification and classification of surge-type glaciers, which is hence increasingly performed not on a binary, but rather on a probabilistic basis (Jiskoot et al., 2000). Because of the complexity of surge-related phenomena some researchers have proposed to redefine the concept of a surge and to treat it as part of a broader spectrum of flow instability (Jiskoot et al., 2001).

4.2. Performance of SAR methods

The SAR-based methods discussed in section 3 have their advantages and limitations, documented in the literature on glacier dynamics and glacier surges. Since the launch of the first satellites, many of these limitations have been removed owing to technological advances and greater availability of high-quality data. However, some of them may still affect the choice of particular research methodology.

Methods based on interferometric phase and offset tracking can be used to monitor changes in the surface velocity of a surging glacier. InSAR allows terrain displacement to be determined with an accuracy of one centimeter or even a few millimeters. A full 3D velocity vector can be derived from several interferograms (Dirscherl et al., 2020). The most important step in the process is phase unwrapping, which remains a challenge, despite the introduction of advanced algorithms. InSAR methods fail mainly because of low coherence between SLC images, which can be caused by rapid flow, changing properties of glacier surface due to intense deformation, snowfall or melting, and by insufficient acquisition frequency (Sandwell et al., 2025). As a result, interferometric methods have limited applicability in the case of fast-flowing glaciers and acquisition intervals of more than several days or tens of days. This risk of decorrelation, or actually observed decorrelations, have caused some authors to abandon InSAR in favor of other methods (e.g., Gray et al., 2001).

Offset tracking is a popular alternative to InSAR for measuring displacement and velocity. One of its variants, intensity tracking, requires only some identical features on the glacier surface that can be identified on each intensity or amplitude image in the time series. High coherence between images is not required in this technique. However, it produces less accurate results, because the area covered by terrain features is usually larger than the area covered by a single image pixel. Sub-pixel accuracy is available in coherence tracking or speckle tracking, which involve analyzing partial echoes of the radar signal. They are also effective in homogeneous areas which lack distinctive features. Their limitation, however, results from the need to maintain correlation. They can be therefore disturbed by the same factors as in the case of interferometry, with the only exception being speckle tracking of ground range detected (GRD) images, which do not store phase information (Joughin et al., 2010b; Schubert et al., 2013).

Elevation changes in individual parts of a surging glacier can be measured with InSAR or radar altimetry, and each of these methods has its advantages and limitations. SAR altimeters measure elevations only for points along the track, and therefore a continuous value map requires interpolation (Rémy and Parouty, 2009). The revisit time for the CryoSat-2 satellite is 369 days. Changes can be observed at 30-day intervals, when new tracks intersect with previous ones, but with limited geometric repeatability (Wingham et al., 2006). The accuracy of altimetry is relatively high, but still lower than of laser instruments. In addition, the results of swath processing are subject to systematic errors which may exceed 10 m in areas with complex topography (Haacker et al., 2023). On the other hand, altimetry provides elevation directly, and its results do not depend on data coherence between acquisition periods. In effect, altimetry methods are more suitable for monitoring long-term changes in glacier elevation and for estimating total mass redistribution over a surge cycle.

In interferometry, vertical displacements are measured by combining data from at least two observation angles. InSAR provides highly accurate results and continuous spatial information in each pixel of the interferogram. It is therefore useful for studying spatiotemporal patterns in glacier dynamics. However, it requires advanced processing to provide elevation changes, and it is prone to potential decoherence, as is the case in tracking surface velocity changes. In effect it is useful only in well-defined case studies with sufficient data availability (Dirscherl et al., 2020).

Unlike the three above-mentioned methods, backscatter and coherence maps provide diagnostic information rather than direct quantitative results. They are also used to observe different surge aspects. An increase in backscatter values may indicate crevassing in the active phase of the surge. However, such processes as snowfall and seasonal melting also affect signal scattering and may complicate surge detection. Potential solutions include analyzing only images acquired in winter or using appropriate statistical tools to filter seasonal variations from the backscatter signal in the time series (Guillet et al., 2025). This

https://doi.org/10.5194/egusphere-2026-3849
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method is effective in monitoring surges of glaciers with intense surface changes. However, slower and less significant changes may remain undetected by the algorithm, and manual interpretation of backscatter values may be occasionally needed (Strozzi et al., 2026).

The coherence map method, like the backscatter method, does not quantify surge parameters such as velocity increase and elevation changes. However, it can track the propagation of the glacier instability front in each phase of the surge cycle. This propagation is visible in coherence rasters, which are a direct product of interferometry. Therefore, the method does not require complex processing and does not cause problems related to phase unwrapping. Coherence is sensitive even to subtle changes in the surface and structure of the glacier, and in effect it enables the detection of surge activity long before an increase in velocity or the formation of crevasses are observed. Therefore, it can be implemented in early warning systems and prediction models (Mannerfelt et al., 2025), with a reservation that a decrease in coherence may result from factors unrelated to glacier dynamics, such as precipitation, melting, and temperature changes. Also, if surge symptoms are weak, coherence changes and the instability front may be difficult to track. The coherence map method is relatively new and so far has been tested only in Svalbard. Therefore, more studies are needed to better understand its advantages and limitations.

The performance of SAR methods in surge studies is summarized in Table 1. Although the selection of data and methodology should be tailored to each case, no universal set of criteria determines which method can be applied to a specific case, for example to expected surface velocities or the time interval between images. The priority is to characterize the study area, including the topography and local climatic conditions. Previous studies of the glacier should also be consulted, if available. This information helps identify factors likely to interfere with satellite observations and aids the development of mitigation strategies. It also helps to predict the nature of the surge and its possible manifestations, and so to choose appropriate data sources, processing methods, and temporal sampling frequency. A precise definition of surge aspects for analysis requires the ability to distinguish between signals directly related to surge activity and those resulting from other glaciological, meteorological, or climatic processes. Contemporary studies tend to analyze several parameters simultaneously, in particular surface velocity and changes in ice elevation (e.g., Wendt et al., 2017; Guillet et al., 2025). They also use auxiliary data, such as optical imagery, to facilitate the visual interpretation of ground events (e.g., Leclercq et al., 2021; Mannerfelt et al., 2025). Many studies combine different observational methods and approaches so as to compensate for their individual limitations (e.g., Luckman et al., 2002; Kääb et al., 2023).

Table 1. Performance of SAR methods in surge studies.

Method	Measured quantity	Surge aspects captured	Accuracy	Limitations	Recommended use
InSAR	LOS displacement	Ice velocity changes, deformation	mm-cm	Temporal/spatial decorrelation, phase unwrapping errors, sensitivity to rapid motion	Slow/moderate surges, short time intervals, initial or final phases of the surge

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Offset tracking	Intensity	Horizontal displacement	Ice velocity changes	m (resolution-dependent)	Lack of characteristic or repeat land features	Fast surges, large areas, large displacements, culminating phase of the surge
	Speckle			m (sub-pixel, resolution-dependent)	Decorrelation, lack of repeat speckle patterns	Moderate/fast surges, areas with limited optical texture
	Coherence				Sensitivity to surface properties changes	Alternative in case of loss of coherence, complementing other tracking techniques
SAR altimetry		Surface elevation	Elevation changes	dm-m	Sensitivity to very steep areas, limited number of measurement points	Long-term analyses, mass redistribution studies
Backscatter analysis		Radar backscatter intensity	Surface properties changes (crevassing)	Indicator	Sensitivity to weather and ice conditions	All types of surge, long-term analyses, intense deformations
Coherence maps		Coherence between acquisitions	Propagation of instability front	Indicator	Sensitivity to weather and ice conditions	Build-up phase of the surge, short time intervals

4.3. Current research trends

Although approaches to surge research have evolved since the first applications of SAR methods, they still follow trends established in studies from the turn of the twentieth century. While the methods and processing technologies used in these studies may be out of date, their findings on surging remain valid. They are considered classic and continue to be frequently cited. The current literature on remote sensing in research on surging glaciers indicates several trends that can be classified by the research problem or the study purpose. The research motivation and the expected results inform the choice of input data and the processing methods.

The first trend is to detect surge activity and surge events occurring over a specific period (e.g., Leclercq et al., 2021; Kääb et al., 2023; Koch et al., 2023). Such analyses are typically based on a multi-year or multi-decade time series of SAR images and involve identifying surge symptoms from anomalies in glacier parameters, e.g. sudden increases in surface velocity, elevation changes, or intense crevassing. The detection mechanism is based on an algorithm that identifies such exceeded parameter threshold values to automatically or semi-automatically classify the anomalies as related to surge activity. Research into surge activity detection can be conducted on a global scale or for selected regions and is rather not aimed at monitoring the long-term behavior of individual glaciers.

Another trend is to produce or update inventories of surge-type glaciers (e.g., Bouchayer et al., 2022; Guillet et al., 2022; Lovell et al., 2026). Therefore, they require unambiguous glacier classification against established criteria. Longer time series are preferable, as they provide better temporal context and reveal recurring surge symptoms. Glacier classification is complicated, as surges have a variety of manifestations which need to be considered from many glaciological and

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geomorphological perspectives. Because of these difficulties, researchers often use ready-made datasets, for example, to track velocity changes. The probability of a glacier surge can be estimated with the use of machine learning models. Because of individual approaches to inventory construction, new inventories almost always differ from earlier inventories constructed for the same area. Also, research is typically limited to one of the documented big clusters of surge-type glaciers.

Still another trend in the study of glacier surges is to focus on one or several glaciers which have already been observed to surge (e.g., Mouginot et al., 2018; Solgaard et al., 2020; Devaux-Chupin et al., 2025; Zhao et al., 2026). This approach consists in studying all of the glacier's available surge history, which sometimes goes back as far as to the first half of the previous century. The results of these historical studies are then compared with the results obtained from both archival and new satellite data, or from existing databases. Such research results in a continuous and chronological record of surge activity and allows conclusions about the long-term dynamics of the investigated glacier.

The proposed classification does not include all publications on glacier surge studies. Some of them, for example, combine several approaches: they detect surge events and simultaneously analyze the involved processes and mechanisms (Guillet et al., 2025) or they detect surges while tracking changes in the behavior of a group of glaciers over long time periods (Strozzi et al., 2026). Some approaches are strictly methodological, and their main goal is to test and compare SAR data processing methods and algorithms without detailed monitoring of a specific surge event (e.g., Strozzi et al., 2002; Schubert et al., 2013). Other studies apply glacier physics to investigate the connections between surge activity and environmental conditions and events (e.g., Sevestre and Benn, 2015; Lovell et al., 2023). Still other researchers attempt to reach a broader understanding of the phenomenon and its mechanisms or to formulate a general surging model (e.g., Murray et al., 2003b; Sevestre et al., 2018; Benn et al., 2019).

4.4. Potential for future research and the role of SAR

Current directions in research on glacier surges seem promising and therefore future studies may benefit from following and further exploring them. Short-term observations of surge events advantageously rely on the latest high-quality data. The results of such studies can be used in automatic detection models, or to map areas prone to surge effects, as well as to identify regions worth more detailed analyses. Also, inventories of surge-type glaciers may be useful in case studies or as training data for machine-learning models. Investigations of the relationship between the spatial distribution of surging glaciers and environmental conditions, such as climate or topography, may reveal factors determining the likelihood of a surge. Long-term monitoring is crucial for studying individual cycles, developing criteria for the classification of surge behavior types, and understanding how glaciers might respond to global climate change. Methodological studies are also important, as they may provide the much needed strict criteria for selecting a method best suited to a specific case. This literature review indicates that when considered individually, the current trends do not provide universal solutions, and therefore they should be considered as complementary elements of a coherent system. All identified current research trends and their future development potential are summarized in Table 2.

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Table 2. Current research trends in SAR-based glacier surge studies and their development potential.

Research trend	Main objective	Spatial scale	Temporal scale	Main challenges	Future development potential
Surge detection	Identification of surge events within a defined period	Regional/ global	1-25 years	Threshold definition, false positives, heterogeneous surge behavior	AI automation, near-real-time monitoring, hazard mapping
Classification and surge-type glaciers inventories	Systematic identification of surge-type glaciers	Regional/ multi-regional	Decadal	Ambiguous criteria, incomplete historical records	Machine learning classification, probabilistic surge likelihood models
Long-term case studies	Reconstruction of surge history	Individual glaciers	Multi-decadal	Incompatible datasets, lack of temporally continuous data	Multi-mission integration, upcoming data utilization
Methodological studies	Testing and comparison of the methods	Variable	Variable	Risk of too small research sample, impact of changing glacier conditions	Integration of multi aspect indicators
Controls and surge mechanisms	Finding correlation between surge activity and environmental conditions	Regional/ global	Multi-decadal	Multitude of factors, limited amount of in situ validation data	Upcoming data utilization, integration SAR observations with physical modeling

The increasing applications of artificial intelligence (AI) in geosciences justify its further implementation, also in the study of glacier surges. Machine-learning and deep-learning models have the potential to detect surge symptoms and identify surge-type glaciers in SAR imagery at a rate comparable to the acquisition frequency. They could be trained on data describing various aspects of surges, such as surface velocity, elevation, and backscatter. This research direction is an opportunity to provide valuable products and effective tools for glaciology, including surge susceptibility maps, surge hazard category maps, glacier instability indicators, or practical software like AI agents dedicated to specific regions. An important research gap in the field can be closed if tests show that such models can be implemented in early warning systems and in predicting future surge events.

Over the past years, the number of SAR satellites has significantly increased, and currently researchers have access to large archives of high-quality data, which are expected to further expand owing to current and future satellite missions. As a result, researchers will be able to analyze increasingly longer time series and will have greater chances for direct observations of full surge cycles. Larger research samples will enable more in-depth conclusions about the temporal and spatial patterns of glacier dynamics. This progress is accompanied by developments in SAR-processing algorithms and methods for utilizing SAR data, as evidenced by the relatively recent approaches based on backscatter and coherence maps. Observations of glacier surges are becoming increasingly multivariate. Recent studies expand classic approaches based only on changes in velocity or/and elevation, to include such new aspects as changes in glacier surface properties and the propagation of instability front. These methods should certainly be further developed and tested on examples from other periods and regions. The results should be confronted with the results obtained with other methods and independent datasets to determine the scope of applicability. The

https://doi.org/10.5194/egusphere-2026-3849
Preprint. Discussion started: 29 September 2026

coherence map method deserves special attention, as it innovatively uses InSAR products and is both intuitive and computationally efficient. It also shows significant potential in addressing the research gap of lacking effective methods for early detection of surge activity and predicting future surges.

5. Conclusions

This study presents a review of SAR methods used in research on glacier surges. Although this phenomenon is relatively rare, it has a significant impact on the global dynamics of glaciers and on the cryosphere. Its unpredictability, complexity, and long-term characteristics cause it difficult to observe and fully understand. With the development of satellite remote sensing, glacier behavior can be monitored over large areas and with high sampling frequency. In monitoring glacier surges, active imaging gives SAR data an advantage over optical data.

None of the discussed SAR-based methods fully describe glacier surging. They provide information on different aspects of this phenomenon. For example, InSAR and offset tracking provide information on ice velocity changes, displacements, and deformations; SAR altimetry – on elevation changes and mass redistribution; backscatter – on changes in surface properties; coherence maps – on the propagation of the glacier instability front. Therefore, for best results, glacier-surge research should combine the above approaches by integrating various SAR products and methods.

Some of the challenges in surge studies result from the nature and ambiguity of the SAR data signal, which must be correctly interpreted. Additional limitations unrelated to observational technologies include long and irregular surge cycles, diverse surge behaviors, and ambiguous definitions and classification criteria. The solution seems to lie in the combination of remote sensing and geoinformatics with glaciology and physics. Still, however, caution is required in formulating assumptions and evaluating results. In the future, growing data archives are expected to enable the analysis of surges in a broader temporal context. The significant potential of SAR methods is demonstrated by new approaches, such as tracking backscatter changes and monitoring the propagation of low-coherence areas. In a long-term perspective, the range of such traceable surge manifestations will expand and further aid SAR-based research.

Author contributions

M.C. and W.M. conceived the idea for this review article and developed its overall concept. M.C. conducted the literature review, compiled and synthesized the information, drew the conclusions, and wrote the original manuscript. W.M. supervised the study and provided scientific guidance throughout the project. Both authors approved the final version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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