A REVIEW OF SURGE-TYPE GLACIERS

Zixiang Sun , Gang Qiao*

[1] College of Surveying and Geo-Informatics, Tongji University, 1239 Siping Road, Shanghai, China – (1933658,qiaogang) @tongji.edu.cn

Commission TCIII, WG III/9

KEY WORDS: Glacier surge, Surface displacement, Glacier thickness, Mass gain, Mass loss.

ABSTRACT:

The study of glacier surges is meaningful for the understanding of glacier dynamics and the mechanisms of surge-type glaciers. Here, we briefly introduce the distribution of surge-type glaciers and the reason of their tendency to cluster within particular regions. Then we make a review of optical and SAR remote sensing methods for the spaceborne measurement of the surface velocity about surge-type glaciers and show the details of characteristics of Surging Glaciers including the acceleration and deceleration of the velocity of the glacier surface, the terminus may move forward a few kilometers in just a few months, then we give a specific example of surge-type glacier, Sortebræ. Finally, we summarize the existing mechanism of the glaciers surging.

1. INTRODUCTION

Glacier surging is a phenomenon that the speed of glacier movement alternates between slow and fast and regularly. The surface velocity of a surge-type glaciers fluctuates between a long-term low velocity (a period of tens or even hundreds of years) and a short-term high velocity (1-10 years) (Clarke et al. 1984; Jiskoot et al. 1998). The speed of ice flow during the surging phases is dozens or even hundreds of times faster than that during the quiescent period. The occurrence of the surging phenomenon is usually considered to be due to internal instabilities such as the hydrological conditions at the glacial bed or the topographical factors and are not thought to be directly triggered by external climate forcing (Sevestre and Benn 2015; Sharp 1988). During the quiescent periods, the surface velocity of the entire glacier is in a very low state. At this stage, the upper reservoir area of the glacier is supplied with ice mass due to factors such as precipitation and snowfall. Converging ice flow thickens the upper reservoir area, the lower part stagnates and thins by ablation, and the front end of the glacier usually retreats. The surge appears to start when the state of the entire glacier reaches a certain critical state. Since a large amount of ice is redistributed in a short period of time, the occurrence of the pulsation phenomenon is usually accompanied by a rapid advance of the front end.

Only~ 1% of the world’s glaciers have been observed to have surging behavior (Jiskoot and others, 1998; Sevestre and Benn, 2015). The surge-type glaciers cover a wide range of types, including land-terminating and tidewater glaciers, temperate and polythermal glacier, cirque glaciers, valley glaciers as well as ice streams (Murray, 2003). One of the most distinct facts about surge-type glaciers is that they are not randomly distributed, but concentrated in certain areas. The surging behavior in different regions of the world is also very different. For example, glaciers in Svalbard tend to have surge periods lasting 3-10 or even decades, and the static periods lasting between 50 and 500 years (Dowdeswell et al. 1991). For the surge-type glaciers in Alaska and Yukon, the surge period is generally 1-3 years, and the quiescent period is 20-40 years (Dowdeswell et al. 1991; Murray et al. 2003). These two different regions of surge-type glaciers also correspond to two different types of surging mechanisms: thermal (Clarke et al. 1984; Murray et al. 2003) and hydrological (Kamb 1987) mechanism. Although surge-type glaciers are rare, it is of great significance to the study of glacier dynamics and the mechanisms of surge-type glaciers. The study of glacier surges in the north-west West Kunlun Shan indicates that surging may be related to climate change (Chudley et al. 2018). In addition, this kind of study can provide valuable insight into internal evolution of glaciers and global climate change. The movement of a large amount of ice during glacier surging may have a huge impact on the life safety of people in the downstream area and through their influence on glacial lake outburst floods (GLOFs) (Bhambri et al. 2020).

The study on surge-type glaciers is mainly carried out from two aspects. One is the surface velocity, mainly through SAR and optical remote sensing methods. Optical imaging technology generally traces the characteristics of the glacier surface (e.g., crevasses, rifts, cracks) (feature tracking) or the cross-correlation of entire image patches (image matching) in successive co-registered satellite images of the same location (Heid and Kääb, 2012; Lucchitta and Ferguson, 1986). The way to use SAR remote sensing to derive surface velocity is mainly divided into two technologies: phase-based and offset-based. Phase-based methods include differential interferometric SAR (DInSAR) and Multiple-Aperture Interferometry (MAI) while offset-based methods can be categorized into speckle, co-herence and intensity tracking (Dirscherl, 2020). Another aspect is the elevation decrease in the upper reservoir area of the glacier and the increase of the terminal part of the glacier during the surging periods. Elevation information can be obtained through airborne laser scanner (ALS), ICESat-mission, or two TanDEM-X, ASTER,DISP images.

* Corresponding author

In this study, we briefly introduce the characteristics of surface velocity and elevation changes during the surging period, and summarize the mechanism of the glaciers surging.

2. THE DISTRIBUTION OF SURGE-TYPE GLACIERS

Although the number of surge-type glaciers in the world is very small, they show obvious aggregation in spatial distribution. They are mainly distributed in Alaska-Yukon, parts of the eastern and western Greenland, Svalbard, Iceland and the Karakoram Mountains, Pamirs, and Tianshan Mountains. Other regions of the world such as the Caucasus Mountains rarely exist or do not exist. No glacier surging behavior has been observed in Antarctica so far (Sevestre and Benn, 2015). The study of their tendency to cluster within particular regions is controlled by what factors are of great significance for surging mechanisms. The study on the climate and geometric conditions of the 2,317 surge-type glaciers worldwide distribution regions indicates that the highest densities of surge-type glaciers occur within an optimal climatic envelope bounded by temperature and precipitation thresholds (Sevestre and Benn 2015), which is explained by a new enthalpy cycle model. In the process of ice mass accumulation, the enthalpy will be in an increased state. In cold and dry areas, glaciers are thinner, with lower flux and can conduct effective heat conduction. Amid glaciers in warm and humid environments usually have a large amount of melt water discharge. Heat conduction and melt water discharge will release increased enthalpy. Therefore, the glaciers in these areas are stable. The regional environment where surge-type glaciers gather is often located in intermediate conditions, where neither heat conduction nor runoff can effectively discharge enthalpy gains. Fluctuations between quiescence periods and active periods can happen (Sevestre and Benn 2015).

Surge-type glaciers can be divided into two types: Alaska type and Svalbard type. These two types can both be observed in Greenland. The surge-type glaciers in East Greenland, Harald Moltke Bræ, and Northwest Greenland are identified as Alaska type (Jiskoot et al., 2003; Hill et al. 2018). However, the Storstrømmen Glacier and Bistrup Bræ in East Greenland are probably the largest surge-type glaciers in the world showing characteristics of Svalbard type (Mouginot et al., 2018). The 35-year investigation of ice velocities in combination with observations of surface elevation and glacier area change of Hagen Bræ in the north of Greenland shows that Hagen Bræ Glacier is a glacier with two characteristics of Alaska and Svalbard (Solgaard et al., 2020). In addition, some surging glaciers are known to exist on Disko Island (Qeqertarsuaq) and the Nuussuaq peninsula in West Greenland (Yde and Knudsen, 2007). The surge-type glaciers in the Qinghai-Tibet Plateau are mainly distributed in the Karakoram and Kunlun Mountains (Chudley et al. 2018; Paul et al., 2019).

The distribution of surge-type glaciers within the globe based on Randolph Glacier Inventory (RGI) version 6.0 is shown in Figure 1 (RGI Consortium, 2017).

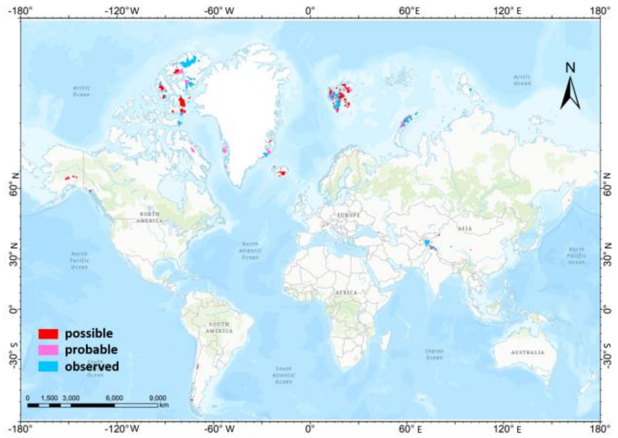

Figure 1. Global distribution of surge-type glaciers based on Randolph Glacier Inventory (RGI) version 6.0.

3. THE CHARACTERISTICS OF SURGING GLACIERS

3.1 Review of methods for the spaceborne measurement of ice motion

The most typical feature of surging glaciers is the abrupt change in surface velocity. There are mainly two methods for measuring ice velocity: optical remote sensing method and SAR remote sensing method. The method of deriving flow velocity from optical images is mainly by image matching in the spatial domain or the frequency domain. Image matching in the spatial domain is performed using the normalized cross-correlation (NCC). This method mainly uses a small image chip in a reference image and searching for correspondence within a limited area of the second image (Haug et al., 2010; Scambos et al., 1992). On the other hand, the calculation speed in the frequency domain is very fast as a result of inclusion of Fourier Transforms (FFTs). For example, the Co-registration of Optically Sensed Images and Correlation (COSI-Corr) software package is based on phase correlation in the Fourier domain and has a good performance in deriving the surface velocity of Antarctic glaciers (Chen et al., 2016; Li et al., 2018; Miles et al., 2018; Shen et al.,2018).

Both DInSAR and MAI use two images obtained at slightly different look angles and at different times to obtain the phase difference through interference. The way to use DInsar requires the topographic phase term removed by external DEM or deriving surface displacement and topography with two InSAR pairs simultaneously (Joughin et al., 1998). SAR offset tracking is another way when accurate elevation information is not at hand or when interferometric coherence cannot be maintained (Joughin et al., 2010). The optical remote sensing velocity measurement techniques only require a single image pair with long time spans or covering regions of particularly fast ice flow (Bindschadler and Scambos, 1991; Haug et al.,2010). For the SAR velocity measurement techniques, the main advantage is the ability of active imaging sensors to see through clouds (Joughin et al., 2010). Besides, the accuracy of the obtained ice velocity map using SAR measurement techniques can reach very high precision (mm-cm level) (Nagler et al., 2017; Rignot et al., 2011). Nevertheless, the applicability of SAR techniques depends on the time between acquisitions, and will fail under the condition of fast ice motion (Joughin et al., 2010). Therefore, the trend in studying ice dynamics is towards using a combination of optical and SAR techniques.

https://doi.org/10.5194/isprs-archives-XLIII-B3-2021-503-2021

3.2 The details of Characteristics of Surging Glaciers

The pattern of medial moraines on surging glaciers is typical, this is the most obvious surface feature of surging glaciers and can be observed from optical images. The loop is formed by the flow of ice from a tributary glacier while the main glacier is quiescent and moves downstream along with the ice flow when the surging behavior of the main glacier occurs. Hispar Glacier is one of the largest glaciers in the Central Karakoram mountain range. The surging behavior of this glacier was observed during the recent surge (2014–2016) (Guo et al. 2020). We can clearly see the features from the optical images (Figure 2) and roughly infer that the amount of movement of the loop moraine during June 2014 to July 2016 is about 4,400 m from the optical image.

The Alaska-type glaciers (Murray et al., 2003) usually initiate and terminate suddenly, which can be deduced from the sudden increase or decrease speed of ice flow in the beginning and end of the surging. The surface displacement of these surge-type glaciers during the surge period will be very high. For example, Variegated Glacier, a temperate glacier located in southeastern Alaska, has a maximum ice velocity of 50 m/d in the lower region of the glacier during the surging period (Kamb et al., 1985). Such type of surges usually has relatively short cycles and about 1 to 2 years surge phases.

The Svalbard-type glaciers exhibit slow initiation and termination, and the surface displacement during the surge period is low, generally less than 6 m/d. The surge phases are longer, usually continue for several years or even decades. A large mass is transported from the upstream reservoir area to the downstream receiving zone during the active phases. Therefore, the change of glacier thickness is also an important feature for the surge-type glaciers. Hispar Glacier is one of the largest glaciers in the Central Karakoram mountain range. The lower part of the glacier was thickened by 180 m, and the elevation of the main supply tributaries decreased by 50 m during February 2013 to September 2016 (Guo et al., 2020). If we know the change of the flow velocity and elevation of the glacier, then we can calculate the amount of an upper 'reservoir zone' mass loss and the lower 'receiving zone' mass gain during the active period.

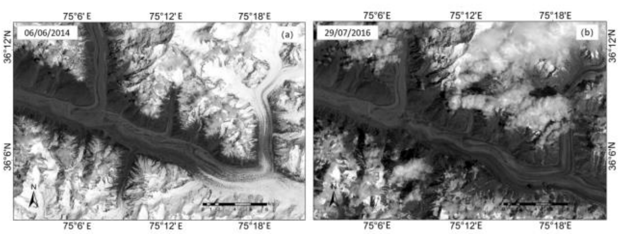

Figure 2. Hispar Glacier, Karakoram mountain. (a) The beginning of surging behavior (June 6, 2014). (b) the Ending of the surging behavior (July 29, 2016). The image is Landsat-8 OLI (bands 8).

3.3 An example of surge-type glacier, Sortebræ

Sortebræ, (68°45'N, 27°05'W) is a 65 km long tidewater-terminating glacier in central East Greenland (Fig. 3). Sortebræ surged around 1950 and again between 1992 and 1995, giving a quiescent phase of 39~49 years (Murray et al., 2002; Jiskoot et al., 2001). We can clearly see the tear-like moraine in the middle of the glacier, between 6 October 1991 (Fig. 4a) and 6 September 1992 (Fig. 4b). The tear-like moraine had almost no movement at all, and at this time the glacier was in a quiescent period, with the terminus advancing about 360 m (~480 m/y). Sortebræ West dominated the calving front. From September 6, 1992 (Fig. 4b) to June 5, 1993 (Fig.4c), it is very conspicuous that the tear-like moraine on the surface of the glacier moved about 1,800 m (~2400 m/y) and the terminus advanced about 1,470m (~1960 m/y) in 9 months with the beginning of the surge. From October 11, 1993 (Fig.4d) to June 8, 1994 (Fig.4e), the tear-like moraine moved approximately 3,800 m (~15km/y), the terminus advanced about 1370 m (~480m/y) with the surging of the glacier. Between June 8, 1994 (Fig.4e) and June 27, 1995 (Fig.4f), the moraine on the surface of the glacier moved forward about 3,000 m (~3 km/y). The terminus advanced 520 m (~620m/y) between June 27, 1994 and July 13, 1995 (Fig.5). Glacier surface velocity slowed down ever since. The DEM of pre-surge and post-surge shows that the elevation of the reservoir area has dropped by about 270m, and the receiving zone rises by 145m(Pritchard et al., 2003).The ice front location of the glacier will continue to retreat due to disintegration during quiescent period, it retreated about 6200 km from 1997 to 2007 (Fig.6). The best explanation mechanism at present is Kamb's linked cavity sliding model (Pritchard et al., 2005).

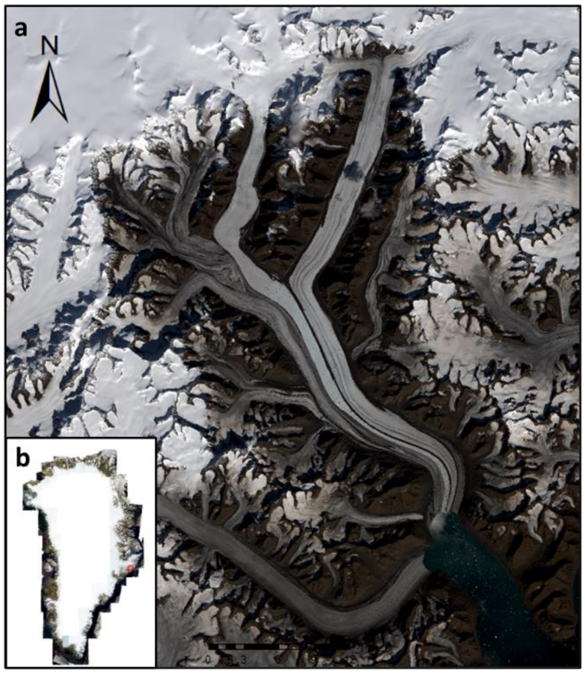

Figure 3. (a) Overview of Sortebræ Glacier (image from Landsat-8 OLI (band 4,3,2), 20 August 2020). (b) Location of Sortebræ in Greenland.

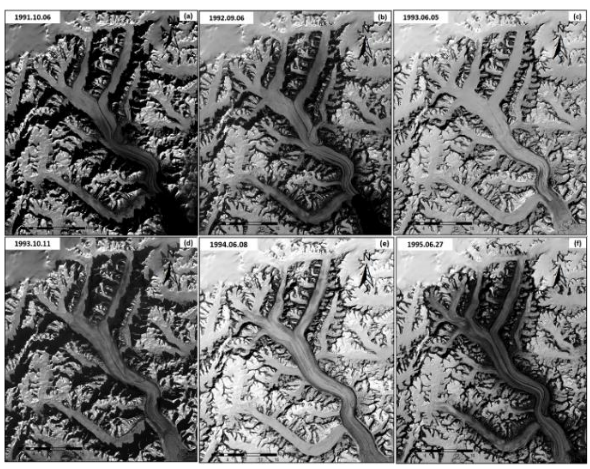

Figure 4. Sortebræ Glacier, central East Greenland. (a-e) tear-like moraine in Landsat-5 TM (bands 4) image from 6 October 1991 to 27 June, 1995.

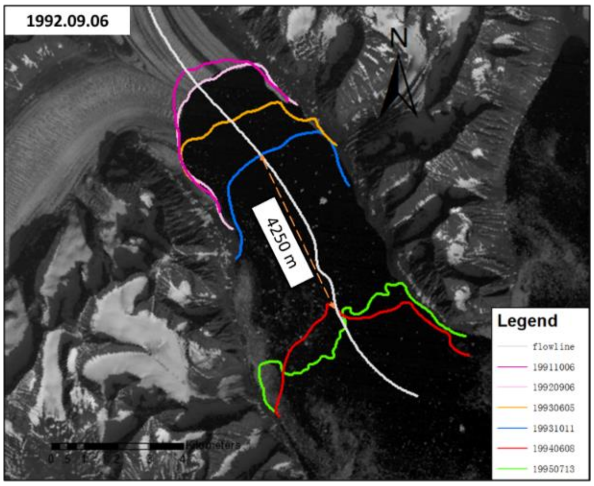

Figure 5. Sortebræ Glacier, central East Greenland. Ice front location from October 6, 1991 (peony pink) to July 13, 1995 (medium apple) overlaid on Landsat-5 TM (bands 4). Dashed grey lines the central flowline.

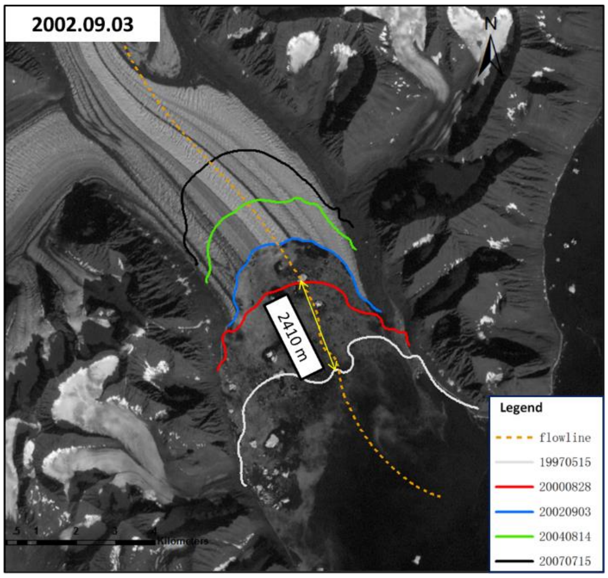

Figure 6. Sortebræ Glacier, central East Greenland. Ice front location from May 15, 1997 (Gray) to July 15, 2007 (Black) Background image is Landsat 7 ETM+ image (bands 8; September 3, 2002). Dashed Seville Orange lines the central flowline.

4. THE MECHANISMS OF SURGE-TYPE GLACIERS

Due to the diversity of surge-type glaciers distribution and different characteristics, there is no unified mechanism that can be applied to all surge-type glaciers and to argue for one basic mechanism that can explain all surges may be unrealistic (Cuffey et al., 2010). Two mechanisms have been proposed to explain the observed surging behavior, thermal regulated and hydrological regulation, for the explanation of Svalbard-type and Alaska-type glacier surging, respectively. Thermal regulated surges are due to the cold-based ice in quiescence converting to warm-based ice during the surge because of the geothermal and frictional heating. Such type of glaciers likely overlies a soft and deformable substrate (Murray et al., 2003). Hydrological regulation surges generally switch from the channelized glacier basal water system in quiescence, to the distributed glacier basal water system, leading to cavity formation and increasing the bottom water pressure. The increased water pressure further decouples the glacier from its bed and fast sliding (Kamb et al., 1987). Recently, a theory based on enthalpy and mass balance has been proposed to explain the surge behavior that includes both temperate and polythermal glacier surges in a single framework. The theory attributed the surging behavior to the imbalance between enthalpy gain (geothermal heating plus frictional heating) and enthalpy losses (conduction and loss of meltwater) and offers an explanation of why the majority of glaciers do not surge (Benn et al., 2019).

ACKNOWLEDGEMENTS

This research was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19070202), the National Key Research & Development Program of China (2017YFA0603102 and 2017YFB0503502), and the National Science Foundation of China (41771471, 41941006, and 42011530088).

REFERENCES

Benn DI, Fowler AC, Hewitt I, Sevestre H., 2019. A general theory of glacier surges. *Journal of Glaciology*, 65, 701–716.

Bhambri, Rakesh & Watson, C. Scott & Hewitt, Kenneth & Haritashya, Umesh & Kargel, Jeffrey & Shahi, Arjun & Chand, Pritam & Kumar, Amit & Verma, Akshaya & Govil, Himanshu., 2020. The hazardous 2017–2019 surge and river damming by Shispare Glacier, Karakoram. *Scientific Reports*, 10. 4685. 10.1038/s41598-020-61277-8.

Bindschadler, R.A., Scambos, T.A., 1991., Satellite-image-derived velocity field of an Antarctic Ice Stream. *Science*, 252, 242–246.

Chen, J., Ke, C., Zhou, X., Shao, Z., Li, L., 2016. Surface velocity estimations of ice shelves in the northern Antarctic Peninsula derived from MODIS data. *Journal of Geographical Sciences*, 26, 243–256.

Clarke, G.K.C., Collins, S.G., & Thompson, D.E., 1984. Flow, thermal structure, and subglacial conditions of a surge-type glacier. *Canadian Journal of Earth Sciences*, 21, 232-240.

Cuffey K, Paterson WSB., 2010. *The Physics of Glaciers. Elsevier*, Amsterdam.

Chudley, Tom & WILLIS, IAN., 2018. Glacier surges in the north-west West Kunlun Shan inferred from 1972 to 2017 Landsat imagery. *Journal of Glaciology*, 65, 1-12.

Dowdeswell, J.A., Hamilton, G., & Hagen, J.O., 1991. The duration of the active phase on surge-type 585 glaciers: contrasts between Svalbard and other regions. *Journal of Glaciology*, 37, 388-400.

Dirscherl, Mariel & Andreas, Dietz & Dech, Stefan & Kuenzer, Claudia., 2020. Remote sensing of ice motion in Antarctica - A review. *Remote Sensing of Environment*, 237, 10.1016.

Guo, L., Li, J., Li, Z. w., Wu, L. -x., Li, X., Hu, J., et al., 2020. The surge of theHispar Glacier, Central Karakoram:SAR 3-D flow velocity time series and thickness changes. *Journal of Geophysical Research: Solid Earth*, 125, e2019JB018945.

Heid, T., Kääb, A., 2012. Evaluation of existing image matching methods for deriving glacier surface displacements globally from optical satellite imagery. *Remote Sens.Environ*, 118, 339–355.

Hill, E. A., Carr, J. R., Stokes, C. R., & Gudmundsson, G. H., 2018. Dynamic changes in outlet glaciers in Northern Greenland from 1948 to 2015. *The Cryosphere*, 12(10), 3243–3263.

Haug, T., Kääb, A., Skvarca, P., 2010. Monitoring ice shelf velocities from repeat MODIS and Landsat data – a method study on the Larsen C ice shelf, Antarctic Peninsula, and 10 other ice shelves around Antarctica. *Cryosphere*, 4, 161–178.

I. R. Joughin, R. Kwok and M. A. Fahnestock., 1998. Interferometric estimation of three-dimensional ice-flow using ascending and descending passes, *IEEE Transactions on Geoscience and Remote Sensing*, vol. 36, 25-37.

Jiskoot H, Boyle P and Murray T., 1998. The incidence of glacier surging in Svalbard: evidence from multivariate statistics. *Computers & Geosciences*, 24(4), 387–399.

Jiskoot, Hester & Pedersen, Asger & Murray, Tavi., 2001. Multi-model photogrammetric analysis of the 1990s surge of Sortebræ, East Greenland. *Journal of Glaciology*, 47, 677-687.

Jiskoot, H., Murray, T., & Luckman, A., 2003. Surge potential and drainage-basin characteristics in East Greenland. *Annals of Glaciology*, 36, 142–148.

Joughin, I.R., Kwok, R., Fahnestock, M., 1998. Interferometric estimation of three-di-mensional ice-flow using ascending and descending passes. In: Presented at the *IEEE Transactions on Geoscience and Remote Sensing*, 25–37.

Joughin, Ian & Smith, Ben & Abdalati, W., 2010. Glaciological advances made with interferometric synthetic aperture radar. *J. Glaciol*, 56, 1026-1042.

Kamb, B., 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *J. Geophys. Res*, 92(B9), 9083-9100.

Kamb, B., C. Raymond, W. Harrison, H. Engelhardt, K. Echelmeyer, N. Humphrey, M. Brugman, and T. Pfeffer., 1985. Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska, *Science*, 227, 469 – 479.

Lucchitta, B.K., Ferguson, H.M., 1986. Antarctica: measuring glacier velocity from satellite images. *Science*, 234, 1105–1108.

Li, T., Liu, Y., Li, T., Hui, F., Chen, Z., Cheng, X., 2018. Antarctic surface ice velocity retrieval from MODIS-based mosaic of Antarctica (MOA). *Remote Sens*, 10, 1045.

Mariel Dirscherl, Andreas J. Dietz, Stefan Dech, Claudia Kuenzer., 2020. Remote sensing of ice motion in Antarctica – A review. *Remote Sensing of Environment*, 237, 0034-4257.

Miles, Bertie & Stokes, Chris & Jamieson, Stewart., 2018. Velocity increases at Cook Glacier, East Antarctica linked to ice shelf loss and a subglacial flood event. *The Cryosphere Discussions*, 12, 3123–3136.

Murray, Tavi & Strozzi, Tazio & Luckman, Adrian & Pritchard, Hamish & Jiskoot, Hester., 2002. Ice dynamics during a surge of Sortebræ, East Greenland. *Annals of Glaciology*, 34, 323-329.

Murray, T., Strozzi, T., Luckman, A., Jiskoot, H., Christakos, P., 2003. Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions. *J. Geophys. Res.: Solid Earth* 108, 1–15.

Mouginot, Jeremie & Bjørk, Anders & Millan, Romain & Scheuchl, B. & Rignot, E., 2018. Insights on the Surge Behavior of Storstrømmen and L. Bistrup Bræ, Northeast Greenland, Over the Last Century. *Geophysical Research Letters*, 45, 10.1029.

Nagler, T., Floricioiu, D., Groh, A., Horwath, M., Kusk, A., Muir, A., Wuite, J, 2017. Algorithm Theoretical Basis Document (ATBD) for the Antarctic_Ice_Sheet_cci Project of ESA's Climate Change Initiative. (version 3.0, 28 June 2018).

Pritchard, Hamish & Murray, Tavi & Strozzi, Tazio & Barr, Stuart & Luckman, Adrian., 2003. Surge-related topographic change of the glacier Sortebræ, East Greenland, derived from synthetic aperture radar interferometry. *Journal of Glaciology*, 49, 381-390.

Pritchard, Hamish & Murray, Tavi & Luckman, Adrian & Strozzi, Tazio & Barr, Stuart., 2005. Glacier surge dynamics of Sortebræ, east Greenland, from synthetic aperture radar feature tracking. *Journal of Geophysical Research*, 110.

Paul, Frank., 2019. A 60-year chronology of glacier surges in the central Karakoram from the analysis of satellite image time-series. *Geomorphology*, 352, 106993.

RGI Consortium (2017). Randolph glacier inventory—A dataset of global glacier outlines: Version 6.0: *Technical report*. In Global land ice measurements from space. Colorado: Digital Media.

Rignot, E., Mouginot, J., Scheuchl, B., 2011. Antarctic grounding line mapping from differential satellite radar interferometry. *Geophys. Res. Lett*, 38.

Sharp, M.J.,1988. Surging glaciers: behaviour and mechanisms. *Physical Geography*, 12, 349-370.

Sevestre H and Benn DI., 2015. Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging. *Journal of Glaciology*, 61(228), 646–662.

Shen, Q., Wang, H., Shum, C.K., Jiang, L., Hsu, H.T., Dong, J., 2018. Recent high-re- solution Antarctic ice velocity maps reveal increased mass loss in Wilkes Land, East Antarctica. *Sci. Rep*, 8.

Solgaard, A. M., Simonsen, S. B., Grinsted, A., Mottram, R., Karlsson, N. B., Hansen, K. et al., 2020. Hagen Bræ: A surging glacierin North Greenland—35 years of observations. *Geophysical Research Letters*, 47, e2019GL085802.

Scambos, T.A., Dutkiewicz, M.J., Wilson, J.C., Bindschadler, R.A., 1992. Application of image cross-correlation to the measurement of glacier velocity using satellite image data. *Remote Sens. Environ*, 42, 177–186.

Yde, J.C. and N.T. Knudsen., 2007. 20th-century glacier fluctuations on Disko Island (Qeqertarsuaq), Greenland. *Ann. Glaciol*, 46, 209–214.

https://doi.org/10.5194/isprs-archives-XLIII-B3-2021-503-2021