New data, new techniques and new challenges for updating the state of Svalbard glaciers (SvalGlac)

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1. Introduction

Svalbard is among the fastest warming regions on Earth (Nordli et al. 2014; Isaksen et al. 2016). Ongoing climate change alters the energy and mass balances of its glaciers, which in turn affects global sea level, and which has further implications on regional scales. Glacier retreat leads to significant topographic changes, such as increases in fjord length and the area of glacier forefields (e.g. Błaszczyk et al. 2013; Grabiec et al. 2018). Moreover, glaciers temporarily store water on a range of time scales, with its release controlling the hydrology of most Svalbard catchments, as well as influencing terrestrial and marine ecosystems and fjord circulation.

The climate of Svalbard is characterized by strong gradients, ranging from milder and more humid conditions in the South and West, to the colder and drier conditions in the Northeast. These gradients are reflected in the spatial pattern of glacier mass balance, and therefore also in the distribution of glacier-covered area. The largest glaciers are found in the colder northeast, whereas glacier coverage is much less in the milder and drier area of central Spitsbergen.

Glacier monitoring programs have so far been mostly located near the permanent settlements (Ny-Ålesund, Hornsund, Longyearbyen, Barentsburg, see Figure 1), due to the ease of access, but these sites may not optimally represent conditions across Svalbard. However, gaps in survey design and representativeness issues can be addressed using modelling and remote sensing, to optimally link with adjacent disciplines in an Earth System perspective.
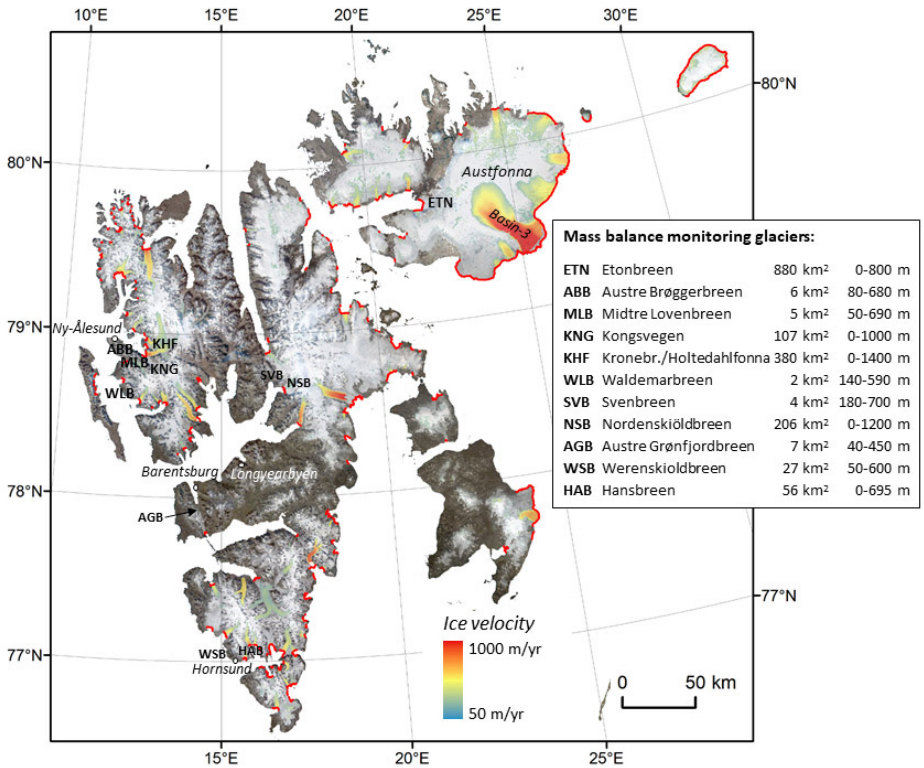
Figure 1: Overview map of Svalbard, showing glacier-covered areas (white) with color-shaded surface velocities for 2018 in cases where glaciers moved faster than 50 m a⁻¹. **Surface velocities** have been retrieved from Gardner et al. 2019: ITS_LIVE Regional Glacier and Ice Sheet Surface Velocities. Data archived at National Snow and Ice Data Center; doi:10.5067/6II6VW8LLWJ7. The red coastal lines show termini of tidewater glaciers from 2018. The background image is a Landsat-mosaic from toposvalbard.npolar.no. Abbreviated labels show the location of present mass balance monitoring glaciers on Svalbard, along with glacier area and elevation range.

To address the overarching, strategic question of "What next in Svalbard glacier studies?", we review the current state of Svalbard glaciers and update previous assessments (Hagen et al. 2003 a, b). Starting from available long-term observations, we discuss new technologies and data that have become available in the past 20 years. We further highlight the important knowledge gaps and outline future research that is needed to close them (including but not limited to ways how SIOS could contribute).

2. Overview of existing knowledge

About 34000 km², i.e. 60% of the land area of Svalbard is covered by glaciers (Nuth et al. 2013), corresponding to ~10% of the glacier area in the Arctic, outside the Greenland ice sheet. The more than 1000 individual glaciers larger than 1 km² comprise a wide range of glacier types from small cirque glaciers and valley glaciers that mainly terminate on land to large ice fields and ice caps (up to ~8000 km²) each feeding several outlet glaciers. About 15% of all glaciers on Svalbard by number and as much as 60% by area (Błaszczyk et al. 2009) are tidewater glaciers, which terminate into fjord or ocean water. Tidewater glaciers introduce freshwater at depth into the marine waters, both from subglacial channels and submarine melting, as well as icebergs, which calve off of the glacier fronts. Svalbard's total ice volume has been assessed using different methods, with estimates ranging from 4000 km³ to 9600 km³ but most studies (Hagen et al. 1993; Martín-Español et al. 2015; Fürst et al. 2018) more closely agree on a value of around 6200 km³, corresponding to a sea-level equivalent of 1.5 cm. Most Svalbard glaciers are polythermal (Hagen et al. 1993), they consist of both cold and temperate ice (temperate ice is at the melting point, thus permitting the presence of liquid water in the glacier body even during the cold winter period).

Annual mass balance surveys of Svalbard glaciers have been conducted since 1966 (Hagen and Liestøl 1990). Traditionally, regular measurements have been performed on glaciers in the vicinity of settlements, but also dedicated measurement campaigns have been conducted on the less accessible ice caps in the eastern parts of Svalbard (e.g. Ahlmann 1933; Schytt 1964; Pinglot et al. 2001). At some locations, these measurements have been maintained on a regular basis, and now provide invaluable data for assessing the climate-glacier interaction. Hagen et al. (2003 a, b) reviewed the data available at that time and used different approaches to assess the Svalbard-wide glacier mass balance. More than 15 years have passed since these reviews, and measurements have been continued, new series from formerly under-represented areas have been initiated and new techniques have become available.

Here, we give a new account of the recent development of glacier mass balance for all of Svalbard. We also highlight the activities and recent developments and discuss the intersection with other disciplines; where relevant, these points are coordinated with other SESS reports (Köhler et al. 2020; Gallet et al. 2019).

2.1   New mass balance data

The *glaciological mass balance* is obtained from repeated field visits, and comprises end-of-winter snow-depth sounding and repeated height measurements of an array of stakes. Balance estimates are extrapolated over the entire glacier basin by determining the balance terms as functions of elevation, and averaging them applying weights determined from the distribution of glacier area as a function of elevation. This method quantifies the surface mass balance (SMB), i.e. the mass changes at the surface of the glacier, exposed to the atmosphere, but does not comprise frontal ablation (calving and sub-marine melting at the front of tidewater glaciers).

The *geodetic mass balance* is computed by differencing elevation data from two or more different times. Elevation data can be from a variety of sources: surface surveys; contours from older maps; digital elevation models made photogrammetrically from aerial photographs or satellite imagery; or satellite altimeters. This balance estimate accounts for frontal ablation, hence represents the total mass balance.

Mass balance models, forced either by meteorological observations or output from regional climate models, evaluate the surface energy balance to reveal the climatic mass balance (CMB). The most complete models contain a subsurface routine to account for the impact of water storage and refreezing on the mass and energy budgets. Field data are used to calibrate model parameters and to validate model output. The CMB differs from the measured SMB in that it more accurately accounts for subsurface mass changes that are difficult to measure.

A direct method for estimating mass change by *gravimetry* comes from the GRACE (Gravity Recovery and Climate Experiment) satellites, which mapped the time-varying gravity field of the Earth over the period 2002-2017. However, the values still need to be disentangled from crustal changes due to long-term isostatic rebound. Regional gravitation change is also prone to "leakage" from regions outside of the area of interest. Furthermore, there are certain technical challenges to the data analysis.

2.1.1 Northwest-Spitsbergen

Austre Brøggerbreen (ABB) and **Midtre Lovénbreen** (MLB) are both small glaciers (ca. 5-6 km^2), and neither reach higher than ca. 700 m a.s.l. Both have had consistently negative net balances since measurements started in 1966 (Figure 2), due to their relatively low-lying and small accumulation areas. Mass balance on MLB[1] is less negative than on neighboring

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1   https://wgms.ch/products_ref_glaciers/midtre-lovenbreen-svalbard/

ABB[2], in part due to its slightly higher elevation and steeper valley sides, both of which contribute to more accumulation on MLB. The time series for **Kongsvegen** (KNG) is shorter, starting in 1986 (Figure 2). KNG is a larger glacier (ca. 107 km[2]), with elevations up to 850 m a.s.l. Because of its higher elevation, it has a larger accumulation area, and therefore its net balance record is higher than that of the lower-lying ABB and MLB. The same is true for the larger (ca. 380 km[2]) and higher elevation (up to 1400 m a.s.l.) neighboring glacier system **Holtedahlfonna/ Kronebreen** (KHF), with measurements since 2003.
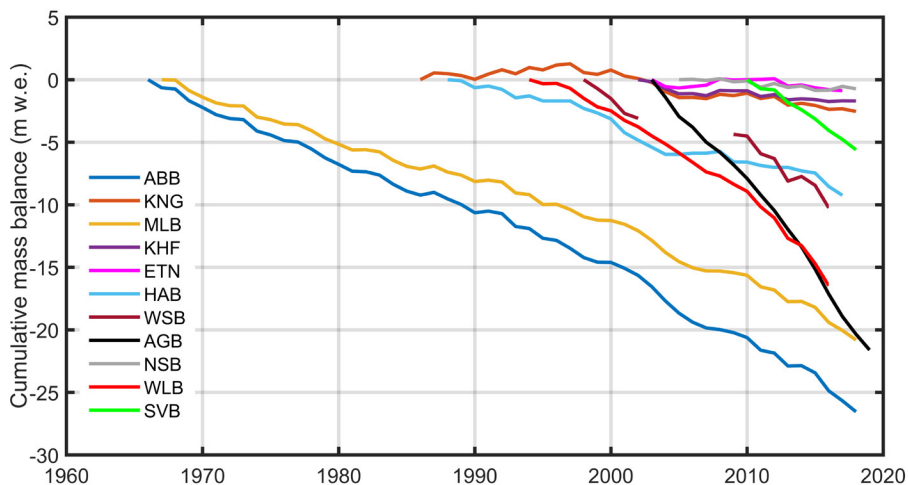

Figure 2: Cumulative surface mass balance (excluding frontal ablation) from in-situ measurements at selected Svalbard glaciers

Waldemarbreen (WLB) is a 3 km[2], low-elevation (up to ca. 600 m a.s.l.) land-terminating glacier, 27 km south of Ny-Ålesund. It has been monitored since 1995, with average 1995-2016 mass balance of -0.75 m w.e. a[-1], and an acceleration in mass loss after 2011, leading to its ELA above the glacier top (Sobota et al. 2016).

2.1.2 Central Spitsbergen

Central Spitsbergen is characterized by relatively dry conditions, due to precipitation shadowing. **Svenbreen** (SVB) is a small (4 km[2]) valley glacier, north of Billefjorden, whose elevation ranges from 180-700 m a.s.l. Geodetic measurements show that SVB has been losing volume since at least the 1960s, with an apparent acceleration after 1990 (Małecki 2013, 2015, 2016). The mean geodetic balance of the glacier over the period 1990-2009

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2   https://wgms.ch/products_ref_glaciers/austre-broeggerbreen-svalbard/

was -0.58 m w.e. a^{-1}. Annual mass balance measurements of the glacier started in 2010, and show that the glacier has been steadily losing mass, including in its high-elevation cirque, in agreement with the geodetic data.

Mass balance measurements on **Nordenskiöldbreen** (NSB), an outlet glacier of the Lomonosovfonna ice cap in central Svalbard, have been performed annually since 2006. NSB is ~25 km long, has an area of 206 km^2, and elevation ranges from 0-1200 m a.s.l. The mean glacier-wide net climatic mass balance for 2006-2018 is -0.06 m w.e. a^{-1}. The mass balance data have contributed to a range of studies on the glacier's climatic mass balance, dynamics, and snow/firn conditions (e.g. Marchenko et al. 2017a, b; Van Pelt et al. 2012, 2018; Vega et al. 2016), and to Svalbard-wide climatic mass balance modelling experiments (e.g. Aas et al. 2016; Østby et al. 2017; Van Pelt et al. 2019).

2.1.3 Southern Spitsbergen

Glaciers in this region have undergone strong mass losses in the last two decades, with rates of annual ice surface lowering nearly twice as much as in previous decades. For the period 2004-2011 mass losses were -1.25 m w.e. a^{-1} for Vøringbreen, -1.08 m w.e. a^{-1} for Aldegondabreen, -0.8 m w.e. a^{-1} for Vestre Grønfjordbreen, and -1.35 mw.e. a^{-1} for **Austre Grønfjordbreen** (AGB) (Mavlyudov et al. 2012). Geodetic measurements supported with some stake measurements on Aldegondabreen shows that in 2015-2018 its mean balance was -1.83 m w.e. a^{-1} (Terekhov et al. 2020).

AGB is nearly 7 km^2, with elevations from 40-450 m a.s.l. Annual mass balance surveys have been performed each autumn. Winter snow accumulation has not been measured regularly, so for some years the winter and summer balance components were not measured directly, but estimated using empirical relationship with air temperature (Chernov et al. 2019).

Hansbreen (HAB) is a medium-sized (56 km^2) tidewater glacier located in the southern part of Wedel Jarlsberg Land, close to the Polish Polar Station in the fjord Hornsund. The glacier is ~16 km long, and elevations extend up to 550 m a.s.l. Surface mass balance monitoring started in 1988/89. Over the period of 1989-2017 the net surface mass balance has been continuously decreasing (Figure 2), with a mean of -0.36 m w.e. a^{-1}. Frontal ablation, measured along the c. 1.5 km long ice cliff shows that mass loss by calving contributes substantially to the total mass loss (23-50%, i.e. additional ablation by an equivalent of c. -0.7 m w.e. a^{-1} on average) and varies interannually.

Werenskioldbreen (WSB) is a medium-sized (27 km^2) land-terminating valley glacier to the west of HAB, with elevations from 50-600 m a.s.l., and has been monitored with some interruptions since 1999. The average mass balance is -0.57 m w.e. a^{-1}.

2.1.4 Northeast-Svalbard

In 2004, the University of Oslo and the Norwegian Polar Institute established a network of mass balance stakes along several profiles crossing the **Austfonna** ice cap (~8000 km^2), by far the largest ice body in Svalbard. Since then, annual measurements of surface elevation changes (Moholdt et al. 2010a; Gray et al. 2015), mass balance (Schuler et al. 2007), surface velocities (Dunse et al. 2012; 2015), snow distribution (Taurisano et al. 2007; Dunse et al. 2009), near-surface meteorology and energy balance (Schuler et al. 2014; Østby et al.. 2013) have been conducted. These activities have been based mainly on research project funding and their focus has varied. Nevertheless, mass balance has been measured each year on **Etonbreen** (ETN, ~880 km^2), and is a part of the MOSJ database[3]. The net mass balance has typically been close to zero, except for an exceptionally positive year in 2008 and two very negative years in 2004 and 2013. The surface mass balance of Etonbreen is representative for the Austfonna ice cap as verified by some years of mass balance surveys over the entire ice cap. Calving and marine melting at the terminus of Etonbreen cause a small additional mass loss. However, for the entire ice cap calving loss is important and gives a mass loss of ca. 2 Gt a^{-1} and for periods surging glaciers may have a very important impact on the overall mass balance as shown by the surge in Basin3 when the surge almost tripled the calving loss of the ice cap to about 5.5 Gt a^{-1} (Dunse et al. 2015). The data from Austfonna have proved valuable for Svalbard-wide glacier models (Aas et al. 2015; Østby et al. 2017; Van Pelt et al. 2019) since they are the only data from a glacier of significant size and from the heavily glacier-covered, but logistically more challenging eastern part of Svalbard.

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3   http://www.mosj.no/en/climate/land/mass-balance-glaciers.html

2.2   New technologies

The most striking evolution since the Hagen et al. (2003 a, b) assessments is the more widespread availability of different remotely sensed measurements. Since the 2000's, the number of sensors and platforms has grown considerably, and the resolution, accuracy and frequency of measurements have increased. Access to these data has become easier for a growing number of glacier-relevant measurements, such as surface elevation changes, DEMs as well as land-surface temperatures, albedo, and glacier facies (e.g. Nuth et al. 2010; Moholdt et al. 2010b; Gray et al. 2015). Spaceborne gravimetry allows monitoring mass changes, which, if corrected for a range of other gravitational effects, can provide information on regional glacier-related mass changes (Wouters et al. 2008, 2019; Matsuo and Heki 2013; Gardner et al. 2013).

The availability of global atmospheric reanalyses at improved spatial and temporal resolution, and improved consistency with available observations (e.g. Schuler and Østby 2019), has sparked the application of gap-free meteorologically-forced glacier mass balance models that cover the entire archipelago (e.g. Østby et al. 2017; Van Pelt et al. 2019). These models either directly incorporate local measurements or have been optimized to ensure agreement between simulated and observed values and therefore play an important role in synthesizing the wealth of information that became available.

In addition to increases in the number of stake measurements, and more extensive availability of satellite products around Svalbard since 2003, we are now collecting a broader set of on-glacier data; GPSs (velocities and surface height) Automatic Weather Stations (AWS), wireless-sensor networks (WSN), radar, seismology, time-lapse photography, Terrestrial Laser Scanning (TLS), Structure from Motion (SfM) applied on imagery from unmanned vehicles (UAV), and smart tracers (e.g. Alexander et al. 2019).

There has been a great increase in the use of UAVs, for high-resolution remote sensing tasks. Glaciological applications have focused on optical sensors to make digital elevation models (e.g. Girod et al. 2017), detect changes in surface properties, and resolve ice speed. Submarine UAVs are used to measure oceanic properties and mapping submarine hypsometry in glaciated fiords. The ongoing miniaturization of sensors helps overcoming payload limitations of UAVs and enables multi-sensor measurements over glaciated terrain. One promising example is the development of UAV radar systems that may soon be operational.

Low-cost, autonomously recording and transmitting systems (SIOS project SWAG-Net RiS ID 11214) improve coverage of basic meteorological and glaciological measurements in areas of difficult or even dangerous access. When set up in a communication network, these systems can be enhanced to conduct more specialized and individually tailored measurements.

2.3 New synthesis

2.3.1 Mass balance modelling

Relative to 2003, numerical modelling now plays an increasingly prominent role in glacier studies on Svalbard. Stimulated by the growing availability of observational data for model optimization, models have been increasingly used to simulate climatic mass balance (e.g. Lang et al. 2015; Aas et al. 2016; Østby et al. 2017; Möller and Kohler 2018; Van Pelt et al. 2019) and ice flow (e.g. Gladstone et al. 2014; Schäfer et al. 2014; Vallot et al. 2017; Gong et al. 2018). The climatic mass balance (CMB) refers to mass changes at the glacier surface and in snow/firn, but does not include frontal ablation (calving and sub-marine melting) of tidewater glaciers. Modelled mass balance is spatially complete and covers the entire glacierized area of Svalbard, providing information at relatively high temporal resolution (sub-daily to hourly), depending on the meteorological forcing (Figure 3; Table 1). These products can therefore be understood as spatial-temporal interpolators and have great potential to synthesize a large amount of individual measurements for regional assessments.

CMB models have been used both inline, coupled to regional climate models (Lang et al. 2015; Aas et al. 2016), and offline, forced by downscaled meteorological variables. Offline applications have used an entire spectrum of downscaling procedures, ranging from statistical relations (Möller and Kohler, 2018), intermediate-complexity methods (Østby et al. 2017; Van Pelt et al. 2019), and dynamical downscaling (Hanssen-Bauer et al. 2019). Temporal coverage varies and is either limited by computational cost (Aas et al. 2016; Hanssen-Bauer et al. 2019) or by availability of atmospheric reanalysis data. For instance, ERA-interim (Dee et al. 2011) reanalysis data are available since 1979, ERA-40 (Uppala et al. 2005) start in 1957, allowing longer-term simulations (Østby et al. 2017; Van Pelt et al. 2019), and the ERA-20C reanalysis dataset (Poli et al. 2016) pushes the limit even back to 1900 (Möller and Kohler 2018).

Table 1: Comparison of several Pan-Svalbard estimates of glacier mass balance using different methods. The "flux" method refers to a combination of remotely sensed velocity fields and frontal area changes. "dh" refers to differencing elevation measurements by ground-based GPS profiling, air- and spaceborne photogrammetry, laser and radar altimetry. "Gravimetry" refers to estimates derived from GRACE measurements. The estimates refer to different components of the total mass balance, calving and climatic mass balance (CMB) and are marked in the table, where Total = CMB + Calving.

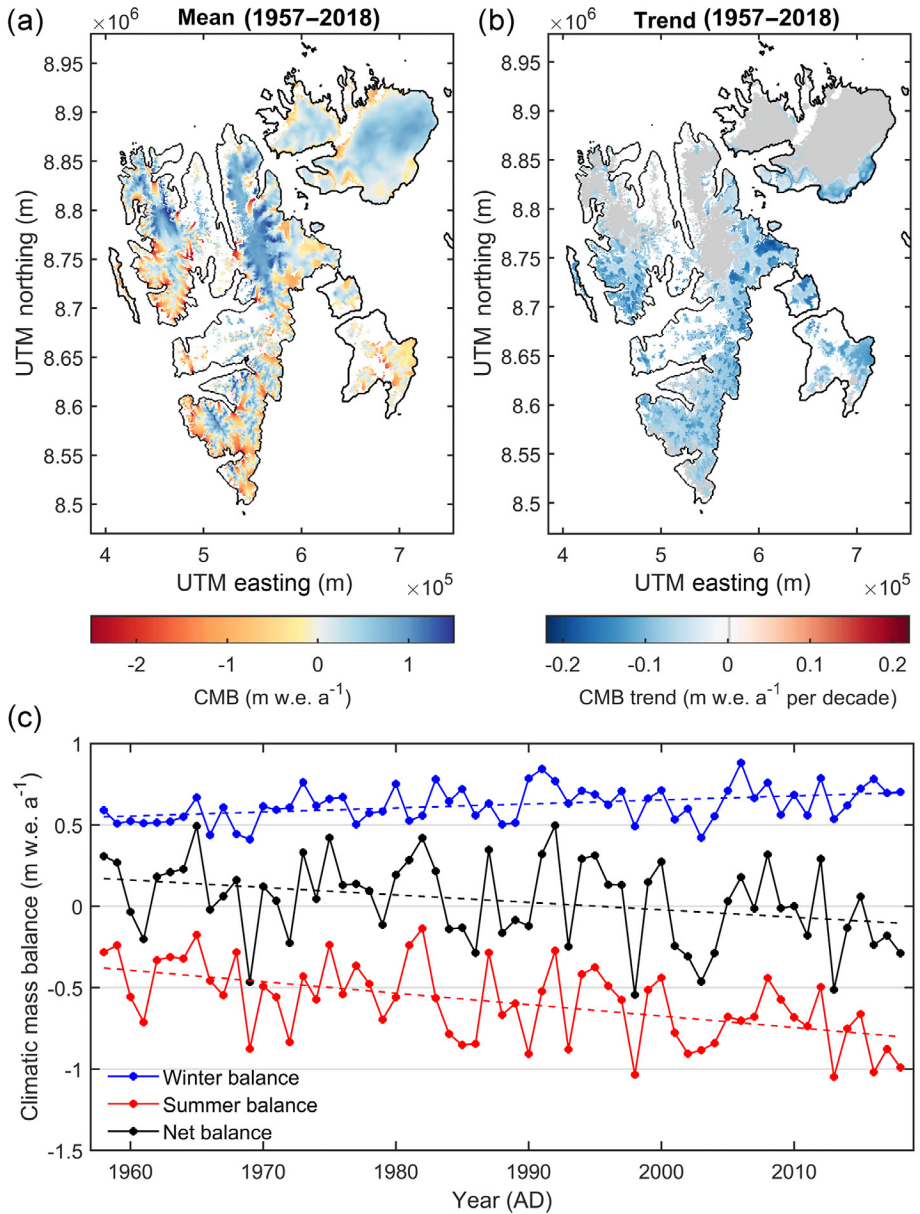| Reference	Period	Method	Specific B_n (m w.e. a^{-1})	B_n (Gt a^{-1})	Balance component
Hagen et al. 2003a	~1970-1999	Interpolation 1	-0.38 ± 0.33 -0.11	-14 ± 12 -4	Total Calving
Hagen et al. 2003b	~1970-1999	Interpolation, 2	-0.12 ± 0.03	-4.5 ±1	Total
Błaszczyk et al. 2009	1999-2006	Flux	-0.18 ± 0.05	-6.75 ± 1.7	Calving
Dunse et al. 2015	2013 (Basin-3)	Flux		-4.2 ± 1.6	Calving
Nuth et al. 2010	1965/90-2003/7	dh	-0.36 ± 0.02	-9.7 ± 0.55	Total
Moholdt et al. 2010b	2003-2008	dh	-0.12 ± 0.04	-4.1 ± 1.4	Total
Lang et al. 2015	1979-2013	Model (10 km)	-0.04	-1.6	CMB
Aas et al. 2016	2003-2013	Model (3km)	-0.26	-8.7	CMB
Østby et al. 2017	1957–2014	Model (1km)	0.08	2.7	CMB
Möller and Kohler 2018	1900-2010	Model (0.25 km)	-0.002	-0.07	CMB
Hanssen-Bauer 2019	2004-2017	Model (2.5km)	-0.26	-8.7	CMB
Van Pelt et al. 2019	1957-2018	Model (1km)	0.09	3.0	CMB
Wouters et al. 2008	2003-2008	Gravimetry	-0.26 ± 0.09	-8.8 ± 3	Total
Jacob et al. 2012	2003-2010	Gravimetry	-0.09 ± 0.06	-3 ± 2	Total
Mémin et al. 2011	2003-2009	Gravimetry 1 Gravimetry 2	-0.27 ± 0.03 -0.46 ± 0.07	-9.1 ± 1.0 -15.5 ± 2.4	Total Total
Matsuo & Heki 2013	2004-2012	Gravimetry	-0.11 ± 0.09	-3.7 ± 3.0	Total
Gardner et al. 2013	2003-2009	Gravimetry 1 Gravimetry 2	-0.20 ± 0.06 -0.13 ± 0.12	-6.8 ± 2.0 -4.4 ± 4.1	Total
Wouters et al. 2019	2002-2016	Gravimetry 1 Gravimetry 2	-0.21 ± 0.04 -0.27 ± 0.21	-7.2 ± 1.4 -9.1 ± 4.1	Total

Figure 3: Simulated long-term CMB distribution (a) and trends (b). In (c) time series of area-averaged summer, winter and annual (Sep – Aug) net CMB are shown, along with corresponding linear trends. Figure from Van Pelt et al. (2019). Glacier outlines were extracted from A digital glacier database for Svalbard (chapter in Global Land Ice Measurements from Space by König et al. 2014): **https://doi. org/10.21334/npolar.2013.89f430f8**.

To various degrees, all model studies made use of an extensive set of measurements from mass balance stakes, AWSs, and firn cores across Svalbard for calibration and validation. Table 1 provides an overview over the different applications, their temporal coverage as well as spatial resolution. All models reveal a distinctive pattern, ranging from negative CMB in southern Spitsbergen to more positive values in northeast Svalbard (Figure 3a), reflecting the gradient of air temperature (Hanssen-Bauer et al. 2019). Over the long-term (>50 years), all studies indicate a slightly positive CMB, but all show clearly negative CMB for more recent periods, especially after 2000 (Figure 3c). The results by Van Pelt et al. (2019) shown in Figure 3 agree with the other model-based assessments, with record negative years in 2004 and 2013, and a close to zero balance for the period 2005-2012, before mass balance turns consistently negative. Although there is agreement on a tendency towards more negative CMB, trend analysis reveals its significance is restricted to southern Svalbard (Figure 3b) with a trend of -0.06 m w.e. a^{-1} decade^{-1}. Both Van Pelt et al. (2019) and Østby et al. (2017) find that increased melt and reduced refreezing leads to doubling in glacier runoff over the simulation period. In addition, Østby et al. (2017) find a strong correlation between mass balance and summer temperature.

2.3.2 Frontal ablation

When the only available estimate of ice discharge from Svalbard glacier calving (Błaszczyk et al. 2009) of nearly 7 Gt a^{-1} is added to the different CMB results, the overall Svalbard mass balance becomes clearly negative (Table 1, Figure 4). The Błaszczyk et al. (2009) calving estimate is based on glacier flow velocities and front position changes extracted from ASTER images acquired from 2000–2006. However, due to its close dependence on glacier dynamics and ocean temperature (Luckman et al. 2015), frontal ablation varies over many time scales: seasonal, annual and especially, from irregularly occurring surges. For example. Dunse et al. (2015) quantified the sea-level effect of a single surge in Austfonna over the period 2012-2013, and found that the surge contributed 7 Gt a^{-1}, approximately matching the Błaszczyk et al. (2009) estimate, hence doubling the sea-level contribution per year of entire Svalbard during the surge period.

Because of reduction in ice discharge, marine termini can quickly retreat. Many areas around Svalbard are experiencing rapid ice cliff recessions (10s to 100s m a^{-1}), which significantly affects the marine physical environment and ecosystem. One special case is Hornsund: bed elevations for the Hornbreen – Hambergbreen glacier system have been found approximately 40 m below sea level, such that a new strait between the Greenland Sea and the Barents Sea is expected within the next 2-3 decades, once the glacier termini have retreated (Grabiec et al. 2018).
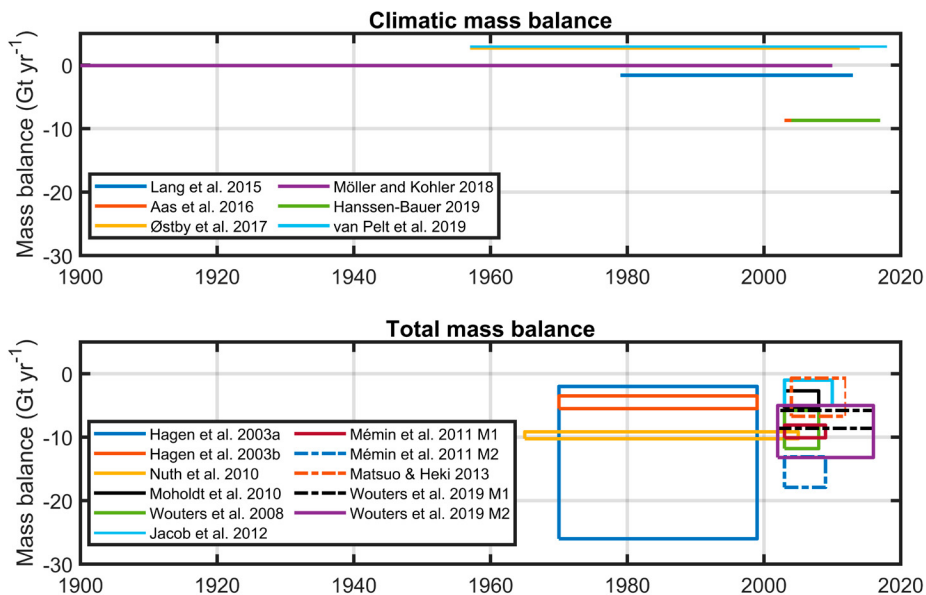
Figure 4: Graphical representation of the mass balance estimates for glaciers on Svalbard (Table 1). The top panel compares the estimates of climatic mass balance, derived from several model studies. The bottom panel compares total mass balance estimates derived from extrapolation of direct, geodetic and gravimetric measurements.

2.3.3 Geodetic mass balance

Nuth et al. (2010) compared satellite altimetry data from the ICESat mission for the period 2003–2007 to older topographic maps and digital elevation models for different epochs (1965–1990). Because the ICESat tracks are relatively sparse, they extrapolated along-track changes to the larger regions using glacier hypsometry. Significant thinning was detected at the lower elevations of most glaciers, and either slight thinning or thickening in the accumulation areas, except for glaciers that surged during the observation period; these glaciers showed thickening in the ablation area and thinning in the accumulation areas. However, the overall balance was very negative at -0.36 m w.e. a^{-1}, corresponding to -9.7 Gt a^{-1} (Table 1). As with the modelling results, the most negative geodetic balances are found in the South and the least negative balances in the Northeast.

Moholdt et al. (2010b) determined elevation changes along the ICESat tracks for the period 2003-2008, extrapolating these changes to the remaining glacier area using the same hypsometric approach as Nuth et al. (2010) to yield a Svalbard-wide estimate of -0.12 m w.e. a^{-1}, or -4.3 Gt a^{-1}. They found that most regions experienced low-elevation thinning and high-elevation balance or thickening, and that the largest ice losses occurred in the West and South, while northeastern Spitsbergen and the Austfonna ice cap slightly gained mass.

This general pattern, however, does not apply for central Spitsbergen, with its mostly small alpine glaciers. Małecki (2016) demonstrated that glacier thinning here has been occurring at all elevation up to 1000 m a.s.l., for the period 1990-2011.

Analysis of older maps and modern DEMs (Kohler et al. 2007) shows that mass loss rates at MLB and Slakbreen, near Svea, appears to have accelerated. For MLB, thinning rates for 2003–2005, were more than four times the average for the first measurement period 1936–1962. On Slakbreen, thinning rates for the period 1990–2003 were more than four times that of the period 1961–1977. James et al. (2012) and Małecki (2013) found a similar increase in thinning rates for other glaciers around Svalbard, particularly in high-elevation areas. More pronounced thinning has been noted for HAB and Hornbreen for two recent periods 2011-2015 and 2015-2017 based on differencing elevations obtained by photogrammetry using high-resolution satellite images (Błaszczyk et al. 2019). This increasingly negative mass balance trend is consistent with both worldwide glacier trends as well as developments in the Arctic (Kaser et al. 2006).

2.3.4 Gravimetry

While satellite gravimetry provides an absolute measure of the total mass change in the region the spatial resolution of GRACE is typically in the order of 0.5°-1° (Wouters et al. 2019) and determination of glacier mass balance is challenging. A number of studies (Wouters et al. 2008; Jacob et al. 2012; Mémin et al. 2011; Matsuo and Heki 2013; Gardner et al. 2013) working with the same dataset but covering slightly different periods, and using different data filtering methods, obtain a range of values for the total mass loss (Table 1). However, the main conclusion one can reach from the body of GRACE analyses is that all find a negative mass balance for the Svalbard archipelago, with values ranging from -0.46 to -0.09 m w.e. a^{-1}, or -15.5 to -3.0 Gt a^{-1} (Table 1), even if the error range for some of the estimates extends into the positive territory. The most recent regional estimate, covering the entire GRACE mission from 2002-2016, indicates an average mass balance of -7 Gt a^{-1} (Wouters et al. 2019).

2.3.5 Summary

Figure 4 shows some variation between the different estimates due to different periods covered and different methods employed. Nevertheless, the different results are consistent in that the surface mass balance of glaciers is negative in general and significantly more negative when frontal ablation at tidewater glaciers (Figure 1) is accounted for. The latter can cause drastic recession and thinning of marine terminating glaciers and extension of new branches of fjords. Analysis of time series indicates that there is a tendency towards increased mass loss over time.

Available long-term mass balance observations (Figure 2) reveal a complex picture of different glacier evolutions. These clearly demonstrate differences between small glaciers (<10 km²) that are rapidly losing mass (ABB, MLB, WLB, SVB, AGF) and larger glaciers (>50 km²) like KNG, KHF, NSB, ETN and HAB. These are typically outlets of larger contiguous ice masses (ice fields and ice caps). The steeper slope of the cumulative mass balances shows that glaciers in southern and central Spitsbergen (WSB, SVB, AGF) have more negative mass balances than those located in NW Svalbard (ABB, MLB). Similarly, larger glaciers such as HAB are losing mass more rapidly than at KNG, KHF, NSB or ETN. The latter is an outlet from Austfonna and shows surface mass balance conditions close to zero with little variability, though with a tendency towards more negative values after 2012.

The in-situ measurements (Figure 2) align well with model results (Figure 3). The simulated CMB distribution in Figure 3a shows a pronounced gradient from higher CMB in NE-Svalbard to lower values in S-Svalbard, where trends are significantly negative (Figure 3b). This spatial distribution is equally reproduced in the remotely-sensed geodetic mass balance estimates. The simulated time series support the view that most of the variability of net mass balance is largely due to variability in summer mass balance whereas winter mass balance is more stable (Figure 3c).

The spatial coverage of available mass balance measurements has improved over the past 20 years, especially with the inclusion of data from Austfonna, NSB and SVB, filling gaps both in terms of glacier types and location. Therefore, the presently available data are more representative for Svalbard than the pre-2000 record that was heavily biased towards smaller glaciers in the vicinity of settlements in western Spitsbergen. For a representative picture of Svalbard glacier mass balance, it is therefore imperative to have adequate spatial sampling and include records from the logistically more challenging eastern parts of Svalbard. Mass balance modelling is a valuable tool to link these measurements and to provide a gap-free product with high spatial and temporal resolution.

The total mass balance of Svalbard glaciers consists of two main parts, the climatic mass balance and the frontal ablation (calving and submarine melting). The only available estimate of current ice discharge from Svalbard glaciers (Błaszczyk et al. 2009) is a composite of snapshots in the period 2000-2006 and amounts to 5.0-8.4 Gt a^{-1} (mean 6.75 Gt a^{-1}), hence, ice discharge is roughly equivalent to the mass loss by climatic mass balance in the same period. This work urgently needs to be updated, especially in light of several large glacier surges which discharged large volumes of ice into the ocean over short periods. There are some suggestions that increased melt hastens the triggering effect on surges (Dunse et al. 2015) and a number of other large-scale surges events have been reported in Svalbard (Sund et al. 2014) as well as other Arctic regions (e.g. Willis et al. 2018). These events affect the total ice discharge and have the potential to considerably increase the sea-level contribution from land ice over short time periods.

2.4   New challenges

In concert with warming of the atmosphere, glaciers experience more surface melting. However, due to the polythermal nature of Svalbard glaciers, they have a considerable retention capacity and huge amounts of meltwater refreeze in the porous snow and firn areas. Model estimates described above account for this process (in simplified ways), and all agree that this retention capacity has considerably decreased due to general warming and a reduction in the size of firn areas (Østby et al. 2017; Van Pelt et al. 2019). Analysis of satellite data of Hansbreen, Storbreen and Hornsbreen showed a significant decrease in the firn area between 2013 and 2018, by 30% - 40% (Barzycka et. al. 2019). Consequently, refreezing capacity in the firn is depleted, and more surface meltwater will exit the glacier as runoff, although some of this water may be temporarily stored in surficial lakes or within perennial firn aquifers (Christianson et al. 2015). Due to their potential to release large amounts of water, for instance when intercepted by a crevasse, firn aquifers are of considerable interest for glacier dynamics and hydrology. Furthermore, these aquifers may promote microbial production (e.g. Anesio et al. 2017), and are the focus of ongoing research on glacier ecology (Hodson et al. 2015). In general, a more sophisticated model of drainage system for Svalbard polythermal glaciers has to be developed to follow the novel approach of discrete recharge of an aquifer (outside of the firn zone) via moulins (Gulley et al. 2012; Decaux et al. 2019). However, our understanding of processes that control the vertical percolation of surface meltwater and associated firn warming needs to be refined, and studies of horizontal water motion are largely absent

Changes in the size and volume of temperate ice bodies in polythermal glaciers is important for understanding their hydrothermal regime, potential dynamic instability, and therefore, their response to climate change. Data analysis of ground-based radio-echo sounding of 16 glaciers at Nordenskiöld Land in Spitsbergen shows that 11 of them are polythermal type (Macheret et al. 2019). The volume fraction of temperate ice in total volume of these glaciers varies from 1 % to 74 %. Repeated GPR surveys on selected polythermal glaciers along the same tracks serve as a useful tool in long-term glacier observation projects.

As mentioned above, several major surges have been observed since 2000 (Dunse et al. 2015; Sund et al. 2014; Nuth et al. 2019; Sund et al. 2009), despite earlier prognoses of a decline with ongoing warming (Dowdeswell et al. 1995). Instead, there is an apparent increase in the number of surges, although it is still unclear whether this is due to more frequent surging or to improved observation capabilities (cf. Farnsworth et al. 2016). A related issue is the seasonal dynamical adjustment of ice speed during the start of the ablation period, due to the decrease of basal friction. The use of continuous GPS on Svalbard glaciers has shown a relation between water availability and ice speed-ups (Vieli et al. 2004; Van Pelt et al. 2018; Dunse et al. 2012; Vallot et al. 2017). Even though the ice discharge has been assessed for a number of glaciers, an observational regional assessment

is not yet available. Due to the large mass fluxes involved in these events, such a Svalbard-wide assessment of ice discharge is urgently needed to get a reliably updated view on total mass losses.

Measurements of surging glaciers on Svalbard (e.g. Nuth et al. 2019) have led to recent theoretical progress in understanding the mechanics of destabilisation and surge propagation (Thøgersen et al. 2019; Sevestre et al. 2018) and climatic controls on the global distribution of surging glaciers (Sevestre et al. 2015; Benn et al. 2019). While frequent surging in Svalbard imposes a challenge in determining the mass flux to the ocean, it also represents an opportunity for improving our understanding of dynamic instabilities and potential links to climate warming. Svalbard is an ideal field laboratory for advancing our understanding of these processes, given the relative ease of access and an already existing knowledge and research infrastructure. Better understanding of glacier flow instabilities will provide important insights into the stability of the larger ice sheets of Greenland and Antarctica in a warming climate. The underlying processes could be studied on Svalbard not only at considerably lower logistical efforts but also under actually ongoing warming that may anticipate what the ice-sheets yet have to face.

2.5   New relevance

Glaciers represent a long-term storage element in the **water balance**, hence, in regions with considerable glacier cover, such as Svalbard where almost 60% of the land surface is covered by ice, glaciers have a dominant role in hydrology which in turn links the glaciers to a plethora of other fields such as **hydrology, oceanography and ecology**. For instance, meltwater runoff from glaciers strongly **influences downstream ecosystems** both from marine-terminating (plume, fjord circulation, ecological hotspot) and well as land-terminating glaciers (dominance/modulation of surface runoff). Meltwater migrating through both paths are reaching fjords causing significant freshening of their waters (e.g. Błaszczyk et al. 2019). On the other hand, en- and subglacial drainage have **implications for glacier dynamics** through effects on the thermal regime and glacier sliding and hence is tightly related to instabilities (surges). A recent assessment of climate change on Svalbard and its related impacts (Hanssen-Bauer et al. 2019) demonstrated the close linkage between glaciers and hydrology on Svalbard, with present-day glacier runoff about four times larger than the runoff from ice-free land (Van Pelt et al. 2019).

Seismological measurements by the existing operational seismic network have been successfully used to monitor glacier calving (Köhler et al. 2016) and surges (Nuth et al. 2019). However, the geometry of the network has deficiencies with respect to detecting and locating events in the Eastern part of Svalbard (Köhler et al. 2020).

Furthermore, specially tailored, temporarily installed seismometer arrays have proved valuable in a number of glacier-related projects to detect and quantify calving (Köhler et al. 2019a) and to collect unprecedented on-glacier data that gave new insights into details of glacier motion and meltwater drainage (Gajek et al. 2017; Köhler et al. 2019b). While present-day satellite remote sensing allows measurements of velocity fields at time intervals of about 10 days, GNSS systems on the glacier surface can record hourly displacements (depending on overall flow speed). However, theory suggests that short-lived (seconds-minutes) motion events may have significance. With scanning rates of several Hz, cryoseismology hence fills this observational gap and opens the pathway for better process understanding.

3. Unanswered questions

The ultimate, overarching question concerns **the future evolution of the land-based ice mass on Svalbard and the related release of freshwater to the terrestrial (streamflow) and marine (fjord circulation) systems and associated impacts on ecosystems and socio-economy**. We break this question into more specific parts that address knowledge gaps related to the current status and the future evolution.

<u>Current status:</u>

- How large is the **frontal ablation**? How much does it vary on different time scales (seasonal, interannual, decadal)? How large are the relative contributions of the two components calving and submarine melting? What are the governing processes?
- What is the importance of **surges** for the mass balance? What are the mechanisms that trigger instability and how does it propagate? Does climate change have an influence on surging?
- How large is the **retention capacity** of Svalbard glaciers? How does it change and what is the partitioning between refreezing and liquid water storage? What are the implications of firn aquifers and supraglacial lakes for biogeochemistry and glacier dynamics?

Process understanding and quantification of these components is imperative for reliably assessing the **future evolution**:

- How will glacier **melt, refreezing and runoff** evolve in the future?
- How do **dynamics and geometry** of Svalbard glaciers respond to climate change?
- What are the **impacts** on calving, surging and frontal ablation?

4. Recommendations for the future

Above, we have identified a number of important knowledge gaps, and to resolve them, the consortium requests a number of research projects. We recognize that funding research projects falls outside the scope of SIOS, but we believe that **concerted efforts regarding networking and research infrastructure** can pave the road towards implementation of these urgently needed research projects.

Specifically, we identified **research needs** concerning:

1. Process studies of **unstable glacier flow** and its potential relationship to surface meltwater
2. Development of a **coupled glacier mass balance-glacier dynamics model** that can be applied to investigate the effects of different climate scenarios
3. Detailed measurements to quantify and understand **frontal ablation and its drivers** and to separate its components submarine melting and calving and their relative importance related to surface mass balance.
4. Geophysical characterization of **firn aquifers** and changes thereof, along with multi-disciplinary efforts to understand their implications for biogeochemistry.

By improving critical infrastructure, providing data services and supporting community efforts, SIOS can significantly contribute to developing Svalbard as a field laboratory for polar glaciology where research projects will address the above listed knowledge gaps.

To that end, we recommend SIOS to:

•   Strengthen the **network of Svalbard glaciologists** by supporting more regular, community-wide activities, for instance by workshops to coordinate research efforts and infrastructure needs, conduct comparative studies or collectively attack grand challenges. For instance, the present SvalGlac report brought together scientists dealing with mass changes of Svalbard glaciers, and should serve as a kick-off to a wider collaboration. Seed support from SIOS will nurture the positive ambitions created herein, and would stimulate further development. We recognize that glaciological activity on Svalbard comprises much more and propose **a follow-up report on glacier dynamics and novel field techniques**. These aspects are related to but outside the scope of this report, and their review will involve a different part of the glaciological community.
•   Support community efforts to collect **a Svalbard-wide dataset of near-front ice thickness**, for instance by using airborne ground-penetrating radar. Combined with available remotely-sensed velocity, this will immediately enable quantifying calving rates at unprecedented accuracy and serve as a baseline for any further efforts

- regarding frontal ablation and its temporal variations.

- Further develop **data services improving cross-disciplinary use of open data**. Many scientists are not aware of already available datasets from other disciplines; this could be alleviated by development of a Svalbard-specific **Data Discovery Tool** within SDMS. Many research datasets are not published in repositories due to high requirements on documentation. This could be alleviated by developing a **Dataset Registration Interface** that interactively aids the scientist to compile metadata complying with standards.

- Stimulate **enhanced communication and cooperation** between the remote sensing and the ground based glaciological groups. The fast development of new sensors increases the potential for assessing key questions stated above.

- Support **homogenization of methods** and improve the collective quality of Svalbard-wide data. This could be achieved through investing in a pool of instruments that are compatible with a common data transmission protocol thus ensuring that all partners can follow the same procedures, for instance when **increasing spatial coverage of mass balance monitoring** to currently underrepresented regions. Having homogenized methods will ultimately increase the value of Svalbard-wide datasets that have been collected by different teams.

- Support development of a **'real-time' (online) database of simulated climatic mass balance**, melt, runoff, etc. across Svalbard to directly reach out to glacier-related disciplines (e.g. marine biology, hydrology, seismology), for instance similar to http://polarportal.dk/en/greenland/mass-and-height-change/.

5. Data availability

Glaciological and glacier-related data from Svalbard are available from different repositories and metadata bases. The most important examples are:

- A **digital elevation model** at https://doi.org/10.21334/npolar.2014.dce53a47 and the **glacier outlines** at https://doi.org/10.21334/npolar.2013.89f430f8 (König et al. 2014), the latter is part of the Randolph Glacier Inventory (RGI consortium 2017).

- **Glacier-wide mass balances** in the database of the World Glacier Monitoring Service (WGMS; https://wgms.ch/), and Environmental monitoring of Svalbard and Jan Mayen (MOSJ): http://www.mosj.no/en/climate/land/mass-balance-glaciers.html,

- The Centre for Polar Studies, University of Silesia data are accessible through the Polish Polar Data Base (www.ppdb.us.edu.pl). **The mass balance data**: http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search?node=srv#/home; **the glaciers inventory**: http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/fb01ad1f-41d8-47f6-b5a2-2c0833b9e772, http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/a0f670ad-0c1e-4cd5-a66d-1366cdfc9428; **the**

positions and velocities of the front: http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/05e2c69a-5645-4488-bc88-630beb03a462, http://ppdb.us.edu.pl/geonetwork/srv/eng/catalog.search#/metadata/37a59a98-835f-4f98-ab39-52c8d9cb7290.

- Unrestricted access to the **point stake mass balance**, and the remaining **AWS time series** is provided upon request by contacting the institutes that collected the data.
- **Meteorological records** for Ny-Ålesund, Hornsund and Longyearbyen are accessible through the eKlima portal (http://eklima.met.no/); and Kongsvegen AWS data at https://doi.org/10.21334/npolar.2017.5dc31930 (Kohler et al. 2017).
- **Surface velocities** shown in Figure 1 have been retrieved from Gardner, A. S., M. A. Fahnestock, and T. A. Scambos, 2019: ITS_LIVE Regional Glacier and Ice Sheet Surface Velocities. National Snow and Ice Data Center; DOI: 10.5067/6II6VW8LLWJ7.

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