THE UNIVERSITY CENTRE IN SVALBARD

DEPARTMENT OF ARCTIC GEOPHYSICS

AGF-212 SNOW AND ICE PROCESSES

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# Glacier Mass Balance Measurements using Ablation Stakes

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# 1. Glacier Mass Balance Measurements using Ablation Stakes


**Abstract**

Ablation stakes drilled in to Tellbreen and Blekumbreen were visited in March 2018 to perform in situ measurements of ice melt and snow height for mass balance calculations, and to continue the annual mass balance data collection that dates back a decade. The measurements showed ablation at all elevation levels, with a glacier-wide annual mass balance of -0.77$\pm$0.02 m w.e. for Tellbreen and -0.84$\pm$0.02 m w.e. for Blekumbreen. Time series dating back to 2008 for Tellbreen and 2010 for Blekumbreen yielded a mean increase of mass balance with height of 4.89 $10^{-3}$ m w.e. $m^{-1}$ for Tellbreen with a slight increase over time, and a mean increase of mass balance with height of 3.75 $10^{-3}$ m w.e. $m^{-1}$ for Blekumbreen with no clear trend over time. This and previous years' measurements were compared with simulations, which showed that the measurements feature bigger annual differences than the simulation. We argue that measurements from some years contain questionable stake data. When removing these data points there is a good agreement between measurements and model for Tellbreen with a root mean square error (rmse) of 0.30 m w.e., and some agreement for Blekumbreen with a rmse of 1.12 m w.e.


## 1.1. Introduction

Glaciers are very good indicators of climate change (AMAP, 2011). This becomes apparent when seeing how much a glacier grows or shrinks as a response to its environment. This study aims to find the mass balance of Tellbreen and Blekumbreen in western Svalbard using measurements in situ of ablation stakes over the course of a decade. Data is collected in the Arctic mid-winter on the 10-11 March 2018 and compared to yearly measurements dating back to 2009.

Modelling shows that climatic mass balance of glaciers in Svalbard had a shift in linear trend from a positive to a negative regime around 1980 (Schuler et al., 2017). Nearly 40 years later, this study finds that Tellbreen and Blekumbreen are losing mass at a rate of, on average, $-0.86$ and $-0.83$ m w.e. yr$^{-1}$ respectively. This is a large number compared to pertinent studies, being up to seven times bigger than other estimates for the average mass balance of all Svalbard glaciers (Hagen et al. (2003) and Moholdt (2010)). This may tell how sensitive in particluar small Arctic glaciers are to a global rise in temperature.

This report sectionally presents a summary of a theoretical basis, the methods used for obtaining and processing stake data, a presentation of the results, discussion and interpretation focusing on the current state of the glaciers, time series compared to simulations, the glaciers in a larger context and a final conclusion — all following an introduction to the studied glaciers below.

### 1.1.1. The Study Sites

Tellbreen and Blekumbreen are located north-east of Longyearbyen, centrally on Spitsbergen in the Svalbard archipelago at $46°24'N$, $8°02'E$ as shown in Figure 1.1. Tellbreen is categorized as a valley glacier by WGI (1989), with Blekumbreen not being officially recognized. Resting between sharp mountain peaks, both glaciers flow in opposite directions from a common pass. The altitudes of the glaciers range from 270 to 630 m a.s.l for Tellbreen, and 320 to 620 m a.s.l for Blekumbreen. Their areas are currently 3.6km$^2$ and 2.04km$^2$ (NPI, 2011). Tellbreen is at present time approximately 4 km long, and Blekumbreen is 3 km long[1]. The glaciers are surrounded by steep mountains, of which the highest peak is 981 m a.s.l. (Birkafjellet). In this study, both glaciers are treated as independent glaciers.

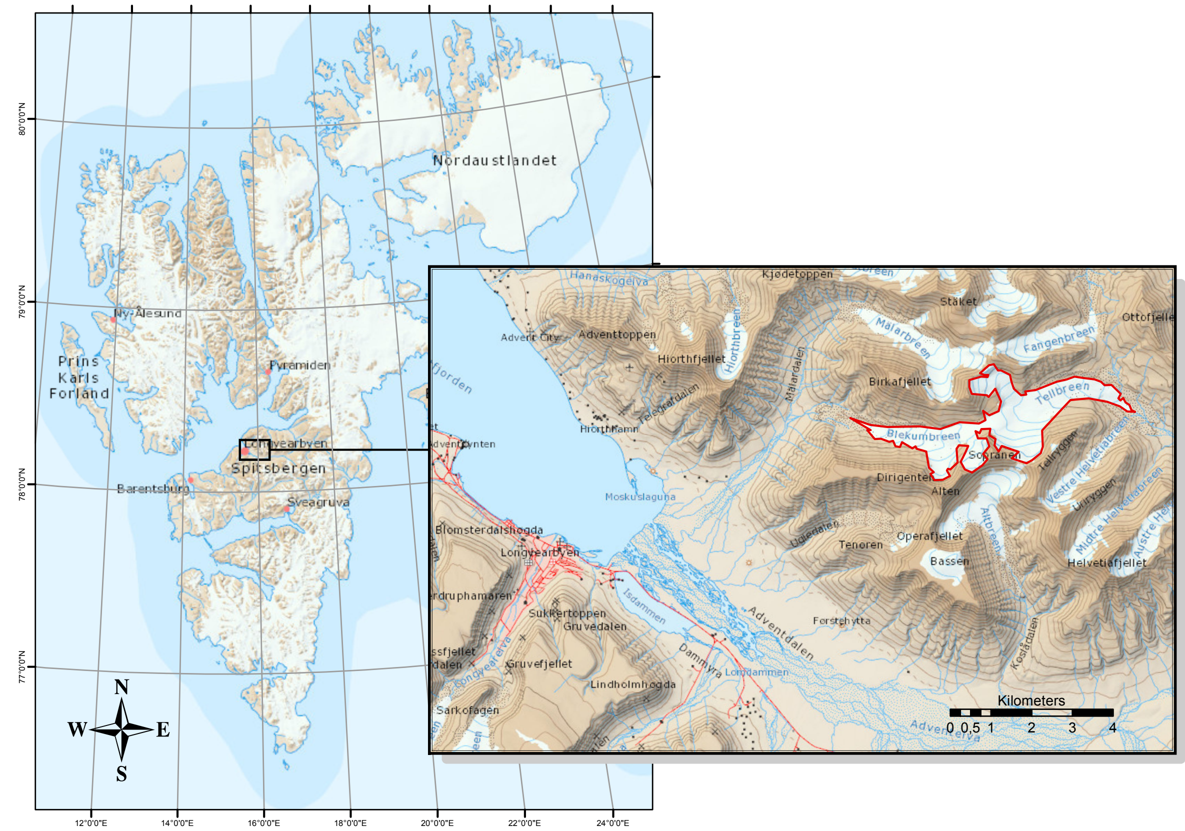


Figure 1.1.: Tellbreen and Blekumbreen (outlined in red) in the perspective of Svalbard and Longyearbyen.

## 1.2. Background and Theory

Having a systematic, concise and unambiguous terminology as a foundation to build research on is important for carrying out mass balance measurements. In this study, the definitions and terminology recommended in *Glossary of Glacier Mass Balance* (G. Cogley

[1] toposvalbard.npolar.no

et al., 2011) is used. Key concepts and theoretical groundwork are presented in the following section.

*Definition* — Mass Balance
The change in the mass of a glacier, or a part of a glacier, over a stated span of time.

### Surface Mass Balance

A glacier can change its mass in numerous ways. Determining the glacier mass balance may be difficult work because of all the different ways a glacier reacts to the local environment, i.e. the air, ground and sea. Narrowing the scope to only the surface mass balance simplifies the problem by focusing on where the major mass changes is happening. The surface can change its mass in two ways: it can gain mass from processes such as precipitation, avalanches, riming, and wind depositions (glacier-wide surface accumulation $\mathrm{C_{sfc}}$), or lose mass due to wind erosion, sublimation, evaporation and rain and melt-water runoff (glacier-wide surface ablation $\mathrm{A_{sfc}}$). The surface mass balance ($\mathrm{B_{sfc}}$) is thus the sum of both of these terms:

$$\mathrm{B_{sfc}} = \mathrm{C_{sfc}} + \mathrm{A_{sfc}} \tag{1.1}$$

Throughout the rest of this text, by mentioning mass balance it is referred to the surface mass balance unless otherwise stated.

Collecting this data over a year gives you the annual glacier-wide mass balance. This period is usually divided into two seasons: summer and winter. A glacier typically has its minimum mass in early autumn after a summer melting season, and its maximum mass in late spring after the winter accumulation. What is regarded as the winter mass balance ($\mathrm{B_w}$) is the mass change from the annual minimum to the annual maximum. Furthermore, the summer mass balance ($\mathrm{B_s}$) is the change of mass from the annual maximum to the annual minimum. The sum of both the winter and summer mass balances equals the annual glacier-wide mass balance ($\mathrm{B_a}$):

$$\mathrm{B_a} = \mathrm{B_w} + \mathrm{B_s} \tag{1.2}$$

The dimensions of mass balance is one of the fundamental questions when doing mass balance measurements since it can be expressed both as a mass [M], and volume [$\mathrm{L^3}$]. The units to be used has been subject for great discussion in G. Cogley et al. (2011), as there is many opinions on this matter. In this report all of the calculations are done using the volumetric unit known as the water equivalent, the reasoning being that it provides an ease of visualization. Often the mass balance is presented per unit area, known as the specific mass balance, and has units of meter water equivalent (m w.e.). The meter water equivalent is defined from an extension of the SI that is obtained by dividing the mass in question per unit area by the density of water.

$$1\mathrm{m\ w.e.} = \frac{1000\mathrm{kg\ m^{-2}}}{\rho_\mathrm{w}} \tag{1.3}$$

To get the measurements in terms of water equivalent units the density of the mass in question is divided by the density of water.

$\mathrm{B_a}$ can also be calculated directly, being comprised of mass balance measurements at several points across the glacier surface and their representative areas. This is an informative quantity for studying the glacier as a whole, and largely an important variable in this study.

The annual mass balance at each point on the glacier (referenced hereby as a stake balance, lowercase $b_a$) can be calculated from stake measurements conducted mainly along the flow line of the glacier at different elevations. These are direct measurements of the sum of accumulation and ablation due to the changing elevation of the glacier surface. In a mathematical form, $b_a$ is the local annual thickness change ($\Delta$tti) turned into water equivalent:

$$\mathrm{b_a} = \Delta \mathrm{tti} \frac{\rho_{\mathrm{ice}}}{\rho_{\mathrm{water}}} \tag{1.4}$$

where $\rho$ denotes density.

The winter stake balance ($b_w$) is calculated directly from the height of snow on the glacier surface (hs). Defining tti as the distance from the top of the stake to the surface of the glacier ice, and tts as the distance from the top of the stake to the snow surface (figure 1.2), $b_w$ is found using the simple relation hs = tti − tts, or with direct measurements in the field. The height of snow is then turned into water equivalent using:

$$\mathrm{b_w} = \mathrm{hs} \frac{\rho_{\mathrm{snow}}}{\rho_{\mathrm{water}}} \tag{1.5}$$

The summer stake balance ($b_s$) is estimated using a variant of eq. 1.2 with the added results from the above equations for $b_a$ and $b_w$:

$$\mathrm{b_s} = \mathrm{b_w} - \mathrm{b_a} \tag{1.6}$$

The annual glacier-wide mass balance is calculated from these stake balance results. By letting the stake balance estimate the whole elevation region around the stake the balance represents, one can calculate the regional mass balance. And it is from the regional mass balance the glacier-wide mass balance is finally calculated. The regional mass balance is computed by multiplying the stake balance (b) with the corresponding elevation bin area (S), also known as the the glacier hypsometry.

$$\mathrm{Re} = \mathrm{b} \cdot \mathrm{S} \tag{1.7}$$

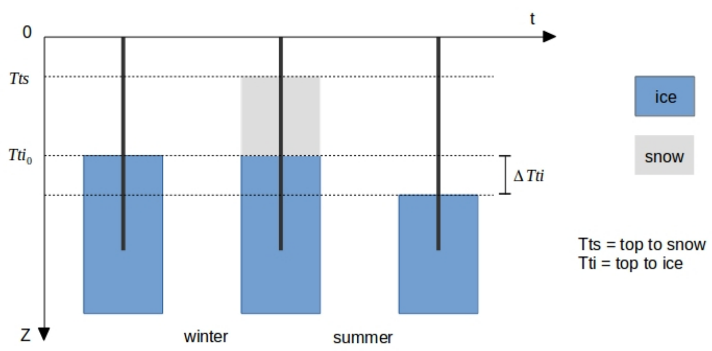


Figure 1.2.: Schematic for measuring the glacier surface in relation to the stake when ablation dominates the accumulation (figure from Siponen and Bendinger (2017)).

Finally, to obtain the glacier-wide annual mass balance, the regional mass balance is summed together and divided with the total glacier area.

$$\mathrm{B_a} = \frac{\sum_{1}^{N} (\mathrm{b}_N \cdot \mathrm{S}_N)}{\sum_{1}^{N} \mathrm{S}_N} \tag{1.8}$$

Where the $\mathrm{b_N}$ is the point mass balance of the stake at elevation bin N, and $\mathrm{S_N}$ is the area of the elevation bin N.
The procedure for calculating glacier wide winter mass balance $\mathrm{B_w}$ and glacier wide summer mass balance $\mathrm{B_s}$ is analogous to the procedure described above.

## 1.3. Methods

This section will provide introductory information about how to collect and process data from ablation stakes on Tellbreen and Blekumbreen. Procedures for working in situ are presented as well as some preliminary conditions for doing measurements, namely the existence of stakes and data from previous years. Techniques for gathering geographical data for further processing and for analysing the data are also mentioned.

For guidelines on behaviour in the field and methods for acquiring data, the procedures established by *Glacier mass-balance measurements — A manual for field and office work* (Østrem and Brugman, 1991) are applied.

Figure 1.3.: Performing a stake measurement with a probe at Tellbreen (left) and probing the snow at several points around a stake at Blekumbreen (right).

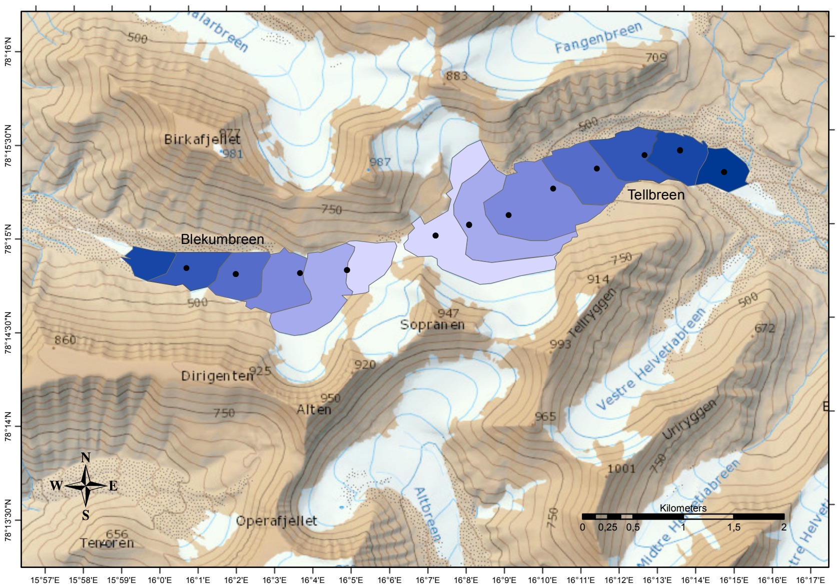


Figure 1.4.: Tellbreen and Blekumbreen with ablation stakes (black circles) and elevation bins. The masks are colored in a gradient from dark to light, corresponding to an elevation gradient from low to high. Masks of equal colour belong to the same elevation interval of 50 m.

### 1.3.1. Instruments

A brief list of equipment needed for performing mass balance measurements is as follows.

**Stake** 6 $m$ tall aluminium pipes with a diameter of roughly 10 $cm$

**Snow probe** from your standard avalanche rescue gear, as a measuring device

**Snow density kit** containing a device for extracting snow samples with known dimensions (we used a cylinder of 550 g with internal volume of 500 ml), a spring weight, a spatula and a wooden hammer

### 1.3.2. Procedure

Ablation stakes are checked to gather data for calculating the mass balance of Tellbreen and Blekumbreen. They are drilled into the glacier surface at the flow lines of both glaciers respectively. One can measure the stakes' extent above the ice and thereby determine how much the glacier surface has grown or shrunk since their last recording. These are specific measurements of the accumulation and ablation of the glacier, and is according to the glaciological method, also known as the direct method, for finding the mass balance (G. Cogley et al., 2011).

The stakes' heights above the glacier ice and the surrounding snow depths are measured once a year (due to the annual AGF-course schedule) and presented in a table in appendix A. The snow depth is measured with a probe at several points around the stake and the median is recorded. From the snow depth and the stake's extent above the snow one can deduce the distance from the top of the stake to the glacier surface. The location of each stake is shown in Figure 1.4.

Additionally, for finding the winter mass balance of the glaciers, the density of the snow is needed. This property can vary by location and throughout the snow pack. To determine this locally, snow pits are dug and the whole snow column is measured, ideally at each stake location. Interval weights of the snow is recorded so that the samples cover the whole snow column from top to bottom. The total weight is then divided by the total volume of the samples to get the bulk density. Most of the density measurements used in this report is obtained by calculating the bulk density with the different sample densities reported by Zweigel et al. (2018).

### 1.3.3. Techniques

The following sections contain topics on post-field data gathering and analysis.

#### Elevation Bins

For extracting data regarding the areas of each given elevation interval on the glaciers, ArcMap (v10.4.1) software is used together with satellite images and digital elevation models downloaded from NPI (2011). For the purpose of this study, the areas of the glaciers inside each 50 m elevation contour line is used (Figure 1.4). The downloaded map provide the desired contour lines and a general outline of both glaciers (white areas), and together with satellite images from 2009-2011 for cross-referencing glacier borders the areas for masking are drawn.

#### Data and Plots

The areas from the previous section are used together with the calculated mass balance values to generate plots presented throughout this report. Python (v2.7 and 3) is used for data processing and producing figures, as well as MATLAB (R2013b) software to read and treat data obtained from various other sources. The tables of all recorded stake heights and snow depths in appendix A is generated using Microsoft Excel 2015.

For comparison between measurements and modelling, mass balance values for Tellbreen and Blekumbreen is extracted from SvalClim simulations. Both the simulation predictions and the MatLab script for downscaling the predictions are provided by Thomas V. Schuler. The model is a coupeled atmosphere-glacier model, with 2.5 km grid spacing. In total 8 grid points are used from the model simulation. Mass balance predicted from these 8 grid points is scaled to a digital elevation model with a grid size of 50 m using multiple regression. To get values for Tellbreen and Blekumbreen specifically, glacier outlines are loaded from Radolph Glacier Inventory (RGI 6.0). Glacier-wide mass balance is then obtained by taking the mean of the glaciers grid values.

In the case where there are no ablation stakes in an elevation interval a least squares linear fit of that year's data is done to obtain a value for the middle of the interval. In some of the previous years there have been a lack of data for the upper and/or lower stakes. Therefore a linear fit of the data from all the stakes is applied, and not just from the stake below and above.

| | |
|---|---|
| **Uncertainties in stake measurements** | |
| Rounding to the nearest cm when reading off probe | $\pm 0.5$ cm |
| Standard deviation in the measured snow depth around the stake | $\pm 6$ cm |
| **Uncertainties in densities** | |
| Standard deviation in measured snow density | $\pm 22.8$ kg m$^{-3}$ |
| Uncertainty in ice density | $\pm 17$ kg m$^{-3}$ |

Table 1.1.: Table showing uncertainties in measurements.

### 1.3.4. Uncertainty

Table 1.1 presents the used values for uncertainties in the measurements.

The density of glacier ice is increasing with depth (Shumskiy, 1960). Since Tellbreen and Blekumbreen shows trends of general melting the ice density at the surface is expected to be higher than if there where accumulation. This is due to the fact that the lighter surface ice is melting, and that there is no accumulation of firn. In this study the ice density is assumed to be 900 kg m$^{-3}$ with an uncertainty of $\pm 17$ kg m$^{-3}$ to cover variations.

The calculations of the regional and the glacier-wide mass balance does not take into account that the stake measurements may not be completely representative for the associated region. It is therefore likely that the actual values and the values presented in this report differ more than the error presented. Furthermore, there is also uncertainty related to the stake measurements themselves. This uncertainty is almost impossible to give a realistic estimate for, due to the fact that one cannot know if the uncertainty exists there in the first place, or how substantial it is. The measurements are only reliable if the stake can be assumed not to be floating in water, or to have sunk further into the ice due to firn contained within the drill hole. The stake must also protrude vertically from the ice, or else the stake measurements yield wrong values. This can sometimes be difficult to determine, due to the apparent curvature of the glacier around the stake.

Moreover, when the snow height is measured with a probe there is in some cases a possibility that an ice layer in the snow is hit instead of the glacier surface. To prevent this, the measurements are repeated several times, and ideally the snow height is compared to a snow pit close to the stake.

### 1.3.5. New Stakes

As the glacier surface shrinks, the ablation stakes melt out of the ice and falls flat. To ensure steady and reliable measurements each year, new stakes are drilled into the glacier on the locations where it is presumed a stake will fall out in the course of the next year. New stakes are usually drilled within a meter radius of the old. The stake-table in Appendix A is updated with data regarding new stakes drilled in 2018, continuing the intuitive naming trends already established.

## 1.4. Results

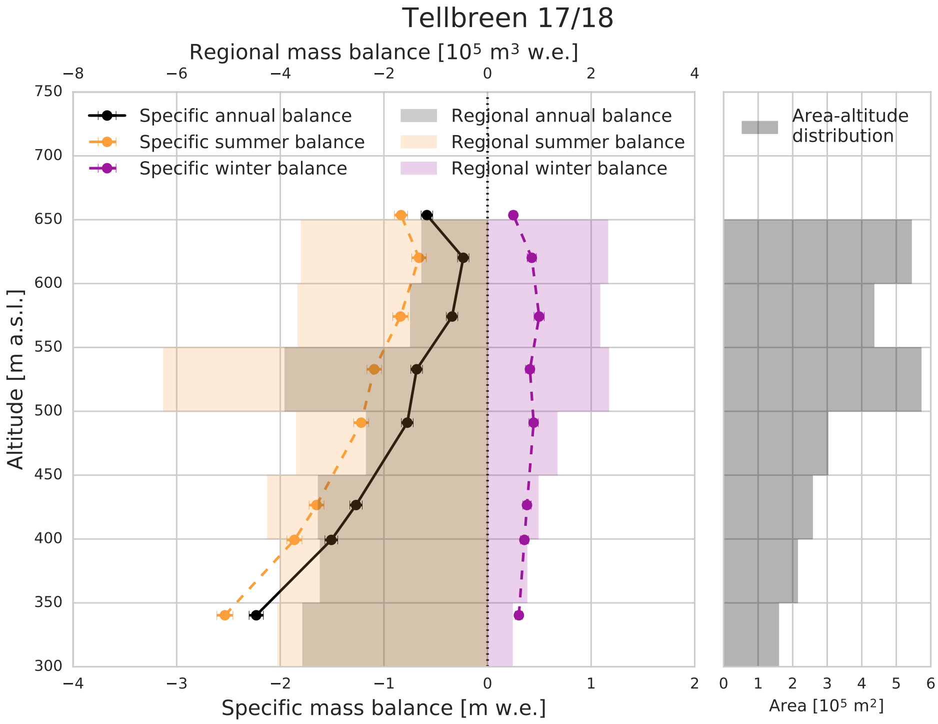


Figure 1.5.: Annual, summer and winter mass balance for 2017/2018 Tellbreen. The specific mass balance recorded at the stakes is visualized as connected points. The regional mass balance, calculated using the area-elevation distribution, is visualized with the shaded area.

Figure 1.5 shows annual, summer and winter mass balance for Tellbreen for 2017/2018. Connected points represents the specific mass balance at each stake. The annual and summer balance shows ablation along the whole glacier. Maximum annual and maximum summer ablation took place at the lowest stake with respectively $-2.23 \pm 0.07$ m w.e. and $-2.53 \pm 0.08$ m w.e. Ablation decreases with height until a minimum value at the second highest stake with respectively $-0.23 \pm 0.06$ m w.e. and $-0.66 \pm 0.07$ m w.e. The winter balance shows accumulation at the whole glacier and varies less with height. Minimum and maximum winter accumulation is $0.25 \pm 0.05$ m w.e. and $0.50 \pm 0.05$ m w.e.

Regional mass balance for each elevation interval is represented by the shaded area. Each elevation interval has a specified area shown to the right in the figure. The regional annual ablation tends to decrease with height, but with a maxima of $-3.9 \pm 0.3$ $10^5$m$^3$ w.e. between 500 and 550 m a.s.l. Regional summer ablation varies less, except a peak of $-6.3 \pm 0.4$ $10^5$m$^3$ w.e. in the same elevation interval as the annual balance maxima. Regional winter ablation tends to increase with height, with a maximum value of $2.3 \pm 0.2$ $10^5$m$^3$ w.e. and a minimum value of $0.48 \pm 0.06$ $10^5$m$^3$ w.e. All the maximum values is found in the interval with the largest area.

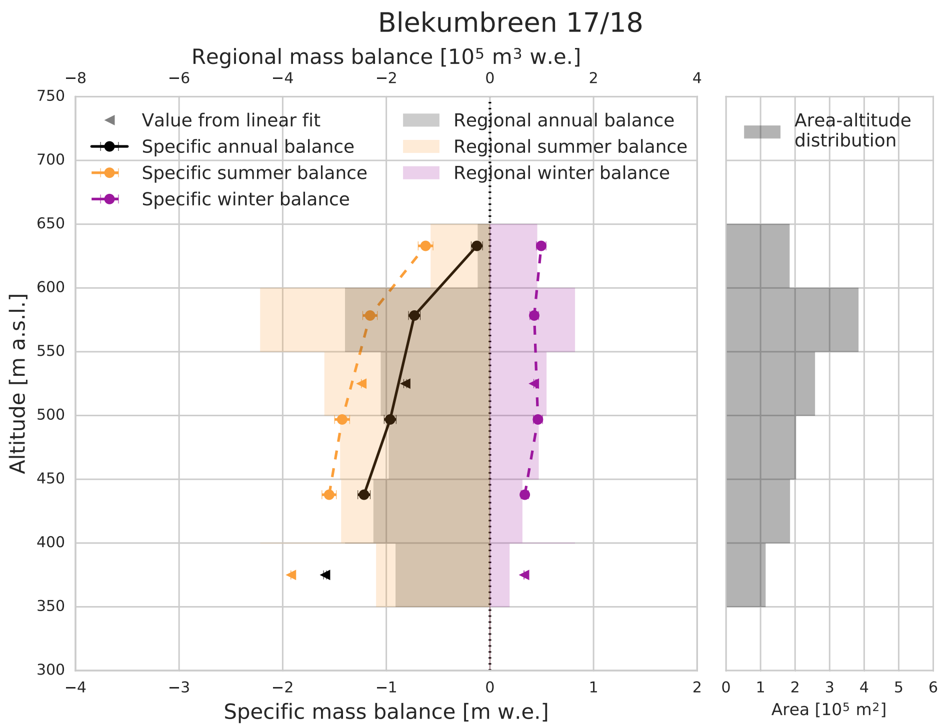


Figure 1.6.: Annual, summer and winter mass balance for 2017/2018 for Blekumbreen. The specific mass balance recorded at the stakes is visualized as connected points. The regional mass balance, calculated using the area-elevation distribution, is visualized with the shaded area.

Figure 1.6 shows the corresponding figure for Blekumbreen. The specific mass balance at the stakes shows the same trend as for Tellbreen, with annual and summer ablation decreasing with height, and with winter accumulation varying less. Minimum and maximum ablation for the annual balance is $-0.13 \pm 0.05$ m w.e. and $-1.22 \pm 0.06$ m w.e. The summer minimum and maximum ablation is $-0.62 \pm 0.07$ m w.e. and $-1.55 \pm 0.07$ m w.e., while the winter minimum and maximum is $0.16 \pm 0.02$ m w.e. and $0.49 \pm 0.05$ m w.e.

The regional balance tends to increase with height, as the area-altitude distribution also increases. An exception is the interval between 600 m and 650 m a.s.l., where both the summer and annual ablation has its minima. The winter accumulation is also lower here. In general the regional balance at Blekumbreen shows less ablation and less accumulation than on Tellbreen. Maximum annual ablation happens between 550 m and 600 m a.s.l. with $-2.8 \pm 0.2$ $10^5 m^3$ w.e. The same area has maximum summer ablation and maximum winter accumulation, with respectively $-4.4 \pm 0.3$ $10^5 m^3$ w.e. and $1.6 \pm 0.2$ $10^5 m^3$ w.e.

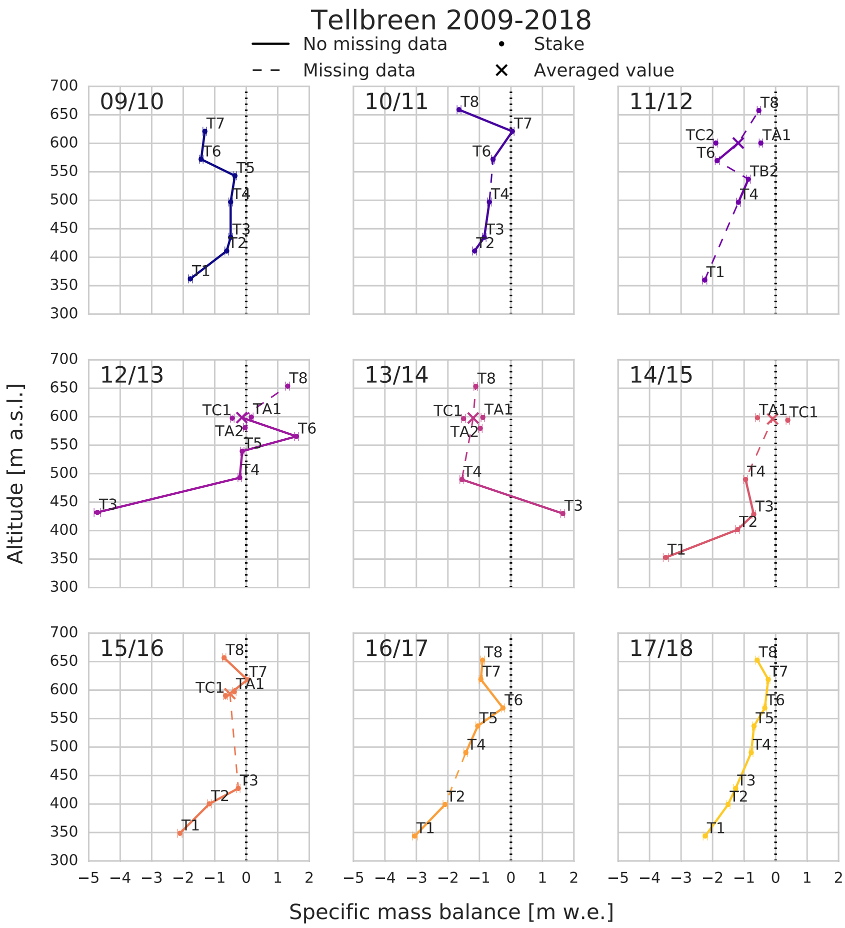


Figure 1.7.: Annual specific mass balance measured at the ablation stakes at Tellbreen from 2009 to 2018. Missing data between two points is shown as a dashed line. When two or more stakes are close in elevation the mean is shown as a cross.

In Figure 1.7 the annual specific mass balance at Tellbreen for each year since 2009 is shown. Ablation is taking place along the whole glacier most years. Only the measurements from 12/13 and 13/14 show significant accumulation at some points. In 12/13 there is an anomaly at T3 showing accumulation at lower elevations.

The year 16/17 and 17/18 show a similar trend with linearly decreasing ablation with elevation and a minimum value around 600 m a.s.l. In general there was more ablation in 16/17 than in 17/18.

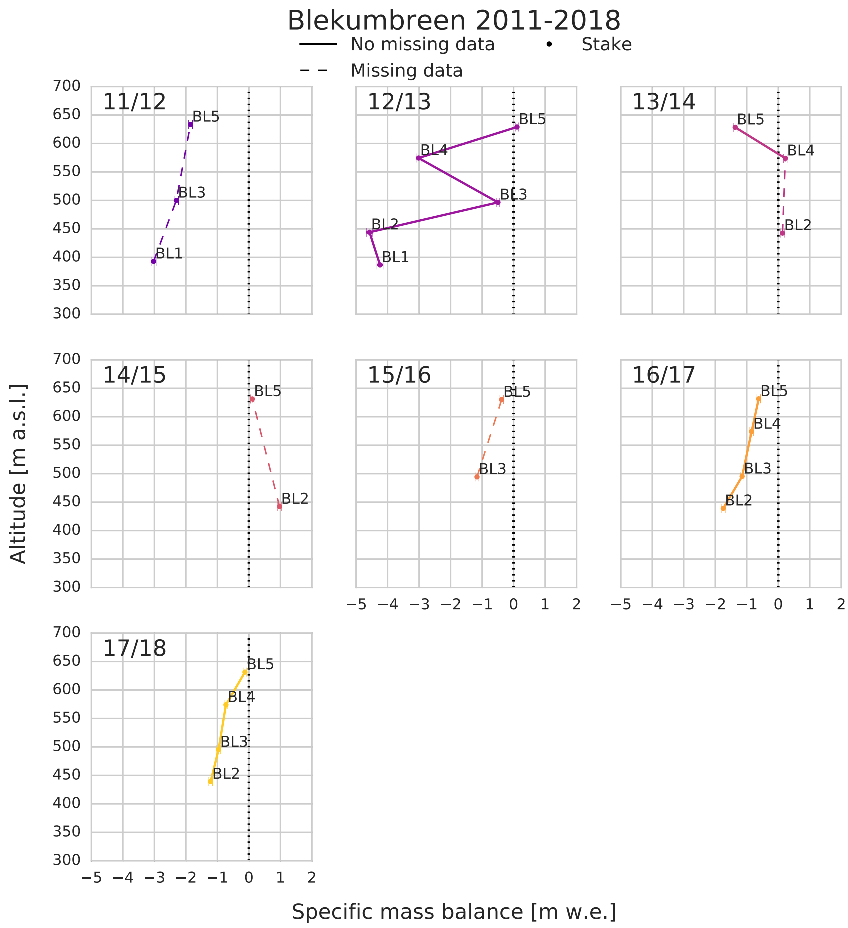


Figure 1.8.: Annual specific mass balance measured at the ablation stakes at Blekumbreen from 2011 to 2018. Missing data between two points is shown as a dashed line.

Figure 1.8 shows a similar diagram for Blekumbreen, with measurements going back to 2011. Four of the seven data sets show ablation decreasing with elevation, while the measurements from 13/14 and 14/15 show accumulation. The one from 13/14 shows ablation for the uppermost stake, while the data set from 14/15 shows accumulation at both the measured stakes, with less accumulation at higher elevation.

As in the case with Tellbreen, there is a similar trend in the measurements at Blekumbreen from 16/17 and 17/18, with slightly more ablation in 16/17 than in 17/18.

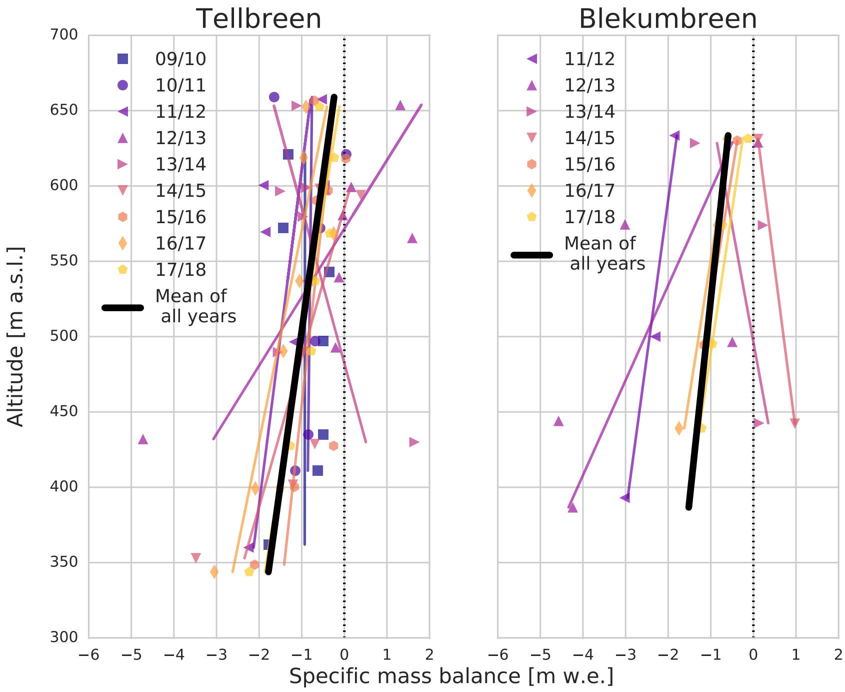


Figure 1.9.: Linear regression of the measured mass balance along the flow lines at Tellbreen from 2009 to 2018 and at Blekumbreen from 2011 to 2018.

Figure 1.9 shows a linear regression of the annual mass balance for each year together with the mean of all the regression lines. Results from the two glaciers are shown separately. The regression lines for Tellbreen all show a similar trend, except for two outliers (12/13 and 13/14). If the two outliers are excluded the set of regression lines show a weak signal of an increase in the slope with time. The slope of the mean regression line is 4.89 $10^{-3}$ m w.e./m.

Measurements from Blekumbreen show more spread in the regression lines than for Tellbreen, but the measurements from the three last years are significantly alike. The slope of the mean regression line is 3.75 $10^{-3}$ m w.e./m.

Figure 1.10 and 1.11 show the glacier-wide mass balance for Tellbreen and Blekumbreen, together with SvalClim simulations. The year refers to the year when the summer and most of the recorded winter balance took place, so that what has previously been denoted as 17/18 is here written as 2017. Glacier-wide annual balance for Tellbreen 2017 is $-0.77 \pm 0.02$ m w.e. The corresponding value for Blekumbreen 2017 shows slightly more ablation, with $-0.84 \pm 0.02$ m w.e. Both glaciers show less ablation in 2017 than in 2016.

Comparing the measured mass balance with the model, one can see that the measurements of the annual and summer balance varies more than the model output. This is especially evident in the data for Blekumbreen. The winter balance is more stable, with a mean of 0.50 m w.e. for Tellbreen and 0.46 m w.e. for Blekumbreen. As for summer balance, Tellbreen had an ablation of $1.19 \pm 0.02$ m w.e. in 2017, while Blekumbreen had an ablation of $-1.26 \pm 0.04$ m w.e.

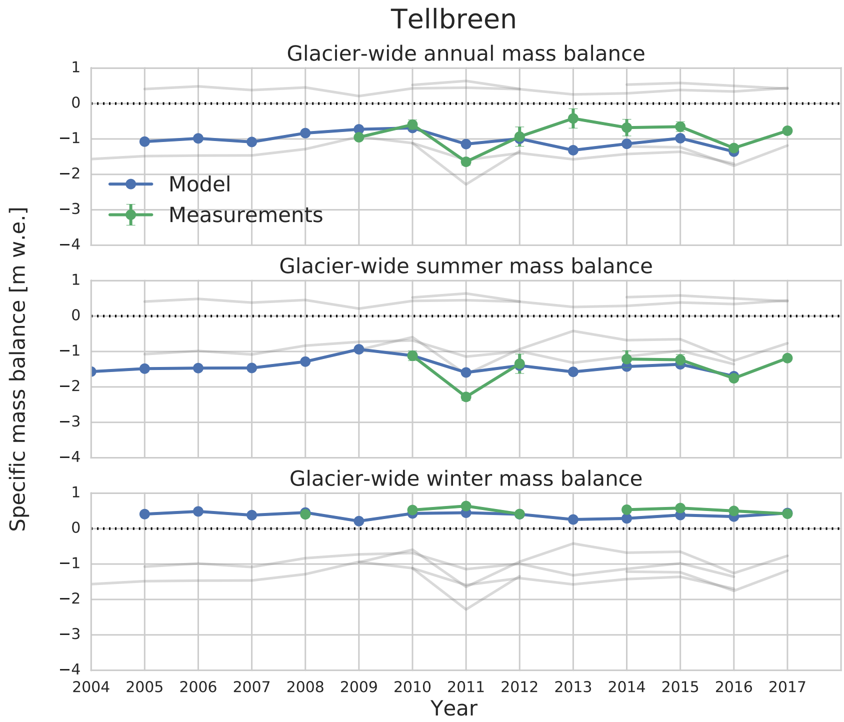


Figure 1.10.: Three subfigures of the annual, summer and winter glacier-wide mass balance for Tellbreen. Model and measurements values are displayed in blue and green respectively. The grey lines is the results from the other two subfigures.

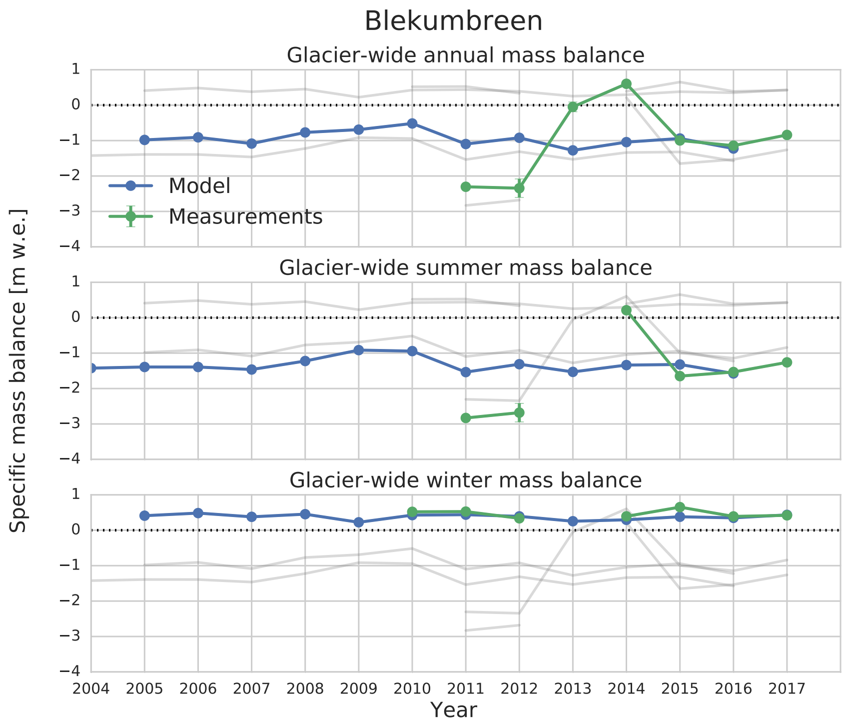


Figure 1.11.: Three subfigures of the annual, summer and winter glacier-wide mass balance for Blekumbreen. Model and measurements values are displayed in blue and green respectively. The grey lines is the results from the other two subfigures.

# 1.5. Discussion

This section delves into the implications of the results and aims to set the mass balance measurements into a wider perspective.

## 1.5.1. The Current State of the Glaciers

Being two glaciers flowing from the same hilltop, they are roughly exposed to equal large scale weather throughout the year, i.e. temperature fluxes and precipitation. Both glaciers are shadowed by similar mountains due north and south. Conditions are present for the glaciers to behave similarly, and this is indeed reflected in the results.

Both Tellbreen and Blekumbreen are showing negative mass balances, and they are losing mass faster towards their bottoms than at their tops. This is expected and likely a consequence of the lapse rate. The air temperature is estimated to differ with 2 K in the elevation range of our glaciers[2], thus increasing melting as elevation decreases. Blekumbreen is losing its mass faster than Tellbreen, which may be explained with a similar argument, taken into account that the average elevation for Blekumbreen is at a lower elevation than its neighbour. It is apparent in Figure 1.5 that there is an increase in ablation from the second highest to the highest stake at Tellbreen. Less ablation at the lower stakes may be explained by the concave shape of the glacier, resulting in more accumulation of wind driven snow and therefore more winter accumulation.

Also clear from Figures 1.5 and 1.6 is the glacier-wide ablation zone. No stake measurement show accumulation zones for either glacier, meaning there is no equilibrium line altitude (ELA). From *Glacier Atlas of Svalbard and Jan Mayen* (Hagen et al., 1993), the ELA is averaged to be at around 500 m a.s.l. for glaciers around the south-eastern coast of Isfjorden. This may indicate a change in ELA since this 1993 publication due to climate change, or Tellbreen and Blekumbreen deviates from the average glacier in this area by having no accumulation zone.

## 1.5.2. A Look Through the Years

As can be seen in Figure 1.10 and 1.11 the glacier-wide annual balance varies from year to year. It is also clear that the measured mass balance varies more than the model simulations. When comparing to Figure 1.7 and 1.8 one can see that there is a connection between years with a big difference in measured and modelled mass balance, and years with few or non-linear data points. A linear regression is used to fill in missing measurements. Since some years do not show a clear linear trend this method may not always be ideal.

The difference in the model and the measurements are especially evident for the annual and summer balance at Blekumbreen between 2011 and 2014. Both 13/14 and 14/15 (noted as 2013 and 2014 in Figure 1.11) show accumulation at the lowest part of the glacier, which is questionable. This is seen in the glacier-wide annual mass balance as almost no ablation in 2013 and even summer accumulation in 2014.

[2] The international standard atmosphere is defined by International Civil Aviation Organization (1993) to have an average lapse rate of 6.49 K km$^{-1}$

The root mean square error (rmse) between the measured and modelled annual mass balance at Blekumbreen is 1.13 m w.e., which is in the same order of magnitude as the modelled value. The summer rmse is 1.10 m. w.e. If only 2016 is considered, which is one of the resent years with the most complete and linear data set, the difference between the model and the measured annual balance is 0.08 m w.e. One data point is too little to draw a conclusion, but it is an indication that with a more complete data set there would be a better agreement between the model and the measurements.

The year 2013 is the year with the lowest ablation at Tellbreen. This year there is a questionable measurement showing accumulation at the bottom, even though there is ablation at higher elevations. This can be due to a icy layer in the snow mistakenly being interpreted as the glacier surface when measuring the stake height. This possible mistake leads to a higher calculated regional balance at that elevation, and also affects the slope of the linear fit used to fill in data gaps. It is therefore likely that the mass balance calculated from measurements underestimate the ablation that year.

When excluding the 2013-value, the rmse between the modelled and measured annual mass balance from 2009 to 2016 is 0.30 m w.e. The rmse for the summer balance is 0.30 m w.e.

For both Blekumbreen and Tellbreen there is a good accordance between the modelled and measured winter balance, with a rmse of respectively 0.13 m w.e. and 0.16 m w.e. This may be due to the somewhat easier process of measuring snow depth used for calculating winter balance, and therefore also a better data set.

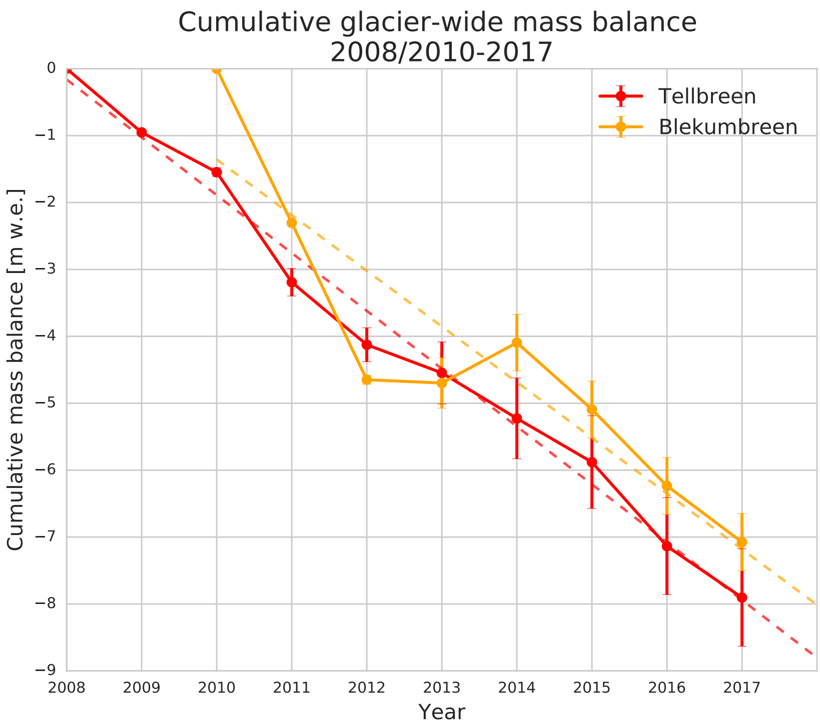


Figure 1.12.: Cumulative glacier-wide mass balance for Tellbreen and Blekumbreen. Recordings started in 2008 for Tellbreen and in 2010 for Blekumbreen.

Figure 1.12 shows the accumulative annual mass balance for Tellbreen and Blekumbreen. On average Tellbreen melts 0.86 m w.e. per year, while Blekumbreen melts 0.83 m w.e. per year. The value for Blekumbreen is most likely higher, since in this calculation the somewhat doubtful value for Blekumbreen from 2014, showing summer accumulation, is included. The Ice radar group found a mean ice thickness of 32 m for Tellbreen and 42 m for Blekumbreen. Assuming that the accumulative mass balance follows the trend in Figure 1.12, and only considering the mean thickness of the glaciers, Tellbreen will be gone in approximately 34 years while Blekumbreen will be gone in approximately 46 years.

### 1.5.3. A Larger Perspective

Seeing Tellbreen and Blekumbreen in a wider scope and comparing them to other glaciers on Svalbard, it is found that the loss of mass balance much larger than the average. The overall mass balance of Svalbard in the short time period 2003-2008 is estimated from ICESat data to $-0.12 \pm 0.04$m w.e. yr$^{-1}$ (Moholdt, 2010) (including the $\sim$ 8000km$^2$ Austfonna ice cap), which is over seven times smaller than the mass balance of either of Tellbreen and Blekumbreen. The Svalbard archipelago has a glacier coverage of $\sim$ 36000km$^2$, and studies have shown western Svalbard glaciers to have a negative mass balance over the last century (Schuler et al., 2010). Tellbreen and Blekumbreen makes up only 0.015% of this area and as concluded in this study to show a large ablation rate, perhaps because of its small size.

Austre Brøggerbreen with its 6.1 km$^2$ and Midtre Lovénbreen with 5.5 km$^2$ are glaciers of comparable size to Tellbreen and Blekumbreen, located outside Ny Ålesund on the western coast of Spitsbergen. A study of these glaciers show a specific mass balance of $-0.42$m w.e. yr$^{-1}$ and $-0.33$m w.e. yr$^{-1}$ respectively as an average from 1967-1991 (Hagen et al., 1993), about half the ablation of this study's results. Both glaciers are land-terminating and therefore the reporting of a surface mass balance, similar to the simplification made in this study. In contrary to here, Austre Brøggerbreen and Midtre Lovénbreen data is compiled on the basis of topographical maps, aerial photographs, Landsat satellite images and radio-echo soundings.

The differences in total annual ablation may be explained by looking at the seasonal balances. The specific winter balances by Ny Ålesund are roughly 1.5 times the balances by Longyearbyen, indicating more precipitation in the winter. Meanwhile, the specific summer balances are very similar, meaning there is more snow to melt during the summer for the northernmost glaciers and thereby less ice melt, resulting in a lesser total mass balance. Whether the extra snow height in winter for Brøggerbreen and Lovénbreen is reasonable for twice the ablation at Tellbreen and Blekumbreen is uncertain, but we can expect it to contribute to the explanation.

## 1.6. Conclusion

Ablation stake measurements can give direct data for the mass balance of the glaciers. This was compared with SvalClim simulations to asses if the model was in accordance with the measurements. Non-standardized routines for previous years' data collection challenges the reliability of the timeseries. This has been a source of uncertainty in the final results, but comparisons with similar studies using various methods indicates a correlation with the general trend.

Tellbreen and Blekumbreen are losing mass just like other Svalbard glaciers, although at a somewhat faster rate. There is no existense of an equilibrium line for either of the glaciers. Both glaciers have a negative surface mass balance of $-0.77 \pm 0.02$ m w.e. and $-0.84 \pm 0.02$ m w.e. in 2017/2018 respectively, largely continuing the trend from the last ten years.

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# Appendices

# A. Appendix — Glacier Mass Balance Measurements using Ablation Stakes

| Table Info | | n.f | Stake not found | Stake no. | Stake found in 2018 |
|---|---|---|---|---|---|
| ** | Stake Tilted | n.a | Data not avaliable | Stake no. | Stake not found in 2018 |
| / | Data can't be avaliable | | See comment | Stake no. | Stake found in 2018, and there is a stake comment |
| # | Cable (installed in 2012) | ?? | Data hole | Stake no. | Stake not found in 2018, and there is a stake comment |

Figure A.1.: Table info

| Tellebreen Stakes | | Top to ice (tti) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** |
| T1 | T1-2009 | 1 | 2,97 | n.f | | | | | | | |
| | T1-2011 | / | / | 1,95 | 4,45 | n.f | | | | | |
| | T1-2012 # | / | / | / | n.a. | 1,95 | ?? | | | | |
| | T1-2014 | / | / | / | / | / | 0,22 | 4,09 | n.f | | |
| | T1-2015 | / | / | / | / | / | / | 1,84 | 4,18 | n.f | |
| | T1-2016 | / | / | / | / | / | / | / | 0,03 | 3,42 | n.f |
| | T1-2017 | / | / | / | / | / | / | / | / | 1,04 | 3,52 |
| | T1-2018 | / | / | / | / | / | / | / | / | / | 0,46 |
| T2 | T2-2009 | 0,98 | 1,67 | 2,95 | n.f | | | | | | |
| | T2-2012# | / | / | / | n.a. | n.f | | | | | |
| | T2-2013 | / | / | / | / | 5,51 | n.f | | | | |
| | T2-2014 | / | / | / | / | / | 3,61 | 4,95 | n.f | | |
| | T2-2015 | / | / | / | / | / | / | 3,35 | 4,65 | n.f | |
| | T2-2016 | / | / | / | / | / | / | / | 0,97 | 3,29 | 4,95 |
| | T2-2017 | / | / | / | / | / | / | / | / | 1,30 | 2,99 |
| | T2-2018 | / | / | / | / | / | / | / | / | / | 0,45 |
| T3 | T3-2009 | 0,96 | 1,51 | 2,45 | n.f | | | | | | |
| | T3-2012 # | / | / | / | 0,43 | 5,68 | 3,85 | 4,62 | n.f | | |
| | T3-2015 | / | / | / | / | / | / | 2,84 | 3,12 | ?? | n.f |
| | T3-2017 | / | / | / | / | / | / | / | / | 1,19 | 2,60 |
| | | | | | | | | | | | |
| T4 | T4-2009 | 1[A] | 1,55 | 2,31 | 3,62 | 3,85 | 5,58[B] | 6,64[C] | n.f | | |
| | T4-2014 | / | / | / | / | / | 0,4 | n.f | n.f | | |
| | T4-2016 | / | / | / | / | / | / | / | 1,35 | 2,94 | 3,80 |
| | T4-2018 | / | / | / | / | / | / | / | / | / | 0,43 |
| T5 | T5-2009 | 0,78 | 1,18 | n.f | | | | | | | |
| | T5-2012[A] | / | / | / | 2,5 | 2,64 | n.a.[B] | n.a | n.f | | |
| | T5-2016 | / | / | / | / | / | / | / | 1,55 | 2,72 | 3,48 |
| | T5-2018 | / | / | / | / | / | / | / | / | / | 0,28 |
| T6 | T6-2009 | 0,55 | 2,14 | 2,77 | 4,83 | 3,06 | n.f | | | | |
| | T6-2013 | / | / | / | / | 4,46 | n.f | | | | |
| | T6-2016 | / | / | / | / | / | / | / | 3,47 | 3,75 | 4,13 |
| | T6-2018 | / | / | / | / | / | / | / | / | / | 1,82 |
| T7 | T7-2009 | 1,64 | 3,1 | 3,05 | 2,93** | 2,79** | 1,82** | n.f | | | ** |
| | T7-2015 | / | / | / | / | / | / | 3,54 | 3,5 | 4,56 | 4,86 |
| | T7-2017 | / | / | / | / | / | / | / | / | 1,13 | 1,35 |
| | | | | | | | | | | | |
| T8 | T8-2009 | n.a. | 1,33 | 3,16 | 3,75 | 2,29 | 3,53 | n.f | | | |
| | T8-2015 | / | / | / | / | / | / | 2,5 | 3,28 | 4,28 | n.a |
| | T8-2017 | / | / | / | / | / | / | / | / | 1,09 | 1,74 |
| | | | | | | | | | | | |

Figure A.2.: Top to ice data for Tellbreen

| **Blekumbreen Stakes** | | Top to ice (tti) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** |
| BL1 | BL1-2011 | / | / | 1,05 | 4,41 | **n.f** | | | | | |
| | BL1-2012 # | / | / | / | 0,52 | 5,23 | n.a [A] | ?? | **n.f** | **n.f** | **n.f** |
| | | | | | | | | | | | |
| BL2 | BL2-2012 # | / | / | / | 0,46 | 5,54 | 5,39 | 4,31 | ?? | | |
| | BL2-2016 | / | / | / | / | / | / | / | 0,17 | 1,94 | 3,29 |
| | BL2-2018 | / | / | / | / | / | / | / | / | / | 0,63 |
| BL3 | BL3-2011 | / | / | 0,68 | 3,24 | 3,79 | n.a | ?? | | | |
| | BL3-2015 | / | / | / | / | / | / | 2,25 | 3,54 | 4,81 | **n.f** |
| | BL3-2016 | / | / | / | / | / | / | / | 1,86 | 3,14 | 4,21 |
| | BL3-2018 | / | / | / | / | / | / | / | / | / | 0,38 |
| BL4 | BL4-2012 # | / | / | / | 0,45 | 3,8 | 3,55 | ?? | | | |
| | BL4-2016 | / | / | / | / | / | / | / | 2,07 | 3,01 | 3,82 |
| | | | | | | | | | | | |
| BL5 | BL5-2011 | / | / | 1,2 | 3,26 | 3,14 | 4,66 | 4,54 | 4,96 | 5,65 | **n.f** |
| | BL5-2017 | / | / | / | / | / | / | / | / | 1,18 | 1,32 |
| | BL5-2018 | / | / | / | / | / | / | / | / | / | 0,76 |

| **Tellebreen Stakes outside of flowline** | | Top to ice (tti) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
| TA1 | TA1-2010 | / | n.a. | 2,81 | 3,33 | 3,15 | 4,14 | 4,78 | 5,2 | ?? | **n.f** |
| | | | | | | | | | | | |
| TA2 | TA2-2010 | / | n.a. | 1,92 | **n.f** [A] | | | | | | |
| | TA2-2012 | / | / | / | 2,09 | 2,13 | 3,21 | ?? | ?? | ?? | **n.f** |
| TB1 | TB1-2010 | / | n.a. | 2,86 | **n.f** | | | | | | |
| | TB1-2012 | / | / | / | n.a. | **n.f** | | | | | |
| | TB1-2013 | / | / | / | / | 5,11 | **n.f** | ?? | 3,73** | ?? | **n.f** |
| TB2 | TB2-2010 | / | n.a. | 3,57 | 4,53 | **n.f** | **n.f** | | | | |
| TC1 | TC1-2010 | / | n.a. | 2,57 | **n.f** | | | | | | |
| | TC1-2012 | / | / | / | 0,96 | 1,45 | 3,12 | 2,69 | 3,42 [A] | ?? | **n.f** |
| TC2 | TC2-2010 | / | n.a. | 2,44 | 4,55 | **n.f** | | | | | |
| | TC2-2013 | / | / | / | / | 1,77 | **n.f** | | | | |

Figure A.3.: Top to ice data for Blekumbreen and the stakes outside of the flowline on Tellbreen

| **Tellebreen Stakes** | | Height of snow (hs) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** |
| T1 | T1-2009 | 1,05 | 1,12 | **n.f** | | | | | | | |
| | T1-2011 | / | / | 1,33 | 1,22 | ?? | | | | | |
| | T1-2012 # | / | / | / | n.a. | 0,65 | ?? | | | | |
| | T1-2014 | / | / | / | / | / | n.a. | ?? | **n.f** | | |
| | T1-2015 | / | / | / | / | / | / | 1,05 | 0,85 | **n.f** | |
| | T1-2016 | / | / | / | / | / | / | / | 0,85 | 0,88 | **n.f** |
| | T1-2017 | / | / | / | / | / | / | / | / | n.a | 0,85 |
| | T1-2018 | / | / | / | / | / | / | / | / | / | n.a |
| T2 | T2-2009 | 1,17 | 1,24 | 1,44 | **n.f** | | | | | | |
| | T2-2012# | / | / | / | n.a. | **n.f** | | | | | |
| | T2-2013 | / | / | / | / | 1,05 | **n.f** | | | | |
| | T2-2014 | / | / | / | / | / | n.a. | ?? | **n.f** | | |
| | T2-2015 | / | / | / | / | / | / | 1,62 | 1,1 | **n.f** | |
| | T2-2016 | / | / | / | / | / | / | / | 1,1 | 0,87 | 1,00 |
| | T2-2017 | / | / | / | / | / | / | / | / | n.a | 1,00 |
| | T2-2018 | / | / | / | / | / | / | / | / | / | n.a |
| T3 | T3-2009 | 1,34 | 1,35 | 1,42 | **n.f** | | | | | | |
| | T3-2012 # | / | / | / | n.a. | n.a. | n.a. | ?? | | | |
| | T3-2015 | / | / | / | / | / | / | 1,27 | 1,25 | ?? | **n.f** |
| | T3-2017 | / | / | / | / | / | / | / | / | n.a. | 1,07 |
| | | | | | | | | | | | |
| T4 | T4-2009 | 1,35 | 1,46 | 1,36 | 1,6 | 0,9 | ?? | | | | |
| | T4-2014 | / | / | / | / | / | n.a. | **n.f** | **n.f** | | |
| | T4-2016 | / | / | / | / | / | / | / | n.a. | 1,45 | 1,25 |
| | T4-2018 | / | / | / | / | / | / | / | / | / | n.a |
| T5 | T5-2009 | 1,33 | 1,33 | 1,41 | **n.f** | | | | | | |
| | T5-2012 [A] | / | / | / | 1,55 | 1,17 | n.a. | ?? | | | |
| | T5-2016 | / | / | / | / | / | / | / | n.a. | 1,47 | 1,15 |
| | T5-2018 | / | / | / | / | / | / | / | / | / | n.a |
| T6 | T6-2009 | 1,55 | 1,52 | 2,02 | 2,13 | 1,4 | n.a. | ?? | | | |
| | T6-2013 | / | / | / | / | 1,36 | n.a. | ?? | | | |
| | T6-2016 | / | / | / | / | / | / | / | 2,8 | 1,74 | 1,4 |
| | T6-2018 | / | / | / | / | / | / | / | / | / | n.a |
| T7 | T7-2009 | 1,77 | 1,72 | 1,67 | 1,71 | 1,36 | n.a. | **n.f** | | | n.a |
| | T7-2015 | / | / | / | / | / | / | 2,05 | 1,35 | 1,51 | 1,2 |
| | T7-2017 | / | / | / | / | / | / | / | / | n.a | 1,2 |
| | | | | | | | | | | | |
| T8 | T8-2009 | n.a. | 1,19 | 1,06 | 1,00 | 0,94 | n.a. | **n.f** | | | |
| | T8-2015 | / | / | / | / | / | / | 1,05 | 1,10 | 1,00 | n.a |
| | T8-2017 | / | / | / | / | / | / | / | / | n.a | 0,7 |
| | | | | | | | | | | | |

Figure A.4.: Height of snow data for Tellbreen

| Blekumbreen Stakes | | Height of snow (hs) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** |
| BL1 | BL1-2011 | / | / | 1,42 | 1,19 | **n.f** | | | | | |
| | BL1-2012 # | / | / | / | n.a | 1,04 | n.a | ?? | n.a | n.a | 0,4 [B] |
| BL2 | BL2-2012 # | / | / | / | n.a. | 0,92 | n.a | ?? | | | |
| | BL2-2016 | / | / | / | / | / | / | / | n.a | 0,78 | 0,85 |
| | BL2-2018 | / | / | / | / | / | / | / | / | / | n.a |
| BL3 | BL3-2011 | / | / | 1,3 | 1,11 | 0,83 | n.a | ?? | | | |
| | BL3-2015 | / | / | / | / | / | / | 1,1 | 1,7 | 1,13 | **n.f** |
| | BL3-2016 | / | / | / | / | / | / | / | n.a | 1,08 | 1,17 |
| | BL3-2018 | / | / | / | / | / | / | / | / | / | n.a |
| BL4 | BL4-2012 # | / | / | / | n.a | 0,85 | n.a | | | | |
| | BL4-2016 | / | / | / | / | / | / | / | n.a | 1,23 | 1,08 |
| BL5 | BL5-2011 | / | / | 1,75 | 1,54 | 1,1 | n.a | | 1,98 | 1,37 | **n.f** |
| | BL5-2017 | / | / | / | / | / | / | / | / | 1,37 | 1,25 |
| | BL5-2018 | / | / | / | / | / | / | / | / | / | na. |

| Tellebreen Stakes outside of flowline | | Height of snow (hs) data [m] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stake No. | | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
| TA1 | TA1-2010 | n.a. | 1,8 | 1,75 | 1,13 | n.a. | ?? | 2 | ?? | | |
| TA2 | TA2-2010 | n.a. | 1,61 [B] | n.a. | ?? | | | | | | |
| | TA2-2012 | / | / | 1,5 | 1,11 | n.a. | ?? | | | | |
| TB1 | TB1-2010 | n.a. | 1,6 | 1,46 | ?? | | | | | | |
| | TB1-2012 | / | / | n.a. | ?? | | | | | | |
| | TB1-2013 | / | / | / | n.a. | n.a. | ?? | 1,85 | ?? | | |
| TB2 | TB2-2010 | n.a. | 1,55 | 1,54 | **n.f** | | | | | | |
| TC1 | TC1-2010 | n.a. | 1,37 | ?? | | | | | | | |
| | TC1-2012 | / | / | 1,23 [B] | 1,01 | n.a. | n.a. | 2,17 [C] | ?? | | |
| TC2 | TC2-2010 | n.a. | 1,73 | 1,45 | **n.f** | | | | | | |
| | TC2-2013 | / | / | / | 1,00 | n.a. | ?? | | | | |

Figure A.5.: Height of snow data for Blekumbreen and the stakes outside of the flowline on Tellbreen