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# Effects of snow-free season, temperature and radiation variations on the retreat of Linné glacier, Svalbard

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# Abstract

Linné glacier has retreated approximately 1.8 km since 1936 and 1 km between 1995 and 2019. Linné glacier is following the same trend as other glaciers around Svalbard. Linné glacier is a well monitored glacier with a time series of air temperature, incoming solar radiation and snow height data since 2003. Annual recordings of the glacier margin from 2007, allows for an accurate reconstruction of the glacier's retreat. The aim of this thesis is to evaluate how climatic factors such as the length of the snow free season, air temperature and incoming solar radiation affect the yearly retreat of Linné glacier over the course of 13 years. This will be done by mapping the annual retreat of the glacier and calculating the length, average air temperature and average incoming solar radiation of each snow free season. In 2019 the glacier margin was recorded by a handheld GPS and a drone to make a comparison between both methods. Linné glacier is negatively affected by an increase in air temperature, increase in incoming solar radiation and longer snow free season. In total the glacier area retreat amounted to about 30.57 ha over the course of 13 years, from 2007 until 2019. An increase of 1 °C in air temperature will result with a glacier retreat of 0.44 ha. Incoming solar radiation has the highest impact on Linné glacier retreat compared to the other climatic factors. When calculating the sum of the daily average air temperature of each snow free season, a stronger correlation was observed with the area of retreat. An increase in the snow free season length is observed, caused by earlier melt onset and later freeze up. Lastly, photogrammetry is a more suitable way of data collecting the glacier margin coordinates than using a handheld GPS. These findings are relevant for glacier retreat studies and contribute towards an improved understanding of glacier behavior in Svalbard.

Contents

# 1 Introduction

The Arctic region has shown the most noticeable warming, an aspect known as the Arctic amplification (Hanssen-Bauer et al. 2019). The Arctic will undoubtedly be affected by the global temperature rise (Kohler et al. 2007). For instance, Svalbard being part of the Arctic has seen a lot of climatic changes. Indeed, what caught the eyes, is the air temperature increase by 3 to 5 °C during the last 4 to 5 decades (Hanssen-Bauer et al. 2019). The west coast of Svalbard has seen dramatic decrease in its sea ice (Day et al. 2012). Svalbard's glaciers have undergone an almost constant retreat since the end of the Little Ice Age (LIA) (Grove 2012). Melting of the glaciers will impact sea level rise (Nuth et al. 2010; Gardner et al. 2013). Svalbard contains an estimated 7000 km3 of ice and were this to melt completely it would cause 0.02 m of eustatic sea level rise (Hagen et al. 2003b). Understanding the rate of retreat of glaciers, would help to predict the future consequences of climate change.

## 1.1 Purpose and study aim

The aim of this thesis is to evaluate how climatic factors such as: the length of the snow free season, air temperature and incoming solar radiation affect the yearly retreat of Linné glacier over the course of 13 years.

The study is based on the following hypothesis:

- *The area of retreat will be more affected with longer snow free season, higher air temperature and higher incoming radiation intensity.*
- *Snow free season length has the highest impact on the glacier retreat.*
- *Photogrammetry is a more suitable way of data collecting the glacier margin coordinates than using a handheld GPS.*

To test the hypothesis the following study questions are set up:

- *What is the annual retreat of the glacier since data collection began?*
- *How are the climatic factors affecting the intensity of the retreat?*
- *What are the differences between collecting the glacier margin coordinates with a GPS versus photogrammetry using a drone?*

# 2 Background

## 2.1 Climate of Svalbard

Svalbard is an Arctic Archipelago located north of Norway, between 74° and 81° north latitude and 10° and 35° east longitude. It has unique meteorological status that is very diverse (Moholdt et al. 2010). Svalbard winters are mainly influenced by semi-permanent low (the Icelandic low in the north Atlantic and the Aleutian low in the Pacific) and high (Siberian high over Russia and the weaker Beaufort high over North America) pressure systems in the mid latitudes (Hanssen-Bauer et al. 2019). Changes in these large-scale atmospheric circulation patterns have brought warm Atlantic Water from the West of Spitsbergen current onto the West Spitsbergen Shelf and further into the fjords even during winter (Nilsen et al. 2016). This has an impact on the sea ice distribution such as opening up large areas of ice-free waters west and north of Svalbard (Tverberg et al. 2014). This will lead to large changes in ocean surface energy flux. A study made in 2012 found that ~66 % of the winter warming and ~54 % of the increase in precipitation was caused by sea ice decline (Day et al. 2012). At Svalbard Airport, the annual measured precipitation has in average increased by 2% per decade (Førland et al. 2011).

## 2.2 Measuring glacier retreat

Satellite images are one of the most used techniques to monitor glacier retreat. By looking at two different satellite images taken at different time, it is possible to notice the retreat or the advance of a glacier. For example, out of 244 glaciers in the Antarctic Peninsula, 87% of the glaciers showed a retreat of the margin using satellite images (Cook et al. 2005). Unmanned aerial vehicle (UAV) such as drones are being used to monitor glacier margin retreat. In Greenland UAV was used to produce high resolution orthomosaic to monitor a tidewater glacier retreating (Ryan et al. 2014).

Glaciological mass balance is the determination of accumulation and ablation for the mass balance year (Cox and March 2004). It is done by visiting the glacier twice a year, to collect the winter and summer mass balance. Winter mass balance is collected in the end of the accumulation season. Snow depth must be measured at many different points covering the whole glacier because snow height can vary throughout the topography. Density of the snow is measured to convert snow depth to water equivalent. The summer balance is collected in the end of the summer when melting has ended. This is done by measuring the changes of the stake's heights over the course of the melting season (Hanssen-Bauer et al. 2019).

Geodetic mass balance is the comparison of two different digital elevation models (DEM) of the glacier taken at different time period. Elevation data can be from a variety of sources: GPS profiling, photogrammetry, airborne laser altimetry (LIDAR) and satellite remote sensing (e.g. ICE Sat). Many of these techniques have been used to evaluate the glacier retreat of Svalbard. For example, in 2010, a study used ICE Sat laser altimetry for estimating 2003–2008 elevation changes of Svalbard glaciers. It was found out that the largest ice losses have occurred in the west and south, while northeastern Spitsbergen and the ice cap have gained mass (Moholdt et al. 2010).

## 2.3 Melting factors

Presently the glaciers in Svalbard are losing more ice through melting and calving than they are accumulating through snowfall (Hanssen-Bauer et al. 2019). That is due to diverse factors. At first hand, during winter, new snow will be deposited over the glacier ice that will work as a protective sheet over the summer. Snow has a high ability of reflecting short-wave radiation (albedo), which is around 90%.The albedo of glacier ice varies between 40 and 50% (Gardner and Sharp 2010). When glacier ice is covered with debris, albedo can go as low as 10% (Brock et al. 2000; Winther et al. 2002). So, when the melting season begins, the snow will take longer time to melt due to the high albedo. But as soon as the snow disappears, the intensity of the melting will dramatically increase, resulting in a faster retreat of the glacier. Air temperature and snow height impact the glacier retreat. Many studies found a clear correlation between air temperature and glacier retreat (Bøggild et al. 1994; Braithwaite and Zhang 1999). Snow height is another major factor affecting the glacier mass balance (Hagen et al. 2003a).

# 3 Method

## 3.1 Study area

The study area is located on the west coast of Spitsbergen, the largest island of the Svalbard archipelago (Figure 1). Linné glacier is a small valley glacier located at 77°57' north latitude and 13°52' east longitude with a current elevation range of 220–550 m a.s.l.. It contributes meltwater to Linnéelva which flows almost 7 km to Linnévatnet. Linné glacier is characterized as a polythermal glacier, where the bottom of the glacier is cold based, and the rest is warm based. This glacier has been retreating since the end of the little ice age in the 19th century (Hagen et al. 1993). The glacier area has shrunk by 60% since the 1930s (Pendleton et al, 2011). The glacier front has retreated approximately 1.8 km since 1936 and 1 km between 1995 and 2019 (Retelle et al. 2019).

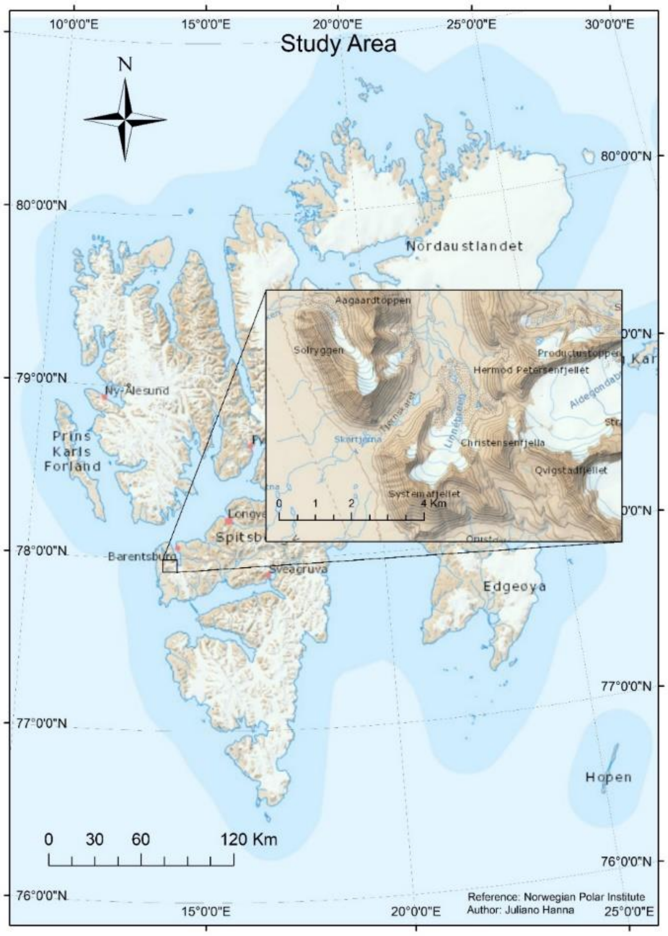

*Figure 1 Study area location in the west coast of Svalbard.*

## 3.2 Data collection

The data of 2019 was collected by the author and other classmates during 9 days of field work in Linné valley, Svalbard. This field work was part of a summer course “Environmental Change in the High Arctic Landscape of Svalbard” at The University Center in Svalbard (UNIS). During this field work, different data sets were collected all over the valley. This has been done for many years starting in 2003. Sponsored initially by US grants, National Science Foundation Polar programs, and monitoring efforts have been supported in recent years by faculty-student research at UNIS. During the summer 2019, the data was collected for this thesis including air temperature, incoming solar radiation, snow height and glacier margin.

### 3.2.1 Air Temperature and Incoming Solar Radiation

Air temperature and solar radiation were collected from the main weather station of Linné valley located 6 km away from the glacier at 78,027N and 13,85E with an elevation of 75 m above sea level (Figure 2a). The weather station records data every 30 minutes throughout the year. The station is an Onset data logger H21-001 and Onset sensors (Onset Computer Corporation 1981; Roof 2012).

### 3.2.2 Snow height

Accumulation and ablation of snow has been measured using a so-called snow tree on the glacier’s moraine at 77,98N and 13,911E.A snow tree is a wooden stick with 10 HOBO Pendant loggers (Onset Computer Corporation 1981) attached to it every 10 cm (Figure 2b). These loggers record both temperature and light intensity every 30 min. When covered in snow, light intensity will drop to 0 Lux, depending on the logger’s height. This data must be collected from the loggers every year due to the battery life. A computer was taken in the field and then by using HOBO software and a transmission cable, it was able to transfer the data of one

*Figure 2 a) The main weather station in Linné valley from where temperature and radiation were collected for the study b) The snow tree located near Linné glacier that is recording snow height and temperature.* *Photos: AL Werner* logger at a time. After the transfer, the logger's battery must be changed and programmed to collect the data every 30 min from a specific date.

### 3.2.3 Glacier margin

Two methods were used in 2019 to map the glacier margin. The first method consists of GPS to map the glacier margin. First the glacier margin must be identified by making different observations on site. Glacier ice can be covered by debris making it hard to separate between the moraine. After this step is done, it is time to walk the glacier margin and collect coordinates with GPS. This traditional method was used in the previous years to collect the glacier margin.

The second method used in 2019 utilizes a Mavic 2 Pro drone to capture images of the glacier forefield, margin and one of the source areas. This drone is equipped with a Hasselblad L1D-20c camera that captures 20-megapixel aerial shots with a 1-inch CMOS Sensor (DJI 2018). The drone was flying at 120m above the glacier and taking pictures manually every 2 seconds. In total 440 images were captured with an overlap of 80%. Three batteries were needed to accomplish the flight plan. This method was used for the first time to map the glacier margin of Linné glacier.

## 3.3 Data Processing

### 3.3.1 Drone images and GPS tracks

One of the first steps was to map the glacier margin of 2019 using the drone images. The images were imported to Agisoft PhotoScan 1.4.1 to create a high resolution orthomosaic. This was done by first aligning the pictures while the rolling shutter compensator is enabled since the Mavic 2 Pro drone has a rolling electronic shutter. When this step was done, manual tie points were added as they would initially not automatically align correctly due to poor feature matches between them. A tie point is one point that is detected in three or more images. They are the link between images to get 3D relative positioning. After aligning all the picture, a dense cloud can be built, using a quality of 'Medium' and a depth filtering of 'Moderate', from the tie points that resulted from the alignment. Based on the estimate of the camera positions, the software measures the depth details for each camera to be merged into a single dense point cloud (PhotoScan 2013). Afterwards the tiled model is built and the orthomosaic was derived from it with a resolution of 7 cm. In ArcMap (ESRI 2011), the glacier margin was digitized using the high resolution orthomosaic.

The second step was to map the glacier margins of 2019 and the previously available years. The data was exported from the GPS as a GPX file. In ArcMap all the GPX files were converted to point layers where each point layer represents the glacier margin with points. Succeeding this, the points of each layers were digitized to get a line layer representing the glacier margin of the different years. Two maps were then created in ArcMap representing the terminus of the glacier for the different years. To calculate the area that has been lost for each year, polygons had to be created. This was done by creating a polygon around two-line layers representing two consecutive years. The area of each polygon was then exported to Excel. During some years, the glacier margin was not recorded. To compensate for that, the area that has been lost between two different years was divided equally between the number of years that had passed. For example, there was no recording during 2007 and 2008, so the area between 2006 and 2009 was divided by three.

### 3.3.2 Detection of the snow free period using the snow tree and air temperature

To detect the length of the snow free season, data from the snow tree located on the moraine of Linné glacier was used. By assuming the ablation process starts when there is 10 cm of snow, meaning that the lowest logger on the snow tree at 10 cm above the surface will be used to determine the start and end of the snow free season. The rest of the loggers will not be used in the study since this study is not looking at the snow accumulation during the winter season. The margin will start melting and retreating when the snow cover will disappear, and the temperature will rise above 0°C for seven consecutive days. The end of the melting season is when the temperature gets below zero degrees Celsius for seven consecutive days. The data that was available is from 2007 to 2019.

The snow tree data has been analyzed using HOBOware software, made by the same company manufacturing the data loggers. The start of the snow free was simple to find. On the other hand, the end of the melting season was more complicated to determine. As there were more fluctuations in the temperature. Using HOBOware to make observations and Excel to calculate the average temperature for 7 consecutive days, it was possible to find the end of the melting season. Having both dates, start and end, the duration was calculated in number of days.

### 3.3.3 Weather station data

All the data that has been collected from the main weather station of Linné valley has been uploaded to the “Arctic Data Center” (Roof 2012). The data was downloaded, and each year was presented in an excel sheet. Using the start and end of the snow free season, it was possible to export the necessary data representing the snow free season to a new excel sheet. During some years, the weather station stopped recording so data from nearby station were used instead. The average temperature and radiation were calculated for each snow free season. The next step was to calculate the daily average, maximum and minimum. This was done in Python 3.7.1 IDLE. A code was written to get the average, maximum and minimum. When this data got acquired, the daily amplitude was calculated in excel.

A combination of daily average temperature and length of the snow free season was combined to get the positive degree day factor (Braithwaite 1995). This was done by summing up all the positive daily average temperature of each snow free season.

## 3.4 Statistical analyzes

The area of retreat was related to the meteorological drivers and the length of the snow free season. For this, correlations were calculated in EXCEL between the area of retreat and (i) the snow free season duration, (ii) mean air temperature during the snow-free season, (iii) average radiation during the snow-free season, and (iiii) positive degree factor during the snow-free season.

# 4 Result

## 4.1 Glacier margin retreat

The orthomosaic created, covers a big area of the glacier forefield and the entire margin (Figure 3). In addition, it covers one of the accumulations areas in the south east (A) and half of the other accumulation area (B). The snow line altitude (SLA) is in the south east of the glacier, in one of the accumulations areas at a high altitude. Yearly glacier margins from 2006 onwards are overlaid over the most recent orthomosaic to present the retreat that the glacier has been ongoing. A clear trend can be seen where the center of the glacier's margin has been retreating the most compared to the edges of the margin where a slight retreat occurred. There is a distinct change in the area of retreat that happened between 2015 and 2016, where a dramatic change occurred to a small part of the margin.

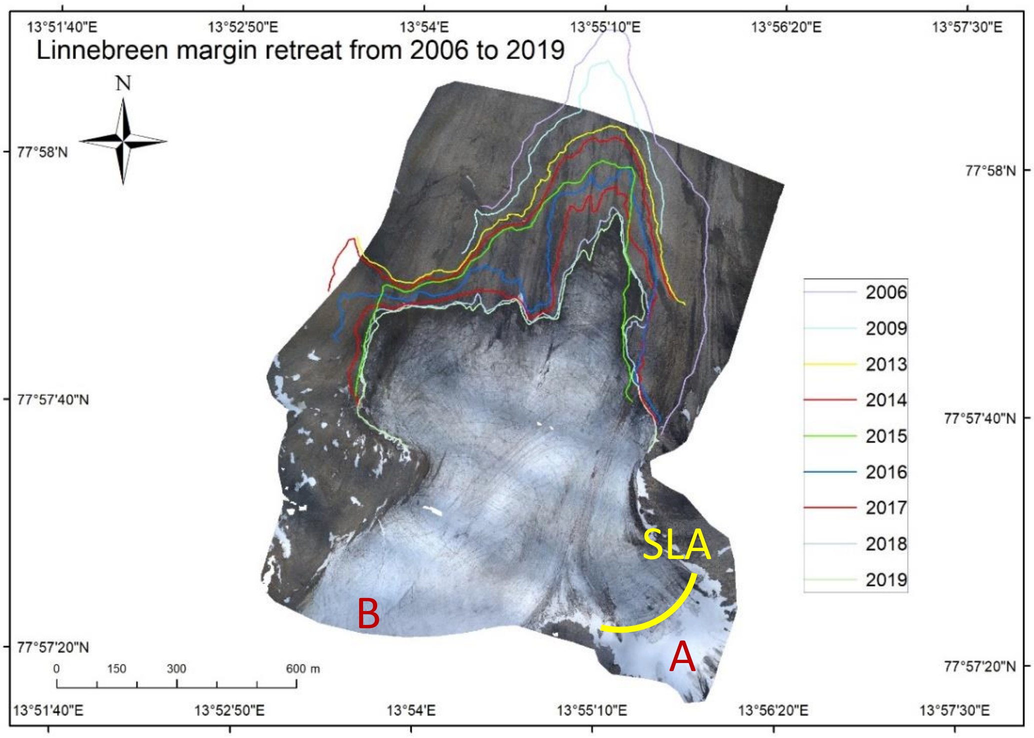

*Figure 3 Yearly glacier margin overlapped with the orthomosaic made in 2019 using drone images. Accumulation area A and B could be seen in the south and the snow line altitude (SLA) is located near accumulation area A*

The points collected with the handheld GPS to collect the glacier margin are scattered around the glacier margin and do not really represent the margin (Figure 4). Form the orthomosaic, a more defined margin was extracted.

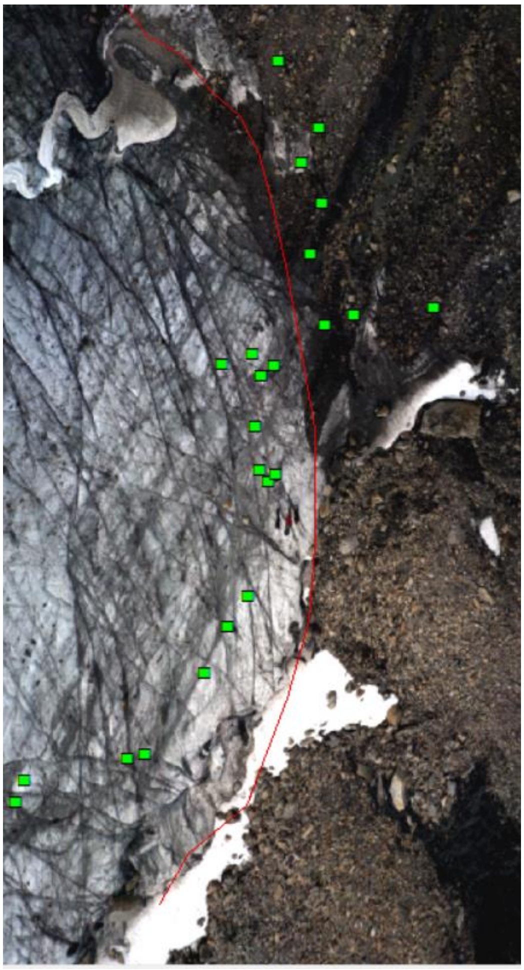

*Figure 4 The points represent the glacier margin collected using a handheld GPS and the red line is the glacier's margin using the orthomosaic created from the drone images*

From 2013 and onward, the margin is presented with one year of interval. But between 2006 and 2013 the retreat is shown over two intervals: 2006-2009 and 2009-2013. The strongest retreat occurred during 2015 with an area loss of 4.33 ha (Figure 5). The smallest retreat happened in 2019 with a loss in area of around 1.65 ha. From 2015 to 2018, the area lost was always higher than 3 ha even reaching higher than 4 ha during 2015 and 2017. In total the glacier area retreat around 30.57 ha over the course of 13 years, from 2007 until 2019.

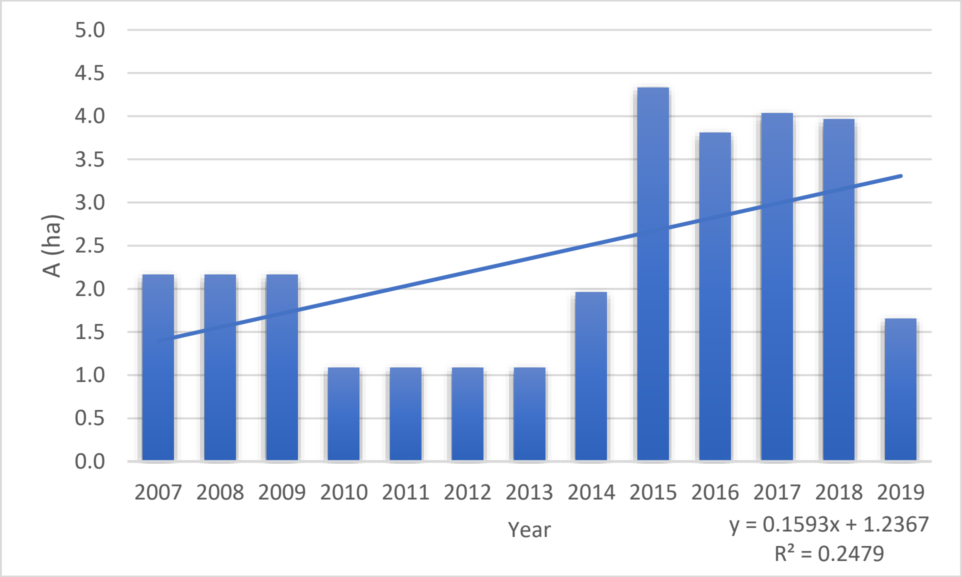

*Figure 5 Annual area of retreat from 2007 to 2019.*

## 4.2 Length of the snow free season

The time series of the start of the snow free season showed a clear negative trend (Figure 6). During 2008, the snow free season started on the 17th of July, making it the latest compared to all the other years. In 2016, the year with the earliest beginning of the snow free season, it started on the 22nd of May. On average, the start of the snow free season occurred 3.3 days earlier per year in the period 2007/2019 ($R^2$=0.6).

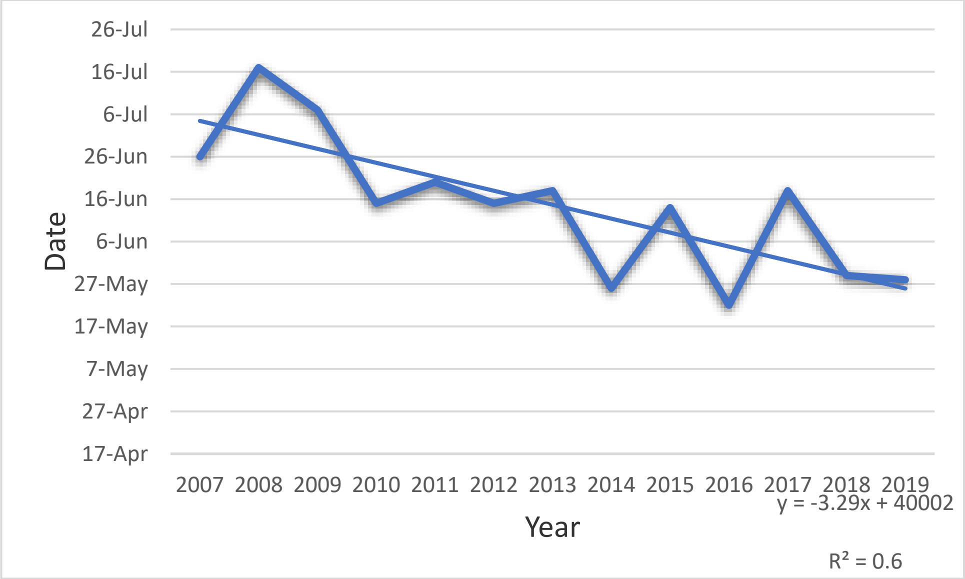

*Figure 6 Yearly start of snow free season.*

The trend in the time series of the end of the melting season (Figure 7), was less clear ($R^2$=0.14). On average the snow free season ended 1.5 days per year later in the period 2007 and 2019.

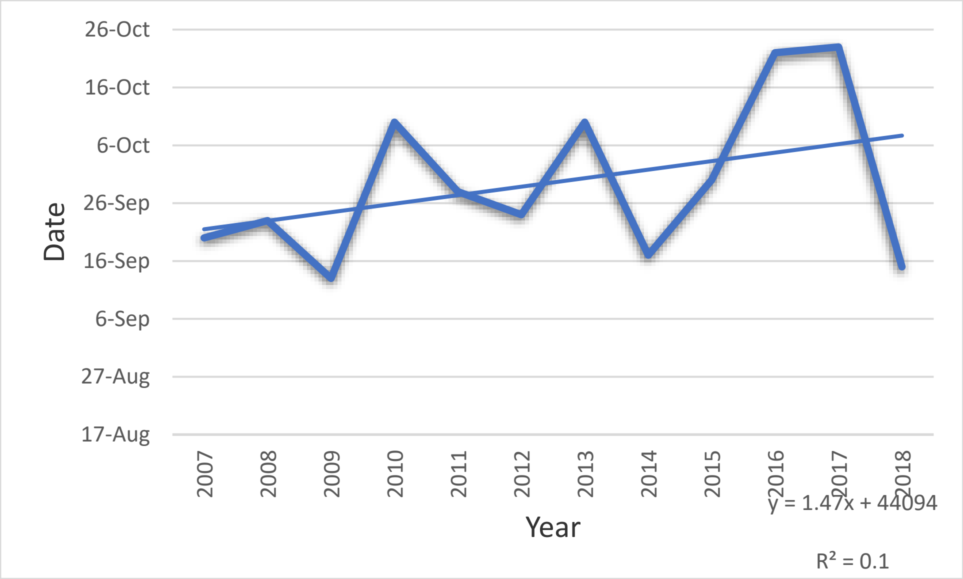

*Figure 7 Yearly end of the melting season.*

The length of the snow-free season was calculated from the difference between its end and its start date (Figure 8). On average, the snow free season length increased 4.8 days per year in the period 2007/2018 ($R^2$=0.5). The longest snow free season occurred during 2016 with 153 days. The shortest snow free seasons happened during 2008 and 2009 with a length of 68 days. During the first 3 years the length of the melting season was always lower than 100 days, but afterwards it has always been higher than 100 (Figure 8).

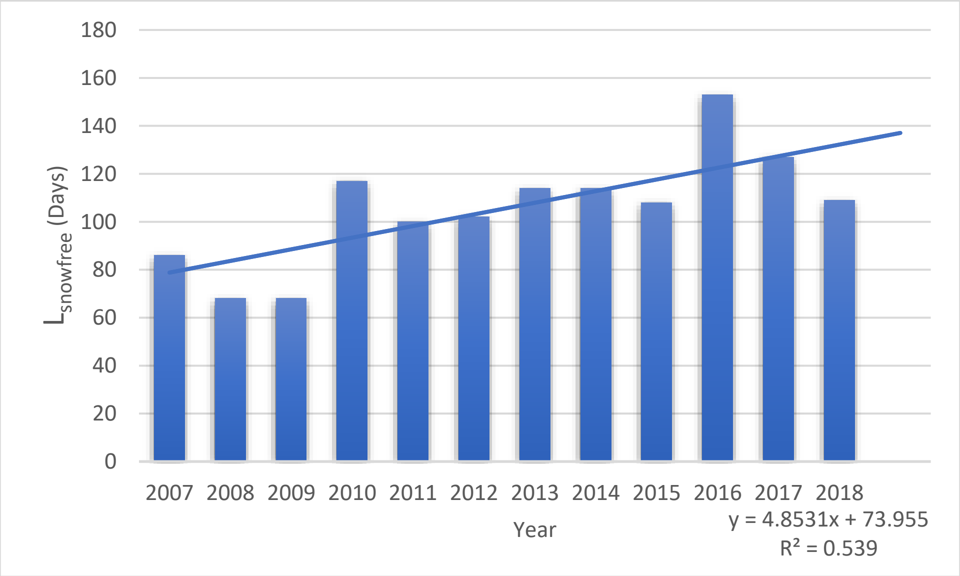

*Figure 8 Annual length of the snow free season from 2007 to 2018.*

### 4.3 Air temperature

By calculating the mean air temperature of each snow free season, it was possible to look at the change over the different years (Figure 9). The average snow free season temperature in the period 2007 to 2019 was 5.2 °C. The highest average temperature of the snow free season occurred during 2011 (6.1 °C). The lowest average temperature of the snow free season was 4.2 °C, recorded in 2010. The slope and the $R^2$ of this trend line are nearly equal to 0, i.e. no trend could be observed.

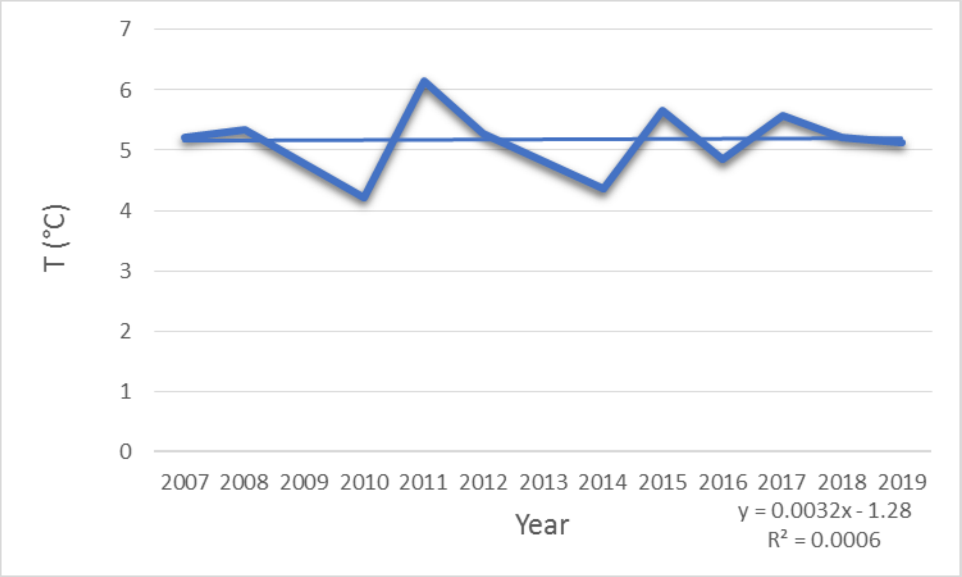

*Figure 9 Average temperature of each snow free season.*

The daily average maximum and minimum of each snow free season show the same pattern (Figure 10) and they correlate well (Figure11). The highest daily average maximum (7.7 °C) and the lowest daily average minimum (4.5 °C) occurred during the same year (2011). Also, the lowest daily average maximum (5.9 °C ) and the lowest minimum (2.5 °C) took place in the same year (2010).

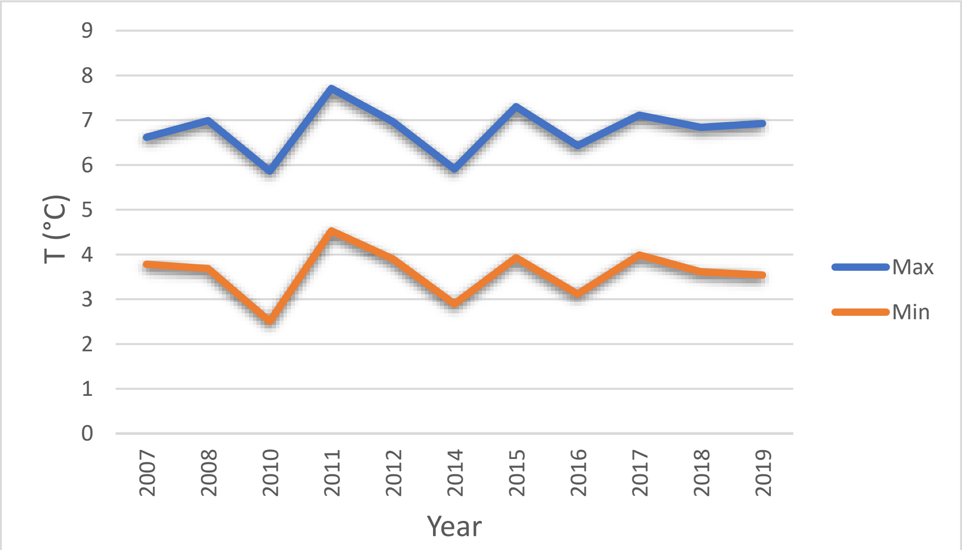

*Figure 10 In blue the daily average maximum of each snow free season and in orange the daily average minimum of each snow free season*

In figure 11, a linear regression where the maximum and minimum were plotted against each other. This linear regression showed a very high correlation with R² very close to 1 and a slope of 1 of the linear regression.

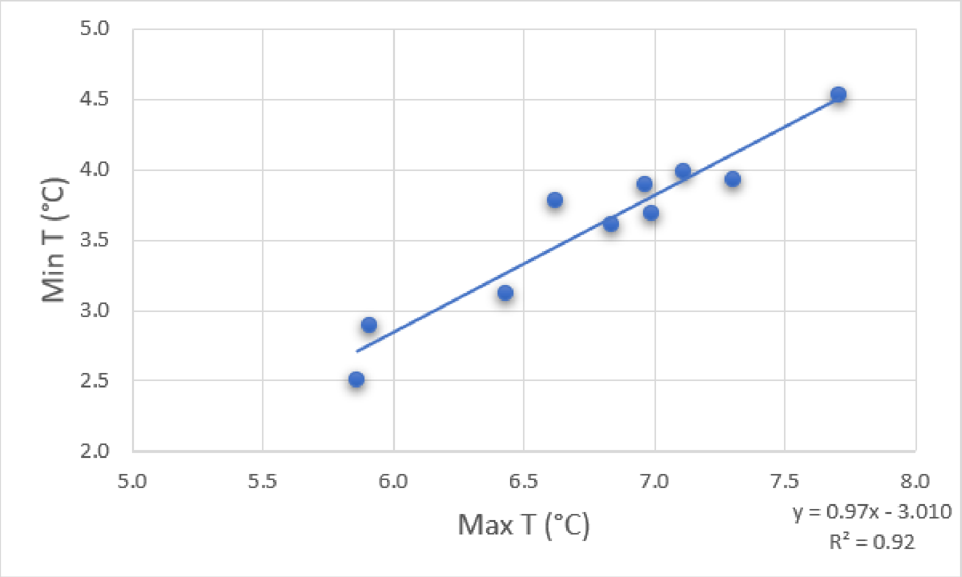

*Figure 11 Correlation chart between the daily average maximum and minimum of each snow free season*

The daily amplitude was calculated from the difference between the daily maximum and the daily minimum There is a slightly positive trend (0.02 °C/year, R²=0.15) in the time series of the average daily amplitude of each snow free season (Figure 12). The largest daily amplitude was 3.4 °C (2015). The smallest daily amplitude occurred in 2007 with a temperature of 2.8 °C.

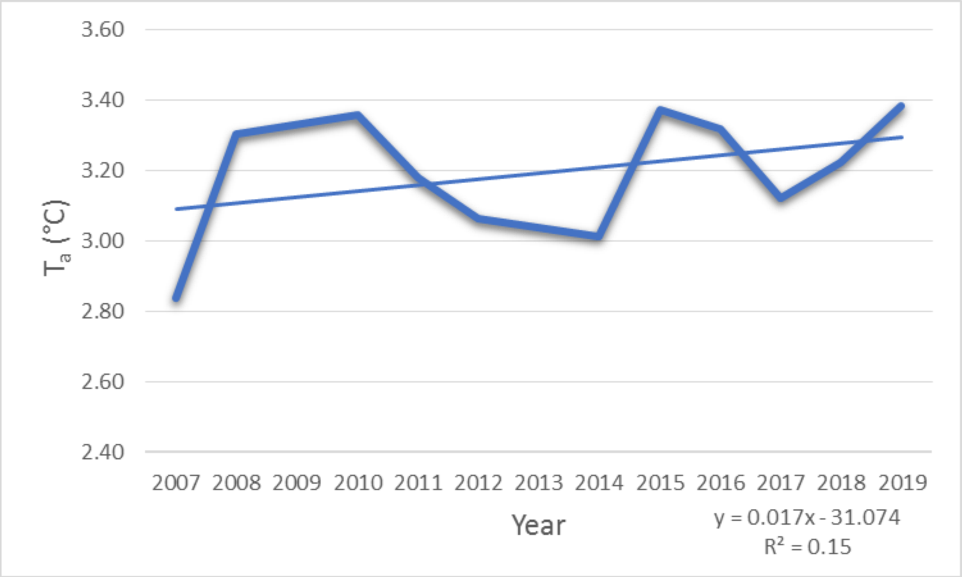

*Figure 12 Average daily amplitude of the snow free season.*

## 4.4 Correlation analysis

The trend line of the plot of area of retreat (ha) against incoming radiation (W/m$^2$), (Figure 13 a), shows an increase of 0.3 ha in area of retreat with an increase of 10 W/m$^2$ in incoming radiation. R$^2$ of this trend line is 0.34, this shows a weak positive correlation.

The trend line of the plot of area of retreat (ha) against length of the snow free season (days), (Figure 13 b), shows an increase of 0.18 ha in area of retreat with an increase of 10 days in the length of the snow free season. This trend line has weaker correlation (R$^2$=0.14) then the previous trend line.

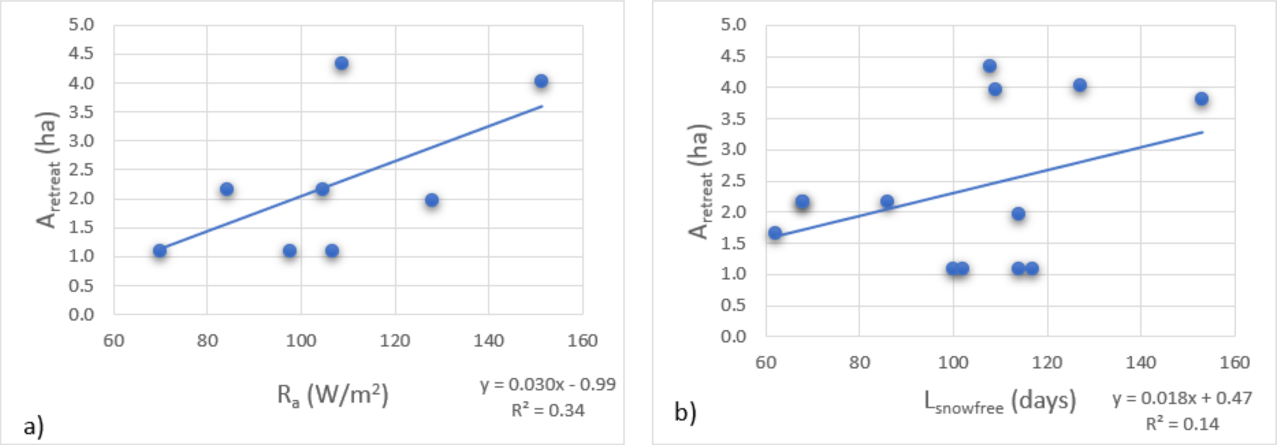

*Figure 13 a) correlation chart between incoming solar radiation and area of retreat. b) correlation chart between snow free season length and area of retreat.*

An increase in the average temperature by 1 °C will result in increase of the glacier retreat by 0.4 ha (Figure 14 a). The correlation between area of retreat and the average temperature has the lowest correlation (R$^2$=0.03) compared to all the 4 climatic factors being studied.

On the other hand, the correlation between the area of retreat and the positive degree factor has the highest positive correlation (R$^2$=0.7) compared to the 4 climatic factors(Figure 14 b). In that case, an increase of 100 °C in the positive degree day will result with an increase in the area of retreat by 0.7 ha.

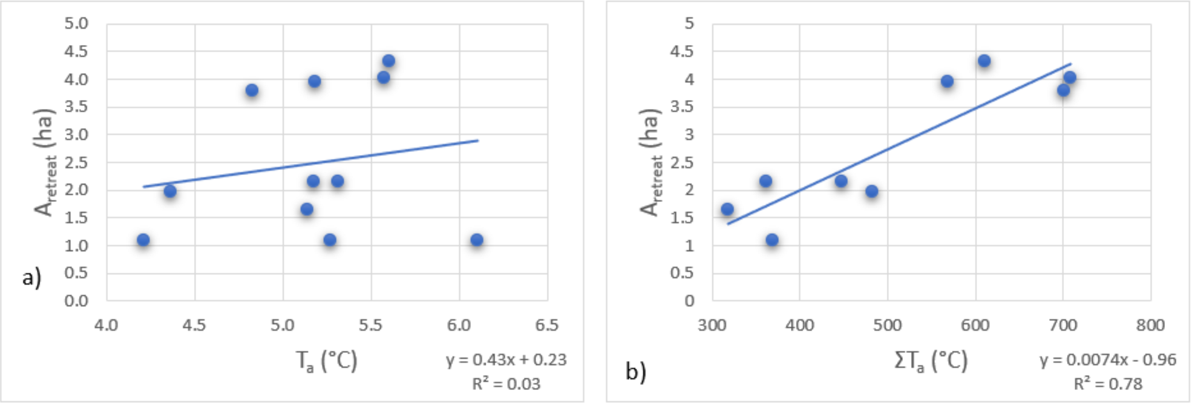

*Figure 14 a) Correlation chart between temperature and area of retreat b) Correlation chart between the sum of the daily average temperature of each snow free season and the area of retreat.*

# 5 Discussion

## 5.1 Glacier retreat

Looking at the orthomosaic in figure 3, it is possible to see the front of the glacier covered by debris making it very vulnerable to melting due to the low albedo. Multiple studies were conducted around the world to analyze the impact of debris cover on glacier melting. One of the studies took place in the Karakoram region of the greater Himalaya. It was found that debris cover can have a positive and negative effect on the ablation rate depending on the thickness of the debris cover (Collier et al. 2015). Debris cover less than a few centimeters thick enhances ice ablation, because of a higher absorption of short-wave radiation. On the contrary, a thick debris cover can act as an insulation layer between the atmosphere and the glacier resulting in a decrease in ice ablation (Takeuchi et al. 2001; Brock et al. 2010). In the case of Linné glacier, a thin layer of debris cover was present in the front, triggering an increase in ablation rate.

It is important to observe the snowline altitude (SLA) of a glacier. The lower the SLA the healthier the glacier (Rabatel et al. 2012). When the glacier was visited to conduct the measurements, the SLA was located at a high altitude very close to the source area. It can be seen in the south east on the orthomosaic. This can give an immediate estimation of the mass balance of the glacier; in that case the mass balance is negative.

During 2018, the glacier margin was recorded in October but not in August like the rest. In that year, the melting season ended in October as well. So, when the glacier margin of 2019 was recorded, there was not any significant retreat like the previous years. This is mainly due to the recording date.

Linné glacier has seen a decrease of 30.57 ha between 2007 and 2019. It is following the same trend as other glaciers around Svalbard. The mean area change of glaciers in Svalbard is -7 % between 1960 and 1990 (Hagen et al. 1993).

## 5.2 Air temperature and snow free season length

Markus et al. (2009) used satellite passive microwave data to analyze trends in melt onset and freeze up for 10 different Arctic regions. They found that for the entire Arctic, the melt season length has increased by about 20 days over the last 30 years. Earlier melt onset and later freeze up were one of the main result. In this thesis a similar result was produced. The results show an increase of 4.8 days of the snow free season length per year (Figure 8). An earlier start of the snow free season by 3.3 days per year is also found (Figure 6). As well as this, the snow free season ended 1.5 days later per year (Figure 7).

Svalbard is experiencing dramatic increase in winter temperature, with an increase of 2-3 °C per decade (Hanssen-Bauer et al. 2019). Temperature variability is much greater in winter than in summer. Ole Humlum's graph (Figure 15), that was presented in a lecture at UNIS, shows this trend. Temperature variation is substantially larger during winter, varying between -25 °C and -5 °C. A much smaller variation could be seen in the summer temperature, the fluctuation is varying by few degrees, ranging from 3 °C to 7 °C. The same trend could be seen in Figure 8, where the average temperature of the snow free season is not showing a big variation over the different years.

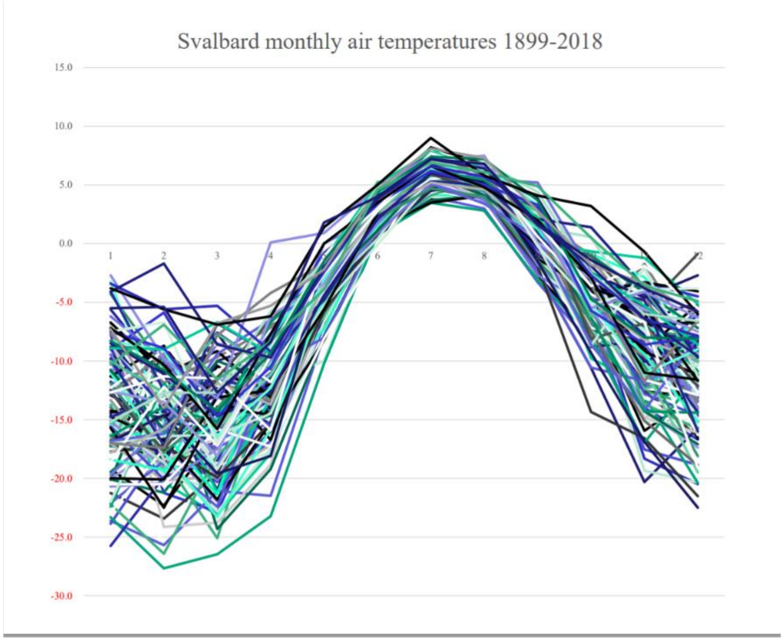

*Figure 15 Svalbard monthly air temperature between 1899 and 2018. Source: Ole Humlum 2019*

## 5.3 Correlation analyses

To compare how each climatic factor affects glacier retreat, the slope of the trend line will be used. We can clearly see that the area of retreat is increasing with longer snow free season, higher air temperature, higher incoming radiation intensity and higher positive degree factor. Similar results were found in different studies looking at how climatic factors affect the glacier retreat. For example, a study in 2009 by Markus et al, shows that an increase in the melting season will negatively affect the glacier mass balance. Other studies (Braithwaite and Zhang 1999; Hagen et al. 2003) found that glaciers are sensitive to temperature increase. Additionally, a study was conducted on how variation in the incoming solar radiation is affecting the ablation rate of different cirque glaciers in Spain. This found that the glacier with the highest incoming radiation had the highest ablation rate (Chueca and Julián 2004). This is similar to what was found out in this study, the more incoming radiation, the bigger the area of retreat.

In the beginning of the study just 3 climatic factors were looked at, the length of the snow free season, air temperature and incoming solar radiation. No strong correlation could be found from these three factors. Therefore, a sum of the daily average temperature of the snow free season was calculated to see how well they correlate. A strong correlation ($R^2$=0.8) was found and this was expected. Because the longer the melting season, the more ice can be melted. And the higher the temperature the more ice is melted.

To compare the 4 different factors to each other, r square of the trend line will be looked at. The individual climatic factor that has the highest correlation with the area of retreat is the incoming solar radiation. This was not as expected as described in the hypothesis, where it was said that the length of the snow free season will have the highest impact.

## 5.4 Comparison between drone and GPS measured glacier margin

There are many benefits in using a drone compared to a GPS. Having pictures of the glacier margin yearly is more beneficial than just having a GPS track. From the pictures, orthomosaic and digital elevation models can be created. Using the orthomosaic, the glacier margin can be mapped, and it is less complicated than using a handheld GPS. Furthermore, it is simpler to differentiate between glacier ice and bare soil by looking at an orthomosaic than in the field. For example, when looking at the GPS data in figure 4, it is possible to see that the points do not really match with the glacier margin. This can be due to the inaccuracy of the GPS.

Mistakes can also occur in the field while walking the glacier margin, which cannot be fixed later in some cases. But having drone pictures is a benefit because you can always refer back and look at the orthomosaic. A digital elevation model of the glacier could be used to determine the glacier retreat in volume. Instead of monitoring the glacier margin and the area that has been lost, you can also monitor the glacier mass balance. This can usually be done using ablation stakes, but it will not cover the whole glacier and interpolation must be done to estimate the ablation over the whole area. A digital elevation model will cover the whole glacier giving us a more accurate data set to use. Ablation stakes must be measured one by one and changed every year. This is very time and material consuming.

## 5.5 Limitation of the study

The glacier margin has been recorded yearly but not at the same time or at the end of the melting season. The start and ending points of the recordings differs, creating problems while estimating the area that has been lost.

Arctic field work is very dependent on weather and scenarios. There were few missing years of data, that resulted after some difficulties that arise in the field. The glacier is not easily accessible and the only way to reach the glacier is by walking from Kapp Linné. Or in the winter by snowmobile, but the glacier margin cannot be recorded due to the snow accumulation

The snow tree record data every 30min with 10 different loggers. Malfunction is common where the logger can stop recording or it has been programmed wrongly resulting in missing data for that period. The equipment is maintained yearly. Due to missing data, calculation of the daily temperature was impossible, and this resulted with different sample size between the different comparison.

The glacier margin has been recorded using a handheld GPS, this will result in an inaccuracy of few meters (Wing et al. 2005). Finding the glacier margin can be challenging, because most of the times, it is covered by debris. It could be quite challenging to determine whether it belongs to the glacier or not. Using a drone could have many limitations as well. Arctic weather is unpredictable. With bad weather conditions the drone cannot be flown. Producing the orthomosaic had few limitations, where the orthomosaic has not been made with the highest resolution because of the computer capability. For a better result, a better computer should have been used.

As of the GPS, drone does not have a 100% accuracy (Küng et al. 2011). Especially in the Arctic where fewer satellites are present. In this study, no ground control points were used due to the low availability of data and resources. If the weather conditions are good, it will still be hard to fly a drone in the Arctic. The average summer temperature in Svalbard is 5 degrees Celsius, this will affect the drone and the pilot's efficiency. The drone will have a shorter flying time and the pilot can get cold, especially in the hands.

### 5.6 Future studies

For future studies glacier mass balance would be interesting to study, especially using a 3D model made from the drone or the traditional method using ablation stakes.

Calculation of the volume of the front that has been lost and the whole volume of the glacier is a very interesting study. To find out the glacier volume studies should be carried out to find out the glacier's thickness. LIDAR could be used, this method has already been used in Svalbard to measure glacier thickness, for example in this study (Johannesson et al. 2013).

Snow height could have a huge impact on the glacier mass balance. Snow height measurements at the end of the accumulation season would be beneficial for a study comparing the area of retreat/mass balance with the snow height.

## 6 Conclusion and summary

The aim of this study was to evaluate how climatic factors such as the length of the snow free season, air temperature and incoming solar radiation affect the yearly retreat of Linné glacier over the course of 13 years. Weather station data, snow height, drone images and GPS data were used to conduct the study.

The results showed a clear retreat of Linné glacier, in total the glacier area retreat was about 30.57 ha over the course of 13 years, from 2007 until 2019. This is following a similar trend as other glaciers around the Arctic. The snow free season length is demonstrating a steady increase. Earlier melt onset and later freeze up could be seen over the years, this means that ablation is occurring over a longer period. Climate prediction shows a dramatic increase in winter temperature and no major change in the summer temperature. This was seen in this study where the average temperature of the snow free season has not increased over the years.

Linné glacier is negatively affected by an increase in air temperature, increase in incoming solar radiation and longer snow free season. The climatic factor that correlates the most with the area of retreat of the glacier is incoming solar radiation. But when combining both temperature and the snow season length together, a much stronger correlation was found.

Photogrammetry is a more suitable way of data collecting the glacier margin coordinates than using a handheld GPS.

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