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Bachelor thesis

The Influence of Melt on a Glacier's Velocity

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Abstract

One of the consequences of global warming is the increase of melt on glaciers. This increase of melt could cause the glacier to move faster in the ablation zone and the glacier could decrease faster in size. The main question asked in this thesis is: what influence does the melt have on the velocity of a glacier? The data shows that the melt only has a short term impact on the velocity. Annual average velocities do not seem to be influenced by the melt, at least not such a big enough influence that it shows in these observations. The data is also used to look at trends in velocity, but no significant trend in the velocity was found over the years 2007-2014. The mass balance of the glacier is used to calculate the total melt of the glacier per year. This total melt per year does not show a significant relation to the average velocity per year.

Contents

1 Introduction

Global warming is one of the most discussed topics the last decade. Society has major concerns about the possible consequences of global warming. One of the common worries is the preservation of glaciers. The concern is that when temperature is increased because of global warming, glacier melt is increased. Besides the direct result of increased mass loss, increased melt might also effect glacier dynamics. There are two different zones on a glacier, separated by the equilibrium line. In the accumulation zone more snow falls than ice or snow melts. In the ablation zone the melt is larger than the snowfall. The change in glacier dynamics could cause more water between the bedrock and the ice of the glacier. This could cause an increased sliding effect of the glacier, which would make it move faster towards lower areas. What would happen in that case is that an increased part of the glacier would slide from the accumulation zone to the ablation zone.

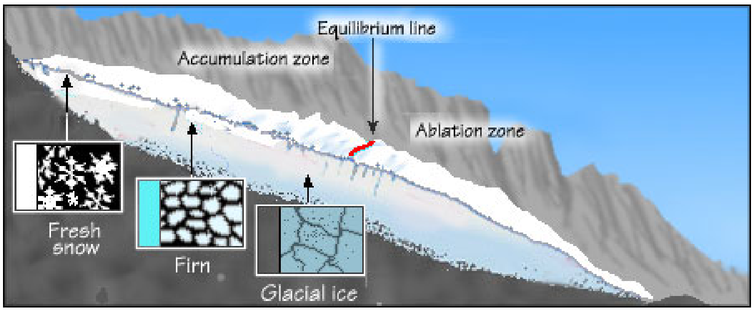


Figure 1: Schematic figure of the accumulation and ablation zone

So a higher velocity of the glacier could cause the glacier to move more ice/snow to the ablation zone, which would mean that the glacier would disappear faster. But is this the case? Does the increase of melt due to global warming really cause an increased velocity that causes the glacier to decrease much faster?

Glaciers are one of the main contributors to the sea-level rise (Church et al., 2013). So it is therefore of major importance to understand the effects that global warming has on glaciers. A rising temperature increases melt and the melt induces an acceleration of the Greenland ice-sheet, because the water causes a sliding effect on the interface between bedrock and ice (see figure 2). This relation between the melt and the ice-sheet velocity shows the accelerating reaction of ice-sheets to the global warming (Zwally et al., 2002).

Research shows that the influences of melt seem to be bound on relative short time-periods (V.d. Wal et al., 2008). They show in their study that the ice-sheet velocity can grow by a factor of four on short time scales due to increased melt. However the annual average velocity of the ice-sheet decreased in the last seventeen years in their study. Which would mean that the increased melt only has a short-term effect on the ice-sheet velocity and that the effect on the average velocity is limited (V.d. Wal et al., 2008). During the melt season an effective draining system is developed through the ice-sheet (Bartholomew et al., 2013). This starts developing simultaneous with the first melt. When the melt increases the effectiveness of the

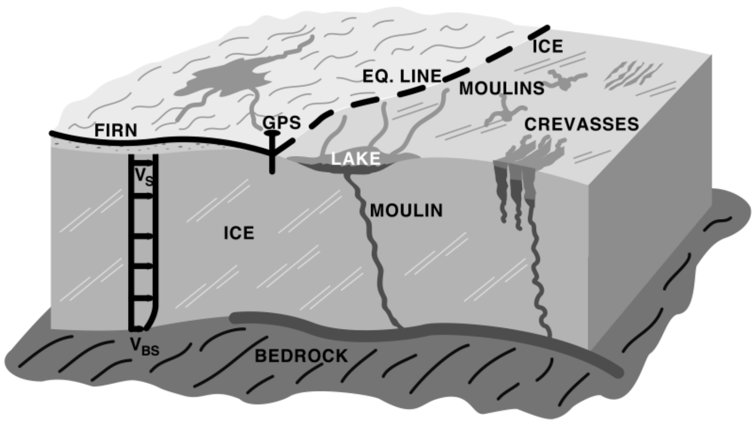


Figure 2: Schematic feature of the melt on a glacier

draining system also increases (Bartholomew et al., 2013). This draining system effectively drains the water originated from the melt to lower altitudes of the glacier (see figure 2). This decreases the sliding effect and reduces the velocity. This effective draining system even decreases the average velocity during winter for a Greenland ice-sheet, so the ice-sheets seem to withstand the global warming better than previously thought (Tedstone et al., 2015).

The main question in this thesis is, what is the effect of melt on the velocity of Nordenskildbreen, a valley glacier on Svalbard? Short term variations in velocities will be studied and these will be linked to the melt. Also the relation between the velocity and the melt will be examined by testing their correlation. The total melt of all the years will be linked to the average velocity of those years. As well as the maximum velocity that year or the average velocity in the winter or summer. The data that will be used is acquired from global positioning systems to determine the velocities of the glacier. A sonic height sensor will be used to determine short term melt variations. Stake observations will be used to determine annual melt.

Svalbard is an archipelago north of Norway. The glacier that is examined in this thesis is called Nordenskildbreen and lies in the central west of Svalbard. Nordenskildbreen is a slow moving glacier with average annual velocities between 40 and 60 meters per year. Average temperatures on Svalbard are in January between -13 and -20 degrees Celsius and in July between 3 and 7 degrees Celsius (Nordic visitor, 2016). Figure 3 shows a schematic map of Nordenskildbreen with the locations of

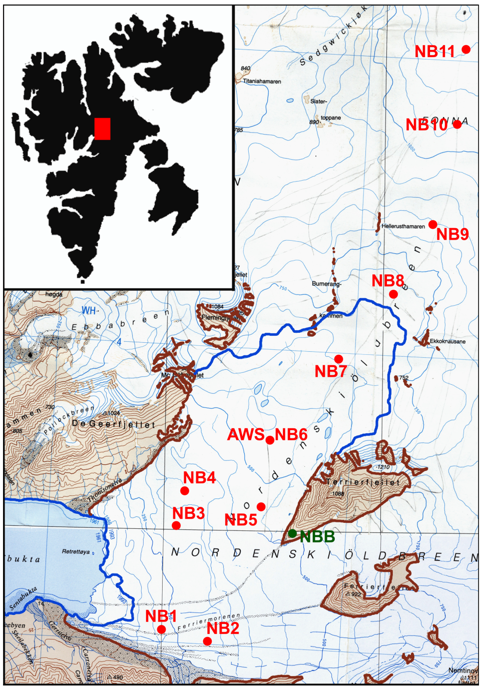


Figure 3: Map of Svalbard and Nordenskildbreen with the locations of the GPS measurement units

the observation sites. Figure 3 also features altitude lines, which tells us that NB10 and NB11 are on the highest altitude and NB1 and NB2 are on the lowest.

2 Method

2.1 Data

The data that is used to determine the velocities comes from GPS measurement units placed on different locations on the glacier (see figure 4). The locations are shown in figure 3. There is also one measurement unit placed on a stationary point marked NBB, which will be used as a reference. The only data that this system stores are the time, the longitudinal position, the latitudinal position but not the constellation of satellites used for the location determination. The uncertainties in the GPS measurements are mostly caused by the uncertainty in the travelled time from the satellite to the system. The data received from the GPS measurement systems is of the period 2007-2014. (For more information see: Den Ouden et al., 2010)

Figure 4: A GPS measurement unit placed on Nordenskildbreen

The melt is calculated by using the data of a sonic height sensor (see figure 5). This sonic height sensor uses a sound pulse. By measuring the time it takes the pulse to travel to the surface and back the height can be determined. The sonic height sensor is corrected for the variations in the speed of sound caused by different temperatures. The sonic height sensor supplies only useful data for 2012, 2013 and 2014 due to sensor problems. As a result of these problems with the sonic height sensor, stake height measurements were used to determine the mass balance per year at each site.

2.2 Velocities

To determine the velocities of the glacier the longitudinal and latitudinal positions are extracted from the data. First the outliers are removed from the data. Then the variations in position of the non-moving reference system are subtracted from the data acquired on the glacier. This is allowed because the reference GPS unit is very close to the moving GPS units. This means that we can assume that they obtain

Figure 5: A Sonic height sensor unit placed on Nordenskildbreen left of the Antomatic weather station

their positions from the same satellites, so the error caused by the satellite affects both the moving and the reference unit.
To exclude outliers a running average is applied to the distances over a period of n hours, also calculating the standard deviation. λ and ϕ are the longitudinal and latitudinal positions. $\bar{\lambda}$ and $\bar{\psi}$ are the average longitudinal and latitudinal position over a period of n hours. σ_λ and σ_ϕ are the standard deviations over a period of n hours.

$$\bar{\lambda} = \frac{1}{n}\sum_{i}^{i+n}\lambda_i \tag{1}$$

$$\bar{\phi} = \frac{1}{n}\sum_{i}^{i+n}\phi_i \tag{2}$$

$$\sigma_\lambda = \sqrt{\frac{1}{n}\sum_{i}^{i+n}\lambda_i - \bar{\lambda}} \tag{3}$$

$$\sigma_\phi = \sqrt{\frac{1}{n}\sum_{i}^{i+n}\phi_i - \bar{\phi}} \tag{4}$$

When the standard deviation crosses a threshold, which in this case is three times the standard deviation of the reference station, the newest point added to the running average will be removed. This running average will run forwards and backwards across the data and in both the longitudinal and latitudinal direction. Then the distance between the remaining, following points is calculated. The data is converted from degrees to meters by using:

$$\Delta\phi = \frac{\pi \cdot R}{180}(\phi_{i+1} - \phi_i) \tag{5}$$

$$\Delta\lambda = \frac{\pi \cdot R}{180}(\lambda_{i+1} - \lambda_i) \cdot \cos\phi_i \tag{6}$$

Note that the $\cos\phi_i$ component changes in movement from λ_i to λ_{i+1}, which is neglected here. This is justified because the distances are very small. After this the velocity in the longitudinal and latitudinal direction is calculated by dividing the distances by the time differences and again a running average is applied this time with a period of m.

$$v_\lambda = \frac{1}{m}\sum_{i-m/2}^{i+m/2}\frac{\lambda}{\Delta t} \tag{7}$$

$$v_\phi = \frac{1}{m}\sum_{i-m/2}^{i+m/2}\frac{\phi}{\Delta t} \tag{8}$$

Where v_λ is the velocity in the longitudinal direction and v_ϕ is the velocity in the latitudinal direction. These velocities can then be used to calculate the total velocity v of the point on the glacier. (For more information on the method for obtaining the velocities see: Den Ouden et al., 2010)

$$v = \sqrt{v_\lambda^2 + v_\phi^2} \tag{9}$$

2.3 Melt

The melt is measured with two different methods. In order to link velocity to melt we need melt observations during a year. Therefore data from a sonic height sensor is used. It measures the distance from a certain height to the surface every hour. When the distance becomes larger, we assume ice/snow has melted. To determine whether ice or snow has melted the ice-level of the two consecutive years is used (see figure 6).

I assume that the lowest level of a melt season is the boundary layer between snow and ice in the next melt season. The horizontal lines in figure 6 are at the heights of the ice surface. I assume that in the next season the change in height above the horizontal line is the melting of snow and change in height under the horizontal is caused by the melting of ice. So, first the distance where the surface becomes ice in each season is determined. Then difference in height between each hour is calculated. The melt is then calculated by multiplying that distance with the corresponding density $\rho(kg/m^3) \cdot dz(m) = melt(mwe)$. Where mwe stands for meter water equivalent. All the melt from now will be in mwe. For the density of snow $\rho_{snow} = 450\ kg/m^3$ is used and for the density of ice $\rho_{ice} = 910\ kg/m^3$ is used. A moving average with a period of $l = 24$ hours is applied, this eliminates small perturbations caused for example by temperature variations or small movements by the sonic height sensor.

Because the first method only gives useful results for the years 2012, 2013 and 2014 another method is used to find the annual melt of all the years to correlate

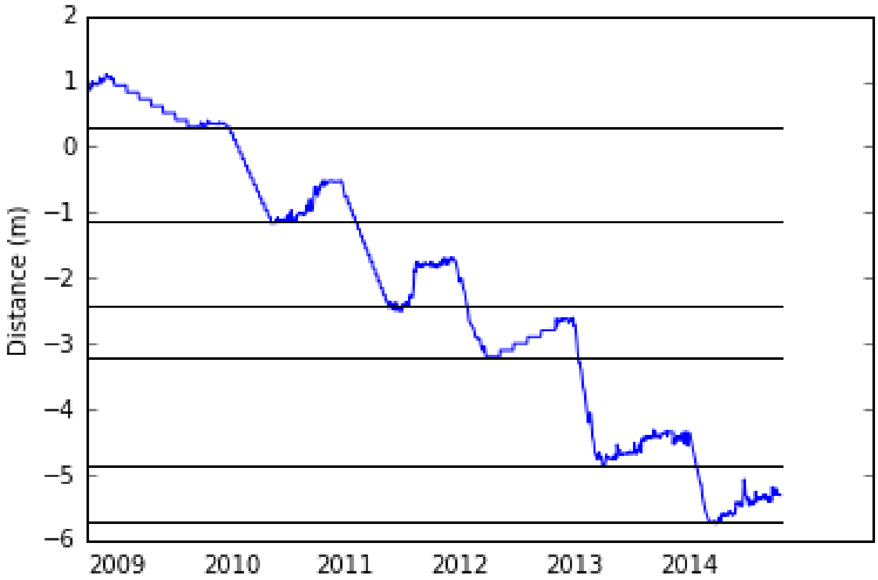


Figure 6: The height measured by the sonic height sensor, the horizontal lines are the lowest points of melt seasons since this site is in the ablation area

with the velocities. The second method is based on stake height measurements every year, determining the thickness of the layer of snow and the height of the surface, ice and snow in early spring. By comparing this to the previous year the total mass balance of one year can be calculated. This contains the summer melt and the accumulation in the winter.

2.4 Correlation

The seasonal melt derived from the sonic height sensor is used to calculate the Pearson correlation coefficient (r) between the melt and the velocity using (Taylor, 1982):

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (10)$$

Where n is the number of datapoints over one period, x_i is the velocity at point i, $\bar{x}$ is the average velocity over the period, y_i is the melt at point i and $\bar{y}$ is the average melt over the period. The correlation coefficient is a measure for the correlation between two quantities. The closer the correlation coefficient is to one, the more correlated the two quantities are.

3 Results

3.1 Velocities

The data extracted from the GPS measuring devices are longitudinal and latitudinal positions. Figures 7 and 8 are showing examples of the data after removing the outliers.

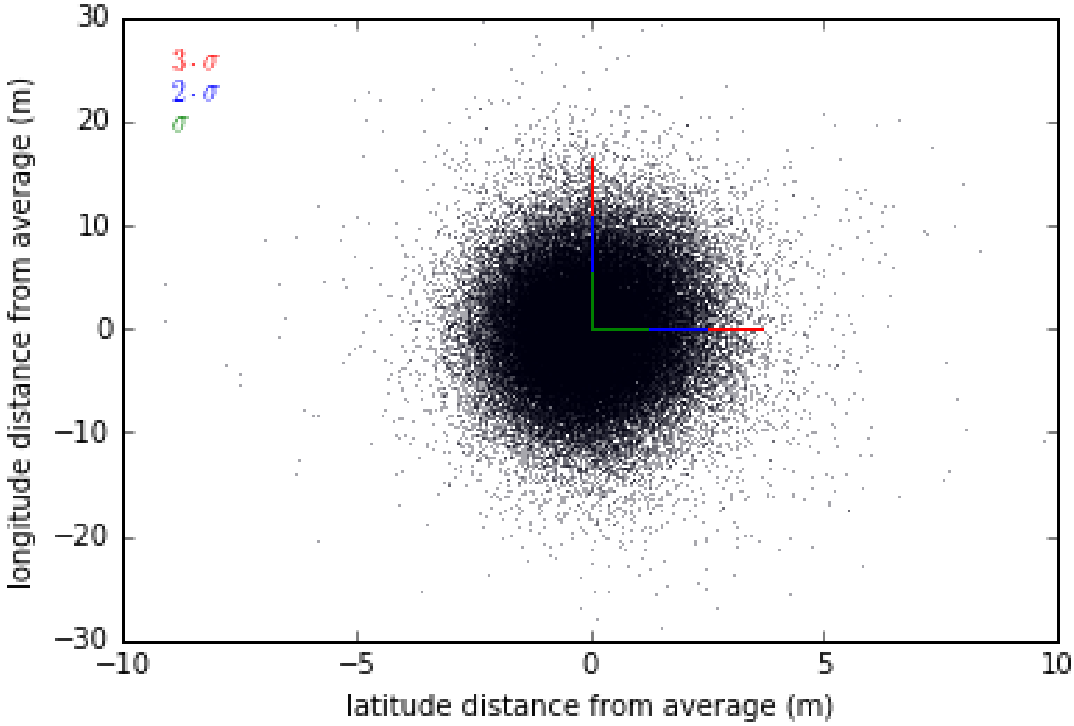


Figure 7: Latitudinal and longitudinal positions in time of the reference station

Figure 7 is showing the reference station, the spread in the data is an indicator of the accuracy of the system. I have chosen to use three times that standard deviation as the threshold explained in chapter 2. Choosing a smaller threshold would result in loss of too much information and choosing a larger threshold would make the data too irregular. Figure 8 shows an example of a site on the glacier. As can be seen, the site was moved twice glacier upwards to prevent it from flowing into a erevasse field. This site moves about fifty meters per year.

In figure 9 the velocities over the years 2008 and 2009 are shown. What stands out are the significant peaks in the beginning of both summers. This feature will be studied later in relation with melt observations. These peaks are caused by an increase of melt at the start of the summer. They decrease after a short period because the glacier developed an effective draining system. After a short period of time for all sites the glacier is able to remove the water caused by melt efficiently. Figure 10 shows the summer of 2008 and it also exhibits interesting features. Every sit has a different winter velocity, related to their location on the glacier. All sites

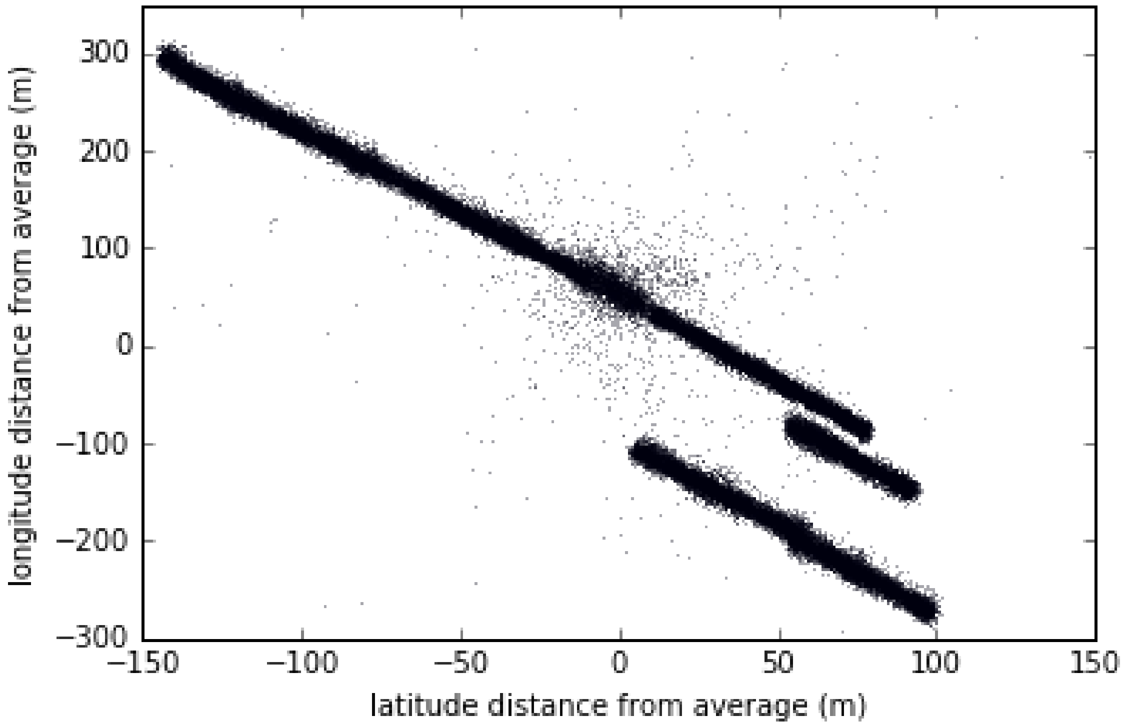


Figure 8: Latitudinal and longitudinal positions in time of moving station 6

show melt related increase in velocity. There is a peak in the velocities in September, which is likely related to extreme rain events that year. The GPS systems 1, 2, 10 and 11 experience a much lower velocity than the other systems. This can be explained by their locations on the glacier (see figure 3). GPS systems 1 and 2 are clearly off the main stream of the glacier and are on another stream line. This stream line does not experience that much of the sliding movement as the main stream does. GPS systems 10 and 11 are situated very high on the glacier where the glacier is not as steep as it is more down the glacier. This causes systems 10 and 11 to move slower. The fact that they are located at a high altitude also means that the temperature is relatively low, so there is not as much melt as lower on the glacier. This is why systems 1,2,10 and 11 are ignored in the following results. Also systems 3 and 4 are ignored, because they only cover a relative short period of time. These locations were to dangerous to reach and discarded after three years of observations. Note that there are gaps, these are related to measurement errors.

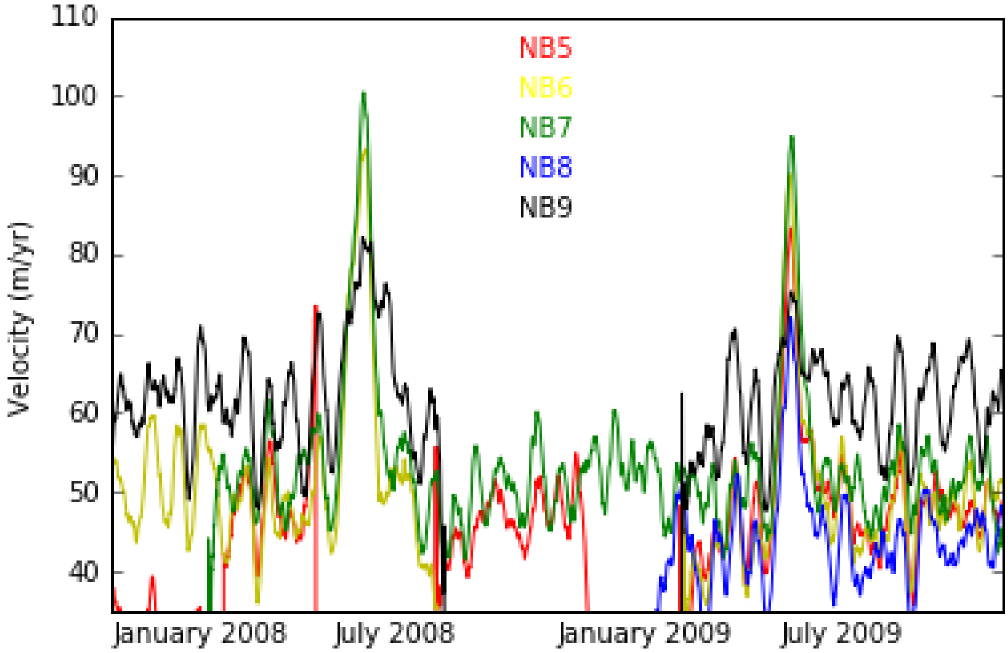


Figure 9: Velocities of some stations in two years

Figure 11 shows the summer of 2013. The figure illustrates that velocities of the stations seem to have their peek quite simultaneous. Which means that they are probably all triggered by the same cause. Furthermore the highest velocity is reached at the beginning of July, this is at the beginning of summer. The melt usually starts around halfway into June and usually stops halfway into September.

In figure 12 the velocities per site per year are shown, including annual, summer and winter averages and the maximum velocity. Summer is defined as June until September and winter is defined as November until April. The results do not show a clear nor significant trend in any of them. The last three years the annual average velocity seems to rise, but this is not by such great lengths that it is conclusive. In about five to ten years it should be clear if that trend continues. The maximum velocity each year does not show any sign of a trend whatsoever. What is clear in these figures is that the average velocity in summer is higher than the average velocity in winter.

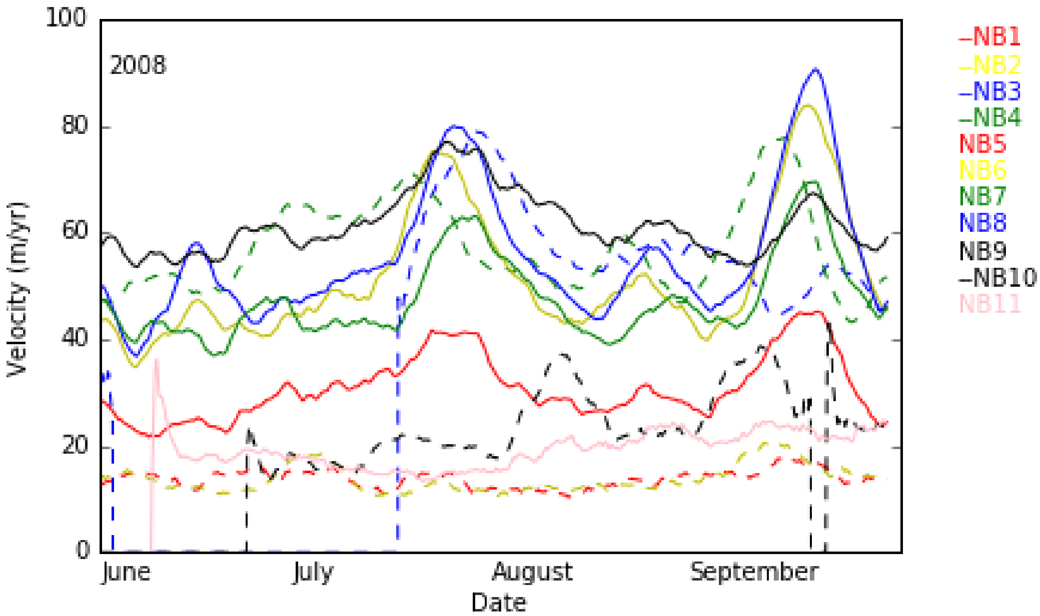


Figure 10: Summer of 2008 with all GPS stations

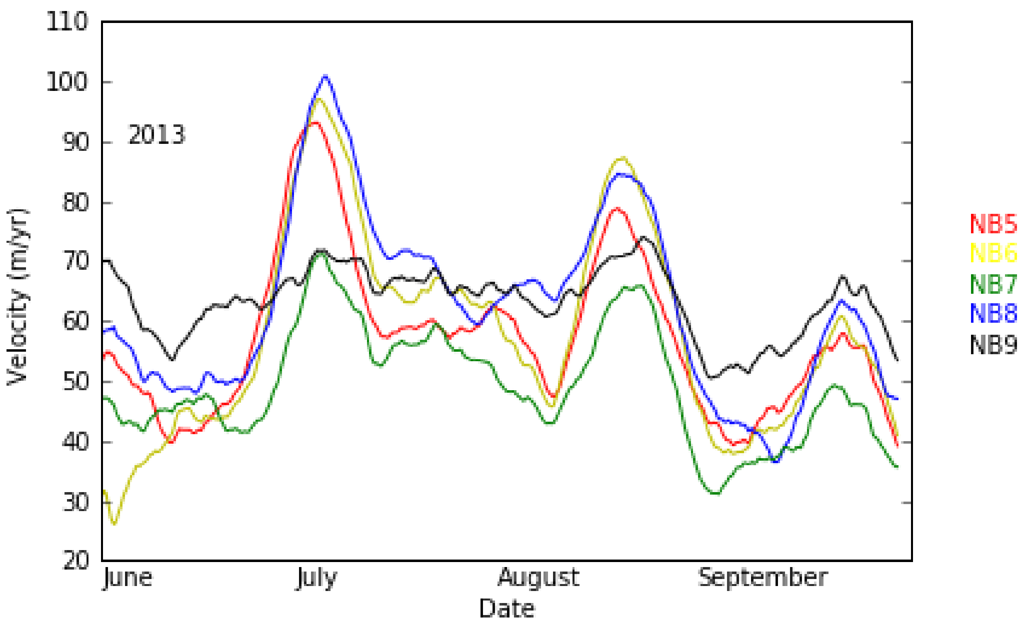
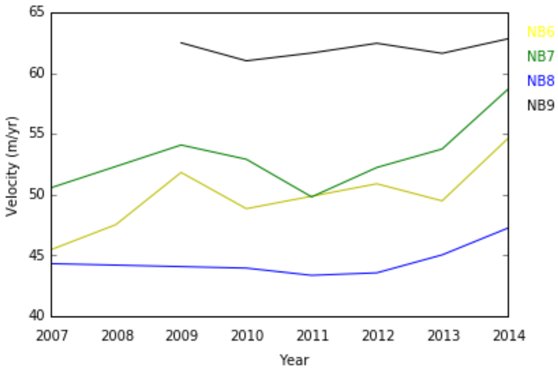


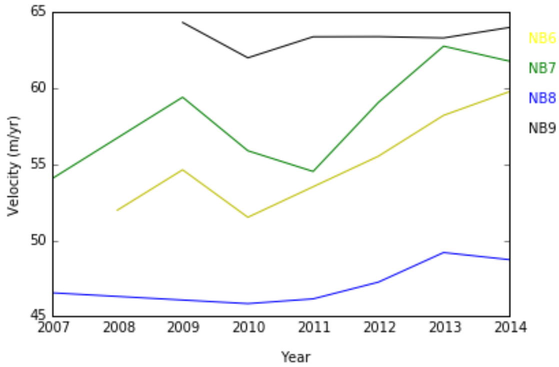
Figure 11: Summer of 2013

3.2 Melt

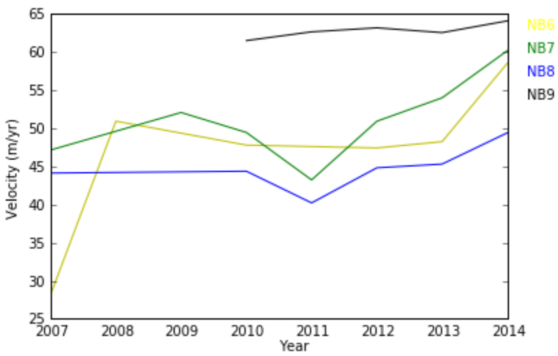
By using the sonic height sensor the melt and velocity can be calculated for the years 2012, 2013 and 2014. In figure 13 both the velocity and the melt rate are displayed. The melt is defined as the amount of *mmwe* (millimeters water equivalent) per hour.



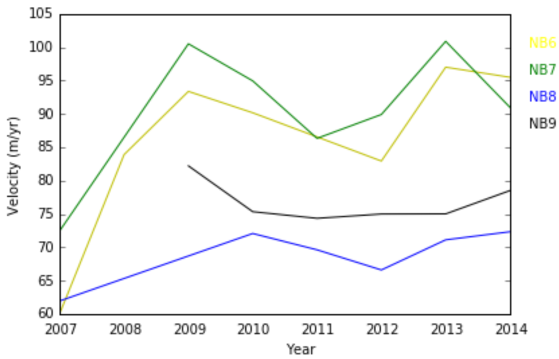
((a)) Total year



((b)) Summer

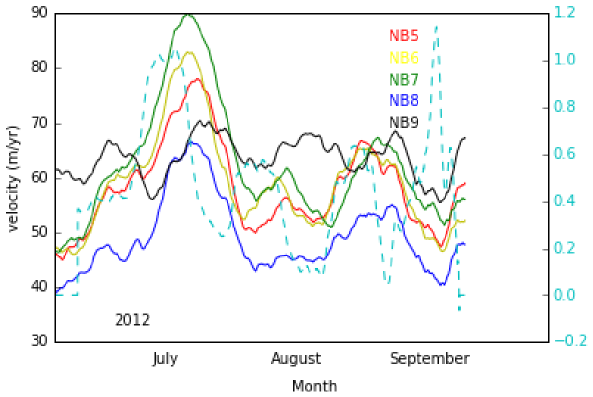


((c)) Winter

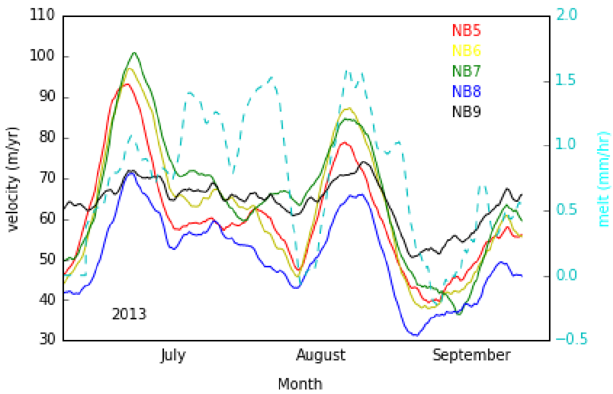


((d)) Maximum velocity

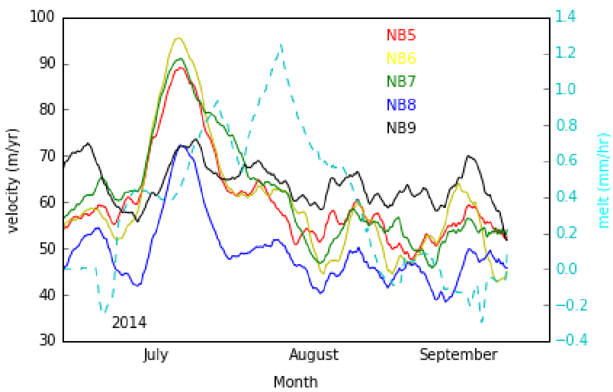
Figure 12: Average velocities in the recent years, a = annual average, b = summer average, c = winter average, d = maximum velocity each year



((a)) 2012



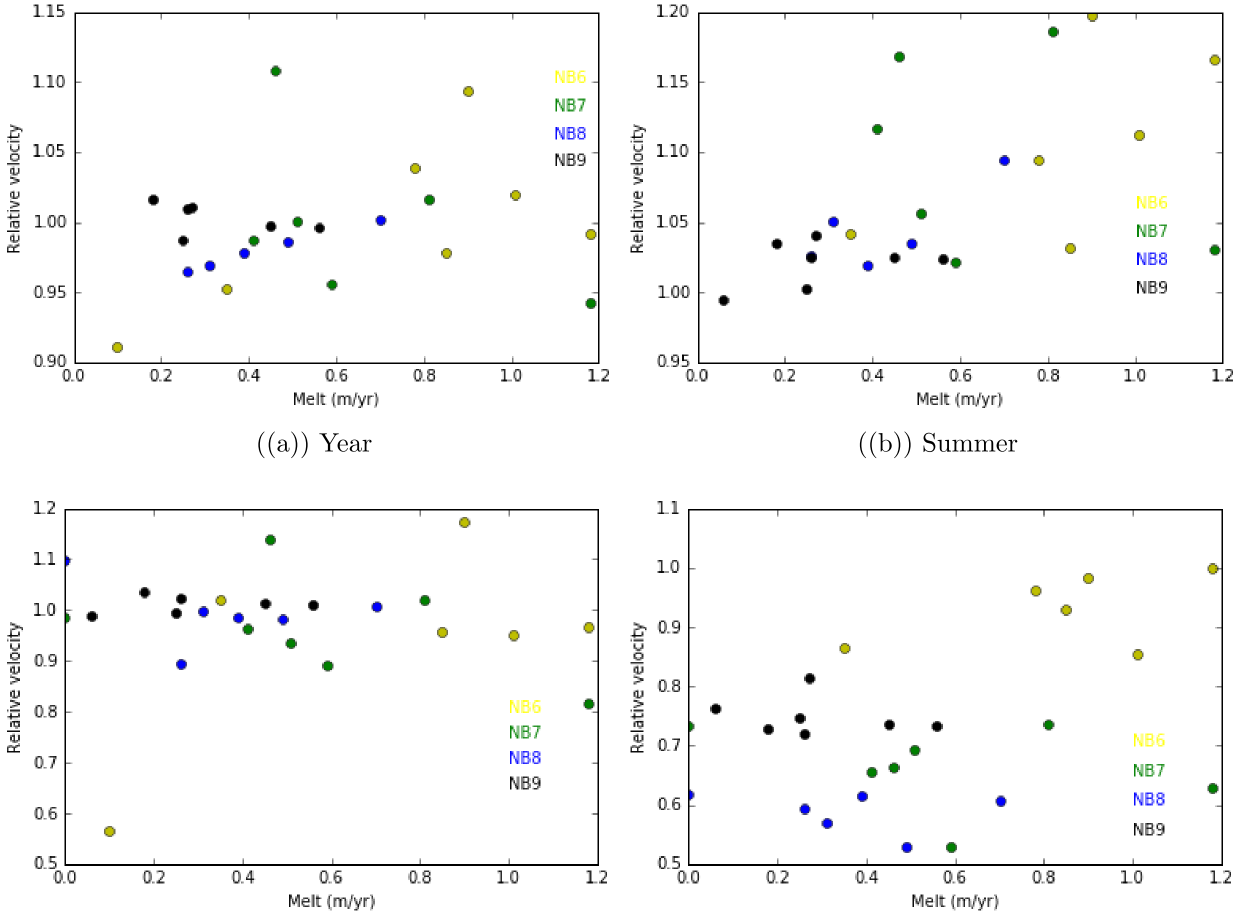
((b)) 2013



((c)) 2014

Figure 13: Melt and Velocities

In these figures there are a few similarities between the velocities and the melt. Mostly in the beginning of the summer, so at the start of the melt season the increase of the velocities seems to match the increase of the melt. Later peaks in the melt do not seem to effect the velocities. Except for one peak in 2012 and one peak in 2013, which both follow a period without melt.



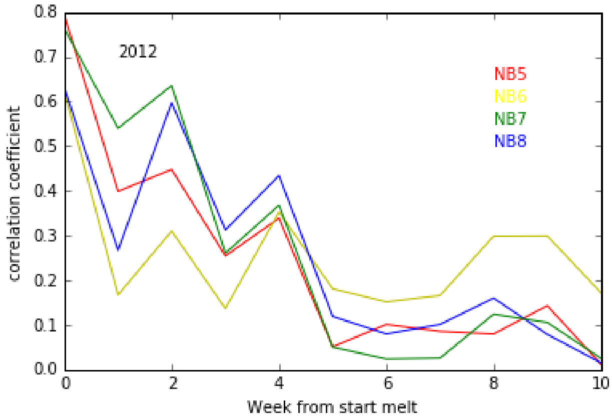
((a)) Year ((b)) Summer

((c)) Winter ((d)) Maximum velocity in year

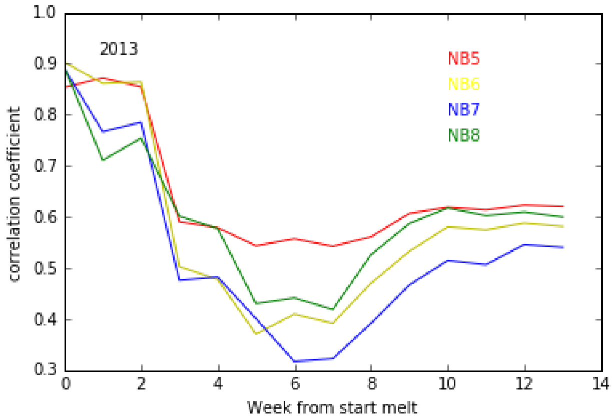
Figure 14: Average normalized velocities against total melt, a = annual relative velocity, b = summer relative velocity, c = winter relative velocity, d = maximum relative velocity

Figure 14 shows the average velocities against the melt at the sites. For each site the velocity at that site and the melt at that site are used. The velocities are normalized with the total average velocity of the corresponding stations. These figures confirm that the glacier has a higher velocity during the summer than during the winter. There are no clear correlations between the total melt and the average velocities. In figure 14.b the average velocity seems to rise a tiny bit when the melt increases. But there is quite some goodwill necessary to notice that, it is far from significant. Just like the average velocity in winter seems to decrease after a high melt, this data can neither confirm nor deny that.

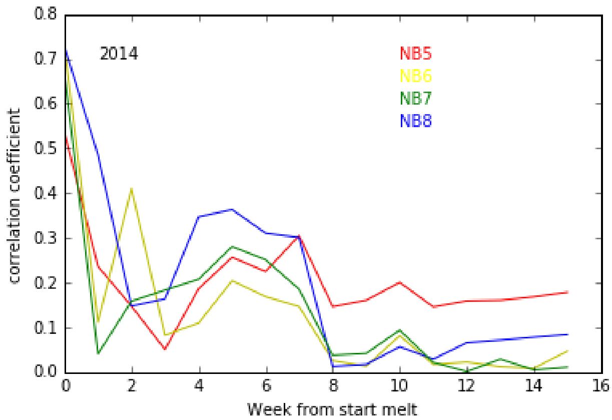
3.3 Correlation



((a)) Summer 2012



((b)) Summer 2013



((c)) Summer 2014

Figure 15: Correlation coefficients per week in the melt season, a = summer of 2012, b = summer of 2013, c = summer of 2014

In figure 15 the correlation coefficient, calculated by using equation 10, is displayed per week from the start of the melt season. It is clear that the correlation takes a dive after the first week of melt. In 2013 the correlation lasts a little bit longer. But in 2014 and 2012 there is only a strong correlation between the velocity and the melt in the first week noticeable. When the correlation coefficients of

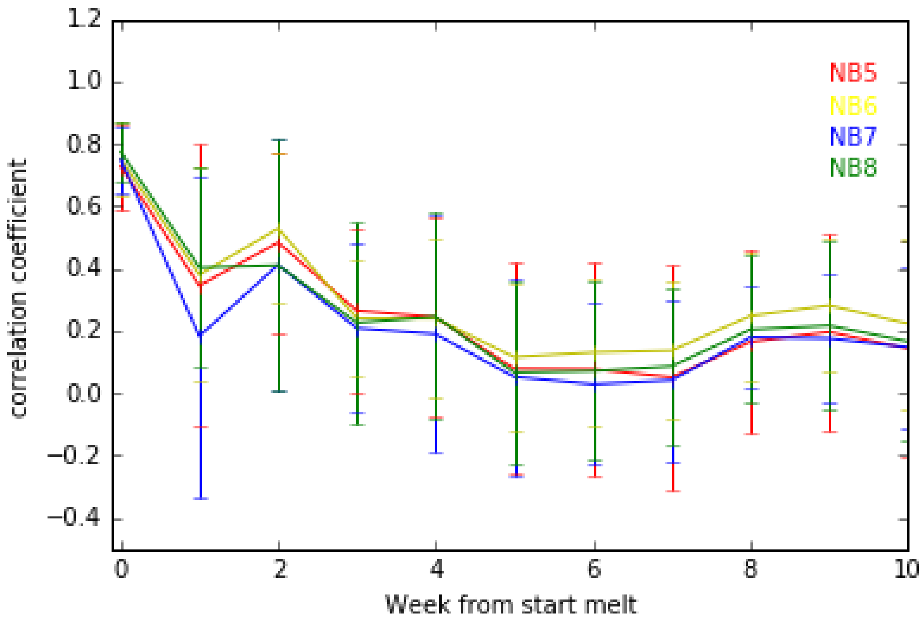
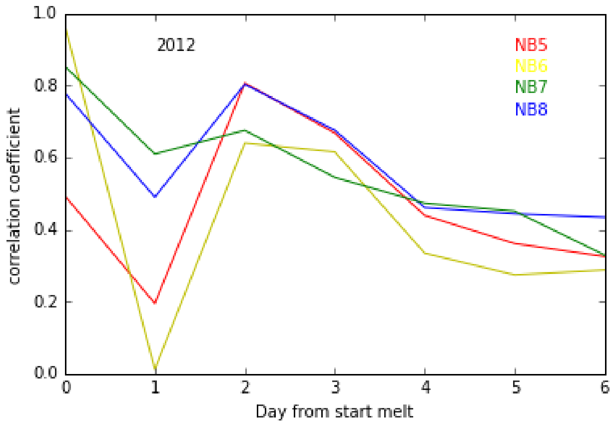


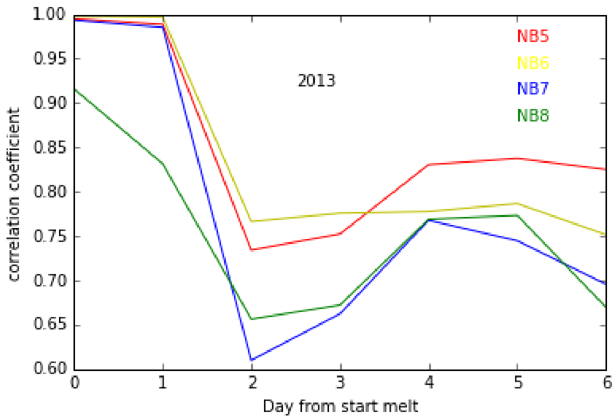
Figure 16: Correlation coefficients with standard deviations

the three years of figure 15 are averaged and their standard deviations are calculated, figure 16 is obtained. This shows that in the first week of the melt there is a significant correlation between the melt and the velocity, but after the first week the uncertainty is to large to correlate the velocity with the melt for the remaining weeks.

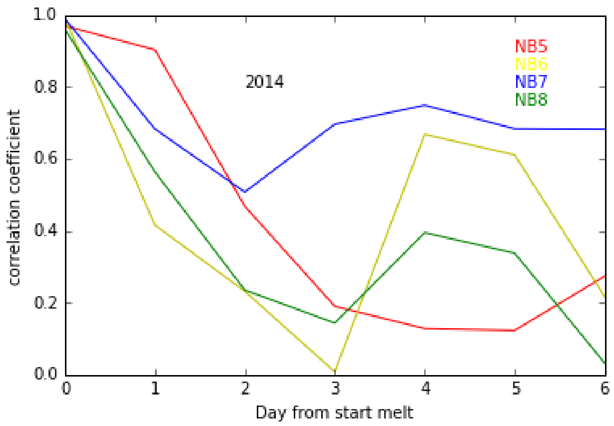
By learning from figures 15 and 16 that the correlation occurs in the first week of melt it makes sense to take a closer look at that first week. In figure 17 the first seven days of the melt are used to calculate the correlation coefficient. What stands out is that the correlation coefficient again decreases significantly very fast. In 2012 after the first day and in 2013 and 2014 after the first two days. This means that the respond time of the glacier to the melt is between one and two days at the beginning of the melt season, later on in the melt season there is no correlation.



((a)) Summer 2012



((b)) Summer 2013



((c)) Summer 2014

Figure 17: Correlation coefficients of the first days in the melt season

4 Discussion

4.1 Velocities

The velocities in Figure 12 show that the glacier has an average velocity between 40 and 65 meters per year and a maximum velocity of around 100 meter per year. This is consistent with the results from Den Ouden (Den Ouden et al., 2010). It is clear from Figure 9 that the highest velocity occurs during the summer. Figure 13 shows that the peak in the velocity is at the beginning of the summer. The peak only lasts a couple of days, which agrees with V.d. Wal et al., (2008). They stated that the influence of melt only has a short-term effect on the ice-sheet velocity. In figure 12 the annual average velocity, winter average velocity, summer average velocity and maximum velocity of the recent years are shown. There is not an actual trend distinguishable. The annual average velocity, summer average velocity and winter average velocity seem to rise since 2012. Thought not by such a rate that it can be called an acceleration of the glacier. To determine if the glacier actually is accelerating, the measurements should continue for at least five to ten years to see if this trend continues.

4.2 Melt

From figure 13, it seems that the velocities only respond to the first peak of the melt each year. In 2013 there is a second peak simultaneous in the velocity and the melt. A possible explanation why the velocity only reacts to the first melt is the development of an effective draining system through the glacier (Bartholomew et al., 2013). Such a system starts to develop when the melt starts. This means that the water is not drained efficiently when the melt starts, hence the acceleration of the glacier. Once that system is sufficient enough to effectively drain the amount of water caused by the melt, the acceleration stops and the ice-sheet returns to a lower velocity. During the winter the drainage system in the ice-sheet freezes. So the next summer the draining system starts to develop again simultaneously with the start of the melt.

The average annual, average summer, average winter and maximum velocities do not seem to be related with the total annual melt. Figure 14 does not show a clear connection. The average summer velocity seems to increase very little with the increase of total annual melt. But the data is not sufficient to be conclusive. Also the winter average velocity seems to decrease very little with the increase of total annual melt. This can be explained, because after a summer with a large melt there is a very extensive draining system which at the beginning of winter helps drain precipitation very effectively. This is in accordance with Tedstone et al., (2015). These are just speculations based on Figure 14, to proof them there should be long-term observations on both velocity and melt.

4.3 correlation

The correlation coefficient quantifies the extent of how correlated two quantities are, in this case the velocity and the melt. Figure 15 shows that in 2012 and 2014 the correlation coefficient takes a dive after the first week. In 2013 it maintains a higher coefficient for two weeks longer. When taking the averages of the coefficients with their standard deviations, figure 16 is obtained. Figure 16 confirms that only in the first week the correlation coefficient is close enough to one and its uncertainty is small enough to say that the quantities are correlated. This agrees with V.d. Wal et al., (2008), who stated that the melt only has a short term effect on the velocity of a glacier. So the glacier reacts within a week to the melt. Figure 17 shows the correlation coefficients of the first week of the melt. What stands out is that the coefficients again, take ad dive very fast. In 2012 after one day, in 2013 after two days and in 2014 after one day again. This means that it is just a matter of days before the glacier has adapted to the melt and an effective draining system is formed. Note that this is based on three seasons of melt, only the summers of 2012, 2013 and 2014.

5 Conclusions

The main question for this research was: what influence does the melt have on the velocity of a glacier? The most important result is that the research showed that the melt and the velocity are only correlated on a short term basis. This can be concluded from figures 13 and 16. Longer and more precise observations should be done to obtain an exact quantity for the amount of time it takes the glacier to develop an effective draining system. Another result is that the total melt of a year does not have a big impact on the average annual velocity of the glacier. This data is not sufficient to conclude whether there is any impact or not. To determine if there is any influence at all of the melt on the velocity of the glacier there should be very exact observations on both the velocity and the melt to notice even the smallest impact. There were also no significant trends detected in annual average velocity of the glacier.

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