External Conditions Effects on the Self-Organised Criticality of the Calving Glacier Front of Tunabreen, Svalbard

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Pontus Westrin
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Abstract

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Mass balance processes in glaciers are important for determining the growth or retreat of ice. Calving, the mechanical breakage of ice bergs from a glacier front, is a poorly understood phenomenon. This process has great importance to the mass balance of many glaciers, for example on Antarctica and in the Arctic. A recent paper by Åström et al. (2014) compare calving fronts to Self-Organized Critical (SOC) systems, especially the Abelian sand pile model, meaning that the calving front will stay at a critical state at all times. Fluctuations in external conditions will cause the glacier front to either retreat or advance.

The calving frequency and size distribution of Tunabreen, a tidewater glacier in Svalbard, was studied during August and September, 2014, with the use of a time-lapse camera set up in front of the calving front. An 11-day period is studied in detail and compared to certain external factors, i.e. tide, air temperature, humidity, atmospheric pressure, wind speed and wind direction. The results are also compared to the relationships found by Åström et al. (2014).

The results vary: tide relationships are found as the amplitude reaches above 1 meter, but seize to correlate as the tide falls off. Temperature trends are found for certain periods, but are of low credibility. Humidity, atmospheric pressure, wind speed and wind direction show low to no correlation with the calving size distribution. Fragment size distribution and calving rates show good correlation with the results from Åström et al. (2014). This helps to confirm the theory of SOC applied to calving fronts. Time-lapse photography is deemed as a good way to observe calving fronts, but have certain problems which are mostly related to the weather.

Longer time periods would be needed to find better long term relationships between external conditions and calving frequencies, but data is hard to acquire and time consuming to process. The theory of SOC applied to calving fronts is promising and opens up new discussions for the research community.

Keywords: Calving, calving model, self-organized criticality, glacier dynamics, Tunabreen

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Externa faktorers effekt på den självorganiserade kritikaliteten av Tunabreens kalvningsfront, Svalbard
Pontus Westrin


Längre tidsperioder behövs för att bedöma om förhållanden stämmer på lång sikt. Data är svår att förvärva och tidskrävande att behandla. SOC stämmer bra in på kalvningsfronter vilket öppnar upp nya diskussioner inom forskningsvärlden.

Nyckelord: Kalvning, kalvningsmodell, self-organized criticality, glaciärdynamik, Tunabreen

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1. Introduction

One of the biggest threats to the modern world is the changing climate and rise of sea levels on Earth. With three millennia of fixed global mean sea levels (GMSL) scientists are now recording a global sea level rise while the planet is experiencing a rapid warming of temperatures (Cazenave, 2006). The present rise of about 3.0 mm/year, recorded through satellite data as well as tide gauges all around the world has doubled in a decade (Cazenave, 2006; Shepherd & Wingham, 2007; IPCC AR5 WG1, 2013). This rise is primarily due to thermal expansion of the water in the oceans as well as the addition of water from land based glaciers and ice sheets, both being a result from rising mean surface temperatures. The contribution of land ice to the GMSL rise comes from many different processes. One of the most important mass balance processes in glaciers that terminate in the ocean is the mechanical loss of ice known as calving, the process where icebergs are broken off from a glacier front that is terminating in water, either in the ocean or in freshwater lakes. This process accounts for a large part of the water being transported from glaciers into the oceans.

Almost half of the total mass loss from several of the largest Antarctic ice tongues is estimated to come from calving (Depoorter et al., 2013). Similar conditions are seen in Greenland as well, as shown in Figure 1 (AMAP, 2011; Johannessen et al., 2011). Looking at this figure we see an increased negative mass balance per year since the 1990s in both mountain glaciers and ice caps as well as in the Greenland ice sheet. The amount of ice stored in the large ice sheets on Antarctica and Greenland is believed to equal a GMSL rise of about 65 meters if allowed to melt, drowning many highly populated areas in low lying lands around the world (Cazenave, 2006).
While a warming air temperature on Antarctica and increased melting of the Western Antarctic Ice Sheet has been recorded the last decade, there is no immediate threat in terms of massive contribution of the rise in GMSL, much due to the stability of the Eastern Antarctic Ice Sheet (Steig et al., 2009; Rignot et al., 2013). The warming of the climate has however been found to be more evident in the Arctic regions than in other parts of the world (IPCC, 2013). As a consequence, the mass loss in Greenland has increased by four times since the 1990s (Straneo & Heimbach, 2013; AMAP, 2011) and glaciers have shown worrying signs of increases in calving frequencies (Nick et al., 2012; Johannessen et al., 2011). The latest report of Snow, Water, Ice and Permafrost in the Arctic (2011), in short SWIPA, estimated that each year about 200 gigatonnes of ice is lost from Greenland, and almost the same from mountain glaciers in the Arctic (AMAP, 2011). Mountain glaciers and ice caps are a small part of the total ice in the world but they have been a large source of the total GMSL rise, and will continue to be in the future, mainly due to their sensitivity to climate change (Nuth et al., 2010; IPCC, 2013).

In the Fifth Report of the IPCC (2013), it is stated that the calving of icebergs is one of the key uncertainties when it comes to assessing the threat of mass loss from the big ice sheets. Calving glaciers have been found to be very sensitive to climate changes, capable of experiencing retreat rates over 1 kilometre per year if external conditions change drastically (AMAP, 2011; Nuth et al., 2010; Venteris, 1999). This leads to calving being increasingly important for GMSL predictions (Benn et al., 2007).
2. Aim

SWIPA (AMAP, 2011) stresses the fact that many uncertainties come directly from a lack of in situ observations. Methods used for observing calving are either criticized with large uncertainties or stated as time consuming and expensive. Detailed in situ observations are necessary to test new theories and learn more about the controlling factors.

With our poor current knowledge about the physics involved in calving, as well as lack of data over how external conditions affects calving frequency, no standard calving law has yet been accepted by the scientific community. A new way to look at calving glacier fronts was presented by Åström et al. (2014), showing how the theory of Self-Organized Criticality can be used on calving glaciers.

This model can be compared to a calving front which is experiencing changes in external factors, such as tide and air temperature, which causes it to sway between the super-critical or sub-critical state. Due to nature, where changes in conditions are happening all the time, the super-critical state is favoured by the system.

By presenting a simple way of observing calving of a glacier front with the use of a time-lapse camera, this project aims to link different external conditions with the size distribution of calving events on Tunabreen, Svalbard. Together with this observation, an explanation over the present calving research is provided as well as a discussion around the self-organized criticality of calving glaciers. A section about time-lapse cameras and their role as an instrument in nature science is also provided.

The study by Åström et al. (2014) identifies calving glaciers as Self-Organized Critical (SOC) systems, more specifically the simplest of these systems, the Abelian sandpile model. This system always tries to stay at a critical state, constantly fluctuating between a sub-critical advance or a super-critical retreat. The size distribution of “avalanches” (defined as sand grains falling on the sand pile or, in this case, calving events) are related to a scale-invariant power law. No event is considered exceptional, meaning that added grains may either cause no change in the structure, or break the whole stability of the sand pile.
3. Background

3.1. Tidewater glaciers and calving dynamics

While calving occurs in both freshwater and tidewater glaciers, the phrase ‘tidewater glaciers’ have been almost synonymous with calving glaciers throughout history (Benn et al., 2007). Tidewater glaciers can be classified as a glacier which terminates in the ocean. The glacier can either be grounded directly at the place where it terminates, called a grounded glacier, or extend further out in water, making it an ungrounded glacier. The part which is extended into the water is called the floating tongue of the glacier (Cuffey & Paterson, 2010). If the glacier were to terminate in a proglacial lake we would call it a freshwater glacier (Benn & Evans, 2010). The calving itself is a consequence of high stress on the front of the glacier. The ice is weakened by a constant longitudinal stretching leading to thinning of the ice which creates fractures propagating throughout the ice (Cuffey & Paterson, 2010; Aström et al., 2014). A picture over how a calving front can look like can be seen below in Figure 2.

![Figure 2. Close up of a calving front. Picture taken during winter time.](image)

A simple flow diagram can be established to understand the reason behind crevasse propagation and calving, as seen in Figure 3. An increase in surface melting over the glacier, as expected when surface temperatures rise, leads to thinning of the glacier tongue. The effective pressure, defined as the pressure difference between water at the base and the ice around it, is reduced due to the thinning, as a less substantial load is present above the water. The loss of the high pressure at the base cause an increase in the velocity of the glacier, leading to an increase in the longitudinal strain rate, further developing a thinning. This feedback loop is called dynamic thinning. The increase of longitudinal strain rates greatly enhances the depth of crevasses, leading to a higher calving rate (Benn et al., 2007; Benn & Evans, 2010; Cuffey & Paterson, 2010).
3.1.1. Calving ‘laws’ and models

While there is no widely accepted calving law in the scientific community, there have been several empirical relationships presented with varying results (Benn et al., 2007; Benn & Evans, 2010; Cuffey & Paterson, 2010). One of the most famous is a model proposed by Brown et al. (1982) which approximates the average calving rate ($\dot{c}$) by just applying the water depth at the terminus of the glacier ($H_w$), as well as an empirically determined coefficient ($k_c$);

$$\dot{c} = k_c H_w$$

This relationship have later been added to and altered through the years, but never with any strong success on shorter time scales (Benn et al., 2007). A relationship is most definitely present, but it is hard to imagine that the only control would be the water depth (Cuffey & Paterson, 2010). Some argue that the water depth is important due to the correlation it has with glacier velocity, posing more of an indirect impact on calving rates (Benn & Evans, 2010). Many observations have found that the water depth poses a great potential in influencing the velocity of both glacier retreat and advance. As a stable glacier terminus is resting on a moraine shoal, the terminus is left at a low water depth. Changes in external factors cause the terminus to retreat into deeper water behind the shoal where the calving is enhanced greatly, leading to further, more rapid, retreat. The process is slowed down as the glacier reaches a position which brings on a lower water depth (Benn & Evans, 2010; Cuffey & Paterson; Warren, 1992). A figure of the famous Columbia Glacier and its rapid retreat during the latter part of the 1900s, by similar processes as explained above, can be seen below in Figure 4.
Some laws have focused more on buoyancy control instead of purely water depth at the terminus (van der Veen, 2002; Cuffey & Paterson, 2010):

$$H_b = H_M - \frac{\rho_w}{\rho_i} H_w.$$ 

Where $H_b$ is the ice thickness present above the water level, $H_M$ is total ice thickness at the terminus and $H_w$ is the water depth. $\rho_w$ and $\rho_i$ stand for the densities of water and ice. The correlation was found by van der Veen (1996) who carefully studied the data over the collapse of the Columbia Glacier in the early 1980s. The idea is that when the ice tongue is approaching floatation, the calving rate increases. In van der Veen’s (1996) case of the Columbia Glacier this was at $H_b < 50m$, disregarding the water depth. While the relationship have proven to be good in some cases (Cuffey & Paterson, 2010), the control is poorly understood. When the ice tongue reaches floatation the effective pressure on the basal plane of the glacier is reduced, leading to increased longitudinal stretching, which in turn means more calving (Figure 3). This is however only applicable if the glacier has a floating tongue.
3.1.2. Self-organized criticality

The initial papers by Bak, Tang and Wiesenfeld (1987, 1988) on Self-Organized Criticality (SOC) have influenced many studies in the last three decades. A general definition of SOC is yet to be established (Turcotte, 1999), though it is most easily described by the simplest of these systems, the Abelian sandpile (Dhar, 1999; Åström et al., 2014). This system consists of a pile of sand with a constant addition of sand grains from the top. As grains are added, the pile reaches its critical slope angle. A rapid relaxation event, an avalanche, occurs when the pile can’t support its weight anymore. The sand pile is attracted to exist in a critical state, where the slope angle is at the maximum carrying capacity. In theory, this system could exist at a constant critical point, though in practice changes in external, as well as internal, factors causes the system to swing around the point of criticality (Dhar, 1999; Åström et al., 2014).

The typical SOC system is a slow driven, non-equilibrium steady-state system. Åström et al. (2014) proposed that the terminus of a calving glacier is comparable to a SOC system, more specifically the simplest of these systems, the Abelian sandpile. The avalanche in the sand pile is equal to a calving event, where the glacier front relaxes from achieving its critical carrying capacity. The relaxation events occur in a non-linear way, responding to either climatic or geometrical changes. The authors explain that the front stays in one of two critical states, either a sub-critical advance or a super-critical retreat. Through observations and models Åström et al. (2014) found that the calving event happens under a scale-invariant power law, much like the Gutenberg-Richter law for earthquakes. No calving event is to be considered exceptional, meaning any event could happen at any time. As said before, the system could be held at its critical point indefinitely due to this fact, though fluctuations happen in nature due to constant changes in external conditions. A high sensitivity to external factors is an important property to SOC.

To further test this theory a numerical particle model was developed. The model was made to help simulate a calving glacier terminus in three dimensions. Simulations of the model existing at its critical point were compared with data over several real examples of calving glaciers, showing many similarities. The data could then be compared with how external parameters impact the super-critical or sub-critical state of the system. A figure of the particle model can be seen below in Figure 5.
3.2. External conditions impacting calving processes

As mentioned in 3.1.1, destabilization of the glacier terminus can cause a large change for the glacier as a whole. These destabilizations are often caused by a change in the climate or other external factors. The study from Åström et al. (2014) propose that changes in external forcing is a very important part in explaining when calving events occur. Internal dynamics of the calving process itself is however poorly understood (Benn et al., 2007), the variability of calving could just as well be a result of the dynamics instead of external factors, or both (Chapuis & Tetzlaff, 2014). A summary of some external factors, and their role in calving frequencies, are given below.

3.2.1. Sea level changes and tide cycles

Positive feedback mechanisms are important when talking about climate change. One of the results of increased global mean surface temperatures is a GMSL rise (IPCC, 2013). If we again take into account the theories given in 3.1.1, we can imagine an increased sea level destabilizing the front of a glacier. If the relationships proposed in 3.1.1 are present, the increased water depth would cause a retreat if the sea level rise is large enough (Cuffey & Paterson, 2010).

Tide cycle analysis of Tunabreen have been made in a study by Åström et al. (2014), showing a good correlation with calving events happening at low tides. An earlier study by O’Neel et al. (2003) investigating short-term effects of tidal variation show little to no correlation. Low significance for tides, as well as air temperature, was also found in two tidewater glaciers from Svalbard in a study by Chapuis & Tetzlaff (2014). With varying results from different glaciers it is hard to tell if tidal variations are impacting calving or not. A change in tides might have an effect in a longer timescale, but it is hard to justify a strong, short term relationship (Chapuis & Tetzlaff, 2014).
3.2.2. Climatic factors

Local climatic factors, e.g. air and ocean temperature, humidity and wind patterns, are poorly studied when it comes to them impacting calving processes. Ice has, as all other materials, mechanical properties that govern how they respond to changes, e.g. in their temperature. Concerning temperature, a generalization can be made that a lower temperatures increases the strength of ice (Petrovic, 2003). This is more prominent in compressive strength, with a factor of 4 going from 0° to -40° C, than tensile with 1.3, shown in Figure 6. While the review from Petrovic (2003) is useful in some cases, it is hard to apply to studies in glacial dynamics as none of the studies are done with glacier ice, which differs a lot from “pure” ice (Mottram & Benn, 2009).

![Figure 6](image_url)

*Figure 6.* Compressive and tensile strength in ice depending on temperature. From Petrovic (2003), reproduced with permission from Springer.

When it comes to how other climatic factors, e.g. humidity, wind and atmospheric pressure, directly influence calving dynamics, few to no studies have been done. The effect of these variables are better understood for a glacier as a whole, but the direct impact on calving is unknown. As an example, increases in air temperature may cause meltwater from the surface of the glacier to fill fractures and further develop them deeper. As calving happens around these fractures, an indirect effect of air temperature may be present.
3.3. Location and Svalbard glaciers in general

The ice-covered area on Svalbard is about 36 500 square kilometres, with the mass representing about 26 mm SLE (sea-level equivalent). Negative mass balance for Svalbard’s glaciers has been a trend for the last century, continuing into the 2000s (AMAP, 2011). A major contributor to mass balance loss on Svalbard glaciers is calving. An estimate of 60% of the aforementioned ice-covered area is classified as marine-terminating, calving glaciers, reaching a combined calving front length of about 1000 km (Blaszczyk et al., 2009).

Below in Figure 7 we see summer temperature anomalies (red) as well as specific mass balance (blue) over the last 50 years on Svalbard. The trend in mass balance has generally been retreating over the last decades, correlating negatively with the summer temperatures as seen below.

This study was conducted on Tunabreen, Svalbard. Tunabreen is a 174 square kilometre large, grounded tidewater surge-type glacier located in the centre of Svalbard at the head of Tempelfjorden (Nuth et al., 2010; Flink et al., 2015), shown in Figure 8. The glacier is an outlet to the bigger ice cap above it, Lomonosovfonna, which covers 600 square kilometres. A recent surge happened from 2003 to 2005, leading to an advance of about 2 kilometres (Flink et al., 2015). However, during the last decade, Tunabreen has been retreating at a rate of -0.35±0.14 m.w.e. (Nuth et al., 2010; Flink et al., 2015; Norwegian Polar Institute, 2015).

Surging, where a glacier advances at a high rate over a short time, is a very common phenomenon on Svalbard. This often happens in individual cycles around a century for glaciers on Svalbard, but Tunabreen has shown to have closer to a 40-year cycle of surging, making it the glacier with the shortest surging cycle in the area (Flink et al., 2015, AMAP, 2011). While surging results in an advance of the front of the glacier, it also enhances the calving frequency of the glacier due to thinning of the ice as well as often bringing it into deeper water (Cuffey & Paterson, 2010). A surge may also cause a lot of crevasses and fractures on the ice surface, leading to increase in calving (Benn et al., 2007).
3.4. Previous studies on calving size distribution

Few studies have been made with direct observations of calving events, much due to the complexity and the inaccessibility of many calving glaciers. A recent study by Chapuis & Tetzlaff (2014) investigate two tidewater glaciers on Svalbard. They use direct visual data, meaning a group of human observers take shifts in monitoring events happening in the glacier terminus while manually recording the perceived sizes. The data is compared with external factors such as air temperature and tidal variations, but little to no correlation is found with the event distribution. As the observations took place for a 4 and 12-day period, nothing can be said of the longer term impact of climatic factors in calving variability.

O’Neel et al. (2003) studied an Alaskan tidewater glacier over a longer time period. The observations were discontinuous, occurring over approximately a month. The methods used were both direct visual monitoring, as well as analysing of time-lapse photographs. While no connection to semi-diurnal tide changes are found, some signs of increased calving is found during bi-weekly tides. One important find is that no correlation is made between calving and increases of ice speed, or the other way around.

Another study by Wadhams (1988) researches calving event distribution and their frequency by the means of looking at icebergs in the ocean. This method is however criticized (Chapuis & Tetzlaff, 2014) due to wave action and melting deteriorating the icebergs.

Åström et al. (2014) use data over several calving glaciers and their size distribution frequencies, as well as additional data from a 3D particle model, to compare calving fronts to Self-Organized Critical systems. More on how Self-Organized Criticality works, as well as more examples from Åström et al. (2014), can be found in 3.1.2.
3.5. Time-lapse cameras

Time-lapse photography has become a very useful tool to scientists in many fields, especially in earth science. The ability to be able to observe a phenomenon over a long time period has made many studies possible. As solar panel technology, as well as batteries, gets better and cheaper, time-lapse camera stations in remote places, like polar areas, become possible. With water-proof boxes and long lenses, cameras can easily be located a kilometre from a glacier and still provide good data.

There have recently been many studies in glaciology using time-lapse cameras, typically studies researching glacier front development like calving (e.g. Walter et al., 2010; O’Neel et al., 2003), surging (e.g. Kristensen & Benn, 2012) and glacier velocities (e.g. Ahn & Box, 2010). The data can be one picture per day, or several pictures per hour.

3.5.1. Issues with time-lapse photography

As with most methods, several issues are present with time-lapse photography, especially when applied in glaciology. Ahn & Box (2010) encountered problems related to the climate of the area studied in Greenland. They report a loss of usable images by about 15-20 % each day, mostly due to clouds and fog covering some observations. Other factors are automatic exposure of the camera, leading to either too bright or dark pictures. As ice is a very reflective, overexposure can become a big problem if there is intense sun. Strong winds, which often is the case in flat landscapes such as glaciated areas, may also cause the camera to get out of focus or change position. Ahn & Box (2010) even report problems with wild animals disturbing the equipment, biting and scratching windows on the water-proofed enclosure.

Problems relating to cameras inner circuits reacting to extreme cold is also a problem. Ahn & Box (2010) report camera shutter problems when temperatures reach below -30° C. One key problem is related to the camera timer. Many scientists count on this timer to provide reliable time stamps for each picture. Ahn & Box (2010) again report difficulties where the camera timer have miscalculated the time by over 10 days in some cases. Welty et al. (2013) present a method for calibration of cameras when used as clocks. Unique values are given for several common cameras at the time. Two case studies over specific glaciological studies where time stamps on pictures were vital are presented to show application of the method.
4. Methodology

4.1. Time-lapse camera

For this project an 11-day period of the time-lapse pictures, between the evening of the 26th of August to the end of the 6th of September 2014, was chosen. The pictures of Tunabreen’s glacier front are taken with a 14 minute interval, leading to a total of over 1100 pictures. The period was deemed good due to low amount of fog and intense sunlight, which can lower the visibility of the glacier front hindering good interpretations of calving events. Though some of the decreased visibility can be fixed with the script (see 4.2.1), it is recommended to not have too much intense sun or fog. The period chosen is also in the middle of the melting season, increasing the chance of high calving frequency. Figure 9 below show the camera station in front of Tunabreen.

As a complement to the pictures from the time-lapse camera, satellite imagery of the same glacier front needs to be added to constrain the position of the glacier relative to the camera. When calculating the real size of the pixels present in the pictures, the focal length of the camera and the physical pixel size of the sensor is important. More about this step will be presented in 4.3.

Figure 9. The camera station standing in front of Tunabreen’s calving front, shown in the far left of the picture. Tempelfjorden, laying in between the camera and the calving front, is frozen and covered with sea ice at the time of the picture.
The camera used in this project was a Canon 450D. The aperture were set to F/2.8 with a shutter speed and ISO value set at automatic, depending on light conditions. The focal length of the lens is 28 mm. Table 1 shows the camera properties.

Table 1. Camera Properties.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Canon 450D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>F/2.8</td>
</tr>
<tr>
<td>Sensor Size</td>
<td>22.2 x 14.8mm</td>
</tr>
<tr>
<td>Focal Length</td>
<td>28 mm</td>
</tr>
<tr>
<td>Image Size</td>
<td>4272 x 2848 (12.2 megapixels)</td>
</tr>
<tr>
<td>Physical Pixel Size of Sensor</td>
<td>5.2µm</td>
</tr>
<tr>
<td>Time-lapse frequency</td>
<td>One picture every 14 minutes</td>
</tr>
<tr>
<td>Position</td>
<td>78°40'57.26&quot;N 16°89'99.35&quot;E</td>
</tr>
</tbody>
</table>

4.2. General Method

A Matlab-script was developed for this project to make it easier to outline and calculate the size of calving events. The script is used to compare two pictures with each other to help outline specific calving events between two pictures. This is done by drawing polygons over the ice where a calving event is detected. The outlined event pixels are extracted and their real size is calculated using additional data from a satellite image, courtesy of Adrian Luckman (unpublished data), acquired from the TerraSAR-X satellite.

4.2.1. Outlining calving events between two time-lapse pictures

Before starting with the outlining, the contrast and/or the luminosity of the pictures was optimized for the pictures. This is because some time-lapse pictures may have intense sun or thick fog decreasing vision of the front. With some alterations to the pictures it becomes easier to see and outline changes.

The user is presented with two time-lapse pictures (picture i and i+1) taken with, in this case, a 14 minute interval between them. By switching between pictures i and i+1, the user can identify and outline calving events with a user control tool designed to draw polygons. When satisfied with the outlines of the events the user moves on to picture i+2 and compares it with picture i+1. The user may also go back in the sequence to edit former polygons. The option of zooming in to different parts of the pictures is also available. The figure below (Figure 10) show how the process is done; points are created to outline the calving event while switching between the two pictures to see the change. The front on the left picture, i, changes when the next picture, i+1, is taken 14 minutes later, outlined in green.
Figure 10. An example of the outlining process.

The polygons, and their position, are then saved by the script. This information is used in the next stage of the processing, when the polygons are calculated to their real size.

4.3. Calculating the real size

Several things need to be done before the real size of the calving events can be calculated accurately. First, the distance between the camera and the glacier front must be calculated. Second, trigonometry is used to find the area of the marked polygons. The steps are explained in detail below. Note that we assume that there is no distortion of the projected pixels in the vertical direction, a discussion on this can be found in 6.3.

4.3.1. Calculate the distance H between the front and the camera

To be able to calculate the real size of the polygons, each pixel needs to be scaled to actual area of the calving front. To do this, the front position of the glacier needs to be set in reference to the camera position. The visible front on the time-lapse pictures is outlined with the help of satellite imagery, which is georeferenced. The distance between the front and the camera position is calculated and stored in a matrix, $H$ (Figure 11), where $h_i$ represent the distance between the front and the camera at the image point $x_i$. The matrix H has the same size, $a \times b$, as the amount of pixels in the time-lapse pictures, i.e. the resolution of the picture. We assume no distortion in the vertical direction (mainly because the front is assumed vertical and the height small compared to the distance to the camera) so that the distance $h_i$ at $x_i$ is the same for the whole pixel column. $H$ is later used to calculate the real size of the calving events, explained below.
Figure 11. An illustration of the matrix $H$. The number of columns, $a$, is the same as the horizontal number of pixels on the image and the number of rows, $b$, as the vertical one.

4.3.2. Convert image pixel size to real size

With the use of the matrix $H$, the focal length $f$, and the physical pixel size of the sensor $x$, it is possible to determine the real size of each pixel, $X$. The physical pixel size is found in the camera properties (see Table 1).

To do this calculation we will use a direct adaptation of Thales Theorem. This theorem tells us that two triangles with different size but equal angles can be related, as illustrated in Figure 12 and the equation below:

\[
\frac{A}{d} = \frac{B}{c}
\]

Figure 12. An illustration of Thales Theorem.

Figure 13a below illustrate the camera projection, where C’ is the lens dividing the time-lapse picture with the real object. Figure 13b illustrate how the projection can be used as triangles which can be related to Thales Theorem. Using Thales Theorem, we find:

\[
\frac{H}{f} = \frac{x/2}{x/2}
\]
Figure 13. Illustration of the variables used to calculate the actual size of pixels. a show the pixels projected through the lens C’. b divides the figure to create two similar triangles, separated by C’.

4.3.3. Calculate the real size of a calving event

As we assume no distortion in the vertical direction, the real area is $X^2$. The real area of each pixel inside the polygon is calculated using the matrix $H$. This area is put into a new matrix with the same size as the matrix $H$, but with the area of each pixel in every field. The matrix only change in x-direction as the h-values only change in this direction, explained previously in 4.3.1. With the polygons of the marked events we can now calculate the real area of each event. As the matrix is the same size as the picture resolution, the pixels in the polygons can be directly related to the specific pixels in the matrix. The area of these pixels are all added up to achieve the area of the whole event.

To convert the calculated area into the assumed vol. of each event, a simple equation is used:

$$CalvingEventVolume = \frac{1}{10} \times CalvingEventArea^{1.5}$$
4.4. Relating the size distribution to external conditions

The data presented in the results are qualitative. Statistical methods, such as a FFT (Fast Fourier Transform) and PCA (Principal Component Analysis) were tested, but were left out due to noisy and poor results. These figures can be found in Appendix 1, but will not be further explained in the text.

4.4.1. Tide calculations with AOTIM-5

To get tidal data over Tunabreen the Arctic Ocean Tidal Inverse Model, AOTIM-5, was used. This model is provided by Padman & Erofeeva (2004) and can be reached through Matlab. The model gives high-resolution tidal height data over the Arctic Ocean area, including Svalbard. By using tide gauge data, both coastal and benthic, as well as altimetry provided by the satellites TOPEX/Poseidon and ERS, the height of the tides can be predicted for all of the Arctic Ocean. For detailed information about the model see Padman & Erofeeva (2004).

4.5. Moving average

When presenting the results, some graphs are showcased with a moving average filter. This filter is applied to smooth out high noise in some of the data. The data consists of a high number of points, leaving the graphs to be noisy and hard to analyse. The moving average filter takes a certain window, given by the user, in the values and makes a mean for each point and window. The window, or order, can be increased to reduce high frequency noise. Below in Table 2 is an example of a time series which is using the order of 3 to achieve a moving average.

<table>
<thead>
<tr>
<th>Table 2. Moving average time series example.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original series</strong></td>
</tr>
<tr>
<td><strong>With the original moving average filter</strong></td>
</tr>
<tr>
<td><strong>With the adjusted moving average filter</strong></td>
</tr>
</tbody>
</table>

One important thing to note is that the first and last value is removed with this method. To compensate for this, the filter is adjusted to divide the values by a lower order if the point have fewer neighbouring values. In this case, the first number is 11. An order of 3 means that one number, to the left, is missing. The first number is therefore only added with the number next to it and divided with an order of 2, giving the adjusted mean of 9.

A discussion of the issues with this way of presenting the data is given in 6.3. A complete definition and theoretical background of the moving average can be found in Dodge (2010).
5. Results

5.1. Fragment Size Distributions

Results from the fragment size distribution, waiting time and calving rates are presented below. Waiting time is the time in between each consecutive event in seconds. Calving rate is explained as a rate of high/low calving in a short amount of time. The threshold between high and low calving rate is given by the mean calving rate. The results will be further explained in the discussion.

![Relative abundance of calving events versus calving size.](image)

**Figure 14.** Relative abundance of calving events versus calving size.
Figure 15. Relative abundance of calving events versus waiting time, explained as the time in between each consecutive event in seconds.

Figure 16. Relative abundance of calving events versus calving size, divided by low and high calving rate.
5.2. External Factors

Below follow the results from the calving frequency and size distribution compared to external factors. The metrological data consisting of air temperature, relative humidity, atmospheric pressures as well as wind speed and direction, are all credit to UNIS, The University Centre In Svalbard. The values were measured each second, at a height of 10 meters above the ground, from the weather station in Adventdalen. The station is located approximately 43 kilometres from the front of Tunabreen.

5.2.1. Tide

Below are the results from the comparison between the calving size distribution and the tidal variations. The tidal data is taken from AOTIM-5, a model developed by Padman & Erofeeva (2004). More information can be found in 4.4.1, as well as in the article by Padman & Erofeeva (2004).

Figure 17. Tidal variations (blue) versus calving size distribution (red) over time.
5.2.2. Air Temperature

Below are the results from the comparison between the calving size distribution and the temperature.

Figure 18. Tidal variations (blue) versus calving size distribution (red) over time. A moving average over 6 hours is applied.

Figure 19. Air temperature (blue) versus calving size distribution (red) over time. A moving average spanning over 14 minutes is applied to smooth out high noise in the data.
Figure 20. Air temperature (blue) versus calving size distribution (red) over time. A moving average spanning over 12 hours is applied to the calving frequency to highlight semidiurnal variations.

5.2.3. Humidity

Below are the results from the comparison between the calving size distribution and the humidity.

Figure 21. Relative humidity (blue) versus calving size distribution (red) over time. A moving average spanning over 14 minutes is applied to smooth out high noise in the data.
5.2.4. Atmospheric Pressure

Below are the results from the comparison between the calving size distribution and the atmospheric pressure.

Figure 22. Relative humidity (blue) versus calving size distribution (red) over time. A moving average spanning over 12 hours is applied to highlight semidiurnal variations.

Figure 23. Atmospheric pressure (blue) versus calving size distribution (red) over time. A moving average spanning over 14 minutes is applied to smooth out high noise in the data.
5.2.5. Wind Speed

Below are the results from the comparison between the calving size distribution and the wind speed.

Figure 24. Atmospheric pressure (blue) versus calving size distribution (red) over time. A moving average spanning over 24 hours is applied to highlight diurnal variations.

Figure 25. Wind speed (blue) versus calving size distribution (red) over time. A moving average spanning over 14 minutes is applied to smooth out high noise in the data.
5.2.6. Wind Direction

Below are the results from the comparison between the calving size distribution and the wind direction.

Figure 26. Wind direction (blue) versus calving size distribution (red) over time. A moving average spanning over 14 minutes is applied to smooth out high noise in the data.

Figure 27. Wind direction (blue) versus calving size distribution (red) over time. A moving average spanning over 24 hours is applied to highlight diurnal variations.
6. Discussion

6.1. Fragment Size Distributions Connected To SOC

In the study by Åström et al. (2014), simulations of a calving system close to its critical point is compared to data over several calving glaciers in the world. The data align well, as seen below in Figure 28, and show high similarities with Self-Organized Criticality (SOC) systems like the Abelian Sandpile Model (ASM). Åström et al. (2014) also conducted research on Tunabreen, but with a shorter time period and different methods.

Figure 14, showing the fragment size distribution, show a similar pattern as Figure 28b. The power law with an exponent of -1.20 proposed by Åström et al. (2014), found in studies investigating ASM, is consistent with this study as seen by the two figures. Åström et al. (2014) even describes a dip in the curve at around $10^4 m^3$ in calving vol., again seen in this study. This is explained as a control based on the size of a grounded calving front. A lower frequency of large-scale events in grounded glaciers is often observed as they won’t reach floatation, or near-floatation, as floating glacier tongues would.

The waiting time, the time in seconds between each consecutive calving event, shown in Figure 28a, trends around a power law exponent of $-1.67 \pm 0.30$. This value is consistent with theory and previous findings on the Abelian sandpile model (Åström et al., 2014). Looking at Figure 15 we see that the waiting time is within the range for most of the chart, with the power law exponent of $-1.37$, but dips at longer waiting times. This dip is similar to the one found in Yahtse glacier, Figure 29, shown in the Supplementary information in Åström et al. (2014). Yahtse glacier is located in Alaska and is, like Tunabreen, a grounded tidewater glacier. This glacier’s waiting time deviate from the others by being described as an exponential function instead of a linear. Reasons for this is unknown, more data would be needed to see better trends, or data from other similar glaciers. Figure 15 is somewhere in between the two models, making it hard to interpret the result. Longer periods of time or a higher frequency of pictures or observations may be needed to get more conclusive results.

Figure 28. Results from the studies done by Åström et al. (2014). a shows the relative abundance of calving events versus the waiting time for several glaciers, including Tunabreen, as well as from the simulations of the particle model in both 2D and 3D. b shows the sizes of events and their trend. Reproduced with permission from Nature Publishing Group.
Figure 29. Waiting times from Yahtse glacier in Alaska. Yahtse was the only glacier to deviate from the trend of the other glaciers, shown in Figure 28a. From Åström et al. (2014), reproduced with permission from Nature Publishing Group.

Below in Figure 30b, the critical regimes of the simulated 3D calving front (based on Figure 30a) are highlighted along the power law of $E_{kin}^{-1.2}$. Looking at Figure 16, we see a similar pattern. The exponent of the power law differs with 0.05 between the simulation from Åström et al. (2014) and this study. The data from Åström et al. (2014) suggests a power law with the exponent differing between $-1.26 \pm 0.20$, which are numbers that resemble previous ASM studies. The results from this study are well within that range which helps to confirm that calving fronts, such as the one present on Tunabreen, are in fact SOC systems, similar to the ASM, that stay close to their critical state.

Towards the right of Figure 16 and Figure 30b a rise in super-critical and high calving rate can be seen, going above the trend line. Super-criticality resembles the high calving rate curve in many ways, showing a dip below the trend to the left and a rise to the far right. High calving rate, as well as super-criticality is here dominated by larger events, while the opposite can be said about sub-criticality and low calving rate. The sub-critical and low calving rate lines hold close to the trend, with a small dip at lower energy or vol.s. As we again see close similarities between the two studies, we can conclude that the theory proposed by Åström et al. (2014) is well described in Tunabreen as a calving glacier front.
6.2. Sensitivity to external controls

One key detail in SOC systems such as the ASM is the extreme sensitivity to changes in external controls (Åström et al., 2014). Without external factors controlling changes in material properties and position, e.g. expansion, vibration, friction etc., a SOC system could in theory be balanced at its critical point for an eternity. As external controls do exist, as well as being plenty and ever changing, large fluctuations within these parameters are expected, leading the system to sway around its own critical point. This sensitivity would theoretically be shown in small glaciers such as Tunabreen by fluctuations in tide, temperatures etc., while in bigger glaciers, like those present in Antarctica, the change is revolved around larger fluctuations, such as seasons (Åström et al., 2014). The data presented in this study is compared with several external factors, i.e. tidal variations, air temperature, humidity, atmospheric pressure, wind speed and wind direction, shown further down.

6.2.1. Tide

In the recent study by Åström et al. (2014), Tunabreen’s sensitivity to tidal fluctuations is studied. The results give a clear view of a relationship between low tide and the occurrences of calving events. While the study show a good correlation, the data is limited. To find longer trends, and see how much changes in the tidal fluctuation amplitude over time affects the calving rate and size distribution, more data is needed. This study presents a longer timescale of data, around 11 days, while still being very detailed.

With tidal variations taken from the AOTIM-5 model presented by Padman & Erofeeva (2004), the results given in 5.2.1 are presented in two ways; unaltered in a simple timeline and with a moving average filter applied over the calving events. The moving average window is set to 6 hours to highlight the 6-hour synchronization trend the tides show, visible in the model results from AOTIM-5. The moving average is applied to smooth out high frequencies and see longer trends.
Looking at the first figure, Figure 17, the noise from the data is significant and trends are hard to see. However, for the first 4 days a negative correlation with the tidal data can be seen, much like the data from Åström et al. (2014) implies. While the tide is low, peaks from the calving size distribution data can be seen. This trend is even more highlighted when certain frequencies are filtered out from the moving average filter, in Figure 18. If we constrain the values to only cover the period in the beginning, we see that the trend is quite clear with the moving average applied, highlighted in Figure 31 below.

![Moving Average 6h](image)

**Figure 31.** Tidal variations (blue) versus calving size distribution (red) over time, with a moving average filter spanning over 6 hours applied to the calving size distribution.

Towards the end of Figure 31, when the amplitude of the tidal variations is reduced to ≤ 1m, we see that the trend declines. Looking past the first part of the period in Figure 17 and Figure 18, little to no correlation is found between the tide and the calving size distribution.

The correlation between a high amount of calving and low tides in grounded glaciers are poorly understood. An explanation can be that high water levels support the front by creating pressure towards the front, preventing blocks of ice from falling. When the tide lowers this support disappears and calving happens more frequently. This effect is the opposite as for floating glacier tongues, where an increase in the water stand would mean that the tongue reaches floatation, meaning more calving events.
6.2.2. Air Temperature

Studies over air temperature correlations to calving frequency are few to non-existent. The background given in 3.2.2 highlight a important fact that ice strength decreases with increasing temperature. This would in theory mean that air temperature impacts calving in a direct way by lowering the strength of which the ice holds itself together. However, as seen in Figure 6, the tensile strength is only changing with a small amount when the temperature changes. This tensile strength, which stand for holding particles together, is more important than the compressive strength when it comes to calving.

Melting on the surface of the glacier, creating meltwater pools and water which fills fractures, could prove to be a better explanation of the impact of air temperature. As temperatures rise, more of these processes occur over the glacier. The effect could however be delayed, as the effect of air temperature and melting affects the entirety of the glacier and not just the front. This indirect effect from air temperature would therefore not be seen in short term observations.

Air temperature is also well known to greatly influence the velocity and flow of glaciers in a longer term (e.g. Zagorodnov et al., 2006), but few observations have been made for short term changes, such as semidiurnal changes where temperatures can increase, or drop, very rapidly.

Looking at Figure 19 we generally see a low correlation to the temperature data. The peak in temperature, happening quite early in the graph, show a negative correlation with the calving data. To specifically highlight semidiurnal variations in the data, a moving average filter of 12 hours was applied. This allow us to filter out trends happening in a shorter timescale, and focus on longer trends to see if air temperature is a factor in the calving size distribution. As seen in Figure 20, short moments of correlation can be seen, especially during the second half of the graph, with a short period of negative correlation happening around the 1th of September. If we assume that the calving front is controlled by the tide for the first third of the graph, as seen above in 6.2.1, it is possible that the calving front is controlled more by temperature as the tide drops. It is important to note that the tide would override the control of air temperature, as no correlation is found in the beginning of Figure 20, even with large fluctuations in air temperature.

Several problems with this assumption arise. One is that the 3 extremes shown (low at 26/8, high at 28/8, low at 1/9) is inconsistent with the correlation. Where we have low temperatures, close to zero, we should see a dip in the calving frequency, but instead we see a rise. The high filtering of the data is causing a large number of frequencies to be filtered out in Figure 20. Looking at Figure 19, where all the frequencies still are visible, we still have large events happening during temperature low points. This leaves us with a low credibility to the results, a longer period of time would be needed to establish whether air temperature is a direct controlling factor for calving or if a delayed control due to surface melting and velocity changes are more important.
6.2.3. Humidity

Figure 21 show the connection between relative humidity changes and the calving size distribution. Looking at the high and low points of the relative humidity, correlations with high or low calving frequency is hard to see. Figure 22 highlight the semidiurnal changes happening in line with the temperature changes. No short-term correlation can be seen in this figure, peaks or lows have seemingly no effect on the calving frequency.

6.2.4. Atmospheric pressure

The atmospheric pressure does not seem to have an effect on the calving frequency over this period. Figure 23 show little to no short term correlation with the calving size distribution data over the period. Figure 24 highlight diurnal variations, with a moving average windows spanning over 24 hours applied. Again, little to no correlation can be seen in a longer term perspective. A longer period of observation would be interesting to see, but atmospheric pressure as an important controlling factor on calving in short term can be ruled out for this study.

6.2.5. Wind speed

Little or no correlation can be found in Figure 25. At the peak wind speed, happening between the 2nd and 3rd of September, a low amount of calving can be seen. The same can be said about the start of the 29th of August, where wind speeds almost reach 10m/s. The few largest events seem to happen around points of low wind speeds, but the correlation is weak. Judging from the data, the connection between wind speed and calving seem to have low credibility in shorter terms.

6.2.6. Wind direction

Much like atmospheric pressure, no general correlation can be found for the wind direction. Figure 26 and Figure 27 show no sign of lower or higher calving frequency of event size during any of the wind directions under the 11-day period.

6.3. Error sources

Several limitations can be found with both the methods and the results. Observation of tidewater glaciers in harsh environments such as Svalbard is problematic. Weather conditions in the High Arctic changes quickly, thick fog can come as quickly as it leaves, highlighted in Figure 32. Time-lapse camera issues in general as well as from previous studies are observed in 3.5.1, but will be discussed further below. Weather and light conditions are a big issue for time-lapse photography, where detail is needed on objects far from the camera position. Some problems were found during several nights when thick fog obscured the view of the calving front, leaving lower credibility to the size of some calving events. An example of bad visibility can be seen in the middle picture of Figure 32. Some of the issues could in this case be resolved by looking at picture i and i+2 to judge if events are happening in i+1. However, some cases have a longer period of time with fog, spanning over several pictures, thus leaving this method unreliable. With options to change the luminosity and contrast of the
pictures some calving events could more easily be seen, but with lower credibility to the size constraints. The time period was chosen to minimize this problem, having generally good weather for the task, but some weather problems were still encountered.

Figure 32. Late evening on the 31st of August. Fog is moving in quickly, obscuring the view of parts of the calving front, but moves away just as quick.

The methods used to calculate the size of the calving events are another possible source of errors in the data. As mentioned in 4.3.1, the assumption is made that there is no distortion of the pixels in the vertical plane. This means that if the front is not aligned vertically to the camera lens, there will be some errors when calculating the actual size of the events. The error source is believed to be small to non-existent to the data itself, and would make no difference to the discussion around the correlation to external factors but more when comparing to other data.

The moving average is another source of potential errors. The moving average produces a mean based on a window of values over every point, explained in 4.5. One problem with this approach is that many values, such as high peaks, are lost in the process. To compensate for this, graphs where a very small window, or with no moving average filter applied at all, are included to every discussion. The graphs where a 14 minute window is applied, as long as the time-lapse frequency, are regarded as close to unaltered for the calving size distribution. This small filter is used to smooth out the noise from the environmental measurements, which were taken each second, leading to a large amount of values. While one can argue that the moving average show a distorted view of the results, it does help to see the longer trends easier, but more from the perspective of the calving rate and not from single events.

The most complete data over weather conditions were found at the closest in Adventdalen, approximately 43 kilometres from the front of Tunabreen. The actual weather conditions may vary at the different locations, which can be noted as a potential source of errors.
6.4. Control of calving processes and future research

Calving processes are poorly understood by the scientific community and environmental control have been studied several times with varying results. This study presents detailed data showing varying correlation between different external controls. No simple relationship can be found for any of the controls. Tidal variations are generally the most discussed parameter in calving dynamics, some correlation is found in this study but a longer timescale would be needed to confirm the true importance of the tidal variations. While time-lapse photography can be deemed as a good method for observing calving fronts, the method is time consuming and comes with several error sources which cannot be, or are not easily, fixed. One of the most important issues are weather. An attempt to make the process automatic is being researched parallel with this project, using some of the data presented in this study as reference (Adinugroho, unpublished data). This would open up for easier research of longer time periods, a necessity to see long term trends in especially the tide and temperature.

The period chosen for the project was specifically picked to reduce the amount of hours where low visibility weather, such as thick fog and intense sunlight, dominated the days. As the weather on Svalbard can change quickly, no amount of time period was perfect. Problems with weather and visibility are important keep in mind when attempting longer studies, where periods of months are being researched. The data available for this project was spanning over the full months of the melting season, but only one 11-day period was deemed acceptable for detailed research. Longer studies would come with large gaps in the data caused by low visibility, where thick fog or intense sun could cover the front for several days.

Where tidal variations might control certain periods of time, presumably when the tidal amplitude reaches above 1 meter, other external factors might control the times when this is not the case. Air temperature show a potential trend of correlation together with the tidal variation, but nothing can be concluded by this study alone. Further studies of these correlations with the use of data spanning over a longer time period, but keeping the same detail, would be needed to confirm any theories. A greater knowledge of these controlling factors would aid in the struggle of developing a general calving law, helping to enhance mass balance calculations of calving glaciers as well as to predict how these glaciers will respond to the changing climate.
7. Conclusion

Studies of mass balance processes will be increasingly important in the future. Calving, the mechanical loss of ice bergs from water-terminating glaciers, stand for a significant knowledge-gap in glaciology, acknowledged by large science communities such as IPCC and SWIPA. A large part of the mass loss from Antarctic ice tongues and Arctic glaciers are estimated to be a result of calving. The highly sensitive Arctic region is responsible for a majority of the predicted addition of water to the ocean from land based glaciers and ice caps. Further research on calving is needed to establish what controls this phenomenon to give better estimations of the projected sea level rise in the future.

A recent study by Åström et al. (2014) compare calving glacier fronts to Self-Organized Critical (SOC) systems, specifically the Abelian sandpile model. These systems stay close to their critical point, much like a sand pile at its critical slope angle. In theory, changes in external factors, such as tidal variations and temperature, causes the glacier front to experience avalanches, or calving events. None of these events are to be considered exceptional, meaning that a change could cause the whole system to collapse, or have no effect at all. Åström et al. (2014) compare several glaciers to experiments using the Abelian sandpile model, with matching results.

By using time-lapse photography on Tunabreen, a grounded tidewater glacier on Svalbard, calving size distribution is studied for 11 days during the melt season, 2014. The results align well with the results from Åström et al. (2014), helping to confirm the theory of SOC when applied to calving glaciers. The calving size distribution from Tunabreen is compared to external factors such as tidal variations, air temperature, humidity, atmospheric pressure, wind speed and wind direction, with varying results. The tidal variations show an interesting connection to the size distribution when the tide amplitude is larger than 1 meter. Air temperature show sporadic correlation in parts where the tide is lower than 1 meter, but are generally unpredictable. Humidity, atmospheric pressure, wind speed and wind direction show low to no correlation with the data.

Several limitations are presented, most due to weather conditions. When thick fog or intense sun covers the front, calving events are hard to distinguish. Longer time scales are hard to study as low visibility weather conditions would leave gaps in the available data. Time-lapse cameras are a good way to observe calving events, improved by some of the methods presented in the thesis, but time consuming.

Longer time periods would need to be studied to confirm if the tidal variations and air temperature fluctuations are important to the calving dynamics of tidewater glaciers. The results show interesting, potential correlations to external factors. Further research would however be needed to confirm the trends highlighted in this study. The application of SOC to calving glaciers open up new fields of discussion of the research community and provide new opportunities to model calving in a controlled environment. In situ observations, such as the data presented in this study, are also important for future research to see further connections to external factors.
Acknowledgements

I wish to thank my supervisor, Dorothée Vallot, for all the help and dedication she put into this project. Without her, none of this would have been possible. Rickard Pettersson helped me find this project, provided valuable help during the project as well as protected us from polar bears on Svalbard, for this I am very thankful. I also gratefully acknowledge Veijo Pohjola for good comments and tips, and Adrian Luckman for providing satellite data necessary for the project.
8. References

Ahn, Y. & Box, J. 2010, 'Glacier velocities from time-lapse photos: technique development and first results from the Extreme Ice Survey (EIS) in Greenland', *Journal of Glaciology*, vol. 56, no. 198, pp. 723-734.


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Appendix 1

Below follows the more advanced statistical analysing tools used for the discussion, the FFT and PCA.

Figure A1. Fast Fourier Transform (FFT) spectrum.

Fig A2. Principal Component Analysis (PCA) results.