Regional and Local Factors Influencing the Mass Balance of the Scandinavian Glaciers

Regionala och lokala faktorer som påverkar massbalansen för skandinaviska glaciärer

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Abstract

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According to climatic models there will be an increase in the amount of greenhouse gases which results in a warming of the earth where the change will be most prominent in the high latitudes. Glaciers mass balance is a good climate change indicator as the response is fast when climate is changing. Glacier mass balance, area of glaciers, elevation line altitude data for 13 glaciers in Scandinavia as well as North Atlantic oscillation (NAO), Arctic oscillation (AO) and sunspot data where gathered and a principle component analysis (PCA) where made. PCA is a multivariate statistical technique with the goal to extract important information and reduce the dimension of data. Three distinct groupings where found within the data set and was identified as extreme years of North Atlantic Oscillation and Arctic Oscillation and one glacier which had the largest area of the 13 glaciers. The PCA explained that all the variables in the data set is correlated with North Atlantic and Arctic Oscillation to about 40 % and we can conclude that there is a regional and local forcing within our data where the regional (NAO and AO) is of more importance for the variance and for the mass balance.

Keywords: Glacier, north atlantic oscillation, arctic oscillation, mass balance, principle component analysis, PCA

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Enligt klimatmodeller kommer en ökning av växthusgaser i atmosfären leda till en ökning av temperaturen på jorden, den ökningen kommer främst att ske på höga latituder. Glaciärer är bra indikation på förändrat klimat på grund av deras korta responstid när klimatet ändrar sig. För tillfället finns det ca 1900 glaciärer utspridda i de Skandinaviska bergen. Eftersom Skandinavien är så avlångt är det en skillnad i meteorologiska och klimatiska förhållanden, både i en nord-syd riktning men även i en öst-väst riktning med kontinentala glaciärer i öst och mer marina i väst. Klimat och glaciärdatal för 13 olika glaciärer i Skandinavien, 5 från Sverige och 8 ifrån Norge har samlats in och en statistisk analys, principle component analysis (PCA) har gjorts för att se vad som påverkar massbalansen för glaciärerna. De klimat parametrar som har undersöks är Nordatlantiska oscillationen (NAO), Arktiska oscillationen (AO) och solfläckar tillsammans med massbalans, equilibrium line altitude (ELA) och area för glaciärerna. Tre grupperingar har hittats som kan kopplas till olika klimatvariabler och PCA visar extremår för NAO och AO samt en glaciär som har den största arean. PCA analyser visade att alla variabler korrelerade till NAO och AO med omkring 40 % och vi kan dra slutsatsen att det finns en drivande regional och lokal kraft inom vårat dataset där NAO och AO är viktigast för massbalansen.

Nyckelord: Glaciär, klimat, PCA, NAO, AO, ELA, solfläckar, massbalans

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# Table of Contents

1. Introduction .................................................................................................................. 1

2. Background ................................................................................................................... 2
   2.1 Glaciers ....................................................................................................................... 2
      2.1.2 Mass balance ........................................................................................................... 2
      2.1.3 ELA .......................................................................................................................... 2
      2.1.2 Glacier fluctuations ................................................................................................. 3
   2.2 Climate variables ......................................................................................................... 4
      2.2.1 Sunspot cycle .......................................................................................................... 4
      2.2.3 NAO ......................................................................................................................... 5
      2.2.3.1 Impacts of NAO ................................................................................................. 5
      2.2.4 Arctic Oscillation .................................................................................................... 6
      2.2.4.1 Impacts of AO .................................................................................................... 7

3. Site description ............................................................................................................. 7
   3.1 Geology ....................................................................................................................... 8
   3.2 Mass balance measurements and Glaciers ............................................................... 8
      3.3.1 Storglaciären............................................................................................................... 9
      3.3.2 Tarfalaglaciären ....................................................................................................... 9
      3.3.3 Rabots glacier .......................................................................................................... 10
      3.3.4 Mårmaglaciären ...................................................................................................... 10
      3.3.5 Riukojietna ............................................................................................................. 10
      3.3.6 Ålfotbreen ............................................................................................................... 10
      3.3.7 Austdalsbreen ......................................................................................................... 10
      3.3.8 Engabreen .............................................................................................................. 11
      3.3.9 Gråsubreen ............................................................................................................. 11
      3.3.10 Hellstugubreen .................................................................................................... 11
      3.3.11 Rembesdalsskåka ............................................................................................... 11
      3.3.12 Langfjordjökulen ............................................................................................... 11
      3.3.13 Storbreen ............................................................................................................. 11

4. Method ......................................................................................................................... 12
   4.1 PCA ............................................................................................................................ 12
      4.1.1 Goals of PCA ......................................................................................................... 12
      4.1.2 Mathematics ......................................................................................................... 13
# Table of Contents (continued)

4.1.3 Eigenvectors ......................................................................................................................... 13
4.1.4 Matlab................................................................................................................................... 14
5. Results ............................................................................................................................................... 14
7. Discussion ......................................................................................................................................... 18
8. Conclusion................................................................................................................................. 20
9. Acknowledgements ................................................................................................................... 20
10. References ............................................................................................................................... 21
Appendix ............................................................................................................................................... 25
1. Introduction

Glaciers mass balance is a good climate change indicator, as the response of mass balance is fast when climate is changing (Holmlund et al. 1996). According to climatic models there will be an increase in the amount of greenhouse gases which results in a warming of the Earth and the change is most prominent in the high latitudes (IPCC, 2014). The increased temperature will likely affect the glaciers size in Scandinavia in a negative way because of an increase in the ablation of the glaciers. The warming may also increase the moisture available in the atmosphere and it is possible that during the winter the increase in precipitation leads to a higher snow accumulation.

The Scandinavian glaciers have a long history of mass balance records, with many of the glaciers reaching their maximum extent from mid 18th century to late 19th century (Zemp 2011). A rapid retreat of the glaciers started in 1930 which was the end of the cold period the “little-ice age”. Since the end of the “little-ice age” there have been periods where the retreat has stagnant with a mass balance budget nearly in balance but with a large yearly variability (Holmlund et al. 1996). This could be due to local factors both in the landscape and meteorological. It has been shown that climatic variability in the northern Europe is linked to atmospheric circulation (Hurrell 1995) and the precipitation correlated to North Atlantic Oscillation (NAO) (Rogers 1984). Signals of the NAO have been found in dendrochronological records in Scandinavia which shows a link between the air temperature and the NAO (D’Arrigo et al. 1993).

The purpose of this thesis is to understand which local and regional factors influence the mass balance of glaciers in Scandinavia. Local climatic conditions are affected by the topography and the elevation and determine the processes for accumulation (snow, avalanches and wind transport) and ablation (melting, runoff, calving and evaporation) which the sum are the mass balance of a glacier. The regional climate affects the amount of precipitation as well as solar radiation and air temperature which influence the melting of the glaciers (Paterson 1994). Where the local climatic parameters are the equilibrium line altitude (ELA) which is a good climate change indicator because of its fast response time and the area of the glaciers, smaller glaciers are shrinking at faster percentage rates and tend do vary across a whole mountain range (IPCC 2014). The regional Arctic Oscillation Index (AO) which is an important mode of the Northern Hemisphere atmospheric variability during winter and is related to climate variations in Europe (Arhens 2008). With North Atlantic Oscillation (NAO) it has been shown that NAO correlates with winter and net mass balance and gradually decreases with more continental glaciers (Nesje et al, 2000). The sunspot cycle which seems to correlate with historic data with very little sunspot activity during the little ice-age (Helama et al, 2010). This is done with a Principle Component Analysis (PCA) (Rogers 1997) where it’s statistically possible to identify which local and regional parameters that correlate with the recorded mass balance and length variations. A total of 13 glaciers where chosen based on available data and the record length. The glaciers where
distributed across a large part of the Scandinavian mountains with five in Sweden and eight in Norway. Some glaciers are located close to each other and some far away with a difference in climate from inland to maritime.

2. Background

2.1 Glaciers

Glaciers is a thick and compact ice mass on land that moves under its own weight, the formation takes place during several years in areas where more snow accumulate than melts and glacier mass balance is characterized by two main components, accumulation and ablation. The accumulation zone is thus constantly covered in snow from precipitation, avalanches and wind transport to the glacier. The ablation zone extends from the terminus up to the accumulation zone and is where the glacier loses snow and ice through melt, runoff, sublimation, evaporation, calving and wind transport from the glacier. The terminus is the edge where the glacier ends and often a stream emerges. Terminus can be in different shapes depending on the size of the glacier, bed rock slope and mass balance (Dobhal 2010).

2.1.2 Mass balance

Definition of the mass balance of a glacier is the difference between the total accumulation and ablation over a glacial or during a hydrological year. Furthermore the mass balance is divided in to two parts, winter, summer and the sum over the whole year is the annual balance. Summer balance (bs) is the loss of mass by ablation or melt of the glacier that, in Scandinavia occur during summer and the winter balance (bw) is the gain of mass as the snow accumulation during winter. The summer melt and winter precipitation period differs from glacier to glacier, it depends on its location and mean air temperature. The accumulation includes all products that add mass to the glacier, such as snow, hail, rain and refrozen water. Ablation includes ice melt, calving, sublimation and wind erosion. Glacier mass balance is often expressed change in water equivalent averaged over the whole glacier (Haeberli 2011).

2.1.3 ELA

The equilibrium line altitude (ELA) divides the glacier in the accumulation and ablation zone. The ELA is best decided by mass-balance measurements at many points so that it’s possible to draw isolines of zero massbalance and may vary sporadically over the glacier. The ELA is the average altitude of the zero mass balance isolines. The ELA concept is not viable on all glaciers for example glaciers with a small altitude range (Braithwaite et al 2009). ELA is closely linked to local climate, primarily summer air temperature, winter precipitation and wind strength which causes transport of snow during the accumulation and are therefore sensitive to local changes in these variables in both
space and time. A year with high accumulation and with low summer temperature results in a low ELA while a year with low accumulation followed high summer temperatures give a high ELA. Fluctuations in the ELA overtime can therefore be an indicator for climate change but much influenced by local factors. A climatic ELA is the average ELA over a 30 year period i.e. a climatic normal, a 30-year mean (Bakke et al 2011).

2.1.2 Glacier fluctuations
During geological time Scandinavia have been glacerized to different extent, it has been estimated that during the last 2.6 million years the Caledonides where covered by glacial ice for 90% of the time (Holmlund 2005). In present time there is about 1900 glaciers in Scandinavia which most are located in Norway and are located in the mountainous areas. Since the latitudinal range of the Caledonides is large there is a difference in the meteorological and climatic conditions. This can be seen not only in a north to south direction but also east to west with more continental to the east and maritime to the west (Whalley 2004).

During the early parts of Holocene most of Scandinavia was still glaciated but the ice sheet was melting fast, in the early to mid Holocene the mean summer temperature where about 1.5° to 2° C warmer than it is today. Mainly the melting occurred when there was high summer temperature accompanied with low winter precipitation (Bjune et al. 2005). There are few advances of the ice margins in the beginning of Holocene; they are dated 9900, 9600 and 9300 BP with a 200 year error margin. After the deglaciation the climate changed and many glaciers disappeared completely and did not form again until 2000 BP, other glaciers melted and reformed many times even during early Holocene. The first prominent glacier advance in Holocene occurred around 7500 BP, there are also evidence of advance in 5100 to 4500, 3200 to 2800, 2200 to 1900, 1500 to 1100 and 350 to 20 BP dated mainly from radiocarbon and lichenometric dates on moraines and the composition of lacustrine sediments of the lakes near the glaciers (Karlén 1988).

In historical times there are documents, sketches, paintings from as far as the 16th century explaining floods caused by glacier-dammed, arable land and farms being destroyed by advancing glaciers. There is also geomorphologic evidence such as moraines which can be used as historic indicators of glaciers during the last centuries (Grove 2004). Many glaciers reached their maximum extent in the mid-1700s but for the southern glaciers it varied extensively from early 1700s to late 1800s, the differences appears to be the relative importance of summer temperature and winter precipitation working on different timescales (Nesje 2008). The reason was a cold period called “little ice-age” due to many glacier advanced.

Continuous records of arctic air temperature started around 1880, temperatures since 2005 have never been this high with about 1.5 °C warmer than the last climatic period 1961 to 1990. The temperatures even exceed the warming period of 1930s and 1940s. The changes in temperatures are most prominent in autumn and early winter across the Arctic Ocean with 4 °C warmer than the
average for 1950 to 2000 (AMAP 2012). Most of the Norwegian glaciers retreated in the 1900s but with several shorter periods of advances has been recorded. Since then it is mostly outlet glaciers from maritime ice caps in southern Norway with advances ending around 1910 and 1930 followed by a significant retreat of the glacier fronts. Maritime glaciers with a short response time (under 10 years) started to advance in in 1950s while the glaciers with a longer response time continued to retreat to the 1970s and in the early 1990s several maritime glaciers started to advance as a response to the high amount of winter precipitation (Nesje et al. 2007; Andreassen 2016). Since 2000 most glaciers have retreated remarkably fast with 100 m annually or more as a response of high summer temperatures. It is mainly the maritime glaciers that have showed small advances for short times while the continental glaciers have more or less constantly retreated (Nesje et al. 2007). The global average annual glacier mass loss from 1996 to 2005 is twice as large as the previous decade 1986 to 1995 and four times the rate of the decade 1976 to 1985 (UNEP, WGMS 2008). Since 2005 the total glacier area has decreased in all regions of the world with a considerable variability within each region, the largest area losses are recorded in Western Canada and US, Central Europe and in the low latitudes (IPCC 2013).

If the glacier retreat will continue at the current rate extratropical glaciers will shrink to their minimum extent that existed between 8000 to 6000 years ago and ice shelves in Antarctica will retreat to an extent not seen throughout the Holocene. When looking into the future a new glacial period does not seem possible if not the CO2 content in the atmosphere drops below pre-industrial level (300 ppm). Climate-carbon models with lowest scenario shows atmospheric CO2 will exceed 300 ppm until year 3000 (IPCC 2013).

2.2 Climate variables

2.2.1 Sunspot cycle
The sunspots impact on earth climate is not that clear, but the climate data seems to be correlated in some way to it. Between year 1600 to 1700 there were very few sunspots this was when Europe experienced the little ice age. Precise data for sunspots over time are lacking since it’s limited to the satellite era but when looking at this time period the solar variability only provides 0.01% of the total irradiance change from sunspots 11 year activity cycle (Bard et al. 2006).

Sunspots are characterized by the umbra which is a dark core and the penumbra which is a less dark halo, the penumbra is what separates sunspots from the smaller pores (Solanki 2003). The sun's magnetic field resets every sunspot cycle which last for about 11 years therefore the sun has a magnetic cycle of 22 years. In reality, sunspots are caused by huge magnetic field bundles that break through the surface of the Sun and create cool and dark regions on the Sun (Solanki 2003). They appear in groups, often pairs and two spots have different magnetic polarities much like the north and south poles on a horseshoe magnet. The latitudes of sunspots vary, in the beginning of a cycle they form at high latitudes with spots down to 40° on both north and south hemisphere. As the cycle prolongs new sunspots appear at lower latitudes with sunspots lying close to the equator at the end of
the sunspot cycle (Solanki 2003). Sunspots can be present for hours to months, their lifetime increases linearly with their size. In the beginning of a sunspot cycle the spots are smaller and form at high latitudes both to the north and south, as the cycle continues to reach its maximum in number the sunspots grow larger and from around the equator. When the number of spots increase so does the solar activity as the sunspot are the source of the solar flares. (Solanki 2003)

2.2.3 NAO
The North Atlantic Oscillation (NAO) is an atmospheric returning pattern over the northern hemisphere especially during the cold winter months. It affects the wind speed, heat and moisture transport and the intensity and the amount of storms (Hurrell et al 2003). The NAO is based of Sea-level pressure (SLP) between Iceland and the Azores, when the SLP is above normal in Azores it is usually below normal in Iceland (Nesje 2000). A strong positive NAO phase has high temperatures in eastern United States and northern Europe and lower temperatures in Greenland and southern Europe (NOAA Internet). The NAO index is defined by the difference of normalized mean winter pressure anomalies at Ponta Delgadas in the Azores and Akureyri in Iceland. The anomalies are divided by year 1895-1980 standard deviation of mean pressure. (Rogers 1984). During winter season December-February the NAO accounts for more than a third of the variance in SLP over the northern hemisphere (Hurrell 2003).

2.2.3.1 Impacts of NAO
The dominant feature of NAO is its influence over the temperature during the winter months across the northern hemisphere and sea surface temperature as well surface air temperatures across the North Atlantic Ocean, North America, Arctic, Eurasia and the Mediterranean are correlated with NAO variability. These changes along with changes in storms, precipitation, ocean currents and their transport and ocean heat content, sea ice cover have an impact on the climate variability (Hurrell 2003).

2.2.3.1.1 Surface temperature
When NAO index is positive an increased westerly flow during the winter moves warmer and moist air over the European continent this while northerly winds over Greenland carries cold air. The capacity of the oceans to store thermal heat are a lot larger than that of on land therefore changes in surface temperature over the continents are much greater and tend to dominate temperature variability. The global temperature change in recent decades have mostly occurred during winter and spring over the northern continents, since the 1980s winters in northern Europe have been 1-2 °C warmer than average while the northern oceans have been colder than average. This reflects a positive index phase of NAO where lower SLP over the north atlantic and the artic. However the warming can’t all be explained by atmospheric circulation, during the record warmth of early 2000 the NAO was weak. (Hurrell et al 2003)
2.2.3.1.2 Precipitation and storms
With changes of atmospheric patterns associated with NAO come changes with storms, their frequency, intensity and paths. With a positive index of NAO winter storms have an increased northeastward shift with greater activity into northern Europe as well as an increase in occurrence and intensity in Iceland and the Norwegian Sea. Changes in the air flow and storms associated with NAO are reflected in the transport of moisture and the distribution of evaporation, in Scandinavia this leads to more precipitation than normal (Hurrell et al 2003). During the early 1980s and through the late 1990s there were unusual dry conditions over southern Europe and Mediterranean and during the same time wetter than normal over Scandinavia and northern Europe. In the late 1990s some of the lowest snow depth of the century were recorded in the alps (Hurrell et al 1996) while during these years Swedish and Norwegian maritime glaciers have increased their mass especially during the early 1990s (Pohjola 1996; Nesje 2000).

2.2.3.1.3 Ocean circulation and sea ice
Sea surface temperature (SST) is driven by surface wind and air-sea heat exchanges that can be related to NAO. The NAO index can also be seen in subsurface ocean observations which are more of a long term climate variability than SST because of the annual cycle and month to month variability in the atmospheric circulation decreases with depth. When NAO is positive the Labrador Sea ice boundary extends to the south.

2.2.4 Arctic Oscillation
The Arctic oscillation is the most dominant atmospheric variability in the northern hemisphere during winter and is calculated from monthly surface pressure anomalies. Similar to the NAO index it explains variance in winter temperature in both North America and Eurasia (Stockdale et al 2015). Atmospheric pressures changes between the artic and regions to the south are causes changes in the upper level westerly winds. When the AO is in a positive phase the pressure differences produces strong and high westerly winds that prevents cold artic air to move south which results in warmer than usual winters outside the arctic (figure 1). During a negative phase there is a small pressure difference which leads to a weakening for the high westerly winds, cold artic air is able to penetrate further south producing colder than normal winters across Europe, United States and Asia while Greenland and Newfoundland experience warmer winters (Ahrens 2008). The tropospheric temperature anomalies extends all the way down do the tropics even crossing the equator, with a cold pole there is a slight cooling of the tropics (Wallace 2000).

During a high AO index a cold low sits at the north pole surrounded by stronger westerlies at about 55°N and weaker westerlies around 35°N this results in a warm high pressure between 55°N and 35°N, increase in trade winds and high level westerlies over the equator. Low ozone values in the troposphere at high latitudes has been seen during high index phase that can be explained by a weakening of the stratospheric Lagrangian mean circulation (Wallace 2000). The Lagrangian mean
circulation, also known as the Brewer-Dobson circulation is a large cell in the stratosphere where air rises in the tropics and moves poleward and downwards and transports ozone from the tropics to the poles (Butchart et al. 2006)

![Diagram of Brewer-Dobson circulation](image)

**Figure 1.** Positive and negative phase of the arctic oscillation (IPCC 2013).

2.2.4.1 Impacts of AO
During the negative phase the warmer waters of the Atlantic keeps to the south which promotes a thicker sea ice in the Arctic Ocean (Ahrens 2008). Contributing to this is the recirculation in the clockwise Beaufort gyre which supports sea ice thickness by allowing the ice to remain in central arctic and growing from year to year. The circulation also causes more piling up of the ice and rafting because of the Ekman transport (wind induced stress on the surface layer of the ocean causing movement of the water) creating thicker ice floes (Wallace 2000). During the positive phase relative warm salty water from the Atlantic is able to reach the Arctic Ocean where it melts the sea ice, during positive years the thickness can decrease up to 40 cm (Ahrens 2008). Promoting this is a reduction in recirculation and shorter ice residence times as well as a decrease in ice advection from western Arctic to the eastern Arctic and an increase in the ice drift from the pole towards the Fram Strait (Rigor et al 2002).

3. Site description
All the glaciers chosen is located in Scandinavia, the glaciers is Sweden are located close to each other while the Norwegian are more spread out. The glaciers have at least 30 years of mass balance measurements but no data set is complete due to individual years have missing data. A map of the locations can be seen in figure 2.
3.1 Geology

Scandinavian Caledonian mountain range spans in a 2000 km long and 100 to 200 km wide belt from Stavanger in the south to Nordkap in the north. Caledonides was formed between 510 and 400 million years ago when the ocean between the former continents Baltica (Northern Europe) and Laurentia (North America and Greenland) started to close, the subsequent collision caused a thrusting between the continental plates the same way as Himalaya is formed in modern times. (SNA, stephens et al 1994) The highest peak today in the Caledonides is Galdöpiggen which reaches 2468 m a.s.l. and is located in the Norwegian area Jotunheim, Swedens highest peak is Kebnekaise at 2110 m a.s.l. (Whalley 2004).

3.2 Mass balance measurements and Glaciers

The measurements are done in the same way on every glacier with the direct method or the Scandinavian method as it’s also called, the difference is how many probing, stakes, pits and snow coring localities that are used. The number of measurements is different for each glacier, typical there are 50 to 150 probing, one to two pits and 5 to 15 stakes on each glacier each year (Andreassen 2016). The winter mass balance is measured in April or May by probing the last year’s summer surface at about the same profile each year. As the winter balance is expressed in water equivalent, it is important to measure the snow depth and applying a snow density factor at each measuring point. The snow density is quite uniform across the glacier but snow depth can vary over short distances so it is important take many snow depth soundings, this is done with probing sticks (Østrem et al 1991). It is difficult distinguish the summer surface by probing alone therefore stake reading is used to verify the results where possible. Since stakes can disappear in very snow-rich winter snow coring is also used confirm probing results where snow density is measured in pits at different locations and elevations on every glacier. The summer and net balances are measured from stakes usually in September to October (Kjøllmoen 2010). The most important factor for ablation in mountain glaciers is the melt which mainly occurs on the surface (Østrem et al 1991). Below a glaciers ELA the net balance is negative, more ice and snow is melting during summer than accumulates during winter. Above the ELA the net balance is positive. The snow density of remaining snow in the accumulation area has a density of 600 kg/m$^3$, after very cold summers or if there is more snow than normal remaining at the end of summer measurements are done and the density is assumed to be 650 kg/m$^3$. Density of firn, depending on its age is 650 to 800 kg/m$^3$ and the density of melted ice is 900 kg/m$^3$ (Kjøllmoen 2010). The mass balance (winter, summer and net balance) is given both in volume and specific water equivalent. The water equivalent represents the average thickness gained or lost that particular year. The converting from snow depth to water equivalent has varied over the years. From the 1960s to 1990s an average density where used of the snow pack for each snow depth. In the next decade a unique snow density for each snow depth where estimated based on density profiles and from
2001 a snow density function derived from snow density measurements was used to convert the snow depth to water equivalents (Andreassen 2016).

3.3.1 Storglaciären

Storglaciären is a polythermal valley glacier located in the Kebenekaise region in northern Sweden. The annual temperature is ca -6°C and the glacier is surrounded by permafrost and its Equilibrium line altitude (ELA) is 1469 m a.s.l. Storglaciären has been in a steady state since 1910 when its reached its maximum as a response of the little ice age cooling, since then it has retreated with interruptions of periods of high precipitation in the middle of 1970 and late 1980s and 1990s (Holmlund et al. 2005). Storglaciären has a mass balance measurement record since 1946.

3.3.2 Tarfalaglaciären

Tarfalaglaciären occupies a under developed cirque in Tarfalatjakkko, 1 km east of Sydöstra Kaskasatjäkkoglaciären. It has an area of 0.86 km² and its altitude reaches from 1390 m a.s.l. up to
1710 m a.s.l. It has an ice volume of $16 \times 10^6$ m$^3$ and a mean ice depth of 19 m with a maximum depth of 51 m (Grud 1990). Tarfalaglaciären has a mass balance measurement record since 1986.

### 3.3.3 Rabots glacier
Rabots glaciär is located close to Storglaciären in the Kebnejaise Massif in northern Sweden and is a polythermal glacier as well. It has an area of 3.9 km$^2$ with an length of around 4 km. The thickness is relatively even over its length averaging around 85 m with its maximum depth at 175 m in the northeastern cirque basin. The ice velocities in the lower 2 km of the glacier reflects both ice thickness and surface slope with a speed of around 7 m a$^{-1}$. (Brugger 2005) Rabotsglaciär has a mass balance measurement record since 1946.

### 3.3.4 Mårmaglaciären
Mårmaglaciären is located in the Mårma massif about 25 km to the northwest of Storglaciären and is a polythermal valley glacier stretching eastward with an average depth of 140 m with the maximum at 270 m. Mårmaglaciären was first documented by Enquist in 1918 and later documented by Schytt in the 1950s. (Bolin center for climate research) Mårmaglaciären has a mass balance measurement record since 1990.

### 3.3.5 Riukojietna
Riukojietna is located 35 km northwest of Kebnejaise in border between Sweden and Norway and is classified as an ice cap. It has an altitude between 1140 m up to 1456 m a.s.l. with an area of 3.4 km$^2$. When the Scandinavian glaciers where at their maximum in the early 1900s Riukojietna was more than 10 km$^2$ larger than it is today, most of the decrease of the ice cap has taken place on the western side. The eastern part now consists of two tongues (Rosqvist el al. 1989). Riukojietna had a mass balance measurement record since 1986.

### 3.3.6 Ålfotbreen
Ålfotbreen is one of the westernmost located and most maritime glaciers in Norway, mass balance measurements has been carried out since 1963. Ålfotbreen is an ice cap with two outlets the eastern outlet has been given the name Hansebreen and has been studied since 1986 (kjöllmoen 2011).

### 3.3.7 Austdalsbreen
Austdalsbreen is an outlet glacier from the Jostedalsbreen ice cap in central-western Norway (Hooke et al 1989). It has an altitude of 1200 to 1747 m a.s.l. and ends in Austdalsvatnet which is a part of a hydropower reservoir (Elvehøy 2011). Austdalsbreen has a mass balance measurement record since 1988.
3.3.8 Engabreen
Engabreen is an outlet glacier of the svartisen glacier in northern Norway and reaches from just above sea level at 89 m a.s.l. up to 1574 m a.s.l. It has an area of 40 km² (Elvehøy 2011) of which 86% lies on a plateau at 1100 m a.s.l. From the plateau the ice flows in a narrow valley where the ice ruptures and makes the glacier tongue very crevassed. The Engabreen front has been monitored since the 1970s but measurements exist back in to the early 1900s. During 1990s the terminus advanced about 200 m but in early 2000s it has started retreating again (Schuler 2005). Engabreen has a mass balance measurement record since 1970.

3.3.9 Gråsubreen
Gråsubreen is a polythermal glacier in the eastern part of Jotunheimen massif located in southern Norway. It has an altitude of 1833 to 2283 m a.s.l. and covers an area of 2.1 km², mass balance measurements have been carried out continuously since 1962 (Andreassen 2011a). Gråsubreen has a mass balance measurement record since 1962.

3.3.10 Hellstugubreen
Hellstugubreen is a north facing valley glacier located in the central part of Jotunheim and reaches from 1482 to 2229 m a.s.l. with an area of 2.9 km². Measurements began in in 1962 (Andreassen 2011b). Hellstugubreen has a mass balance measurement record since 1962.

3.3.11 Rembesdalsskåka
Rembesdalsskåka is the south-western outlet glacier from the larger Hardangerjökulen which is the sixth largest in Norway. Rembesdalsskåka has an altitude range of 1066 to 1854 m a.s.l. with an area of 17 km², it drains in the Simdalen valley who in history has had outburst floods from the glacier dammed lake Demmevatnet. Mass balance measurements started in 1963 by the Norwegian Polar Institute but length measurements started as early as 1917 (Elvehøj 2011).

3.3.12 Langfjordjökulen
Langfjordjökulen is a plateau glacier located between the Finnmark and Troms county in Norway, its altitude reaches from 302 to 1050 m a.s.l. with a total area of about 7.7 km² and drains eastward. Measurements have been ongoing since 1989 but only on the eastward outlet which has an area of 3.2 km² (Kjøllmoen 2011).

3.3.13 Storbreen
Storbreen is located in the central-southern Norway in the Jutonheim massif, the glacier is surrounded by peaks and has well defined borders. Storbreen reaches from 1400 to 2102 m a.s.l. and has an area of 5.1 km², measurements have been ongoing since 1947 (Andreassen 2011c) Storbreen has a mass balance measurement record since 1949.
4. Method

Mass balance, ELA and area extent changes for the 13 glaciers are used; five from Sweden and eight from Norway (table 1) the mass balance, ELA and area change data was gathered from world glacier monitoring service (wgms.ch). There are few longer (> 30 years) glacial mass balance series so the glacier chosen are based on the amount of data available. Six of the glaciers have continuously mass balance records from early 1970s and a few from 1980s most of the glaciers have some years with missing data. A large data set where made with six different parameters: mass balance, ELA, area, NAO, AO and sunspots. Mass balance is usually divided in to winter mass balance (bw), summer mass balance (bs) and net mass balance (bn). The sunspot data used was from WDC-SILSO, Royal Observation of Belgium, Brussels (http://www.sidc.be/silso/datafiles). The North Atlantic Oscillation index data came from Climate Analysis Section, NCAR Boulder USA, (Hurrell 1995; https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based) and is a station based data. The Arctic Oscillation data is from NAOO National Weather Service Center for Environmental Prediction (http://www.cpc.ncep.noaa.gov/products/precip–/CWlink/daily_ao_index/ao.shtml).

4.1 PCA

Principal component analysis (PCA) is a very popular multivariate statistical technique and probably one of the oldest multivariate techniques (Abdi 2010). PCA have many different areas of use; face recognition, clustering, dimension reduction etc (Jeong et al 2009). PCA analyzes large data sets with different dependent variables with the goal to extract important information and reduce the dimensions i.e. only keeping the variables that explains most of the data set to express this information in a new set of variables called principal components (PCs). These PCs are uncorrelated and ordered so the first PCs keep most of the variation of the original data variables (Jolliffe 2002). PCA covers mathematical concepts such as eigenvectors, eigenvalues, deviation and covariance (Smith 2002).

4.1.1 Goals of PCA

The aim in applying PCA is to extract the most important information from a data set, compress the size of data set by keeping only important information, overall simplify the description of data and analyze the structure of the observations (Abdi et al 2010).

The first principal component is required to have the largest possible variance (that explains the largest part of the data.) The second component is computed under the constraint of being orthogonal to the first. The values of these variables are called factor scores, these scores can be interpreted geometrically as projections (Abdi et al 2010).
4.1.2 Mathematics

PCA projects the data to a new coordinate system using eigenvectors and eigenvalues of a matrix. It calculates a covariance matrix of a data set to maximize the variance and minimize the redundancy. The covariance matrix explains the relationship between each of the variables individually and is used to measure how much the dimension differs from the mean. For a detailed description of the mathematics of PCA I recommend reading Jolliffe (2002).

For a PCA to work the mean value has to be subtracted from each of the data variables. The mean subtracted is the mean across each of the dimensions, this leads to all x values have the mean of x subtracted and all the y values have the y mean subtracted from them and so on, this is to create a data set with the mean of zero. After that the covariance matrix is calculated which is where from the eigenvalues and eigenvector are calculated (Smith 2002).

4.1.3 Eigenvectors

Eigenvectors is a special case of combining multiplying matrices with the same size and can only be found on square matrices (a matrix where the number of rows and columns are the same) but not all of them can have eigenvectors. All eigenvectors is also orthogonal which means you can express the data in these eigenvectors instead of in terms of x and y axes. Another important thing is that the eigenvectors should have the length of one, this is because the length does not affect if it is an eigenvector or not it is the direction (Smith 2002). In simple terms eigenvectors represent an orientation and keeps the orientation after being multiplied with squared matrices and the corresponding eigenvalue represent the magnitude.

Eigenvectors provides information about patterns in the data set, the eigenvector with the highest eigenvalue is the first principle component of the data set. From here it can be decided how many of the components that will be taken in to consideration, the eigenvalues are ordered from the highest to lowest and the components with low values can be ignored with some information loss. The final plot is basically the original data but rotated so the eigenvectors are the axes this can be seen in figure 2, component 1 will become the new x-axis, component 2 the new y-axis and component 3 the new z-axis.
4.1.4 Matlab

The matlab script is built in such way that the principal components coefficients or loading (the underlying shared variance between each variable and the component) has the size of $n \times n$ where $n$ is number of the variables in the input. The loading describes what a principal component represents and therefore it’s possible to explain what the scores represents.

Score returns the values for the observations in the principal component domain which is how each individual observation is related to principal components, a scatter plot can be made to see certain groupings in the data. Samples that are close to each other are similar based on what the components represent which is decided by the loading (Bro 2014). From the loading we can create loading tables; these tables are not correlation matrices, parameters with comparable loading can be related to each other when they depend on similar variables.

5. Results

Each red point in the plot is one observation so points along the first principle component axis (PC1) indicate that the observation has a relatively strong correlation with that principle component. A value along the negative side of the first principle component axis indicates that they have a negative dependence on the first principle component. The same goes for the other principle components, points in the far upper left corner (when PC1 is x-axis and PC2 y-axis) is going to have high values of the variables included in both PC1 and PC2.
Running PCA for annual mass balance for both the Swedish and Norwegian glaciers the first three PCs explains a total 78% of variance in the dataset with the first PC almost at 40%. NAO and AO relate with about 0.5 with PC1 and dominate this PC in PC2 area and ELA are the dominating variable and relate around 0.5. Sunspots relate with 0.9 in PC3 and are the only dominant variable for PC3. From the PCA plots in the appendix (figure 6) and the loading table (table 1) we can see that area is correlated (positive) and ELA anticorrelated (negative) in PC2.

Table 1. Loading tables for all the PCs from Swedish and Norwegian glaciers during summer, winter and net balance measurements.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
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<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
<td>PC1 PC2 PC3 PC4 PC5 PC6</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>0.45 -0.41 -0.36 -0.03 0.70 -0.08</td>
<td>0.09 0.66 -0.40 0.00 0.63 0.02</td>
<td>0.51 -0.31 -0.04 -0.44 -0.13 0.66</td>
<td>0.48 0.37 -0.01 -0.36 0.71 0.02</td>
<td>0.42 0.35 -0.02 -0.64 0.54 0.04</td>
<td>0.42 0.35 -0.02 -0.64 0.54 0.04</td>
<td>0.42 0.35 -0.02 -0.64 0.54 0.04</td>
<td></td>
</tr>
<tr>
<td>ELA</td>
<td>-0.33 -0.09 0.77 -0.01 -0.54 -0.06</td>
<td>-0.31 -0.57 0.11 0.23 0.72 0.00</td>
<td>-0.30 -0.41 0.14 -0.01 0.14</td>
<td>-0.30 -0.41 0.14 -0.01 0.14</td>
<td>-0.30 -0.41 0.14 -0.01 0.14</td>
<td>-0.30 -0.41 0.14 -0.01 0.14</td>
<td>-0.30 -0.41 0.14 -0.01 0.14</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>-0.12 0.83 -0.27 0.16 0.44 -0.02</td>
<td>-0.03 0.43 0.83 0.34 0.08 0.03</td>
<td>0.51 -0.13 0.20 -0.28 0.20 -0.68</td>
<td>0.51 -0.13 0.20 -0.28 0.20 -0.68</td>
<td>0.51 -0.13 0.20 -0.28 0.20 -0.68</td>
<td>0.51 -0.13 0.20 -0.28 0.20 -0.68</td>
<td>0.51 -0.13 0.20 -0.28 0.20 -0.68</td>
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</tr>
<tr>
<td>NAO</td>
<td>0.51 0.28 0.27 -0.35 -0.12 -0.68</td>
<td>0.59 -0.13 0.20 -0.28 0.20 -0.68</td>
<td>0.46 -0.45 -0.24 0.12 -0.04 0.72</td>
<td>0.46 -0.45 -0.24 0.12 -0.04 0.72</td>
<td>0.46 -0.45 -0.24 0.12 -0.04 0.72</td>
<td>0.46 -0.45 -0.24 0.12 -0.04 0.72</td>
<td>0.46 -0.45 -0.24 0.12 -0.04 0.72</td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>0.53 0.22 0.30 -0.23 0.02 0.73</td>
<td>0.61 -0.17 0.14 -0.17 0.16 0.72</td>
<td>0.52 0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td>0.52 0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td>0.52 0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td>0.52 0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td>0.52 0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td></td>
</tr>
<tr>
<td>Sunspot</td>
<td>0.37 0.00 0.22 0.89 -0.09 -0.08</td>
<td>0.42 -0.09 -0.27 0.85 -0.13 -0.09</td>
<td>0.30 0.45 -0.02 0.43 0.02 0.72</td>
<td>0.30 0.45 -0.02 0.43 0.02 0.72</td>
<td>0.30 0.45 -0.02 0.43 0.02 0.72</td>
<td>0.30 0.45 -0.02 0.43 0.02 0.72</td>
<td>0.30 0.45 -0.02 0.43 0.02 0.72</td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>43.80 63.50 81.50 93.70 97.80 100.00</td>
<td>37.50 61.00 76.70 88.80 97.80 100.00</td>
<td>10.21 10.30 11.20 11.30 11.40 11.50</td>
<td>10.21 10.30 11.20 11.30 11.40 11.50</td>
<td>10.21 10.30 11.20 11.30 11.40 11.50</td>
<td>10.21 10.30 11.20 11.30 11.40 11.50</td>
<td>10.21 10.30 11.20 11.30 11.40 11.50</td>
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</tbody>
</table>

If we look at the PCA for the winter mass balance for the Swedish and Norwegian glaciers together, the first three PCs explains 82% of the variance in the data again NAO, AO and ELA is dominant at ~0.45 although ELA is in the negative. The PC1 explain 40% of the variance in the data (figure 7). For
PC2 NAO, AO and ELA are negative while area is positive at ~0.45 each (table 1), sunspots are again the dominating variable for PC3 with a score of 0.9 which explain 13.3 % of the data. Again area is correlated and ELA is anticorrelated.

The summer mass balance PCA differs a little from the annual and winter. In PC2 the ELA is negative and area is positive, reverted compared to winter. However in PC3 there is a difference where area is the dominant variable instead of sunspots as can be seen in figure 8 and table 1. NAO and AO is still the dominant variable with ~0.6 each in PC1.

Running a PCA on annual mass balance for Swedish and Norwegian glaciers individually for the Swedish NAO and AO are the dominant variables in PC1 with 0.5 each while ELA alone dominates PC2 with 0.6 and area dominates PC3 with 0.9.

The Norwegian glaciers are more similar to the whole data set with NAO and AO variables dominating PC1 with 0.5 each, area and ELA dominating PC2 with 0.5 and sunspots dominating PC3 with 0.9.

If we look at the individual points in figure 4 we can see that there is difference in the trending of the Swedish and Norwegian glaciers. The Swedish are going from top right to bottom left in the graph while the Norwegian are trending bottom left to top right. There is also a distinct grouping to the far left and right containing both Swedish and Norwegian glaciers, in figure 5 the groupings are identified by different years.
Figure 4. Each symbol represents a glacier, the red symbols are Norwegian and the blue are Swedish.
Figure 5. PCA where the red dots are measurements for year 2010 and blue dots for year 1989 and 1990.

7. Discussion
Interpretation of the loading tables is based on finding the variables which are most strongly correlated with each component. It doesn’t matter if it is positive or negative, it is the magnitude farthest away from zero that matters. The loading tables are not like correlated matrices, NAO and AO are similar because they depend on similar climate variables. It has been shown that NAO and AO are reflected in the mass balance of Scandinavian glaciers (Pohjola 1997; Nesje 2000) and is more prominent for the winter mass balance for maritime glaciers, the opposite is for the more continental glaciers. If we compare the Swedish winter mass balance PCA against the Norwegian the main difference is in PC2 where area is the only dominant variable for the Swedish glaciers while AO, NAO, ELA and area (negative) is dominant for the Norwegian. The difference between NAO and AO for the Norwegian and Swedish population could be because the time interval is different, the Norwegian have five glaciers with data starting in the early 1970s while the Swedish have one glacier. The NAO index was
quite strong in the beginning of the 1970s but not as strong as in the early 1990s this could have influenced the Norwegian glaciers to be more correlated to NAO. Another explanation for the larger impact of NAO and AO could be because the Norwegian maritime glaciers have a larger mass turn over from year to year with the increase in precipitation during the winter months than the Swedish continental glaciers, we can also see that winter mass balance are better correlated with PC1 than the summer mass balance. There is also a difference in how the glaciers are located geographically, the Swedish glaciers are closer to each other and may not have the same climate variability as the more spread out Norwegian glaciers.

In the Norwegian winter balance we can see that ELA I correlated and area anticorrelated. The negative area tells us that glaciers that correlates with PC2 has an big area it also correlates negatively with variables that are important for PC2 (ELA), glaciers with a big area will often have low ELA and glaciers with a high ELA will often have an small area. There is also a difference in response time between the glaciers, if the glaciers have the same climatic condition large valley glaciers respond faster than smaller glaciers to a perturbation in mass balance. For shallow slope ice caps and ice sheets, bigger glaciers have a slower response time than smaller to perturbations in mass balance (Bahr et al. 1998).

In PC3 sunspots are dominant for the Norwegian glaciers and for the annual balance for all the glaciers together. Loon et al. (2012) where able to find trends in sunspots combined with NAO, although the data was limited it is unwise to underestimate the influence of the sun on circulation changes and temperature trends. This can also be a case with different timescales for the different glaciers since the PC3 sunspot dominance is only visible with Norwegian glaciers.

When looking at the individual points for the PCA one of the groupings that was identified was to the far left, it is expected that it has low values for either NAO or AO since the grouping is located in the negative part of PC1. Year 2010 has the lowest NAO values in the whole dataset with -5.96 the second lowest is year 1985 with -3.09. The winter of 2010 was extremely cold across the northern hemisphere, Norway had its fourth coldest December on record. In central England it was the second coldest December since 1659, in Germany and France the mean temperature was between 3°C to 5°C below normal and it was the coldest December for over 40 years. The NAO index for December 2010 was the second lowest since 1825 (Maidens et al. 2013). The grouping the far right is expected to have positive values in variables that is important for PC1 (NAO and AO). Year 1990 has the highest NAO (3,88) and AO (1,02) value in the dataset while year 1989 has the second highest AO (0,95) value. A period with high precipitation (strongly positive NAO) during the year 1988/1989 yielded both a high winter balance and a positive net balance on glaciers in western Norway, this resulted in the largest glacier advancement during the 20th century and possible since the 18th century (Nesje 2005). The third grouping at the top will have positive values for PC2 and the dominant variable is area. The Engabreen is the biggest glacier in the dataset with an area of around 40 km² where the second largest is Rembesdalsskåka with an area of 17 km².
For further research it would be interesting to see longer and mass balance records on more glaciers with in the same time span as the mass balance measurements continue to grow. There are also many more climatic variabilities to investigate, cloud cover, aerosols, albedo, the direction of the glacier to name a few.

8. Conclusion
The PCA explains that all the variables in the data set is correlated with NAO and AO to ~40 % therefore we can say that there is a regional and local forcing with our data set, where the regional (NAO and AO) is of more importance for the variance of the data and for the mass balance.

It was possible to identify groups with extreme values such as the year 1989/1990 and 2010 and Engabreen with its large area and low ELA.

Principal component analysis is very useful to reduce the number of observations while keeping the most of the variance in the data set. Although the PCA technique is old there is a lot of recent research and it can be used in a wide variety of different fields.

9. Acknowledgements
I would like to thank and express my gratitude to my supervisor and examiner Veijo Pohjola for useful comments and remarks. I also want to thank my reviewer Rickard Petterson who introduced me to this topic and for supporting me on the way especially with the MATlab part. Lastly I want to thank my friends and family for love and support who helped me keep my head high during the entire process.
10. References


Internet resources


Appendix

Figure 6. PCA for both Swedish and Norwegian annual mass balance.
Figure 7. PCA for both Swedish and Norwegian winter mass balance.
Figure 8. PCA for both Swedish and Norwegian summer mass balance.
Figure 9. PCA for Swedish glaciers annual mass balance.
Figure 10. PCA for Swedish glaciers winter mass balance.
Figure 11. PCA for Swedish glaciers summer mass balance.
Figure 12. PCA for Norwegian glaciers annual mass balance.
Figure 13. PCA for Norwegian glaciers winter mass balance.
Figure 14. PCA for Norwegian glacier summer mass balance.