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Impacts of Northern Hemisphere teleconnections on the hydropower production in southern Sweden

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Master degree thesis in Physical Geography and Ecosystem Analysis, 30 credits

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Cover photos:

Granö hydropower station in Mörrumsån, photo by Felix Hubertsson

Skogsforsen hydropower station in Ätran, photo made by Fredrik Anker

Skåpanäs hydropower station in Ätran, photo by Sture Petersson

Rydal hydropower station in Viskan, photo made by Vattenfall AB

Preface

For me the Master thesis marks the end of five years of university studies. The road to this point has not always been straight but I am happy for the twists and turns that have brought me here and the experiences they have given me. Ever since first grade geography has been my favorite subject in school and I cannot be thankful enough to the friend that some years ago opened my eyes and said strait out to me that “you should study this professionally”.

Back then my future job plans were something blurry, undefined, because what does a physical geographer really do? Through the studies the picture of opportunities has cleared and after listening to a very inspiring speech about wind power the goal was set: I want to work with renewable energy! The idea of renewable energy is to extract electricity from the Earth’s resources in a sustainable way, which requires knowledge about the Earth and its systems, which in turn is exactly what physical geography is all about!

My Bachelor thesis analyzed the landscapes’ effect on the wind from a wind power perspective and I end my Master years by writing this thesis about the relation between teleconnections and hydropower production. I am happy and thankful that there always have been people to capture my ideas, help me to develop them and make them true. I hope that I get the opportunity to work with this kind of people in the future too and that I get the chance to keep on doing research and work to improve and develop the field of renewable energy.

Acknowledgements

First of all I want to thank Prof. Cintia B. Uvo at the Department of Water Resource Engineering, who was the one to first introduce me to the concept of teleconnections almost two years ago. Through the work with this thesis she has shared her knowledge and passion of climatology and teleconnections, encouraged me and supported me through the process of analysis and writing, I could not have found a better supervisor! I also want to thank the people at the Department of Earth and Ecosystem Sciences who have helped me with everything from discussing the use of statistical methods to entering the computer lab. I send my thanks to Kean Foster for providing me with data from SMHI and Fredrik Hellström at E.ON Vattenkraft Sverige AB and Roger Sandgren at Vattenfall Vattenkraft AB that have provided production data from their hydropower stations in southern Sweden. Last, but not least I also have to send a thank you to family and friends that have been supportive and especially Uriah Gravois who has managed to put up with my endless talk about the thesis and Helena E. Andersson who let me have her computer when my own crashed one week before due date of this paper.

Abstract

45 % of the Swedish energy is produced by hydropower. Previous researches have shown a positive correlation between the North Atlantic Oscillation (NAO) and the hydropower production in Norway and northern Sweden during winter time. The correlation is weak in southern Sweden, which indicates that there might be other climate patterns affecting this area. A Spearman correlation was made between the times series of a Principal Component Analysis (PCA) of the production data from 17 hydropower stations in five different rivers located in southern Sweden and five different teleconnection indices: the NAO, The East Atlantic (EA), The East Atlantic/Western Russia (EA/WR), The Scandinavian (SCA) and the Polar/Eurasia (POL). The result showed seasonal variations in the effect of different teleconnections. In winter time the NAO causes the strongest signal, while the SCA shows an almost as strong negative signal. During spring and summer the EA/WR alone gives a significant negative signal. No significant correlation appeared during the fall.

Based on the assumption that the hydropower production depends on water availability in the dams and the demand from the market, which in turn is closely related to the season of the year and the air temperature, PCA analysis and Spearman correlations with the teleconnection indices were also made for seven unregulated river gages and six temperature stations in the same geographical region. The discharge show more variance than the hydropower production in all seasons and slightly different correlations, while the temperature show very little variability and mainly is ruled by the NAO in all seasons except for in the summer when the SCA and POL show strong positive correlations.

Key words: Geography, Physical Geography, Hydropower, Teleconnection, southern Sweden

Populärvetenskaplig sammanfattning

45 % av Sveriges energi produceras av vattenkraft. Forskning har visat att det finns en positiv korrelation mellan Nord Atlantiska Oscillationen (NAO) och vattenkraftproduktionen i Norge och norra Sverige under vintertid. Korrelationen är svag i södra Sverige, vilket visar på att skulle kunna finnas andra storskaliga klimatvariationer som påverkar detta området. En Spearman korrelation gjordes mellan tidsserierna från en Principal Component Analysis (PCA) av produktionsdata från 17 vattenkraftverk i fem olika floder i södra Sverige och fem olika klimat index (teleconnections): NAO, East Atlantic (EA), East Atlantic/Western Russia (EA/WR), Scandinavian (SCA) och Polar/Eurasia. Under vintern har NAO störst påverkan på vattenkraftproduktionen, medan SCA visar en nästan lika stark negativ korrelation. Under vår och sommar dominerar EA/WR produktionen med en signifikant negativ korrelation. Ingen tydlig signal hittades under höstmånaderna.

Baserat på antagandet att vattenkraftproduktionen dels beror på vattennivån i dammarna, dels på marknadens efterfrågan på elektricitet, vilket i sin tur beror mycket på säsong och lufttemperatur, gjordes även PCA och Spearmananalyser för sju oreglerade vattendrag och sex temperaturstationer i samma region. Vattenflödet visade en större variation än elproduktionen under hela året och något annorlunda korrelationer, medan temperaturerna visade liten variation och i huvudsak styrs av NAO, förutom under sommarmånaderna då SCA och POL visar starka positiva korrelationer.

Nyckelord: Geografi, Naturgeografi, Vattenkraft, klimatvariationer, södra Sverige

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1 Introduction

The Swedish energy system relies heavily on nuclear power and hydropower that together produce 86 % of the Swedish energy (2009). In 2009 96% of the Swedish energy production was carbon dioxide free and the amount of renewable energy sources are steadily growing. Svensk Energi (interest organization for the Swedish energy producing companies) predicts the Swedish wind power to deliver approximately 12 TWh in 2012 and there are several projects investigating and evaluating the potentials for wave and sun power (Svensk Energi, 2010) The European Union given a directive in 2009 that in 2020 49% of all energy used in Sweden should come from renewable sources. The Swedish government has altered the goal to 50%, and also included transportation (Swedish Ministry of Industry, 2011).

The amount of energy produced by hydropower is governed by two main factors: the demand of the market and the available water. In Sweden the demand mainly depends on the temperature, since the cold winter months requires extensive heating, but also on the pricing of the electricity. Figure 1 shows the distribution of electricity use in Sweden in 2009. As can be seen the households hold more than 50 % of the total electricity consumption, a percentage that is considerably higher than in countries having a warmer climate. The second largest electricity users are the industries consuming about 35% of the electricity, while distribution losses, refineries, district heating and transports together count for less than 15 %.

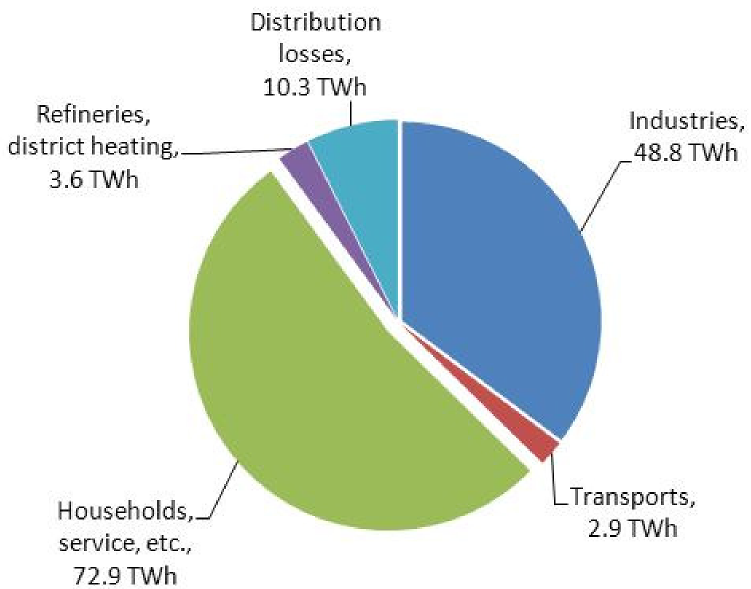

Figure 1. Distribution of the use of electricity in Sweden 2009 (Energimyndigheten, 2010).

The seasonal variations in electricity use can be seen in Figure 2 showing the weekly consumption in the Nordic countries (Iceland, Norway, Finland, Sweden and Denmark) 2000-2011. As can be seen in the diagram there is an increased demand during the winter months when the temperatures are low. What is also interesting to note is the ”dip” between Christmas and January 1st when many factories close down due to holidays.

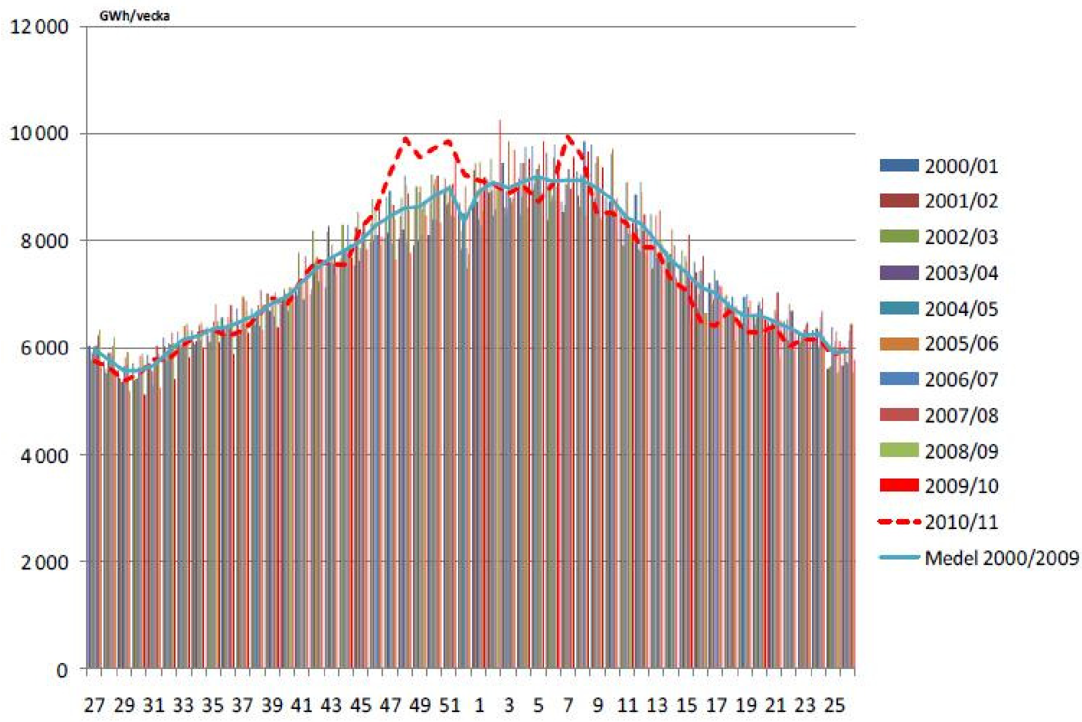

Figure 2. Weekly electricity use (GWh) in the Nordic countries 2000-2011 (Svensk Energi, 2011b).

The fact that 45 % of the swedish energy system is dependent of hydropower makes the country vunerable to climate variations affecting the water avilability and it is therefore important to find links between the natural climate variations and the precipitation patterns (Uvo and Berndtsson, 2002). The same authors, as well as Cherry et al (2005) have found a clear positive correlation between the positive phase of the North Atlantic Oscillation and the available water for hydropower in Norway and northern Sweden. This correlation is, however, weak in southern Sweden, which is also confirmed by Busuioc et al (2001) who have studied the precipitation patterns in Sweden. Still the hydropower production in southern Sweden presents a yearly variability related to climate, which means that possibly other large-scale climate phenomena might affect precipitation and temperature in southern Sweden, and rule its hydropower production.

The precipitation and temperature is governed by natural climate variations. The natural variability in turn is strongly influenced by large scale air pressure anomalies called teleconnections, which affects the atmospheric circulation all around the globe. The aim of this thesis is to analyze Northern Hemisphere teleconnections and how they affect the hydropower production in southern Sweden.

2 Background

2.1 History of hydropower in Sweden

Water mills were introduced in the Nordic countries already in the early 1000's but had been used by the Romans far before that. Back then their energy was primarily used to mill grains, but the technology was soon further developed and the hydropower also became used to drive saws and weaving machines (Areskoug and Eliasson, 2007). The same authors also write that the reason that Sweden was the World-leading exporter of copper and iron in the 1700's was not only due to the findings of the metals, but also the fact that the same geographical region had plenty of forest and waterfalls to provide energy for the extraction of the metals. At this point the waters' energy was extracted by water wheels, but as the electromagnetism was discovered in the 1820s the kinetic energy of the water could be transformed into electricity via a generator (Areskoug and Eliasson, 2007) and only some years later the first hydro-turbine was designed in France by Benoît Fourneyron and was then called a hydraulic motor (Paish, 2002). The first Swedish hydro turbines were constructed in the 1850s (Spade, 1999).

However, transporting energy leads to losses due to the resistance of the cable network (grid), which turns a part of the electric energy into heat energy. Back in the 1800s the losses of transporting electricity from the big waterfalls to the main industries were too big to be economically feasible and instead movable steam engines, driven by fossil fuels, became more popular. In the 1890s a totally new system of energy distribution was built, leading to smaller losses and finally big hydropower stations could be built. However, even the new grid had distribution losses, which lead to the exploration of rivers further south in Sweden, even if these are relatively small (less discharge and lower waterfalls) compared with the capacity of those further north (Areskoug and Eliasson, 2007). Still today the transport of electricity is a problem; the Swedish grids lose about 10 TWh/year, which corresponds to about 7.5 % of the total energy production (Energimyndigheten, 2010).

Today there are roughly 1800 active hydropower plants in Sweden. Together they produce approximately 65 TWh electricity during a normal year, which corresponds to about 45% of the country's total energy production. 80% of the Swedish hydro energy is produced in Norrland, in the northern part of Sweden (Svensk Energi, 2011a), where also the country's biggest hydropower station, Harsprånget is found, with an installed capacity of 977 MW (Vattenfall, 2010). The remaining 20% of the Swedish hydropower are produced in the southern parts of Sweden, called Svealand and Götaland (Svensk Energi, 2011a) (Figure 3). The impact of climate on the hydropower production of southern Sweden is complex and largely unknown. That's the reason the electricity production from the hydropower plants in Götaland will be the focus of the analysis of this work.

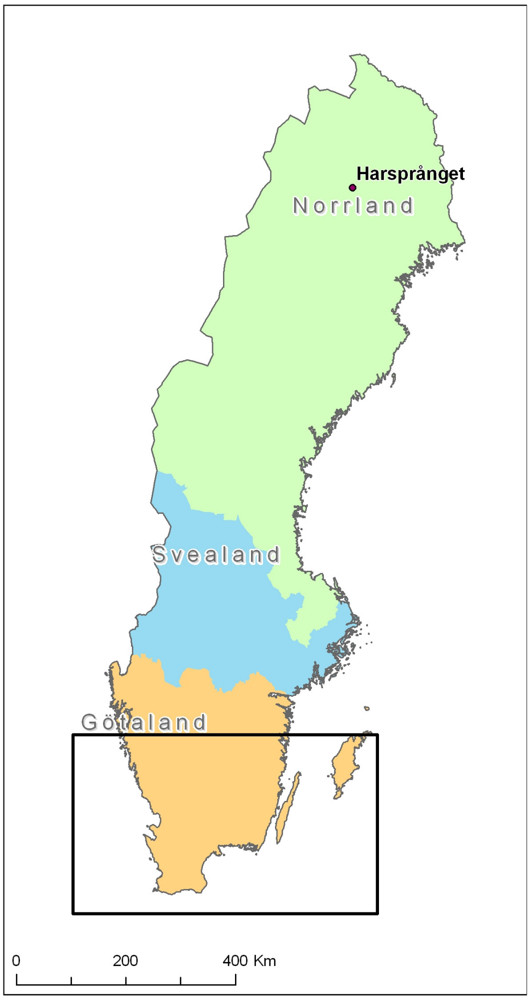

Figure 3. Maps of Sweden showing the three geographical regions Götaland, Svealand and Norrland as well as the location of the hydropower station Harsprånget. The area analyzed in this paper is marked with a square.

A big advantage of hydropower compared with other renewable energy sources is that the energy output can be regulated by dams (Vattenfall, 2011). This means that water can be stored during times of low energy consumption, to be used when the need of electricity is higher. Still, the amounts of energy produced by hydropower vary significantly from year to year (Figure 4) due to varying amounts of precipitation.

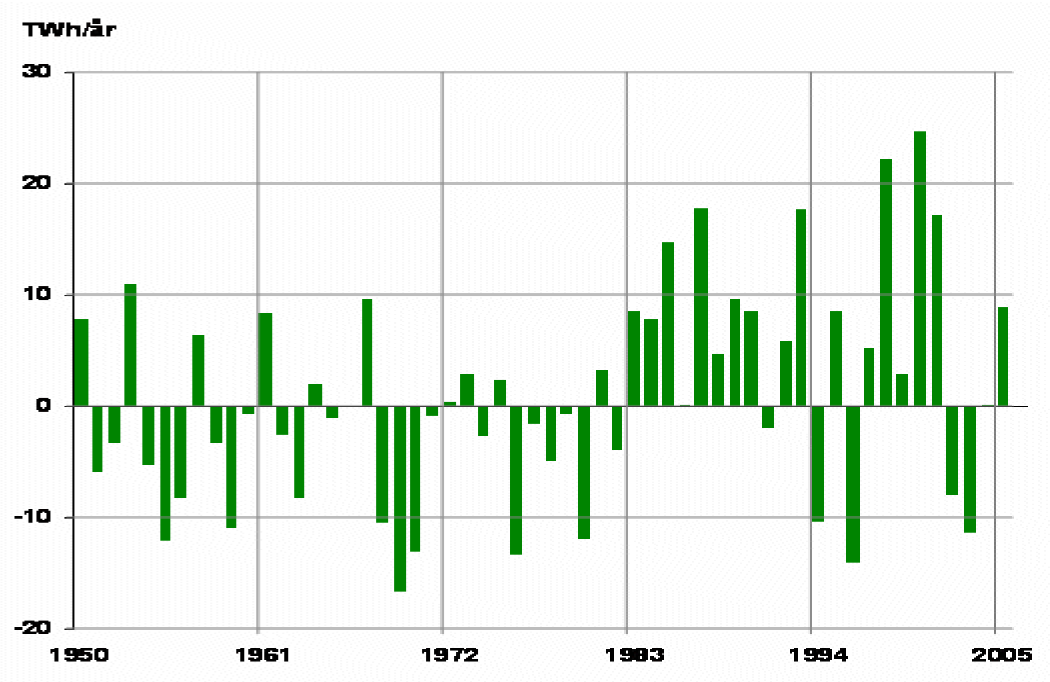

Figure 4. Yearly normalized hydropower production in Sweden 1950-2005. Diagram from Svensk Energi (2007).

2.2 How does hydropower work?

Hydro-turbines convert the energy from falling water into rotating shaft power. There are several different types of modern turbines and their efficiency is high, about 80-90 % of the water's energy can be transformed into electricity. Generally turbines are divided into three major groups; high, medium and low, depending on the height of the pressure head (the height of the waterfall). To minimize the speed change between the turbine and the generator electricity generation, a shaft speed around 1500 rpm is required. Since the speed of a turbine declines in proportion to the square root of the pressure head low-head sites need turbines that are relatively faster (Paish, 2002).

The electric energy produced *P* by the turbine is proportional to the product of volume flow rate and pressure head as expressed in Equation 1.

$$P=\eta \rho g Q H \quad (1)$$

Where *P* is the power output in Watts, η is the hydraulic efficiency of the turbine (%), ρ is the density of water (kg/m^3), *g* gravitational acceleration (m/s^2), *Q* runoff (m^3/s) and *H* the height of falling water (m) (Paish, 2002).

2.3 Precipitation patterns in southern Sweden

Precipitation is one of the meteorological variables that has been measured for the longest time in Sweden. Figure 5 shows the variation of annual mean precipitation over Sweden 1860-2010.

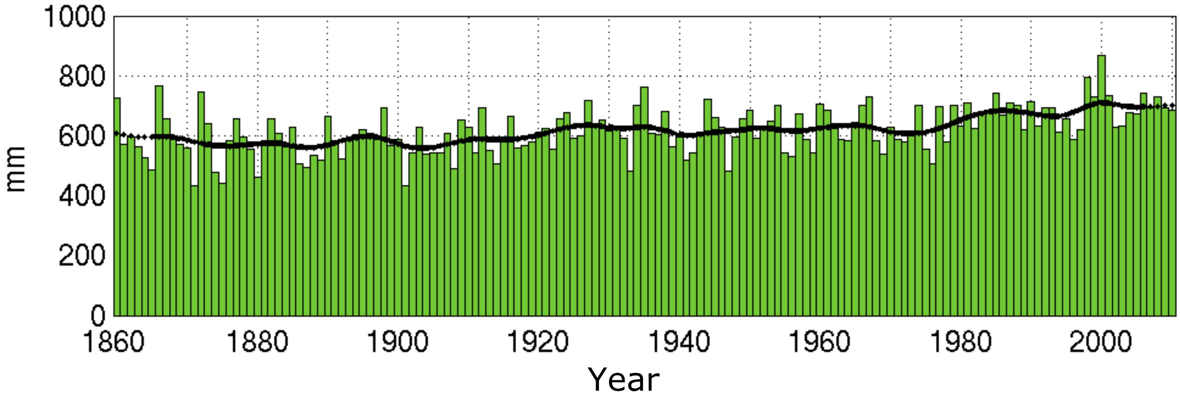

Figure 5. Annual average precipitation in Sweden 1860-2010. The black line indicates the 10 year moving average (SMHI, 2011a).

Figure 6 shows the mean annual total precipitation in southern Sweden. The amounts are generally lower along the coasts, as low as 400 mm/year around the island of Öland, while the regions some tens of kilometers inland from the west coast experience the highest rainfall, up to 1000 mm/year. About 10-25 % of the annual precipitation falls as snow (SMHI, 2011b).

The precipitation patterns are governed by the wind direction. The region where the wind first meets the land mass that lifts the air will experience more rainfall than an area further inland. As westerly winds are dominating over southern Sweden, the west coast receives a significant larger amount of precipitation if compared to the east, as can be seen in Figure 6.

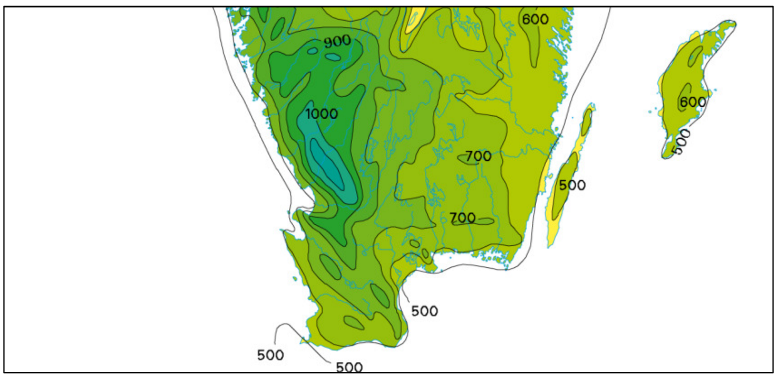

Figure 6. Mean annual total precipitation (mm) 1961-1990 (SMHI, 2011 c)

The direction of winds depends on the location of high-and low pressure centers. A low pressure can be defined as an area with lower air pressure than its surroundings, due to lower air density. According to the law of continuity this is compensated for by air masses moving in from the sides, causing the air to rise in the center of the low pressure (Ahrens, 2009).

The opposite of low pressures are high pressures, emerging in locations where the air has a higher density than its surrounding air masses. This typically occurs when the air is chilled or meets other air masses that have a higher temperature (Ahrens, 2009).

High- and low pressures can be identified by measuring the sea level pressure. When mapping the pressure differences over a larger geographical region it is common to draw the heights of constant pressure, a so called isobaric chart. These charts do not show the pressure differences at a certain altitude, but instead height variations along an equal pressure level (typically 500 mb), where a higher altitude marks a high pressure (ridge) and a trough appears over the low pressures. Isobars are lines of constant pressure which the geostrophic winds blow parallel to. Moreover, the tighter the isobars, the stronger the pressure gradient and the larger the wind speed (Ahrens, 2009).

2.4 Teleconnections

Anders Ångström was the first scientist to use the term “teleconnection” in his study of the North Atlantic Oscillation (NAO) in 1935 (Panagiotopoulos, 2002). Teleconnections are a natural part of the chaotic atmosphere and can be defined like a large-scale (ocean basin or continental size), reoccurring and persistent pattern of pressure and circulation anomalies. The teleconnections affect the climate over a large geographical area, by influencing the intensity and location of the jet stream, rainfall, temperature and storm tracks. The patterns affect both the interannual and interdecadal atmospheric circulation, as the length of their persistence may vary from some weeks to several months and sometimes be prominent for several successive years.

There are a number of different teleconnection patterns acting around the World; maybe the most famous one is the El Niño – Southern Oscillation event in the tropical Pacific Ocean that affects the tropical precipitation all around the globe as well as the storm patterns in the mid-latitudes.

The teleconnections considered in this thesis were first identified by Barnston and Livezey (1987), by applying a Rotated Principal Component Analysis (RPCA) to the mean standardized 500-mb geopotential height anomalies over the Northern Hemisphere from 20^{o} - 90^{o} N. The indices used in the analyses, covering the time period 1950-2010 are constructed by The Climate Prediction Center of National Oceanographic and Atmospheric Administration (NOAA), using the same technic and standardizing the anomalies by the 1950-2000 monthly means and standard deviations. The RPCA revealed 10 dominant teleconnection patterns, of which eight to nine appear in each of the years’ twelve months. By using the Least Square method, the teleconnection indices are calculated from the dominant modes of the RPCA (NOAA, 2008).

In this study five different teleconnection patterns of the Northern Hemisphere will be compared with the runoff and hydropower production of the rivers in southern Sweden. The teleconnections analyzed in this paper are chosen on the basis of their precipitation patterns affecting southern Sweden, as shown by NOAA (2011 a-e). The aim of the thesis is to investigate if there is a correlation between the hydropower production in southern Sweden and these teleconnections.

2.4.1 North Atlantic oscillation (NAO)

The NAO is a natural climatic phenomenon, affecting the climate from United States to Siberia in the east-west direction and the Arctic- subtropical Atlantic in the North-South direction (Hurrell et al, 2003). It was first observed in 1770 by a missionary called Saabye, but not defined until 1932 when it got described it as an alternation of the atmospheric mass between the subpolar low, centered over Iceland and the subtropical high, centered near the Azores. NAO is ranked as the strongest contributor to low frequency variability in the geopotential height fields in the northern hemisphere by Barnston and Livezey (1987) since it is the leading or second dominant mode of the atmospheric circulation during nine of twelve

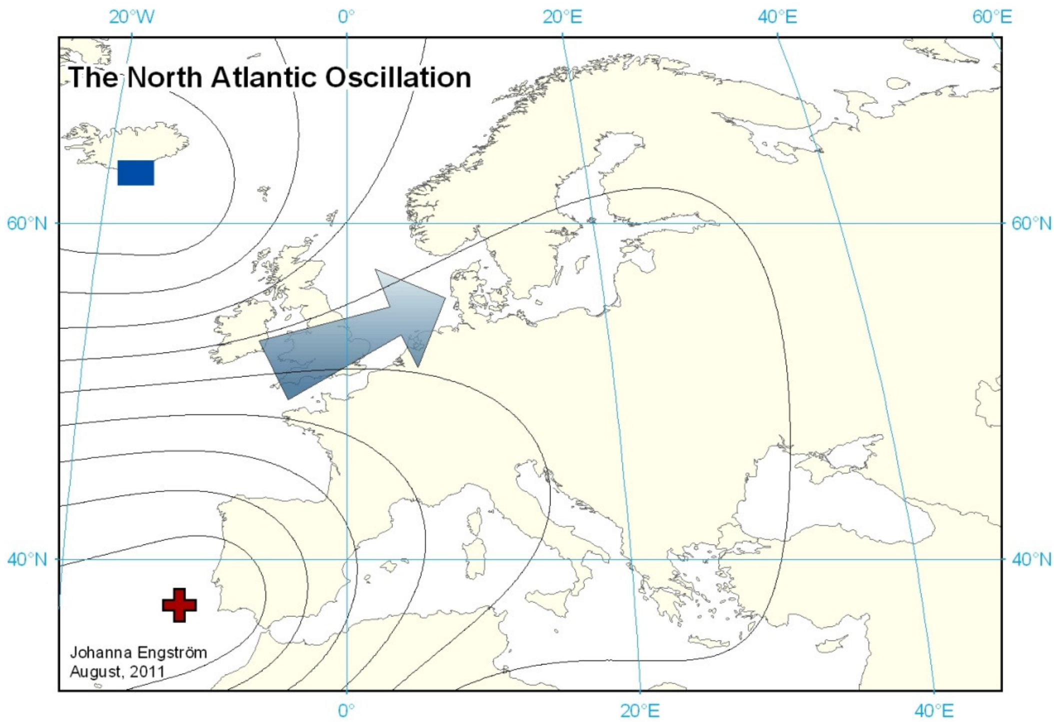

Figure 7. Map of Europe showing the isobars and geostrophic wind over southern Sweden associated with the positive mode of the NAO.

months in the Northern Hemisphere. Hurrell (1995) created a NAO index, based on the mean normalized sea level pressure difference December-March, between Stykkisholmur in Iceland and Lisbon in Portugal. There are also alternative indices, using Ponta Delgada at the Azores or Gibraltar as the southern center, but in this paper Hurrell's index will be used.

A positive state of the NAO is defined by an abnormally high pressure difference between the two mentioned locations, while an abnormally low anomaly is considered as a negative phase. A positive phase is associated with mild and wet weather in northern Europe, western Mediterranean and southeastern US, while the weather in Greenland and the eastern part of the Mediterranean are negatively correlated and these regions experience a winter that is colder and drier than normal (Figure 7) (Cherry et al, 2005). When the NAO is negative the weather patterns are the opposite, leading to anomaly cold and dry winters in northern Europe, western Mediterranean and southeastern US and mild and rainy weather in the eastern Mediterranean and Greenland (Hurrell, 1995; NOAA, 2011a).

The phase of the NAO shows considerable interseasonal and interannual variation (Hurrell and Deser 2009) besides a multidecadal variation in its wintertime phase. The negative phase of the winter NAO dominated from the mid-1950s to the late 1970s while the positive phase was leading during the 1980s and 90s, resulting in mild, wet winters in northern Europe (Hurrell, 1995, Chelliah and Bell, 2004).

Figure 8 shows the variability of the NAO 1950-2010. Due to the extensive effects of the NAO there have been several attempts to forecast its phases. Generally the short-term predictions are better than the long –term ones. As an example NOAA provides 7, 10 and 14 days forecast of the NAO on their homepage (www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). The 7 days forecast shows a correlation of 0.91 with observed conditions, while the correlation for the 14 days forecast is only 0.46. Johansson (2007) has analyzed and compared two atmospheric models used for deterministic forecasting in the short to medium range plus eight fully coupled atmosphere–land–ocean forecast models used for monthly and seasonal forecasting to evaluate the abilities to make monthly and seasonal forecasts of the NAO. The most accurate monthly prediction showed a correlation of 0.63 between observed and forecasted NAO while the corresponding number for seasonal predictions was 0.42, however, the mean correlation was considerably lower (Johansson, 2007).

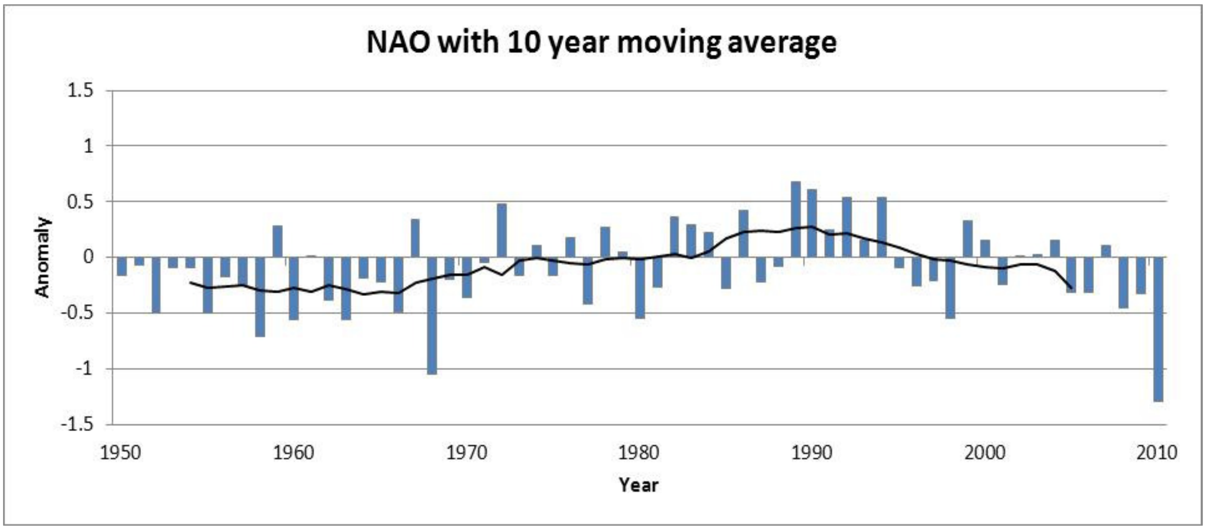

Figure 8. Diagram showing the yearly average pressure difference (mb) between Stykkisholmur and Lisbon, together with a 10 year moving average.

2.4.2 The East Atlantic pattern (EA)

The EA was originally defined by Wallace and Gutzler (1981) as a teleconnection with four different pressure centers: two high pressures located southwest of the Canary Islands and between the Black- and Caspian Seas respectively, and two low pressures located west of the British Islands and over central Siberia (NOAA, 2011b, Panagiotopoulos et al, 2002). The index of the EA was then based on the normalized 500 hPa geopotential height anomalies at the four different pressure centers (Panagiotopoulos et al, 2002). However, in this paper the EA will be defined as by Barnston and Livezey (1987) and NOOA 2. The EA reminds of a south eastward shifted NAO during its positive phase, having a negative pressure anomaly west of Ireland and a positive one stretching across the Atlantic from west to east at the approximate latitude of the Canary Islands (Figure 9).

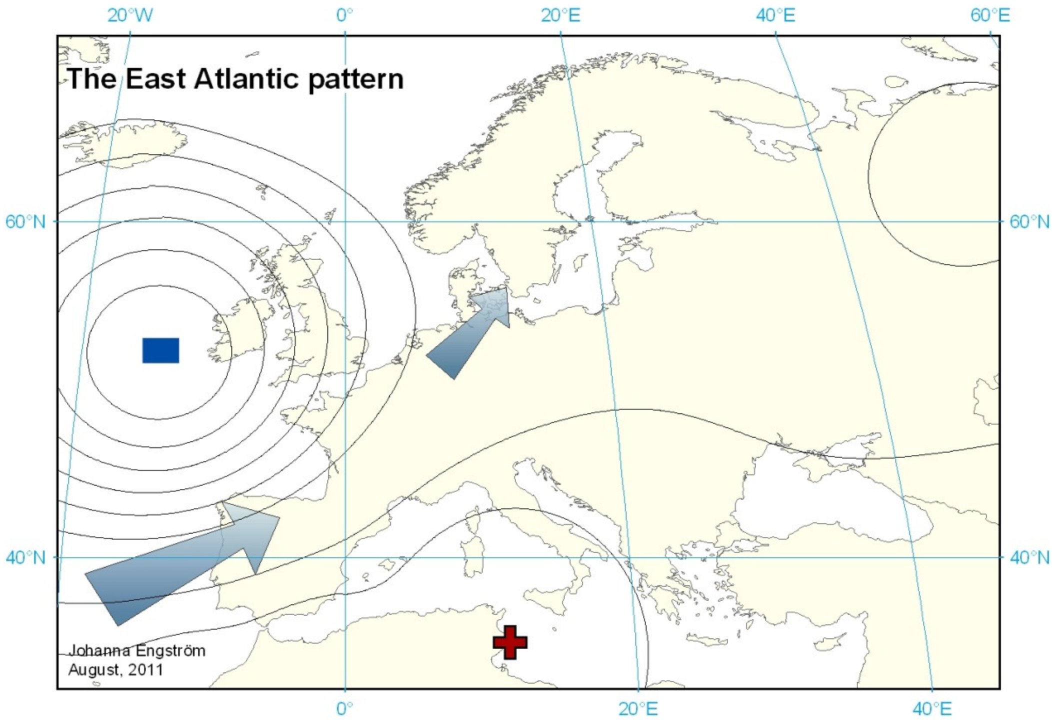

Figure 9. Map showing the location of the pressure centers associated with the positive mode of the EA and arrows indicating the dominant wind directions over southern Sweden.

During the EA's positive phase, the positive pressure anomalies over the subtropics bring warm air, giving Europe above average temperature and Northern Europe get above average precipitation, while southern Europe experiences a season that is drier than average. At the same time some parts of the US have below-average temperatures (NOAA, 2011b). The pattern shows strong multi decadal variability. As example the negative mode prevailed during the years 1950-1976, while a positive phase dominated 1998-2010, which can be seen in Figure 10.

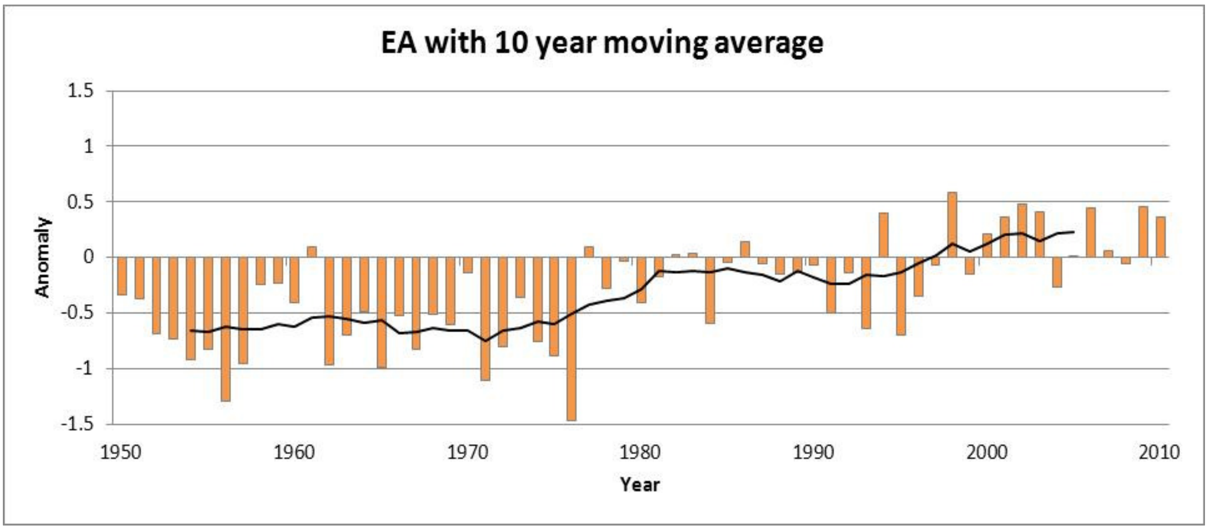

Figure 10. Yearly average EA index with 10 year moving average.

2.4.3 The East Atlantic-Western Russia pattern (EA/WR)

The EA/WR teleconnection is similar to the pattern referred to as the Eurasian pattern Type 2, as defined by Barnston and Livezey (1987). However, in this analysis the pattern will be defined as by NOAA (2011c), which means that it consists of four pressure centers instead of three. The EA/WR anomaly centers located over the North Atlantic, Western Europe, the Caspian Sea/western Russia and northeast China respectively. Figure 11 shows how that affects the winds over southern Sweden.

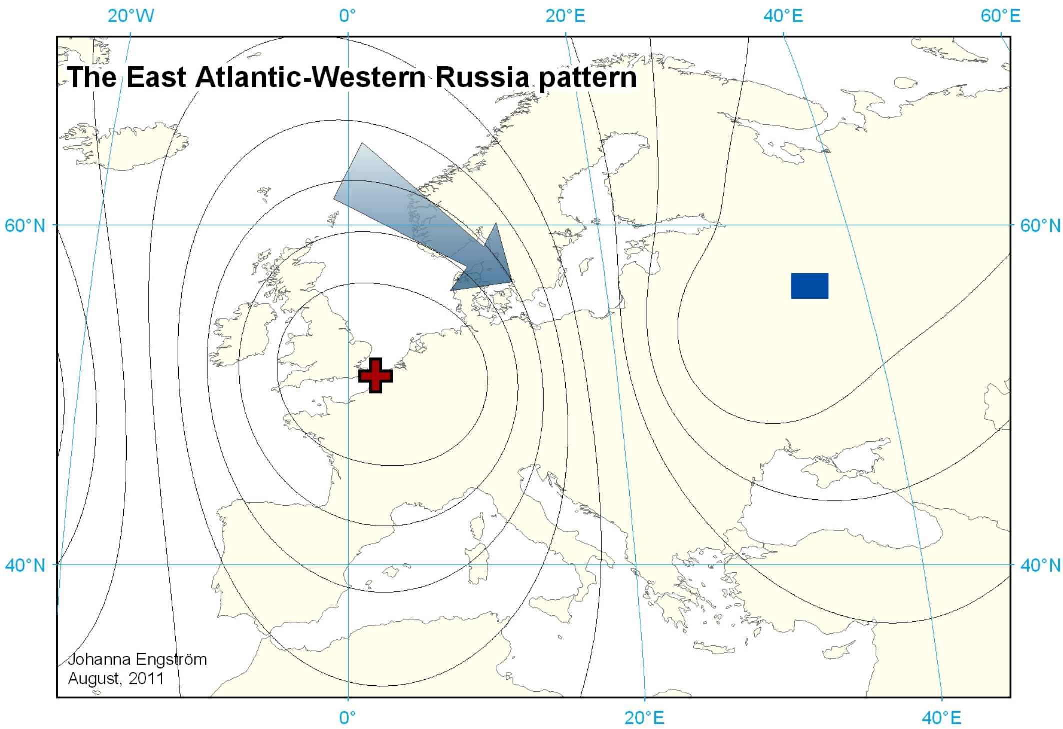

Figure 11. Map showing two of four pressure anomalies, related isobars and geostrophic wind direction over southern Sweden associated with the positive mode of the EA/WR.

The positive phase of the EA/WR gives below average precipitation in central Europe, while eastern China gets above average precipitation. At the same time eastern Asia experiences above average temperatures while western Russia and northeastern Africa have below average temperatures (NOAA, 2011c). The variability of the teleconnection can be seen in Figure 12. The EA/WR pattern affects southern Sweden though increased temperatures during the winter and below-normal precipitation during fall and winter (NOAA, 2011c).

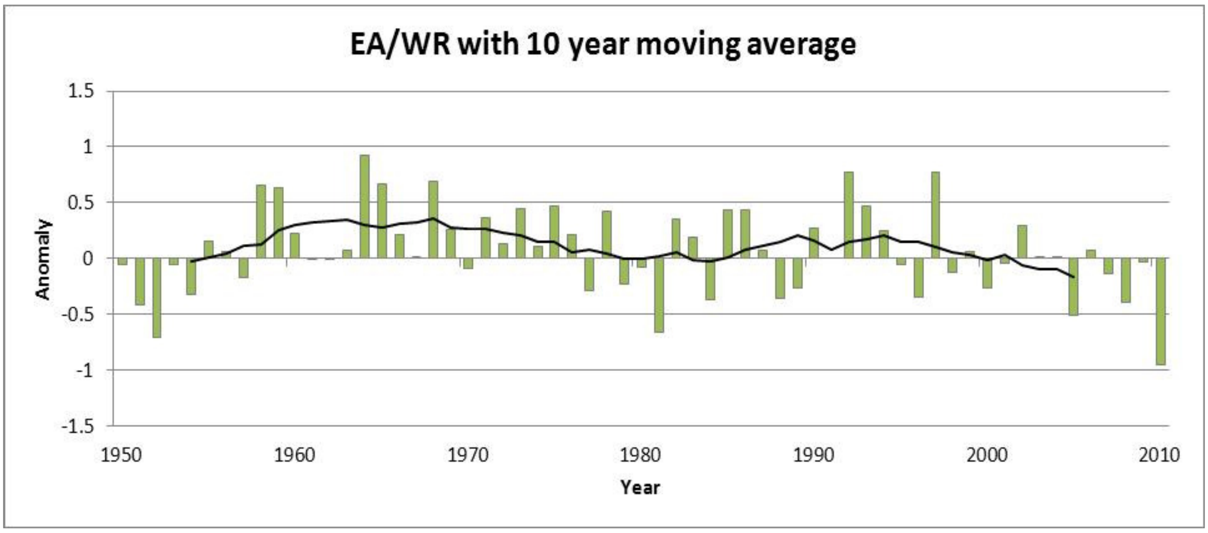

Figure 12. Average yearly value of the EA/WR teleconnections together with a 10 year moving average

2.4.4 The Scandinavian pattern (SCA)

The SCA pattern consists of a high pressure over the Scandinavian Peninsula and two low pressures located over the northeastern Atlantic/western Europe and central Siberia respectively. Sometimes a weak fourth center emerges over Japan (Barnston and Livezey, 1987; NOAA, 2011d). A positive phase is associated with below normal winter temperatures in Russia and Western Europe. At the same time southern Europe receives above normal precipitation while the high pressure over Scandinavia gives that region drier than normal conditions (Bueh and Nakamura, 2007). The same authors also write that a long lasting positive phase even may affect eastern Asia, causing below average temperatures. The pattern was identified first by Barnston and Livezey (1987), which referred to the pattern as the Euroasian Type 1 (EU 1) because of the spread out locations of its different centers of action. Figure 13 shows how the positive phase of the SCA affects southern Sweden.

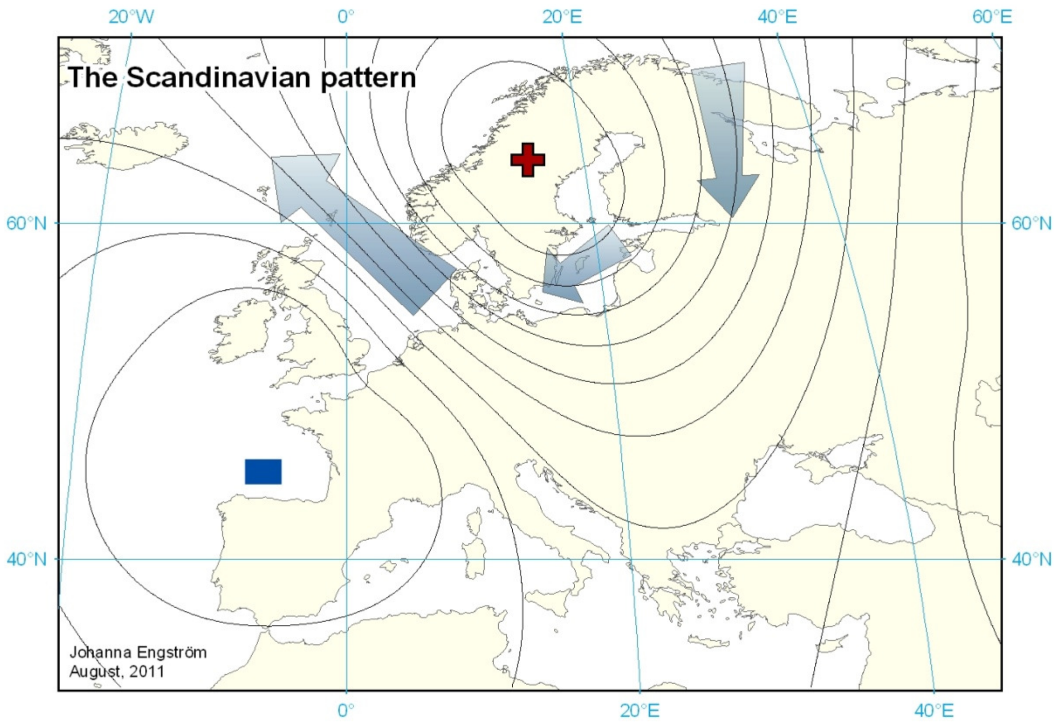

Figure 13. Map showing parts of the pressure anomalies associated with the positive phase of the SCA and the resulting dominant geostrophic wind direction over southern Sweden.

Opposite of some of the other climatic patterns mentioned in this paper, the SCA does not only affect the winter weather. After the extremely wet autumn of 2000 when England and Wales received the highest autumn precipitation since measurements started in 1766 (Panagiotopolous et al (2002); Blackburn and Hoskins (2001)), several places from Norway to France received double their normal autumn rainfall and there was severe floods and mud-slides in the southern Alps, Blackburn and Hoskins (2001) found that the extreme weather was associated with SCA. Its positive phase had shifted the location of the exit of the Atlantic jet stream eastwards, creating a center of cyclone development and growth located closer to Western Europe than normal. Bueh and Nakamura (2007) state that SCA is also dominant during the spring, while less prominent during the summer months. Zveryaev and Allan (2010) confirm the statement, writing that SCA plays its major role of governing the spring and fall precipitation patterns during periods of weak NAO. Toreti et al (2009) have found that there is a weak, but significant negative correlation between the SCA and the summer temperatures in Italy. However, just because the SCA pattern is active does not mean that it always affects southern Sweden. Figure 14 shows a diagram of the variability of the SCA pattern.

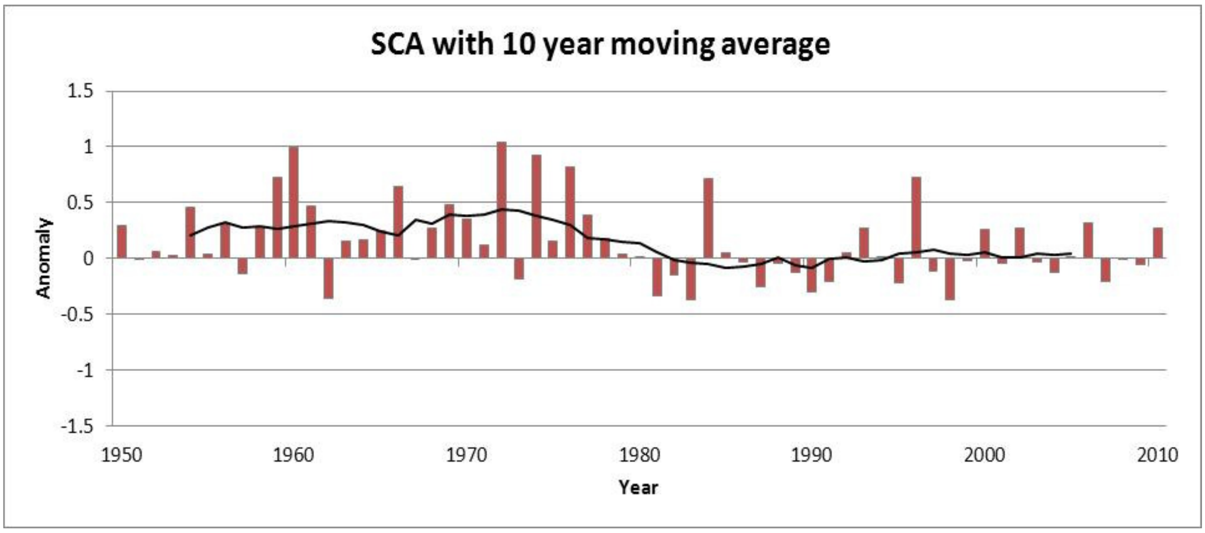

Figure 14. Yearly averages of the SCA index 1950-2010. The black line marks the 10 year moving average.

2.4.5 The Polar/Eurasia pattern (POL)

The POL pattern is associated with variations in the strength of the circumpolar circulation. A positive phase indicates a stronger polar vortex while the negative phase gives a weaker than average polar vortex. During its positive phase the pattern consists of negative height anomalies over the Arctic and two broad pressure centers of opposite signs located over Europe and Eastern Siberia. Figure 15 shows how the atmospheric pressure anomalies affect Europe.

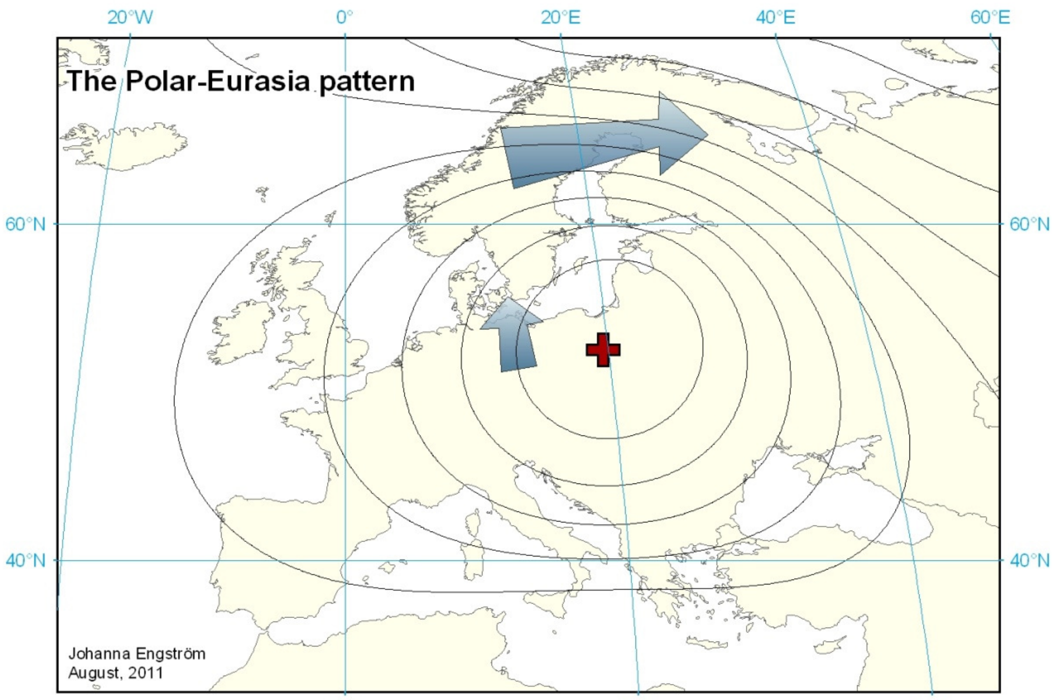

Figure 15. Map of Europe showing parts of the POL pressure anomalies associated with the patterns positive phase and the resulting geostrophic wind over southern Sweden.

The positive phase of the POL results in above average temperatures in eastern Siberia and below average temperatures in eastern China. At the same time the polar region north of Scandinavia experiences above average precipitation (Panagiotopoulos, 2002; NOAA, 2011e). Southern Sweden is mainly affected by the teleconnection during winter and summer, when it may reduce the amount of precipitation over Northern Europe. During the summer months the temperatures are also positively correlated with the POL (NOAA, 2011e).

Compared with the other teleconnections, that show an amplitude of variability of +/-1 (EA/WR and SCA) and +/-1.5 (NAO and EA) the amplitude of variability of the POL is low. However, this is only because the pattern shows a great interannual variability. Considering the monthly averages of its phase the amplitude is just as high as, and even higher than for some of the other patterns.

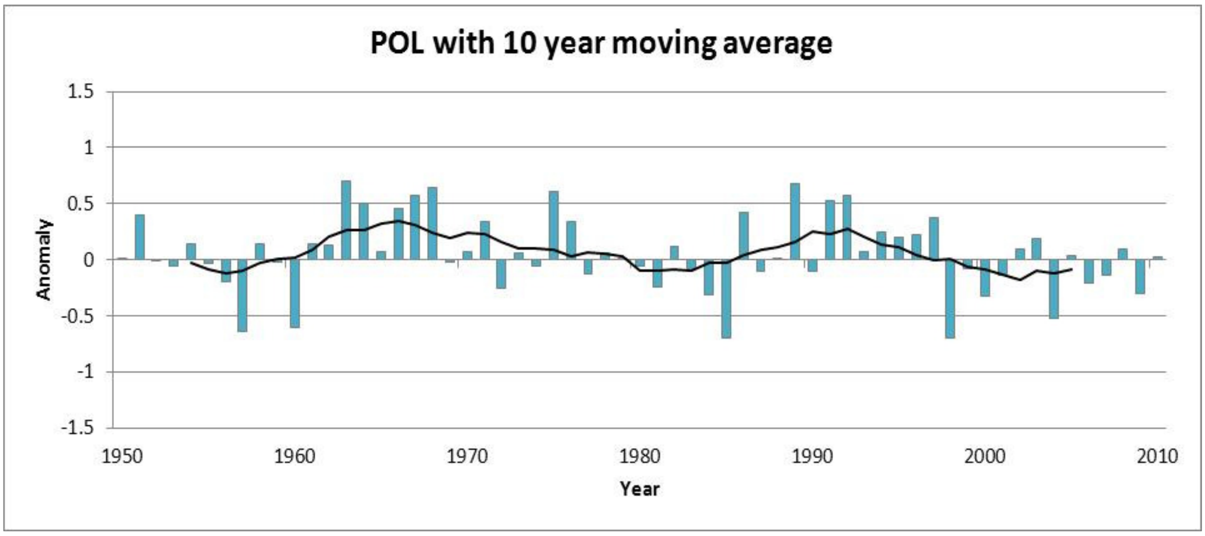

Figure 16. Yearly averages of the POL index with the 10 year moving average marked in black.

3 Data and Methodology

3.1 Data

The analyses developed in this work are based on monthly time series of energy production (MWh/month), discharge (m^3/month) and average temperatures (C°) from stations located in southern Sweden (Figure 17). The teleconnections are represented by monthly standardized anomalies of the 500 mb geopotential height, constructed from NOAAs RPCA (NOAA, 2008).

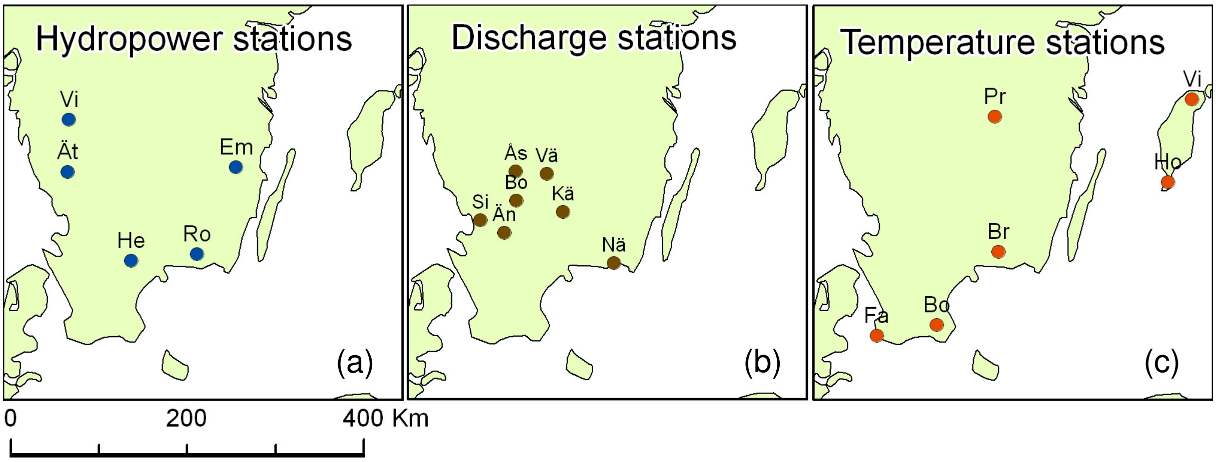

Figure 17. Maps showing the location of the hydropower stations (a), discharge stations (b) and temperature stations (c). The names of the stations are indicated with the first two letters of their name.

3.1.1 Energy production

Vattenfall and E.ON provided monthly energy production for 17 hydropower plants located at the five rivers Viskan, Ätran, Helge å, Emån and Ronnebyån in southern Sweden (Figure 17 a). The data spans from April 1999 to December 2010. As seen in Figure 18, Ätran is the river with the highest energy production (11.4 GWh in average monthly production) whiles the smallest river Emån only produces 1.7 GWh in average per month. The average production for all the hydropower stations together is 28.4 GWh per month. In the same figure the seasonal variations in discharge and temperature can be clearly seen, giving higher production October-April, while the summer months generally are warmer and drier. Some year-to-year variations can also be seen, the winter 2002-2003 the production was abnormally low just as the winter 2005-2006 when the peak production occurred in late spring 2006.

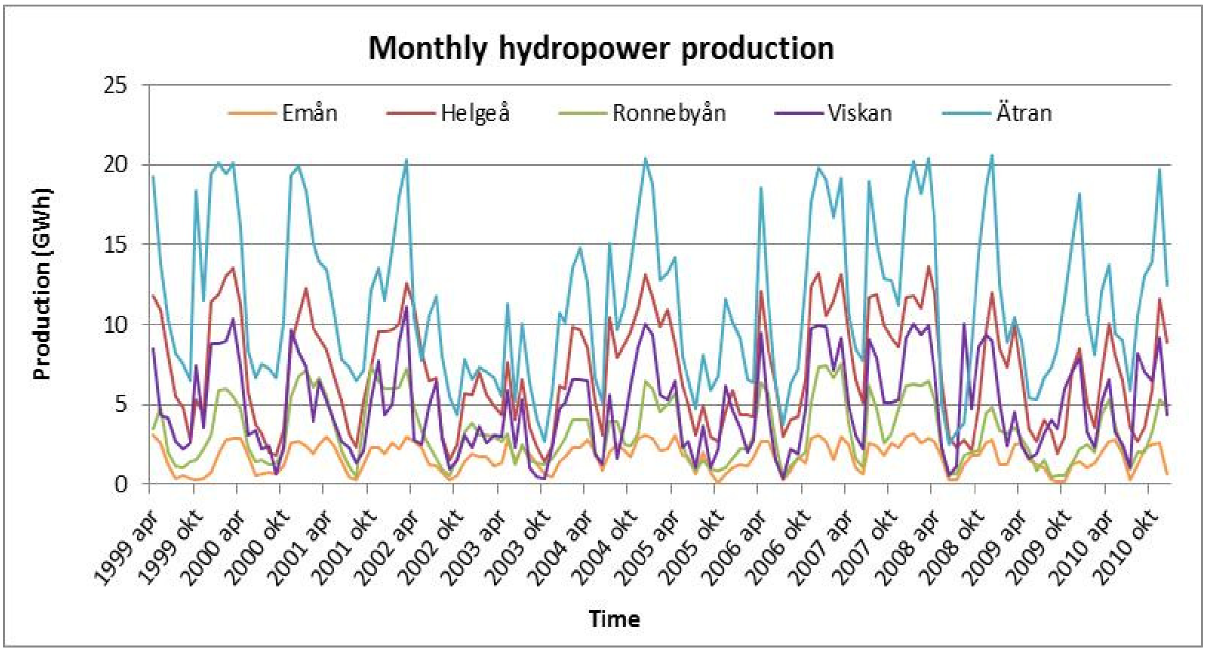

Figure 18. The productions of the hydropower stations are summarized and presented as monthly electricity production per river (GWh) from April 1999-December 2010.

3.1.2 Runoff

Since the water availability is an important factor for the hydropower production, river discharge has also been included in the analysis. Monthly runoff data from seven unregulated gages (Bolmen, Källstorp, Nättraby, Simlången, Värmeshult, Ängabäck and Ås) in southern Sweden was provided by Sveriges Meteorologiska och Hydrologiska Institut (SMHI) and covers the time period 1950-2008. The position of the runoff gages are seen in Figure 17b.

3.1.3 Temperature

Temperature is an important factor governing the electricity use in southern Sweden and data from six stations in the region has been analyzed. Monthly averages of temperature for Falsterbo, Bollerup, Bredåkra, Hoburg, Prästkulla and Visby flygplats were provided by SMHI and cover the time period of 1961-2010. The location of the stations together with the stations providing production and discharge data can be seen in Figure 17.

3.1.4 Teleconnections

The teleconnection indices are constructed by NOAA. The indices are monthly standardized 500-mb geopotential height anomalies, covering the time period 1950-2010.

3.2 Methodology

3.2.1 Filling gaps in the data

All sites having more than 10 % or two or more years in a row of missing data were excluded. When one observation was missing it was set to the average of the prior and following observations. When more than one subsequent observation was missing they were given the average of their respective month, based on the whole data series.

In some cases it is enough to normalize the data by just extracting the mean, resulting in a new data series with a zero average. However, in this case when data to be combined has different amplitudes, standardization with Equation 2 is more suitable, since it leaves the data series "on the same scale" (Björnsson and Venegas, 1997)

All the data has been standardized following Equation 2.

$$y = \frac{x_n - \bar{x}}{\sigma} \qquad (2)$$

Where y is the standardized value, x_n is the observed value, $\bar{x}$ the average of the time series and σ represents the standard deviation of the time series.

3.2.2 Principal Component Analysis

In this thesis several data series of different variables are analyzed. In order to reduce the number of variables and make the data more easily manageable, a Principal Component

Analysis (PCA) (Lorenz 1956) was used. The method finds the spatial patterns of variability in the data (eigenvectors), their variation in time (time series of the PCA) and their rank. The ranks are referred to as modes, where the first mode explains the largest fraction of the variance, the second mode the second most of the variance… etc. All the modes are orthogonal to each other, a reason to why the method sometimes also is called Empirical Orthogonal Function. A mathematical explanation to the method is given by the mathematical transformation represented in Equation 3.

$$L=U'SU \tag{3}$$

Where the diagonal numbers of L are the eigenvalues (modes) of S, S is the covariance matrix of the standardized data series and the columns of U are the eigenvectors of S. The time series of the PCA are constructed according to Equation 4.

$$Z=XU \tag{4}$$

Where Z represents the time series of the PCA, X the original standardized data set and U are the eigenvectors of S (Jackson, 1991).

Since the effect of the different teleconnection indices on southern Sweden varies within the year, all the data is sorted into seasons: December, January, February (DJF) representing the winter, March, April and May (MAM) representing the spring, June, July and August (JJA) representing the summer and September, October and November (SON) representing the fall.

PCA is applied at one data set at the time. In search of a physical explanation for each PCA mode, the mode time series were correlated with the series of teleconnection indices, a method referred to as single-field-based PCA by Bretherton et al (1992).

For a deeper and more detailed explanation of the PCA, the reader is referred to Wilks (1995) and Bretherton et al (1992).

Just like other methods, PCA has its limitations. Dommenget and Latif (2002) give three different examples where they show that the result of the PCA has been misleading, not due to statistical uncertainties but the method itself. Hurrell and Deser (2009) discuss the fact that the eigenvectors of the PCA are mathematical constructs, constrained by their mutual orthogonality and the maximization of variance over the entire analysis domain and that there therefore is no guarantee that they represent the physical modes of the climate system. The same authors also highlight the fact that the PCA does not reveal if two patterns are linearly superposed, if the patterns are not orthogonal to each other.

PCA is still a popular method to use when working with large sets of data, especially in climate research. As example Hurrell and Deser (2009) used it in their analysis of the coupling between sea level pressures and North Atlantic Climate variability and Kim et al (2010) has used the method to analyze the drought vulnerability of the agriculture in Korea.

3.2.3 Spearman correlation

Spearman correlation, sometimes also referred to as Spearman rank-difference or rank-order correlation coefficient was used in the single-field based PCA. This method gives less significance to outliers in the series than the more common Person correlation. The method measures the monotonic relation between the variables, which may be high even though the correlation is not linear (Guertin and Bailey, 1970). To get the percentage of the variance of a PCA mode explained by a specific teleconnection, the Spearman correlation has to be squared.

3.2.4 Plotting eigenvectors

The eigenvectors of the modes of the PCA show the spatial variability of the original data set. Since the stations analyzed in this paper are located geographically close to each other the variation is relatively small. Instead of mapping the eigenvectors they have been plotted in a so called biplot. As the name indicates the biplot normally is a two-dimensional graph, but in this case they are made in three-dimensions, where the x-axis represents eigenvector 1, the y-axis eigenvector 2 and the z-axis eigenvector 3, to make the relations between the stations more visible.

4 Results

The statement in the introduction that the hydropower production is governed by demand and available water is confirmed by Figure 19 a-b. The correlation between temperature and production is -0.54 (>99%) while the correlation between discharge and production is 0.74 (100 %).

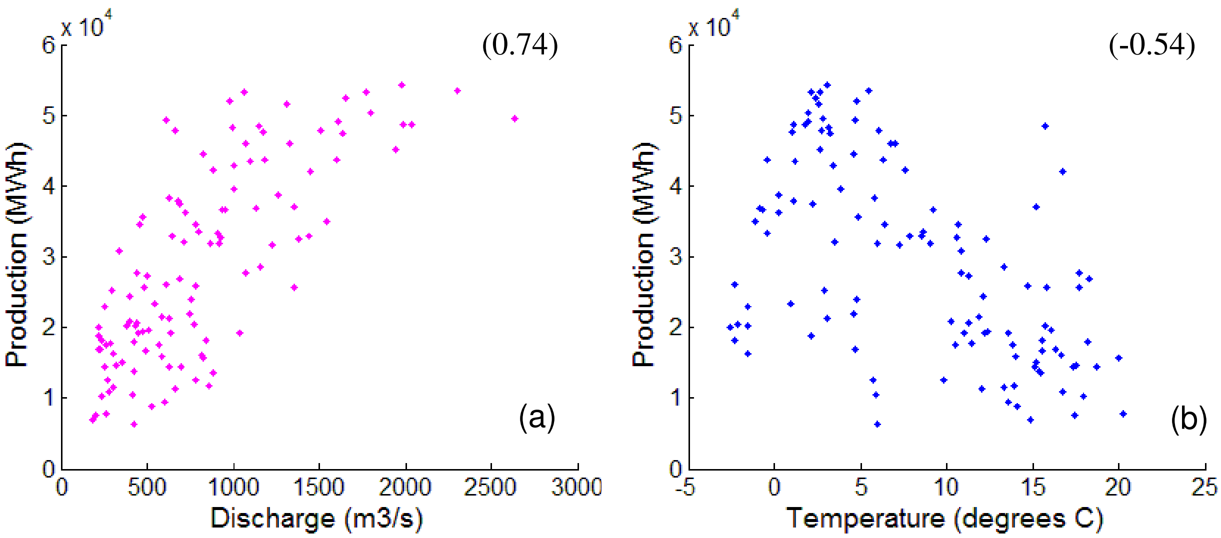

Figure 19. Scatter plots of monthly river discharge and hydroelectricity production (to the left) and of monthly temperature and hydroelectricity production (to the right) in southern Sweden. The Spearman correlation is shown in the upper right corner.

In Figure 2, a clear trend could be seen between the time of the year and the electricity usage in the Nordic countries. The weaker correlation between temperature and production that is shown in Figure 19 b is most likely due to the fact that the region analyzed in this paper is located in the southern part of the Nordic countries where the low winter temperatures are less pronounced than at the higher latitudes.

Figure 20 shows the anomalies of the hydropower production of the five rivers analyzed in this paper. Just like in Figure 18 the dry years of 2002-2003 can clearly be seen. In 2003 the rivers produced 121 GWh less than normal.

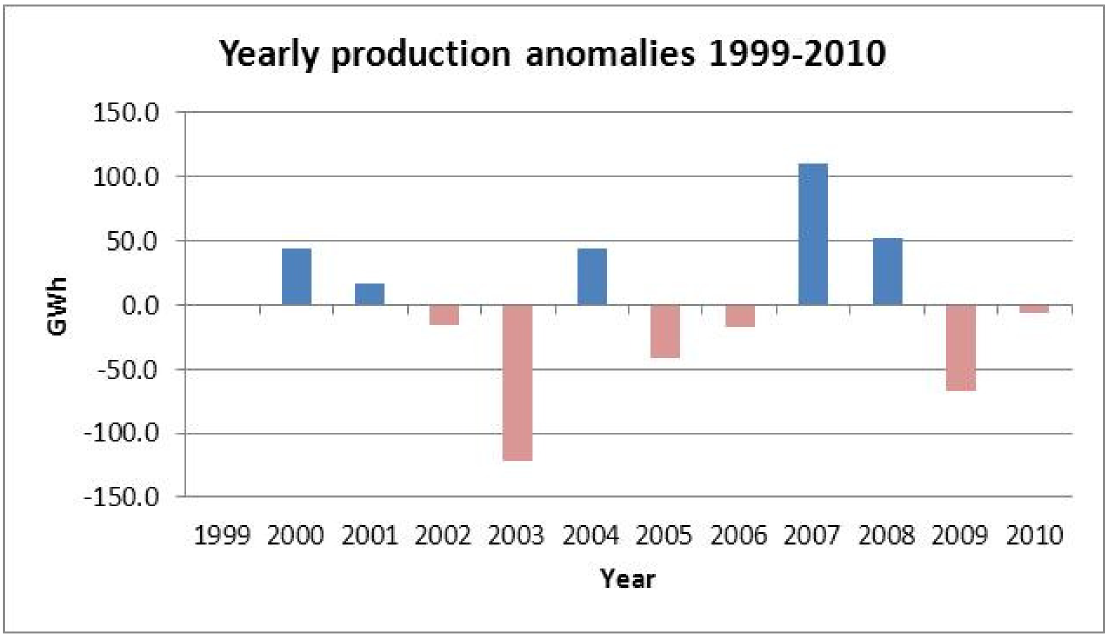

Figure 20. Diagram showing the annual anomalies of the total electricity production of the five rivers used in the PCA.

4.1 Hydropower production

Table 1 shows the correlation between the time series of the first three PCA modes of the hydropower production and the corresponding time series for the teleconnection indices per season. The NAO is strongly positively correlated with the DJF production indicating that the stronger the NAO Index, the higher the production. What also can be seen is that the SCA shows an almost as strong negative correlation with production during the same season that indicates that the higher the SCA index, the lower the production. These results are very important in showing that, during DJF, two teleconnections impact the hydropower production in southern Sweden almost with the same intensity and in opposite direction. Looking at the MAM and JJA production the EA/WR gives the strongest signal of -0.33 and -0.41 respectively. During the fall no teleconnection seems to impact the hydropower production and it tends to vary more, which can be seen by the spread of explained variance among the modes. The EA/WR and SCA show a correlation of -0.20 in the first PCA mode for SON, however, only with a statistical significance of 76 and 77 % respectively.

Table 1. Seasonal correlation between the hydropower production and the climate indices. Correlations showing a significance ≥99% are marked in bold, while correlations having a significance of ≥95% are marked in italics.

Season	**DJF**			**MAM**			**JJA**			**SON**		
Production mode	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Expl. Variance	82.3%	9.7%	5.7%	84.3%	7.3%	4.9%	76.5%	12.0%	7.6%	77.3%	13.5%	4.7%
NAO	**0.54**	-0.02	-0.10	0.02	0.10	-0.24	0.26	-0.14	0.20	0.04	-0.06	-0.02
EA	0.14	-0.20	0.24	0.17	0.17	0.21	-0.23	0.19	0.14	-0.15	0.01	0.05
EA/WR	0.11	*-0.38*	-0.02	*-0.33*	0.08	0.03	**-0.41**	0.07	0.06	-0.20	-0.12	-0.01
SCA	**-0.43**	-0.13	-0.02	-0.13	-0.04	0.03	-0.10	0.14	0.20	-0.20	0.00	0.18
POL	-0.18	-0.05	0.19	-0.16	-0.16	0.19	-0.04	0.17	0.14	0.01	0.02	-0.08

Generally the eigenvectors of the first PCA mode show very little spatial variability, all the stations have positive values in the first mode of the PCA. The eigenvectors of the second and third mode of the PCA show more spatial variability, but explains less of the original variance of the data.

Plotting the eigenvectors of the production PCA per season showed that the relation between the hydropower plants vary seasonally. The production at Emån differs most from the others stations during SON and DJF as it can be seen in Figure 21.

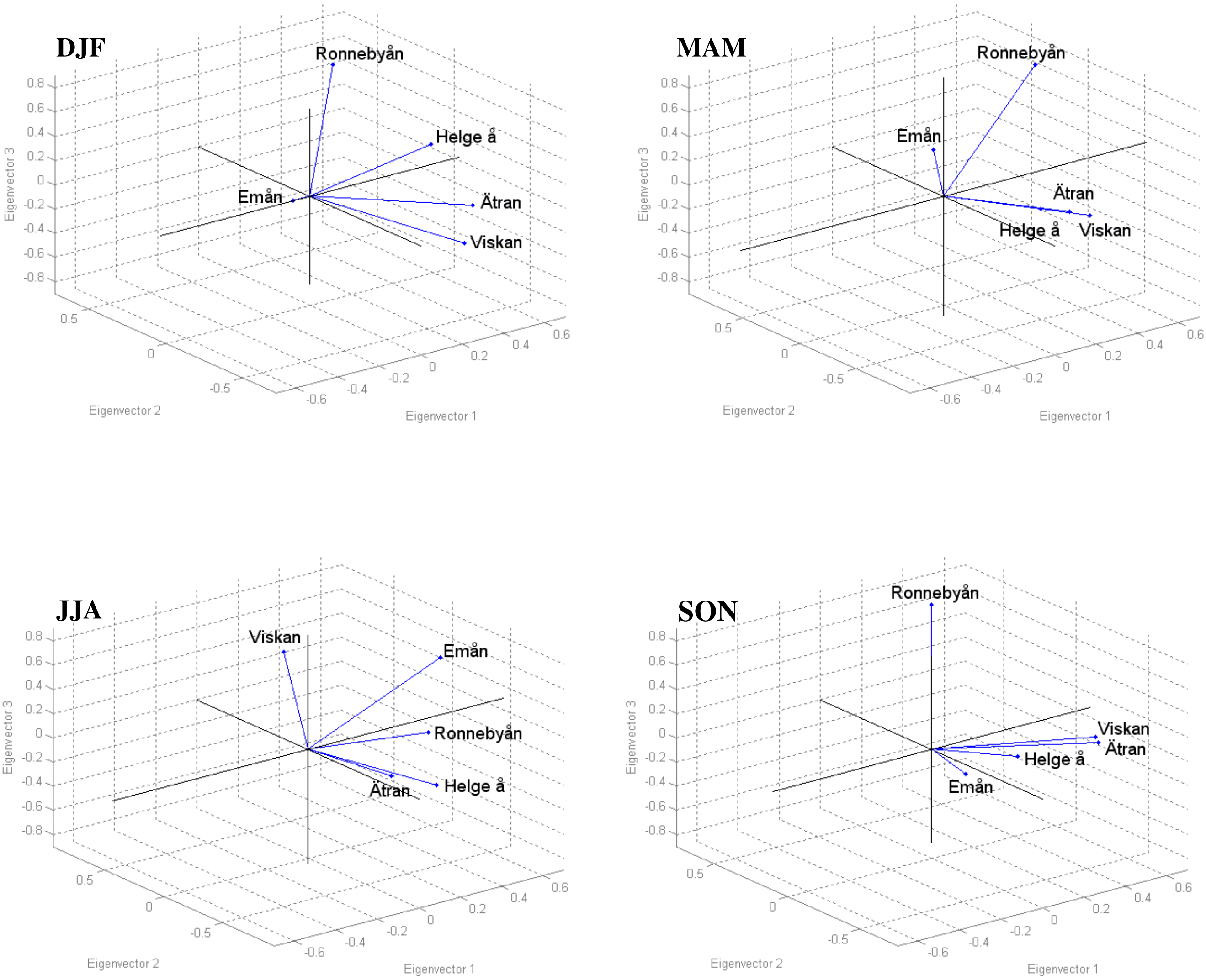

Figure 21. Biplots of the first three eigenvectors of the PCA of the hydropower production, starting with DJF in the upper left corner.

While the pattern of production in Ronnebyån varies differently from the others in all season except for JJA. The production at Ätran and Viskan follow each other closely, which could be explained by their geographical positions on the west coast (Figure 18 a), except in JJA when the representation of the Viskan production by third eigenvector differs significantly from the others.

Similar analysis made for the production was also made for the discharge and temperatures.

4.2 Discharge

Table 2 shows the correlation between the times series of the first three dominating PCA modes of the discharge data and the time series of teleconnection indices. Once again the NAO and SCA are dominating the winter pattern, not as strongly as for the hydropower

Table 2. Spearman correlation between the time series of the three dominating modes of the discharge PCA and the teleconnection indices.

Season	**DJF**			**MAM**			**JJA**			**SON**		
Discharge mode	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Expl. Variance	69.8%	12.7%	12.7%	73.8%	15.9%	4.6%	60.8%	16.4%	11.8%	65.5%	16.1%	12.1%
NAO	**0.42**	**-0.41**	*0.17*	-0.04	-0.09	0.12	-0.10	0.06	**-0.29**	-0.12	*-0.17*	0.08
EA	0.06	-0.05	*0.15*	**-0.22**	0.06	0.14	*0.15*	-0.08	0.02	0.08	0.03	0.14
EA/WR	-0.15	**-0.26**	-0.12	0.05	-0.06	0.05	**-0.20**	0.10	-0.13	**-0.23**	-0.04	-0.12
SCA	*-0.16*	**0.24**	0.00	**0.30**	*-0.17*	-0.11	*-0.18*	**0.20**	-0.10	-0.04	0.02	**-0.32**
POL	-0.13	0.07	-0.04	0.09	0.01	0.05	-0.08	0.02	**-0.20**	0.04	0.05	0.02

production, but in both the first and second mode of the PCA. In the second mode for the same season the EA/WR also shows a strong negative signal, just like the NAO. According to the Spearman correlation the MAM discharge is mostly influenced by the EA and SCA, affecting the discharge in opposite ways. In JJA there are weak, but still significant correlations between the discharge and the EA, EA/WR and SCA in the first mode of the PCA. The SCA also shows a significant correlation in the second mode, which explains 16.4% of the total variance of the discharge for that season. The SON discharge is mainly governed by the EA/WR in the first mode, the NAO in the second mode and the SCA in the third mode of the PCA.

Compared with the production modes of the PCA the variance explained by each PCA modes of the discharge is lower, showing that the discharge patterns are more complex in their nature and one PCA time series alone cannot explain a large portion of its total variability. This fact can be seen in the percentage of variability explained by each mode in Table 2 as well as in the plots in Figure 22. All the eigenvector loads of the discharge are positive in the first mode of the PCA, but in the second and third mode the loads of discharge show a greater variability than the ones of the PCA of the production.

Just like the production stations, some discharge stations show similar behavior. One such example are the Simlången and Ås gages. Looking at the map in Figure 18 b they are located close to each other, but Bolmen that is situated right in between them shows a discharge pattern that differs from both Simlången and Ås, still none of the rivers is regulated. Differences depends most likely on the shape of the river basins

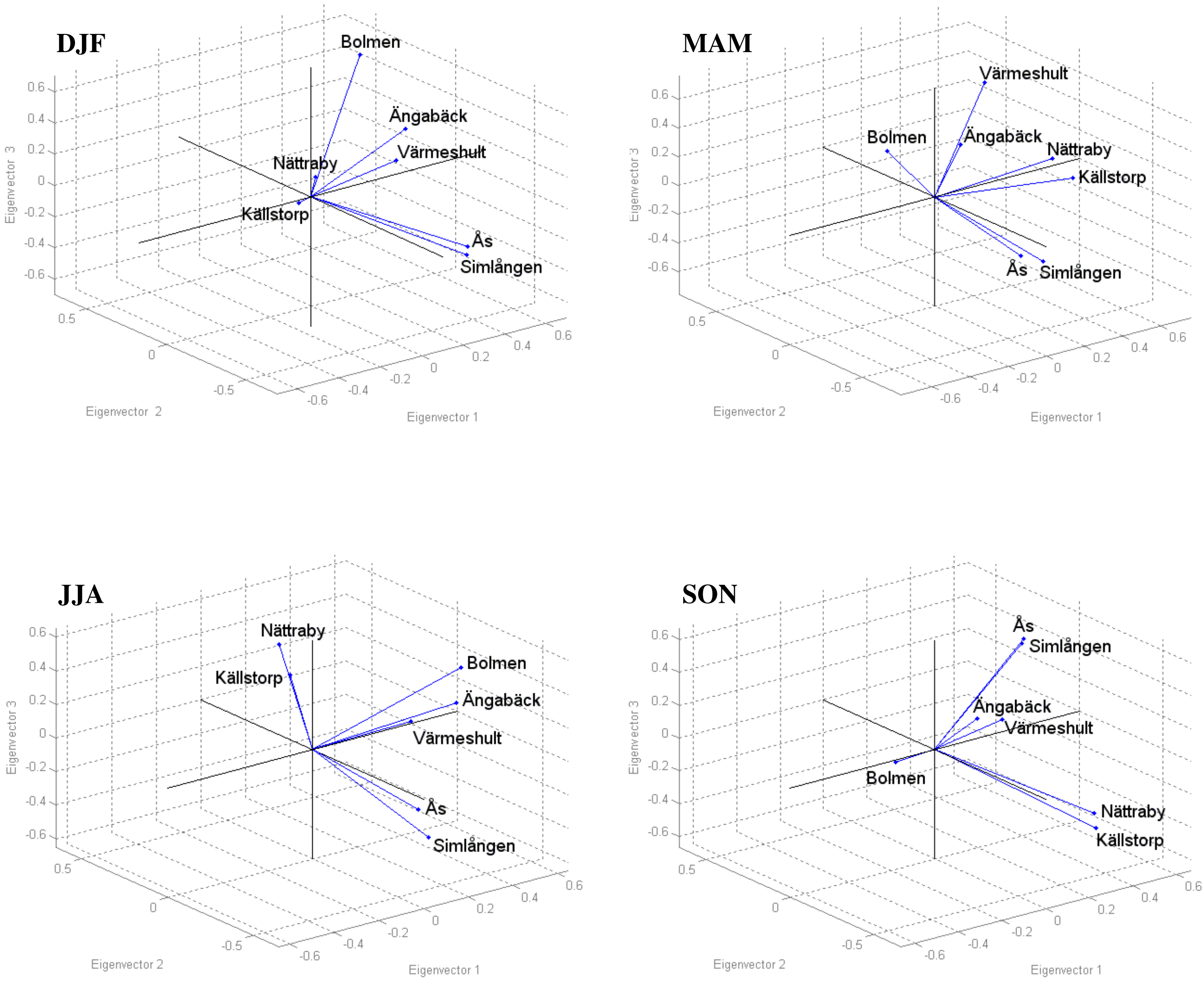

Figure 22. Biplots of the first three eigenvectors of the PCA of the discharge, starting with the winter in the upper left corner.

4.3 Temperature

The temperature time series of the first three modes of the PCA show far less variation than the production and the discharge and almost all the variance is explained by the first PCA mode. The winter season is once again dominated by the positive NAO signal, followed by the EA/WR signal and also a significant negative SCA correlation. The spring is the season showing most variance in the PCA modes, but still the first mode explains 83.3% of the variance of the original datasets. The NAO shows the strongest correlation with the MAM time series of the PCA, both in the first and second mode of the PCA. The JJA temperatures are mainly influenced by the state of the SCA and POL. In SON, the NAO starts to affect the temperatures positively again.

Table 3. Spearman correlation between the time series of the three dominating temperature modes of the PCA and the teleconnection indices.

Season	**DJF**			**MAM**			**JJA**			**SON**		
Temperature mode	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Expl. Variance	96.5%	2.1%	1.0%	83.3%	15.9%	0.4%	93.3%	3.3%	2.0%	99.1%	0.3%	0.2%
NAO	**0.63**	0.10	-0.03	**0.21**	*-0.20*	0.16	0.11	**-0.31**	0.01	**0.26**	-0.11	**0.35**
EA	*0.16*	**0.22**	-0.01	0.09	-0.07	0.08	0.09	-0.03	0.01	0.15	0.10	**0.24**
EA/WR	**0.21**	0.01	0.05	-0.04	0.07	0.01	-0.01	-0.16	0.09	0.03	**0.30**	0.13
SCA	**-0.20**	0.00	0.04	0.06	-0.11	**0.27**	**0.27**	**-0.22**	-0.09	0.10	0.03	**0.30**
POL	-0.04	**-0.23**	*0.17*	0.01	-0.05	0.14	**0.27**	-0.18	0.01	-0.06	-0.07	0.06

Figure 23 shows the eigenvector of the temperature PCA. Just like the eigenvectors of the production and discharge PCAs, the first eigenvector of the temperature PCA show very little spatial variability. More spatial variability can be seen in the second and third eigenvector, but considering the limited amount of data explained by the second and third mode these variations are relatively small

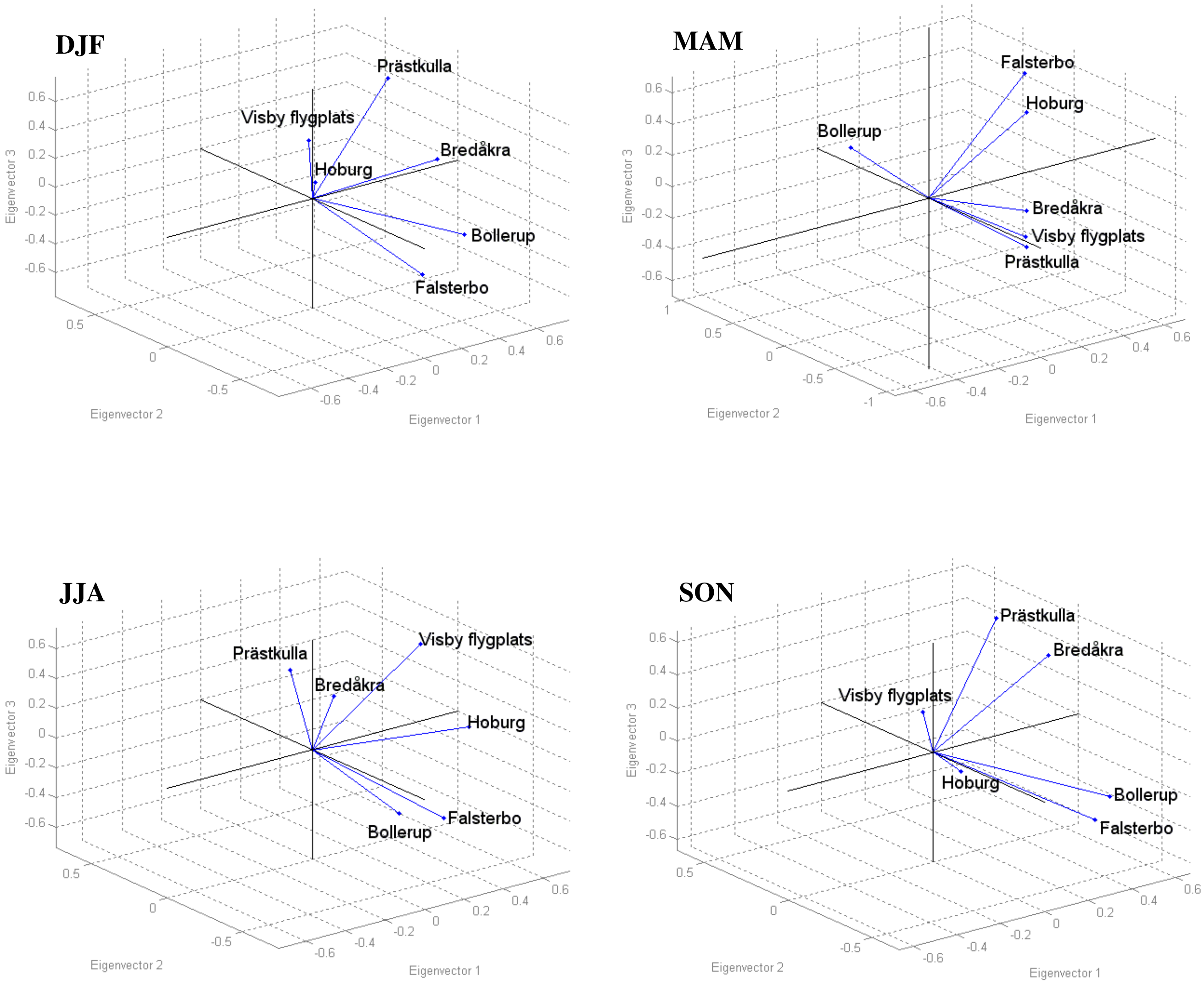

Figure 23. The first three eigenvectors of the PCA of temperatures. The diagrams show the spatial variability per season, starting with DJF in the upper left corner.

5 Discussion

5.1 Discharge and demand

The climate system is complex and the variations in precipitation and temperature in southern Sweden cannot be explained by the teleconnections alone. As stated in the introduction, the amount of electricity produced by the hydropower stations depends on the amount of available water as well as the demand from the market. The demand does not strictly depend on the temperature but also other factors like the current production from other energy sources, like the bigger hydropower plants further north in Sweden and in rare cases also the wind power production.

Compared with the modes of the production and discharge PCAs, a larger portion of the variance of the data is explained in the first mode of the temperature PCA, which indicated that the temperature stations have a more homogeneous behavior.

Even though the rivers gages used in this analysis are located close to each other, their time series are heterogeneous. The reason for this might be the different sizes and shapes of the river basins, which also could be a possible explanation to why the river gages Simlången and Ås show similar behavior, while the gage Bolmen, which is located in between the two, shows a different discharge pattern.

The discharge of the unregulated rivers does not strictly depend on the precipitation. Another important factor is the land use, which may delay the runoff to the rivers through inception and absorption by vegetation and soil or even prevent it completely with impermeable layers and obstacles. In a country like Sweden the temperature is also an important factor. If the precipitation falls like snow it barely contributes to the discharge of the river. This fact, in combination with the iced waters creates a situation where a large portion of the water in the rivers originates from ground water during the winter months.

5.2 Teleconnections

The correlations with the NAO gave results that resemble to the patterns described by NOAA (2011a). The positive phase of the NAO mainly affects the winter months of the year by bringing mild, moist, air to southern Sweden, giving above normal temperature and precipitation.

The EA time series of the PCA show a pattern similar to the NAO but shifted south, which lessens its influence on southern Sweden. According to NOAA (2011b) a positive phase of the EA should be associated with above-average precipitation in Northern Europe and above average temperatures all over Europe. The discharge time series of the PCA are generally positively correlated with the EA even if the correlation not always is significant. The temperature time series of the PCA also show a positive correlation, just as expected.

According to NOAA (2011c) the EA/WR teleconnection causes higher-than normal winter temperatures, and abnormally low precipitation during fall and winter in southern Sweden during its positive phase. The effect on the discharge can be seen in the first PCA mode of the SON as well as in the second mode of the DJF. First mode of the temperature PCA for DJF shows a significant positive correlation, as indicated by NOAA (2011c).

The SCA mainly affects southern Sweden during winter time, giving below normal temperatures and precipitation, due to the dominant wind from the east that brings cold and dry air from Siberia (Barnston and Livezey, 1987; Bueh and Nakamura, 2007). This is confirmed by the correlations in Table 2 and 3, where the SCA is negatively correlated with the first mode of the PCAs of both discharge and temperature.

The POL is associated with variations in the circumpolar circulation. During its positive phase southern Sweden experiences reduced precipitation during winter and summer, and increased summer temperatures (NOAA, 2011e). The only correlation that confirms the statement is the JJA temperature, where the POL has a significant positive correlation in the first mode, which can be explained by the positive atmospheric pressure anomaly located over central-eastern Europe pressing warm air northwards over southern Sweden.

The capabilities to predict and forecast the modes of the teleconnections are limited. The NAO is the only pattern that is measured at fixed points and even though its existence has been known for many years the forecasts made are often proved to be wrong (Johansson, 2007; NOAA, 2011a). The other teleconnections are less known and there are no known attempts to forecast them. Still, we know they are there and that they are affecting our climate and energy production.

5.3 Data and Methodology

What has not been considered in this analysis is the possibility of a time lag between the time series of the variables in the PCA and the teleconnection indices. The seasons of three months have been defined according to the calendar; maybe the result would have been different if the seasons were defined differently.

When using a PCA to analyze the data it is common to map the eigenvectors of the data points (stations) in order to track down regional differences. In that way clusters of station located in areas that show a more similar pattern can be created. The eigenvectors of the production have been mapped in this PCA too; however, no clear cluster emerged. This fact can be explained by the relatively small geographical region covered by the analysis and the fact that the hydropower stations serve areas experiencing a relatively uniform climate situation.

As mentioned in the Methodology chapter the PCA has some proven limitations (Dommenget, and Latif, 2002; Hurrell and Deser, 2009). A simple option would be to basically correlate all the data sets, station by station with the times series of the teleconnection indices. Considering the output of that method it would be difficult to understand “the big picture”. The result would be an average of all the correlations of the production, discharge and temperature respectively and no attention could be put to the differences of the time series. Even if one time series of the discharge would differ considerably from the others it would still be given the same weight in the end. Using the PCA the geographical differences of the time series are represented by the eigenvectors and a time series is created that well represents the data in the original data sets.

It is complicated to measure the reliability of an analysis from the perspective of the time period included, how many years of data is “enough” to give a trust worth answer? All the data variables used in the analysis spanned over different time periods. Only data from overlapping time periods could be used, which limited the amount of data that actually could be included in the PCA and Spearman analysis. The shortest time span of data was used in the PCA of the production, including April 1999-December 2010, while the data of the discharge covers 1950-2008 and the temperatures 1961-2010. The teleconnection indices covered 1950-2010. Of course one could claim that longer time series would give a more reliable result, but still this period analyzed captures the different phases of every teleconnection and the year-to-year variations in electricity production, discharge and temperature of southern Sweden. The fact that the PCA showed that the stations analyzed have a relatively similar behavior that can be explained by their internal relatively short geographical distance and to include more stations within the same area is expected to give similar results.

5.4 Results

5.4.1 DJF

Results obtained show that the wintertime hydropower production, discharge and temperature are mainly ruled by the NAO and the SCA, which positive phases have opposite effect on production, discharge and temperature. NAO is positively correlated with the time series of the first mode of the PCA of the three parameters analyzed. The teleconnection explains 29% of the variability of the hydropower production for DJF. This means that when the pressure difference between the Icelandic low and Azores High is higher than normal westerly winds dominate over southern Sweden, bringing mild, moist air from the Atlantic and, consequently, more precipitation and higher temperatures. The increased precipitation secures the water availability in the dams and the mild temperatures keep the water from freezing, which contributes to a higher hydropower production.

The SCA is the second most dominant mode in DJF, explaining 18 % of the variability of the hydropower production, and acting at the contrary of the NAO in DJF, giving easterly winds over southern Sweden. This can also be seen in Table 1-3 where the SCA almost always has a correlation of different sign than the NAO. The winds from the east originate from the Siberian landmass and are cold and dry, giving colder temperatures, which limits the water availability and increases the demand, and less precipitation, which also can be seen in the correlation with the production and temperature time series of the PCA, where the SCA shows a strong significant negative signal.

The EA/WR dominated the second mode of the wintertime production PCA with a strong negative signal, explaining 14% of the hydropower production in the second mode of the PCA for DJF. Looking back at Figure 11 of the pressure anomalies and wind directions associated with the positive phase of the EA/WR one can see that the positive pressure anomaly located over northern France/southern Great Britain makes the air flow from the north-east over southern Sweden. On its way from the Atlantic it passes over the mountainous region of southern Norway where it loses a lot of its water, resulting in drier conditions in southern Sweden.

5.4.2 MAM

The patterns of the spring are different for every variable analyzed. The EA/WR is the dominant teleconnection, affecting the hydropower production negatively through its positive phase and explaining 11% of its variability. Surprisingly the same teleconnection has no strong correlation neither with the time series of the PCA for the discharge or temperature during MAM. Instead, the spring discharge is positively correlated with the SCA and negatively correlated with the EA, while the temperatures are mainly governed by the NAO, still bringing mild air from the Atlantic.

5.4.3 JJA

In JJA the effect of the EA/WR on the hydropower production is slightly stronger, the teleconnection explains 17% of the variability. The same teleconnection shows a weak, but still significant, discharge signal. Since stated earlier that the hydropower production depends on temperature and demand this result makes sense. In the summer months the temperature is not the critical point for the hydropower production in southern Sweden, but water availability can be an issue.

5.4.4 SON

During the fall no significant correlation appears between the teleconnection indices and the production time series of the PCA. Still, the EA/WR affects the discharge the most, a bit more than during the summer and the temperature is once again ruled by the NAO.

6 Conclusion

In this thesis the relations between Northern Hemisphere teleconnections and the hydropower production in southern Sweden has been analyzed. Northern Hemisphere teleconnections do not alone rule the climate in southern Sweden but they show strong seasonal influences, which in turn affect the hydropower production. The results of the analysis show that the effects of the teleconnections vary with season:

- The DJF hydropower production in southern Sweden is mostly affected by the NAO and SCA that explain 29 and 18 % respectively of the total variance for that season.
- During the MAM months the EA/WR teleconnection explains 11 % of the variance of the hydropower production.
- The production in JJA is mainly ruled by the EA/WR teleconnection, explaining 17% of the variance for that season.
- For the SON season there is no clear relation between the phases of the Northern Hemisphere teleconnections and the hydropower production in southern Sweden.

Hydropower is a worldwide growing industry and an energy source on which many countries rely heavily. This dependency makes the research of what factors that affect the energy output interesting, not only to explain historic and current conditions but also in the development of new power plants and energy sources.

7 Areas of future research

The Swedish government has high goals regarding the development of renewable resources and the future for renewable energy sources in Sweden looks bright. In this paper the focus has been on the effects of teleconnections on the hydropower production in southern Sweden. The same methods could also be used to evaluate the situation for other renewable energy sources, like wind power and wave power. Knowing the dominant wind directions, maybe what temperatures they can be associated with, their strength and their reoccurrence could be important factors to consider when planning the layout of new wind power parks in order to maximize the parks' availability and energy output. Regarding wave power the strength and persistence of the wind should be considered in order to estimate the height and force of the waves. In order to pick a good location the wind directions also need to be considered.

The same type of analysis that has been conducted here could also be done for other regions and countries that rely on hydropower or have plans developing their renewable energy sources.

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