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North Atlantic Oscillation; a Climatic Indicator to Predict Hydropower Availability in Scandinavia

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Climate variability and climate change are of great concern to economists and energy producers as well as environmentalists as both affect the precipitation and temperature in many regions of the world. Among those affected by climate variability is the Scandinavian Peninsula. Particularly, its winter precipitation and temperature are affected by the variations of the so-called North Atlantic Oscillation (NAO).

The objective of this paper is to analyze the spatial distribution of the influence of NAO over Scandinavia. This analysis is a first step to establishing a predictive model, driven by a climatic indicator such as NAO, for the available water resources of different regions in Scandinavia. Such a tool would be valuable for predicting potential of hydropower production one or more seasons in advance.

Introduction

Climate variability and possible climate change have been of great concern to economists and, energy producers and managers as well as environmentalists over the last few decades. There are reasons to believe that society, including its activities related to water resource management and energy production, is affected by climate variability or climate change. Areas that depend on energy generated by hydropower stations are especially likely to be vulnerable. Scandinavia is such an area; it experiences climate variations and both Norway and Sweden are dependent on water resources for energy production. For this reason, it is important to find links between large-scale atmospheric circulation and variations in the water resource availability in this area.

The Scandinavian climate is affected by the variations of the so-called North Atlantic Oscillation (NAO). Simply put, NAO is an atmospheric oscillation that relates the Icelandic Low Pressure and the Azores High Pressure so that when the atmospheric pressure is unusually high around Iceland, it is unusually low around the Azores, and vice-versa (Hurell 1995; Reeds 1999; Kushnir 1999). The effects of this oscillation are noticeable mainly during winter and directly influence the meteorological and climatological conditions in Scandinavia. Thus, there are seasonal variations in precipitation and temperature and consequently in water resources and their use.

A NAO index was defined as the difference between the normalized pressure over the Azores High and Icelandic Low for the winter months (December to March) (Rogers 1984; Hurrell 1995). A positive index corresponds to an intensification of both systems, that is, atmospheric pressure lower than normal in the Icelandic Low and higher than normal in the Azores High, during winter. A negative index indicates the opposite situation. The evolution of the NAO index over time oscillates between positive and negative values from year to year, the so-called NAO interannual variability.

An example of a situation when the NAO affected water resources and consequently energy production in the energy system in the Nordic countries is what occurred during the first half of the 1990s. During this period the NAO was mainly positive and the Nordic countries maintained energy production surpluses that allowed for a considerable increase in the exports of this sector. However, a break in the NAO positive period was observed during winter of 1995/96, when northern Europe and Scandinavia experienced an abnormally dry and cold winter (Halpert and Bell 1997). After this dry winter, the Norwegian newspaper "Aftenposten" (06/March/1997) stated that during the period between January 1996 and January 1997, energy production in Sweden and Norway decreased to the lowest annual value since 1881. In the following winter (1996/97) the NAO returned to its positive phase and a mild, wet winter ensued. As a consequence, snow storage in Sweden/Norway was above normal and, at the time of the snowmelt, Sweden and Norway had a combined energy surplus of 19 TWh. On the 10th August 1998, Aftenposten informed its readers that prices for energy produced by the Nordic Energy System (integration of the Swedish and Norwegian energy production systems) were the lowest for a long time. Data available from the Energy Information Administration – EIA (available on http://www.eia.doe.gov) – corroborate the variation in prices and energy production that made headlines in the Norwegian newspaper. Considering annual hydropower production for Sweden and Norway as a whole, 1996 had the lowest energy production of the decade, 153.8 TWh; a reduction of 18% compared to 1995. On the other hand, the annual average electricity prices for households in 1996 were the highest of the decade.

The objective of this paper is to analyze the spatial distribution of the influence of NAO over Scandinavia. This analysis is a first step to establishing a predictive model between a climatic indicator and the available water resources in different regions of Scandinavia. Potentially, the NAO could act as a predictor for winter precipitation and temperature in Scandinavia at least one season in advance. These in turn are key variables for the estimation of water resources and, in the case of Scandinavia, a valuable tool to predicting the energy potential one or more seasons in advance.

North Atlantic Oscillation and Scandinavian Climate

Precipitation and temperature variability during the European winter has long been associated with the NAO. As mentioned earlier, a positive NAO is associated to the intensification of the Icelandic Low and the Azores High. It is characterized by stronger than average westerly winds across middle latitudes, a shift and intensification of the North Atlantic stormtrack into northern Europe (Rodwell *et al.* 1999), an extension of the axis of maximum moisture transport further to the north and east into Northern Europe and Scandinavia, and the occurrence of enhanced moisture flux convergence from Iceland to Scandinavian Peninsula (Hurrell 1995). As a result of these changes, positive NAO is often associated with above-normal temperatures and precipitation across northern Europe and Scandinavia and below-normal temperatures in Greenland, across southern Europe and the Middle East during winter time (Walker and Bliss 1932; Wallace and Gutzle 1981; van Loon and Rogers 1978). Opposite patterns of pressure, winds, and moisture (and thus precipitation and temperature in Scandinavia and northern Europe) are associated with negative NAO. In fact, the NAO accounts for ~10% of the variance in precipitation for December-February over North Atlantic surrounding regions (Dai *et al.* 1997).

The NAO is a natural mode of atmospheric variability that is not yet completely understood. There is evidence, however, that much of its variability comes from internal atmospheric processes. Furthermore, an important aspect of the NAO is that dynamic coupling with the ocean is not an essential feature of its dynamics (Greatbatch 2000).

The NAO has a known inter-annual oscillation between positive and negative phases, besides this, it has the remarkable characteristic of long–term trends. From the turn of the twentieth century until about 1930, the NAO showed a positive tendency that reversed from the early 1940's to the early 1970's. The last 25 years have seen unprecedented strongly positive NAO values (Hurrel 1995, 1996). As a consequence, winters during this latest period have been predominantly mild and wet over Scandinavia (Hurrell and van Loon 1997).

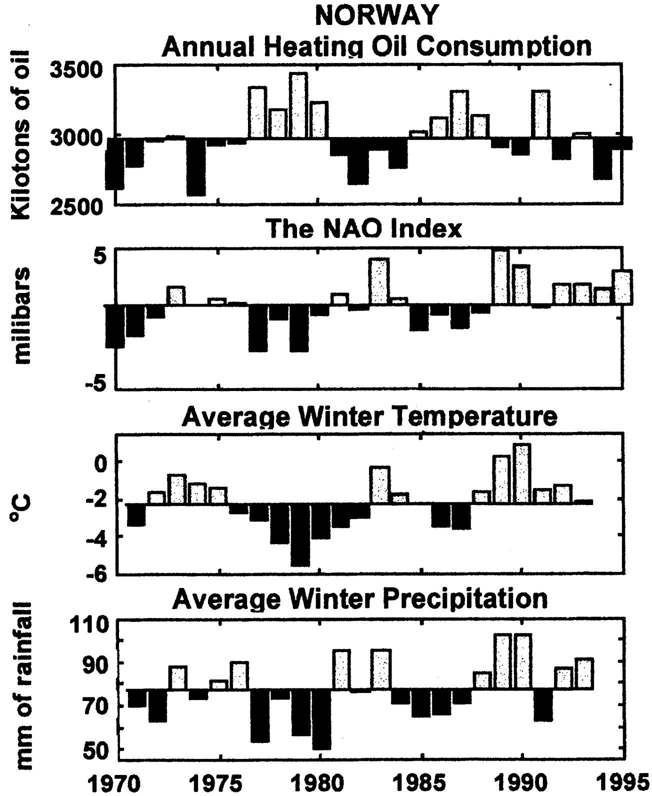

Fig. 1. NAO index, temperature, precipitation and oil consumption in Norway for 15 years.

Fig.1, extracted from Visbeck *et al.* (2001), shows how the NAO index, winter temperature, precipitation, and consumption of heating oil varied together in Norway over a 15 year period. A close relationship among all these variables is shown as is the long–term variability of NAO during these years.

Data and Methods

Data Used

A set of monthly precipitation totals at 102 stations which are well distributed (see Fig.3) over Norway, Sweden, and Finland was analyzed. These data were provided by the International Research Institute for Climate Prediction, the Swedish Hydrological and Meteorological Institute, and the Norwegian Institute of Meteorology and extend from 1967 to 1996. The monthly totals were collated at each station from December to March so that the total winter precipitation could be analyzed. A time series of winter NAO indices (Dec to Mar) was also analyzed. The series was provided by J. Hurrell and is available on http://www.cgd.ucar.edu/cas/climid/nao_winter.html.

Due to recent NAO and precipitation trends in Scandinavia, all the time series were linearly detrended before their use in the analyses described below.

Methodology

Correlation analysis was carried out between every precipitation time series and the NAO index. Further investigation of the precipitation data was then made by means of cluster analysis. Cluster analysis is used to group variables into subsets that are linearly related to each other. Cluster analysis methods are used to develop dendograms that are treelike hierarchical diagrams showing the relationships among all variables in a given set (Krumbein and Graybill 1965). The correlation matrix was used as a basis for discerning the level of the relationship found between variables. Thus, one or more pairs of attributes are selected as highly correlated, and linkages are computed between these pairs and the remaining variables to develop a hierarchy of the interrelations that shows the levels of the linkage in the set of data. It is a common practice to use orthogonal solutions as input for the cluster analyses. In this work, empirical orthogonal functions (EOF) were applied to the precipitation data and the four first modes resulting from the EOF were used in the cluster analysis.

Results

General

The results of the correlation analysis showed that precipitation in several regions of Scandinavia is highly correlated to NAO index, so that a positive NAO index is related to an increase in winter precipitation and a negative with a decrease. The areas for which winter precipitation is significantly correlated to the NAO index are the Norwegian west coast and southern Finland. Fig. 2 shows the correlation coefficients found between winter precipitation and NAO (correlations of 0.6 are >99% significant).

Correlation coefficients of up to 0.8 were observed over the southwestern Norwegian coast. These high correlations are due to the orographic lifting of the moist westerly winds from the Atlantic that are related to the NAO by the local orography.

On the lee side of the mountains, there is a sharp decrease in the correlation coefficients. Lower correlations are found over most of Sweden, especially in the southeastern part of the country where mainly negative values are observed. Further east, over Finland, there is an increase in correlation and the coefficients reach values of up to 0.7.

A reason for this distribution of correlation can be found in the circulation that influences the region during winter-time. Analyses of winter circulation show that the Norwegian coast is directly affected by the westerly winds generated by the Ice-

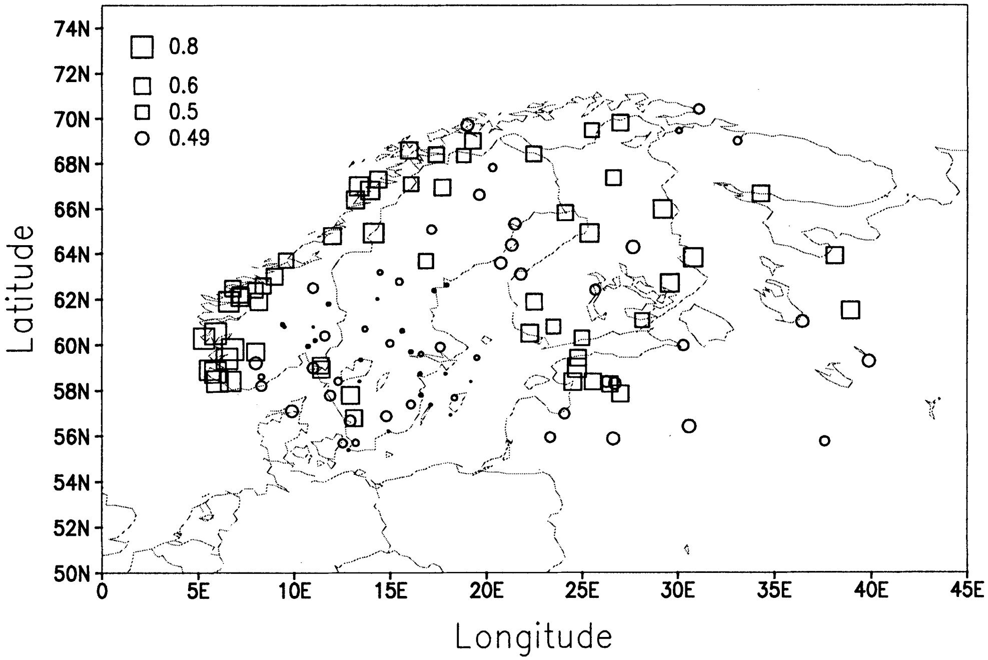

Fig. 2. Correlation between NAO and precipitation in Norway, Sweden and Finland. The size of the symbols is proportional to the correlation. Correlations represented by squares are statistically significant at 99%.

landic Low and Azores High over the Atlantic. This winds also penetrate the European continent further south reaching locations as far away as Siberia (Greatbatch 2000).

The eastern side of the Scandinavian Peninsula is, however, on the lee side of the mountain chain that extends from southwest to northeast of the peninsula and, thus, is less influenced by the westerly winds. Precipitation in the south of Sweden is mainly affected by moisture-bearing winds coming from southeast which collect humidity over the Baltic Sea. This distinct mechanism explains the low correlation coefficients between NAO and precipitation over this area. Finland on the other hand, is also affected by the westerly winds that cross northern continental Europe and reach areas further to the east.

Spatial Variation

To better understand the variability of the influence of the NAO and to better delimit its extent, cluster analysis was carried out using the total winter precipitation for the 102 precipitation stations.

An EOF analysis of the precipitation was made and a cluster analysis was performed using the first 4 modes of the EOF. Together, they explain 78.0% of the vari-

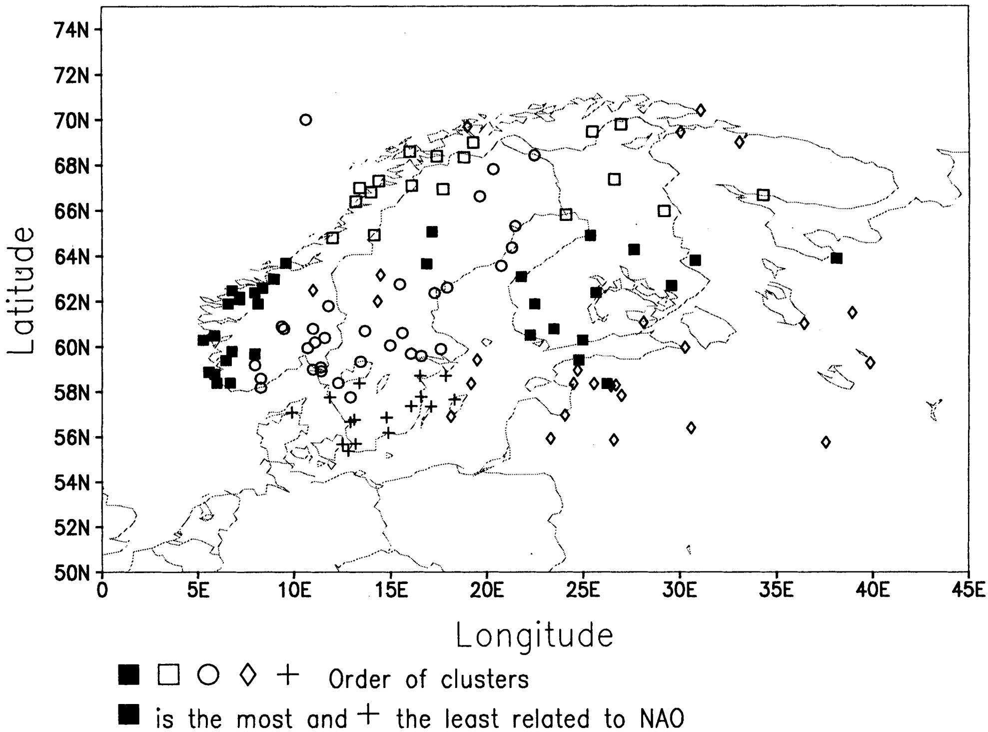

Fig. 3. Result from the cluster analysis. Stations indicated by the same symbol belong to the same cluster.

ance of precipitation. Fig. 3 shows the result of this analysis. The best results were obtained when the region was divided into five areas with distinct influences.

Comparing Fig. 2 and Fig. 3, it can be easily seen that the stations represented in Fig. 3 by closed squares are most influenced by the NAO index, while stations represented by crosses are the least influenced and the remaining categories are in intermediate stages.

This characteristic division is also clear on the first two eigenvectors of the EOF of precipitation (not shown). They illustrate that winter precipitation in the southwestern part of Sweden is characterized by different behavior compared to the rest of the region.

Effect on Hydropower Production

The effect of winter precipitation on hydropower production in Scandinavia is mainly related to the filling of the hydropower reservoirs in spring. Snow accumulated during winter feeds the reservoirs in spring and, thus drives the energy production for the next year, as well as energy prices.

Practically all of Norway's electricity is generated by hydropower (Statnett 2000). Sweden, on the other hand, has 47% from hydropower stations and another 47% from nuclear power stations. Most of the electrical energy consumed is, however, generated by hydropower stations. The consumption of energy generated by nuclear power stations and other thermal power stations is variable both throughout the year (maximum during winter and minimum during summer) and from year to year depending on how much hydropower is available (Electric Power in Sweden 1999).

By way of example, during 2000, when a highly positive NAO index was observed (Hurrell winter NAO index of 2.8), the production of energy by nuclear power stations in Sweden was at a record low due to a good supply of water to the hydropower reservoirs. This supply was also responsible for lowering the energy prices during that year.

The recent policy of closing nuclear power stations in Sweden (reactors at the Barsebäck nuclear power station were turned off in November 1999) is likely to cause further stress in the electricity production of existing hydropower stations and the necessity of river and reservoir management should be strengthened. At the same time, the new Swedish policy of stimulating the construction of small hydropower stations (0.1 to 1.5 MW) will require closer management of reservoirs and consequently, more accurate information about climate variability.

The relationship between winter precipitation and the NAO provides a possibility of predicting precipitation that would be available to hydropower reservoirs in spring. This would be valuable information for reservoir managers, energy producers, and ultimately for the estimation of energy prices.

Conclusion

This work shows by means of simple correlation and cluster analysis how the NAO is correlated to winter precipitation in different regions of Scandinavia and how this may affect hydropower production and energy prices. This analysis constitutes a first step to developing a quantitative model to predict water availability in relation to large-scale climate. In areas that are strongly affected by the NAO, a predictive tool based on it can be developed.

These results clearly show that the influence of the NAO on precipitation in the region is variable. It is strongest over the Norwegian coast and southern Finland, followed by areas in northern Sweden. These are areas which are responsible for most of the hydropower production in these countries. In turn, this means that the results are encouraging to the development of a quantitative model to estimate water and hydropower availability.

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References

Dai, A., Fung, I.Y., and Del Genio, A. D. (1997) Surface observed global land precipitation variations during 1900-88, *J. of Climate*, *Vol. 10*, pp. 2943-2962.

Electric Power in Sweden (1999) Annual Report. Available from http://www.kvf.se/

Greatbatch, R. J. (2000) The North Atlantic Oscillation, *Stochastic Environ. Res. and Risk Assessment*, *Vol. 14* (4/5), pp. 213-242.

Halpert, M. S., and Bell, G. D. (1997) Climate Assessment for 1996, *Bull. Am. Met. Soc.*, *Vol. 78* (5), pp. 1038–1038.

Hurrell, J. W. (1995) Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation, *Science*, *Vol. 269*, pp. 676-679.

Hurrell, J. W. (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature, *Geophys. Res. Letters*, *Vol. 23*, pp. 665-668.

Hurrell, J. W., and van Loon, H. (1997) Decadal variations in climate associated with the north Atlantic oscillation, *Climate Change*, *Vol. 36*, pp. 301-326.

Krumbein, W.C., and Graybill, F.A. (1965) *An Introduction to Statistical Models in Geology*, McGraw-Hill, New York.

Kushnir, Y. (1999) Europe's winter prospects, *Nature*, *Vol. 398*, pp. 289-291.

Reeds, J. (1999) Ocean Review, *Geographical*, *Vol. 71*, pp. 72-74.

Rodwell, M.J., Rowell, D. P., and Folland, C. K. (1999) Oceanic forcing of the wintertime North Atlantic Oscillation and European climate, *Nature*, *Vol. 398*, pp. 320-323.

Rogers J. C. (1984) The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere, *Mon. Wea. Rev.*, *Vol. 112*, pp. 1999-2015.

Statnett (2000) Annual Report. Available from http://www.statnett.no

van Loon, H., and Rogers, J. C. (1978) The Seesaw in Winter Temperatures between Greenland and Northern Europe. Part I: General Description, *Mon. Wea. Rev., Vol. 106*, pp. 296-310.

Visbeck, M., Cullen, H., and J. Cherry (2001) The NAO: A climate phenomena with significant impacts on society. In: Proceedings of the Symposium on Climate Variability, the Oceans, and Societal Impacts. AMS 81st Annual Meeting, 14-19 January, pp. 192.

Wallace, J. M., and Gutzler, D. S (1981) Teleconnections in the Geopotential Height Field During the Northern Hemisphere Winter, *Mon. Wea. Rev.*, *Vol. 109*, pp. 784-812.

Walker, G. T., and Bliss, E. W. (1932) World Weather V, *Mem. Roy. Meteorol. Soc.*, *Vol. 44*, pp. 53-84.

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