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Impacts of the North Atlantic Oscillation on Scandinavian Hydropower Production and Energy Markets

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Abstract. Dramatic swings in the North Atlantic oscillation (NAO) during the 1990s motivated the authors to build a statistical model of NAO impacts on hydropower production and energy markets in Scandinavia. Variation in the NAO index is shown to explain 55% of the variance of streamflow in Norway and up to 30% of the variance in Norway's hydropower output. It is also possible to identify the influence of NAO anomalies on electricity consumption and prices. Government liberalization allowed a financial market to grow around the international trading of electricity, which in Norway is produced almost entirely from hydropower. The model offers a possible tool for predicting the effects of future NAO movements on hydropower production and energy prices in Scandinavia. The potential influence of skillful climate prediction is discussed.

Key words: North Atlantic oscillation, social impacts, energy, hydropower, climate impacts

1. Introduction

1.1. THE NAO AND ITS PHYSICAL CLIMATE IMPACTS

The North Atlantic oscillation (NAO) is the dominant mode of atmospheric variability influencing climate in the nations surrounding the North Atlantic basin (Marshall *et al.*, 2001; Hurrell *et al.*, 2002). Though it was observed as early as 1770 by the missionary Saabye (1942), the NAO was first defined by Walker and Bliss (1932) as an alternation of atmospheric mass between the subtropical high, centered near the Azores, and the subpolar low, centered over Iceland. Changes in the strength of these two cells are coherent; when the sea level pressure is anomalously low near Iceland it tends to be anomalously high near the Azores and *vice versa*. The normalized difference in mean December-March (DJFM) sea level pressure (SLP) between Lisbon (Portugal) and Stykkishomur (Iceland) is defined by Hurrell (1995)

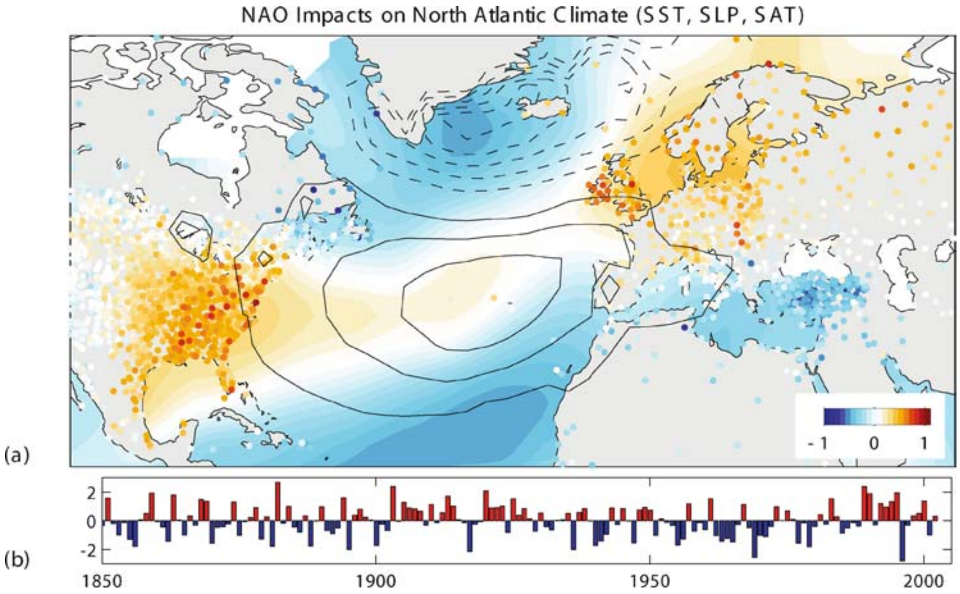

Figure 1. (a) NAO index correlation with DJFM SST from Kaplan *et al*. (1998), correlation with DJFM SAT from NCDC/GHCN, and covariance with DJFM SLP at 0.3 HPa contour intervals (NCEP reanalysis). (b) NAO index from Jones *et al*. (1997).

as the NAO index. This index, as well as proxy reconstructions (Appenzeller *et al*., 2000; Cullen *et al*., 2001; Cook, 2002), shows a broad spectrum of variability, with weak preferences for 2-3 years, decadal, and multi-decadal time scales. The NAO index and some associated physical impacts of the NAO are shown in Figure 1.

While the NAO signal is discernible throughout the year, it is strongest in winter (DJFM). Correlation of the NAO index with North Atlantic sector winter temperature, SST, and covariance with SLP reflects a dipole pattern (Figure 1). During a positive NAO phase, the strong pressure gradient between the subtropics and the subpolar region is associated with strong westerlies and a northward shift of the stormtracks. During a negative phase, the westerlies slacken and storms cross the Atlantic on a more zonal trajectory. Temperature and precipitation in northern Europe, the western Mediterranean, and the southeastern US exhibit a positive correlation to the index; during a positive NAO year, these regions experience anomalously warm and wet conditions and during a negative NAO year these regions are anomalously cold and dry. Temperature and precipitation in southern Greenland and eastern Mediterranean countries exhibit a negative correlation to the NAO index; when the NAO is positive these regions are colder and drier than normal and when the NAO is negative they are warmer and wetter than normal (Hurrell and van Loon, 1997; Hurrell *et al*., 2002).

Figure 2 shows that temperature in Norway, Denmark, Finland and Sweden is strongly correlated with the NAO index. Precipitation in Norway is closely linked

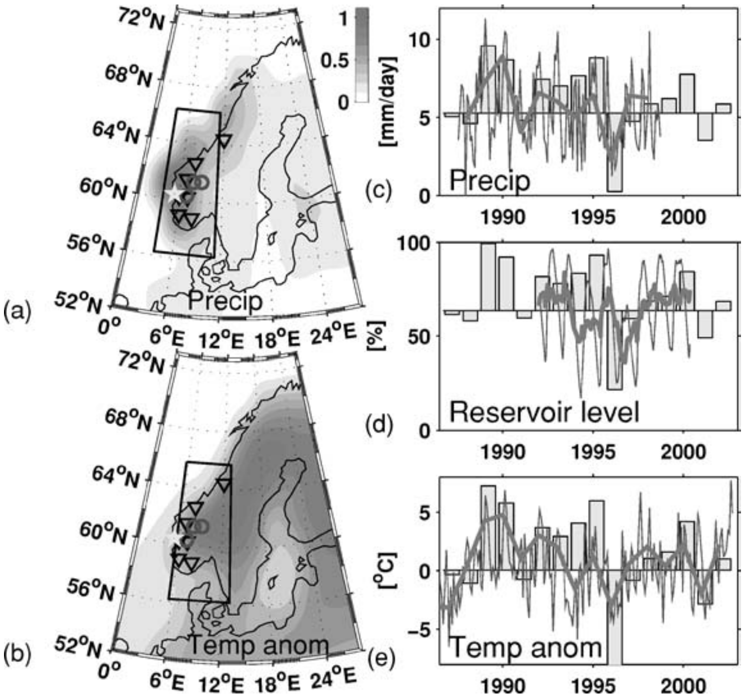

Figure 2. Leading EOFs of Xie and Arkin (1996) precipitation dataset (a) and NCEP Reanalysis temperature field (b) and the corresponding time series from the black box (c) and (e). All are normalized by the maximum covariance. The Bergen station is marked by a star. Triangles are major reservoirs. Circles are Norsk Hydro stations from which data is presented below. (c) and (e) show both monthly and average winter values. The NAOI is shown as bars in (c), (d), and (e). Weekly levels for major reservoirs are shown in (d) along with the running mean.

to both interannual variability in the NAO and the decadal-scale trends in the NAO, also shown in Figure 2. Precipitation in Denmark, Finland, and Sweden, however, is weakly correlated with the index; the impact of the NAO in those countries is thought to be moderated by the presence of the Baltic Sea and the Kjolen Mountains, located between Norway and Sweden.

Previous studies, many which are referenced in Hurrell *et al.* (2002), have described the impact of the NAO on climate which, in turn, affects people and their environment. For changes in physical systems, there is no simple way to assign a dollar value to the impact of climate variability. In this study, we examine an impact of climate variability that has a specific value in the financial market associated with the Scandinavian energy sector. First, the reader is given some background in the Scandinavian energy sector and the 1996–1997 NAO event. Then a conceptual framework is described and tested which links changes in supply and demand to the physical climate impacts. Next, we show how a statistical model can predict price movements associated with the NAO. Finally, the implications of this model are discussed.

1.2. THE RELATION BETWEEN ENERGY IN NORWAY AND SWEDEN AND THE NAO

Norway, and its energy trade with Sweden, is examined as a case study in part because the Norwegian energy sector has qualities that are particularly useful for analyzing the relationship between climate and energy commodities. Norway's climate and topography make it ideal for hydroelectric power generation. More than 99% of electricity generation in Norway comes from hydropower (IEA, 1997). Norway has the highest electricity consumption per capita in the world, due in part to its cold climate. In 1994, 65% of typical household energy consumption was for house and water heating (IEA, 1997). Sweden generates 47% of its electricity from hydropower and 47% from nuclear (SPA, 1999). Swedish households depend on electricity for only 30% of their heating (SPA, 1999). Electricity production for Norway and Sweden is shown in Figure 3. Both Norway and Sweden underwent market deregulation and increased privatization during the 1990s.

1.3. MOTIVATION FOR THIS STUDY: THE 1996–1997 NAO PHASE SHIFT

Norway enjoyed its largest hydropower surplus ever during the late 1980s and 1990s coincident with the strong positive phase of the NAO index, which brought anomalously large amounts of precipitation to Norway. Hydropower generation was 120.1 billion kilowatt hours (kWh) during 1995 and then dropped to 102.6 and 108.7 billion kWh in 1996 and 1997 (Figure 3), respectively (EIA, 2001).

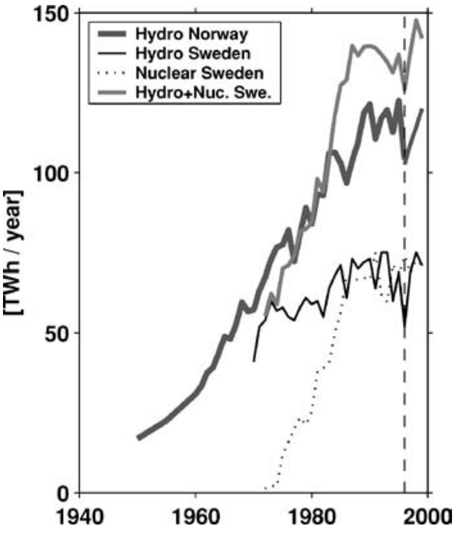

Figure 3. Energy production for Norway and Sweden is shown. Sweden's energy is produced by about 50% hydroelectric and 50% nuclear. Note that part of the interannual variability in hydroelectric energy generation is offset by appropriate adjustments in the nuclear output. However, the 1996 event was still large enough to cause a significant signal in Sweden's overall energy production.

During 1995, contracts were sold by Norwegian producers to utilities to provide power to end-users both locally and abroad.

From 1992 to 1994, the average DJFM NAO index values ranged between 2 and 2.4. In 1995, the index hit 3.4 only to drop down to −4.0 in 1996. In 1997 it remained near zero. The large swing in the phase of the NAO in 1996 brought international attention to the physical connection between the NAO and the availability of water in Scandinavia for hydropower.

When the country faced drought during the winter of 1996, hydropower stations could not produce enough electricity to meet those contracts. In order to do so, producers had to buy power on the short-term markets at a high cost to the industry and consumers (Royal Ministry of Foreign Affairs, 1996). During the spring of 1997, Norway imported a large amount of electricity from coal-fired power plants in Denmark, a management strategy which may be more difficult in the future if these countries are bound to any commitments under the Kyoto Protocol (CADDET, 1997).

Within Scandinavia, Norway has the greatest volume of water in reservoirs and also the highest amplitude of variability in reservoir level. The peak influx is in early summer following snow melt and the peak reservoir level is in late summer or early fall (Figure 2d). During the annual maximum in 1995, reservoirs in Norway were at about 95% of capacity, while during the peak in 1996, they were only at 65% of capacity. In 1998, the NAO returned to a strong positive phase and the reservoirs filled again. Knowing the past variability of the NAO and the relationship between the NAO and water availability may help producers plan the appropriate level of capacity for new infrastructure in the power supply system, which Norway and Sweden are continuing to build.

2. Method

The method for this study is divided into two parts. Ultimately we want to test whether or not it is possible to predict energy prices based on the NAO index. However, the record of market prices for Scandinavian hydropower is short and therefore of limited statistical significance. For this reason, it would be valuable to first look at the climate and energy time series data available (Part I). These time series represent the physical and economic mechanisms behind the NAO impact. These data are examined through a framework from classical economic theory. Because Part I is an intermediate step in this method, results from this part will be presented in the Methods section. Results from Part II, the statistical model, will be presented in the Results section.

2.1. PART I: ASSESSING CLIMATE-DRIVEN CHANGES IN SUPPLY AND DEMAND TIME SERIES

A conceptual framework was devised using basic supply and demand curves from economic theory. This framework (as it applies to the 1996–1997 negative phase

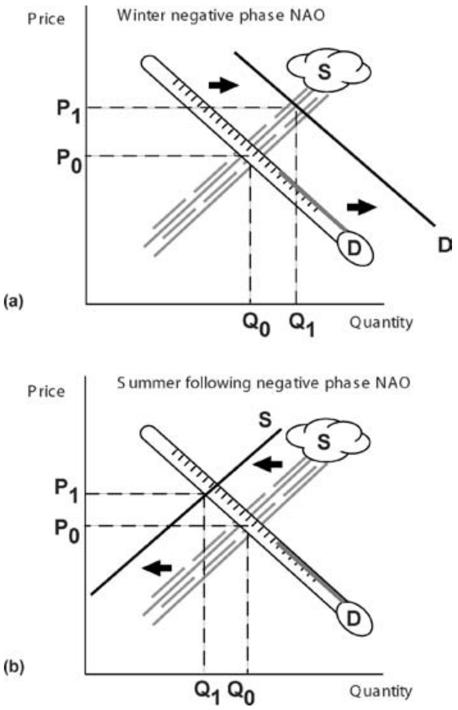

Figure 4. The NAO-negative event economic framework is shown, which describes the 1996–1997 event. The energy supply and demand curves are plotted on axes of quantity and price. During a negative NAO, demand moves first; during a harsh winter more energy is demanded (a). Come spring and early summer, supply decreases as less meltwater is available (b). The result of both shifts is that price is significantly higher. In the winter, equilibrium quantity increases, whereas in the summer it decreases.

NAO event) is illustrated in Figure 4. If price and quantity of hydropower are plotted against one another, two curves can be drawn to represent the hydropower supply and the hydropower demand, assuming the market is competitive. This is a strong assumption, given the tendency for energy firms to be monopolies, however the advent of market liberalization and an international futures market create incentives for the hydropower suppliers to behave competitively. The supply curve represents how much producers are willing to sell for each price they receive in the market (Pindyck and Rubinfeld, 1995). The higher the price, the more firms are willing and able to produce. The demand curve shows how much consumers are willing to buy at each price per unit. The lower the price, the more the consumers are willing and able to consume. The intersection of supply and demand curves determines the equilibrium price and quantity.

During a positive NAO event, which begins in late fall to early winter, Norway is anomalously warm. Households and commercial entities consume less electricity and other heating resources than normal. Because the change has affected the market as a whole, the entire demand curve can be thought of as shifting inward. This should happen almost immediately during the onset of a strong positive NAO event. The equilibrium price and quantity both shift down. Also during a positive NAO winter, precipitation is greater. However this does not affect the hydropower supply until summer and early fall, when the past winter's snow melts and flows into the reservoir. When that does occur, the supply curve effectively shifts out and the equilibrium price will remain low. The resulting equilibrium quantity may be greater or lesser depending on the relative shifts of the supply and demand curves.

During a negative NAO event, Norway is anomalously cold and dry. People consume more electricity than normal, shifting the demand curve outward and pushing the equilibrium price higher. By summertime, it becomes clear that there is less water in the reservoirs and a smaller hydropower supply potential. This maintains the high equilibrium price. The fact that temperature and precipitation are aligned such that cold and dry and warm and wet are paired under the two NAO phases should mean that a clear price signal from the NAO is expected.

A number of datasets are used to test these hypotheses. The supply side (precipitation) is illustrated in Figure 5. Norsk Hydro, a Norwegian utility company, provided data on the stream flow through several of their power stations. Melt season (April–September) mean stream flow anomalies for the Viveli/Roldalsvatn, Tyinosen, and Koldedalen stations are plotted together with the NAO index. Next, the monthly levels of major reservoirs in Norway are plotted against the NAO index. These data are provided by Statistics Norway, as is the time series of annual hydropower production anomaly in Norway. The raw production data have a strong trend, as was shown in (Figure 3), due largely to economic development. In order to study the correlation between climate variability and energy this trend needs to be removed. Here three different detrending methods are compared: a simple linear detrend, a 12-year highpass filter, and dividing by real (constant dollar) Gross Domestic Product per capita (WDI, 2004). All three methods produce similar correlation coefficients (≈ 0.5) with the NAO index. Finally, two different time series are used to illustrate precipitation in Norway. The station data from Bergen is long (more than 70 years), but limited to a single station. A gridded principal component of the leading EOF precipitation station dataset (Xie and Arkin, 1996) provides better spatial coverage, but unfortunately is a much shorter time series. Not surprisingly, there is high covariance between the two time series where they overlap (1987–1996). The interannual variability in both precipitation datasets matches closely that of the NAO index. Correlation coefficients show highly significant correlations between the NAOI and precipitation in Bergen (0.78), streamflow (0.74), reservoir levels (0.62), and hydropower production (0.50).

Next, the demand side of the framework is explored in Figure 6. Consumption data are obtained from Statistics Norway and are detrended in the same manner as for production. The trends in consumption and production follow each other closely. Winter temperature and hydropower consumption anomalies both have a high correlation with the NAOI, with correlation coefficients of 0.67 and -0.55, respectively.

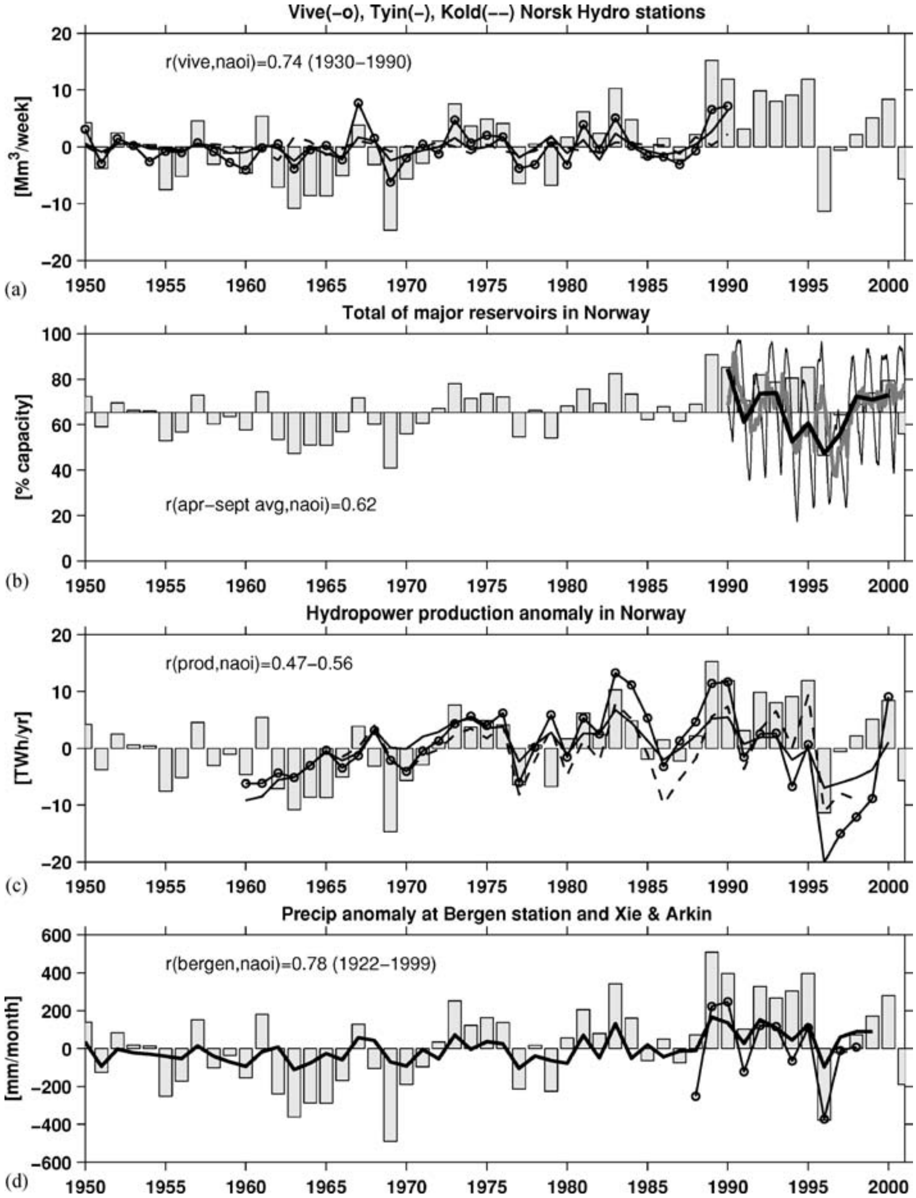

Figure 5. The supply side of the economic framework is shown. The NAO index is plotted as bars. The melt season (April–September) average streamflow anomaly for Norsk Hydro stations Viveli, Tyinosen, and Koldedalen are plotted in (a). The reservoir levels are shown in (b): weekly (thin line), weekly minus seasonal cycle (grey line), and melt season average (thick line). In (c) the annual hydropower production anomaly is plotted, detrended by per capita constant dollar gross domestic product(−), linearly (−o), and a 12-year highpass filter(–). In (d), the precipitation station average winter (December–March) anomaly from Bergen (−) and the principal component of the Xie and Arkin (1996) winter precipitation anomaly (−o) are plotted. Correlation coefficients are shown for several supply time series and the NAOI.

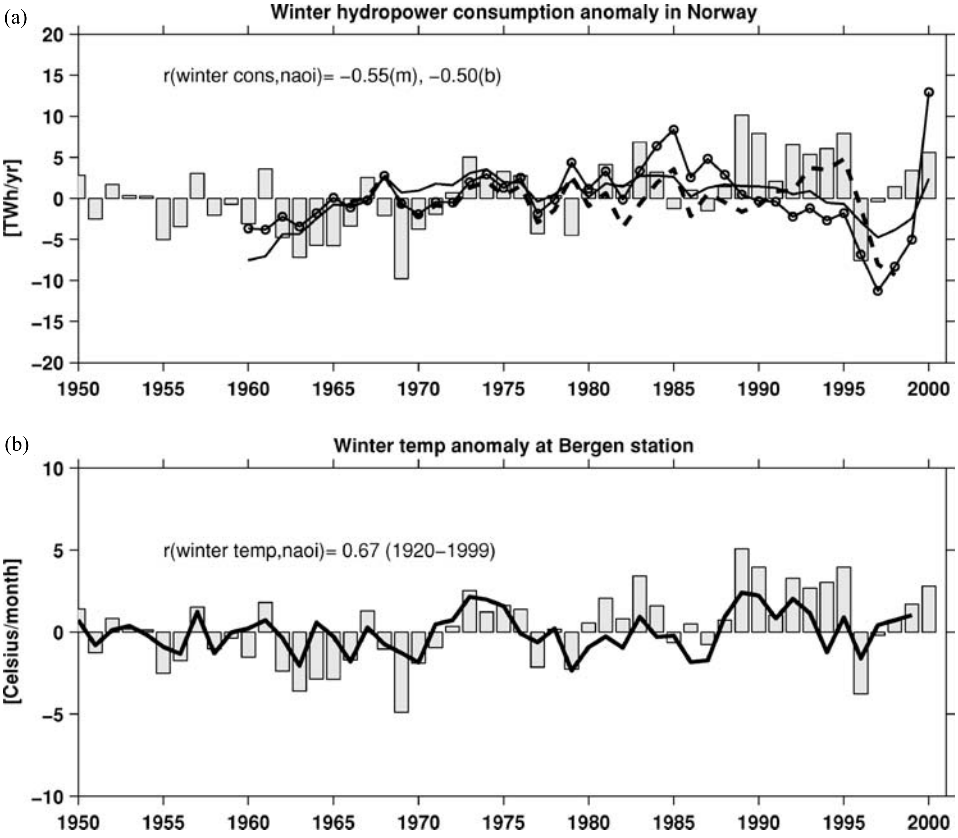

Figure 6. The demand side of the economic framework is shown. The NAO index is plotted as bars. In (a) the winter power consumption anomaly is detrended in the same way as for production in Figure 5c. In (b) the winter temperature anomaly from the Bergen station is plotted. Correlation coefficients between winter consumption and temperature and the NAOI are shown on both figures.

In Figure 7, electricity export and import figures for Norway are shown (negative numbers represent import). After deregulation began in 1992, export and import reflect one another quite closely. Because precipitation in Sweden and Denmark is more weakly correlated to the NAOI than in Norway (Figure 2), one would expect the incentives for trade to be influenced by the NAOI index. During the 1996–1997 and 2001 NAO negative phase events, Norway's export dropped to nearly zero and it relied heavily on imports.

The Nordpool Energy Spot Market trades short-term contracts (usually one day ahead) for the provision of physical power. These began trading in 1992, following deregulation of the market. Since then, the market has been more free to respond to exogenous forces on supply and demand, as well as to forces on supply and demand for substitutes for hydropower, such as fossil fuels. There is a strong seasonal signal

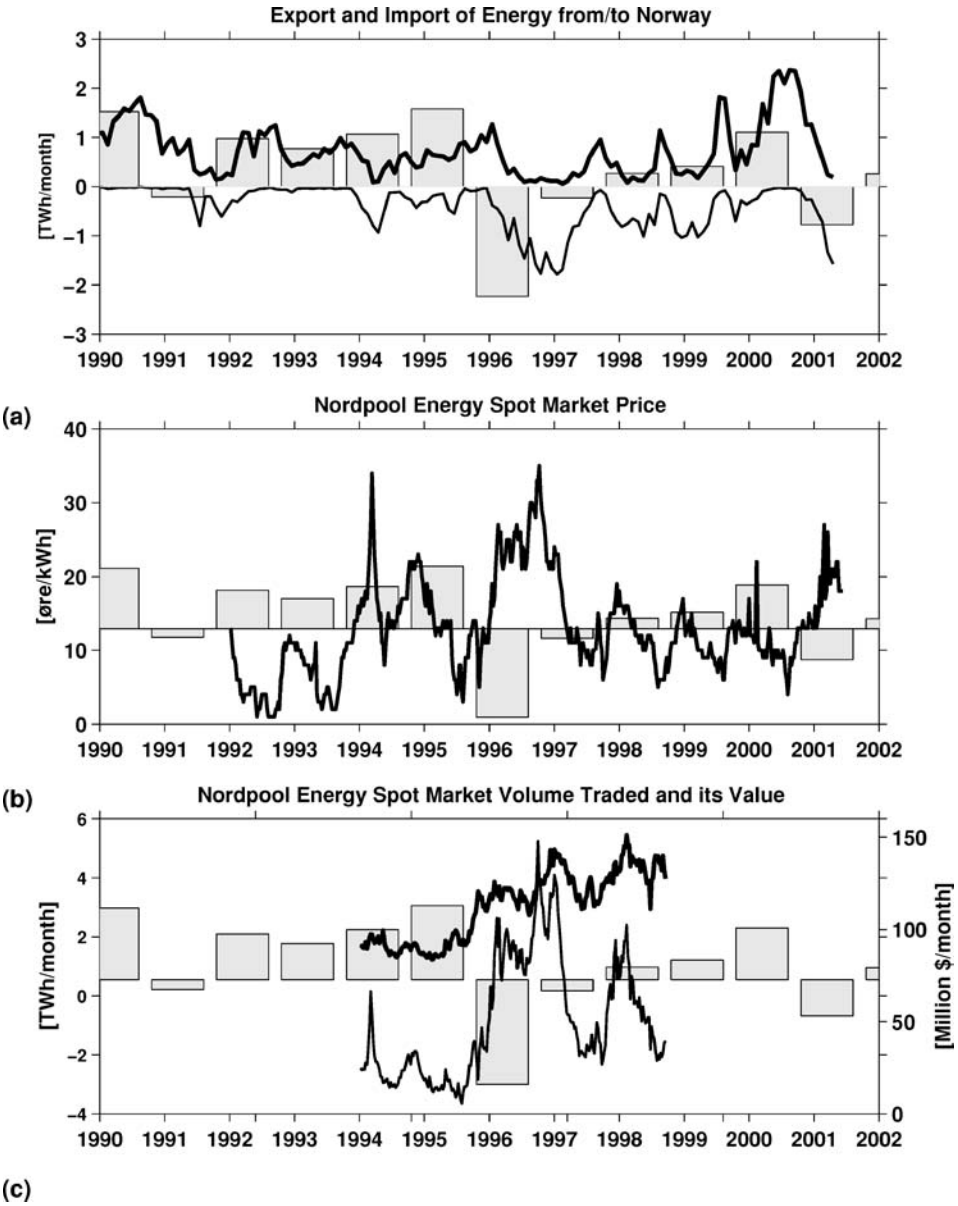

Figure 7. Trade and spot market events during the 1990s are shown. Bars are the NAOI. Export and import of electricity is shown in (a). The spot prices for Scandinavian electricity are shown in (b). It can be seen that there are price peaks in 1996 and 1997, but there is also a strong seasonal cycle. The volume traded on this market and its value are shown in (c).

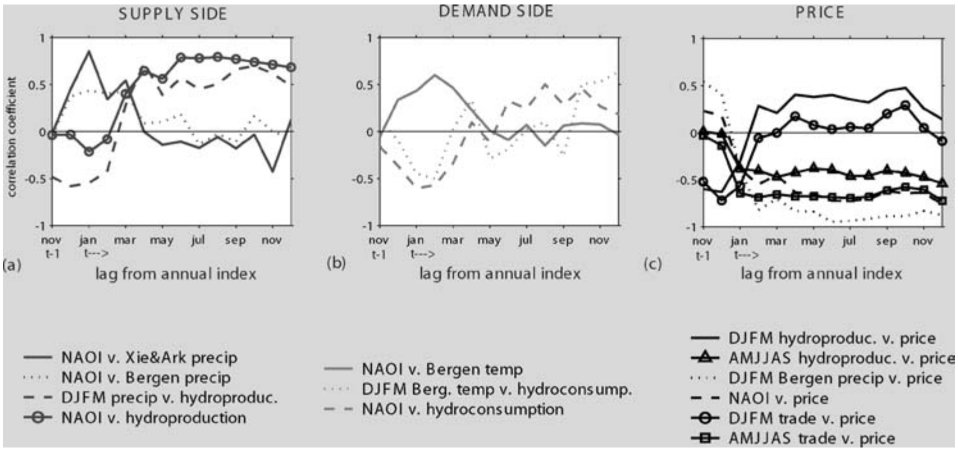

Figure 8. Lag correlations are shown for the time series from Figures 5–7 *versus* the NAOI. All time series have the seasonal cycle removed and are detrended with a 12-year bandpass filter before the correlation is performed. Correlation coefficients vary in their significance. Those involving the price time series are significant at ±(0.5), for the others, coefficients of at least ±(0.30) are significant. January marks the start of the base year, however data are also plotted for the preceding November and December.

in the spot price data from Nordpool and large price peaks in both 1996–1997 and 2001 reflecting NAO-related precipitation shortages (Figure 7b). The volume traded and its value are shown in Figure 7c.

Finally, to summarize the relationships between hydropower supply, demand, and price, lag correlations are shown for various time series in Figure 8. All time series have the seasonal cycle removed and are detrended with a 12-year bandpass filter before the correlation is performed. Those involving the price time series are significant at ±(0.5), for the others, coefficients of at least ±(0.30) are significant. January marks the start of the base year, however data are also plotted for the preceding November and December.

The correlations of the supply side of the framework are represented in Figure 8a. As expected the monthly principal component of the Xie and Arkin (1996) precipitation field over Norway shows maximum correlation with the NAOI in January. The second time series is the monthly precipitation station data from Bergen, Norway correlated with the NAOI, which shows a similar pattern. Next, winter mean precipitation and the NAOI are both lagged with the monthly production of hydropower. Precipitation *versus* the hydro production has a maximum positive correlation in late summer and a maximum negative correlation in that year during January. Similarly, the correlation to last winter's NAO peaks in hydro production in the early summer, and is sustained through the fall.

The demand side of the conceptual framework is illustrated in Figure 8b. Correlations between the NAOI and temperature station data peak in winter and taper off by early spring. The hydropower consumption and winter temperature station data from Bergen correlation is significantly negative throughout the year, with exceptions in spring and fall. It is not clear why there is a positive correlation in the spring and fall. In winter, as temperature drops, more power is immediately consumed. Consumption during the following summer is not highly correlated with winter temperature, but late fall it is. The NAO signal in power consumption is significantly negative during winter.

Movement of the price and electricity trade is illustrated in Figure 8c. Price is lagged behind winter and summer hydropower production to see if there is a supply-driven price signal. Starting in February, winter production has a positive correlation with price while summer production has a negative correlation with price. The summer relationship is straight-forward: if much (little) hydropower is produced the price is low (high). It is likely that prices may anticipate summer production based on winter precipitation. This hypothesis is supported by the lag correlation between the precipitation and price, which has a similar shape. Price is reacting immediately to precipitation, even though the precipitation is largely unavailable for hydropower until it melts in the late spring. Correlation between the NAOI and price remains strong throughout the year, which suggests that the market is aware of large-scale changes in climate over the winter. Finally, summer and winter electricity trade (export–import) is highly correlated to price, though in opposite directions. Price rises as winter trade increases, though the relationship is not highly significant. Summer trade is highly anti-correlated to price: as price goes up, trade goes down and *vice versa*.

2.2. PART II: USING A STATISTICAL MODEL TO PREDICT COVARIANCE BETWEEN THE NAO INDEX AND ENERGY PRICES

Now that the underlying physical mechanisms have been explored, regression tests and their corresponding covariance matrices allow us to quantify the effect of the NAO on spot energy prices with a statistical model. This is a simple least squares estimate of a simple linear regression (vonStorch, 1999). The relationship assumed is the following, where Y_i is the predicted price, x_i is the NAOI index, and E_i is the error

$$Y_i = a_0 + a_1 x_i + E_i .$$

The solutions for the regression coefficients are

$$\begin{aligned} a_0 &= \bar{y} - a_1 \bar{x} \\ a_1 &= \frac{\sum_{i=1}^{n} x_i y_i - n\bar{x}\,\bar{y}}{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2} \end{aligned}$$

where y_i is some known price. Next, the period over which covariances between the NAOI and prices are initially calculated must be defined.

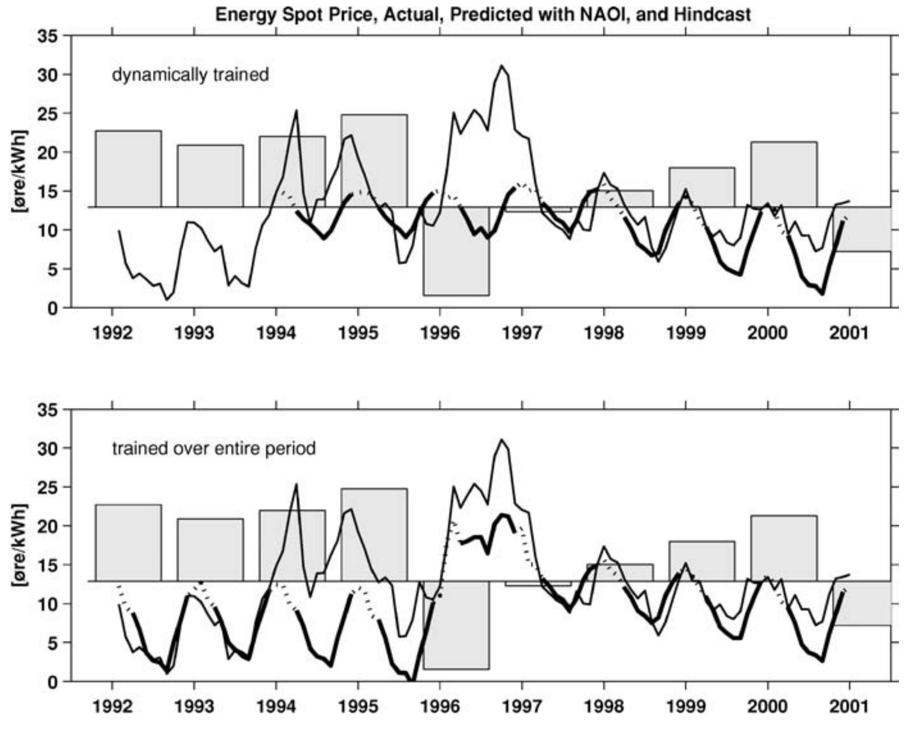

Figure 9. Energy spot prices in Norway are predicted (thick line) using the NAO index (bars). The dotted line represents hindcast prices. Actual monthly mean prices for this period are shown (thin line). Calculation of covariances in (a) and (b) are described in text.

Two experiments are conducted. In the first experiment, years one and two are used to "train" the covariances for the first and second prediction years. Thereafter, covariances are trained on all available past years. This approach will be called *dynamically trained*, and after the second year, represents a true prediction because the model has no knowledge of the covariance until it is in the past. The second experiment is one where all nine years are used to train the covariances. Though this experiment is not a true prediction, it may reflect how the model could improve as more data become available. These are illustrated in Figures 9a and 9b, respectively. Finally, it must be noted that for both experiments winter (DJF) NAOI averages are used in the covariance calculations. Since the winter NAOI value cannot be known with certainty until the end of February, price predictions during winter are in all cases hindcasts. This is denoted in the figure by dashed lines.

3. Results

Both statistical experiments reproduce the seasonal cycle in prices, and the second captures much of the interannual variability. The price peaks in 1996 and 1997 are 14 and 20 ore/kWh more than the peak in 1993. Our second experiment predicts a price peak increase of 9 ore/kWh in 1996 and 10 ore/kWh in 1997 over 1993's price peak. The years 1992–1993 and 1998–2000 are captured relatively closely by the model, though the price trough is exaggerated by the end of 2000.

There is a problem, however, comparing the predicted price increase from 1994–1995 to 1996–1997 with the actual observed increase. The years 1994 and 1995 were themselves anomalously high-priced electricity years. Although the NAOI was very high those years, precipitation was only somewhat higher than average in Norway. On the other hand, Sweden experienced severe flooding during 1994–1995, suggesting that most of the precipitation ended up on the eastern side of the Kjolen mountains during those two years.

While Scandinavia as a whole received more precipitation during these high NAOI years, the fact that the anomalous amount of precipitation landed in Sweden (with less hydropower capacity) instead of Norway means that the observed spot price increase is a reflection of the cost of getting the surplus power supply back to Norway where it was relatively more needed. Our model does not predict that sort of price increase because it does not explicitly contain a term for where the precipitation is distributed, nor a term for capacity limitations in the infrastructure. Despite these shortcomings, our simple NAOI-spot price model does skillfully predict the approximate seasonal cycle and magnitude for the more typical NAOI years during the period of spot price record (1992–2000). Experiment two suggests that the performance of this model could increase when more data is available.

4. Discussion

The sustained peak of spot prices during 1996 shows a significant impact of the NAO on the electricity market. Utilities bought many short contracts at a high price, suggesting that they expected streamflow to return to the 1986–1995 average level by mid-summer. Either precipitation increased by the next winter, or expectations about precipitation were adjusted and trade shifted to longer-term contracts, bringing down the spot price. Though household energy prices in Norway were not attainable for this period, household prices typically relate closely to the spot prices.

The authors chose not to model snowpack for this study, because it adds complexity to the timing of hydropower supply. The EASE-Grid Snow cover dataset (Armstrong and Brodzik, 2002) shows that, on average, while much of Norway is covered in snow during mid-October to early June, only a small portion of land is covered by glaciers and most of the previous winter's precipitation disappears by July. The snowpack integrates the winter precipitation, but most of the NAO signal can be seen in the summer melt.

A previous study by an economist, Johnsen (2001), uses a more sophisticated economic model of temperature, precipitation, reservoir inflow, and snowpack (but no NAO) to predict spot prices. However, most of this data is only available to the public at a high cost (if at all). Also, there is considerable error in long-term weather forecasts, which determine the temperature and precipitation input for this model. This ties the skill of the Johnsen model to the skill of synoptic-scale weather prediction models. For these same reasons, a drought index, such as the Standard Precipitation Index from McKee *et al.* (1993), is not used. Advantages of the NAOI model are that the observation system is simple (just two SLP measurements), free of cost to the user, and available to the public. The NAOI also provides a dynamical explanation for the covariance of temperature and precipitation. Currently, both the Climate Prediction Center of the U.S. National Weather Service and the U.K. Met Office are issuing public NAOI forecasts. Using the method developed by Rodwell and Folland (2002), the Met Office has predicted the correct sign for the winter NAOI in 66% of all years (1948–1998) using North Atlantic sea surface temperatures from the previous May.

The utility of this model for predictions in time is limited to less than a year; however there is further utility in the predictability of NAO-related climate variability in space. The climate time series show predictable spatial patterns of temperature and precipitation related to NAO index value. This is useful for managing risk, especially when a large region is sharing a common financial market. A risk portfolio can be balanced by policies in two different regions which have climates that tend to vary out of phase. Because the climates in Norway, Sweden, Finland, and Denmark are affected somewhat differently by the NAO, and the electricity generation sources are distributed differently between hydropower, nuclear power, and fossil fuels, each country may have a natural competitive advantage under particular climate events.

The spike in spot prices meant household customers down the line paid more for their electricity during the NAO events of 1996–1997 and 2001, but did the Norwegian power industry lose money during those events? While the NAO event did create costs for the economy, there is tentative evidence (Figure 10) that these costs were borne primarily by power consumers, rather than by producers. However, to understand in detail how the cost shock is translated into changes in prices, profits and other economic outcomes would require an investigation into the economics of the Norwegian power sector beyond the scope of this study. Figure 10 shows that operating income and expenses were both very high in 1996, suggesting suppliers raised prices to at least partially offset their expenses.

While the authors primarily wish to demonstrate how interannual climate variability impacts the energy sector, trends on the scale of decades and longer may be important to energy infrastructure planning, particularly in a region where electricity generation depends so heavily on hydropower. Though the NAO is a mode of natural climate variability, recent characteristics of the index suggest that it may also be affected by increased levels of CO_2 in the atmosphere. Dominant features of the NAO index in the 1970s through the 1990s included a remarkable upward trend and a tendency to persist in one phase for approximately a decade. While the NAO's tendency to prefer the positive phase could be related to increased greenhouse gas concentrations (Palmer, 1999; Corti *et al.*, 1999; Graf *et al.*, 1995; Shindell *et al.*,

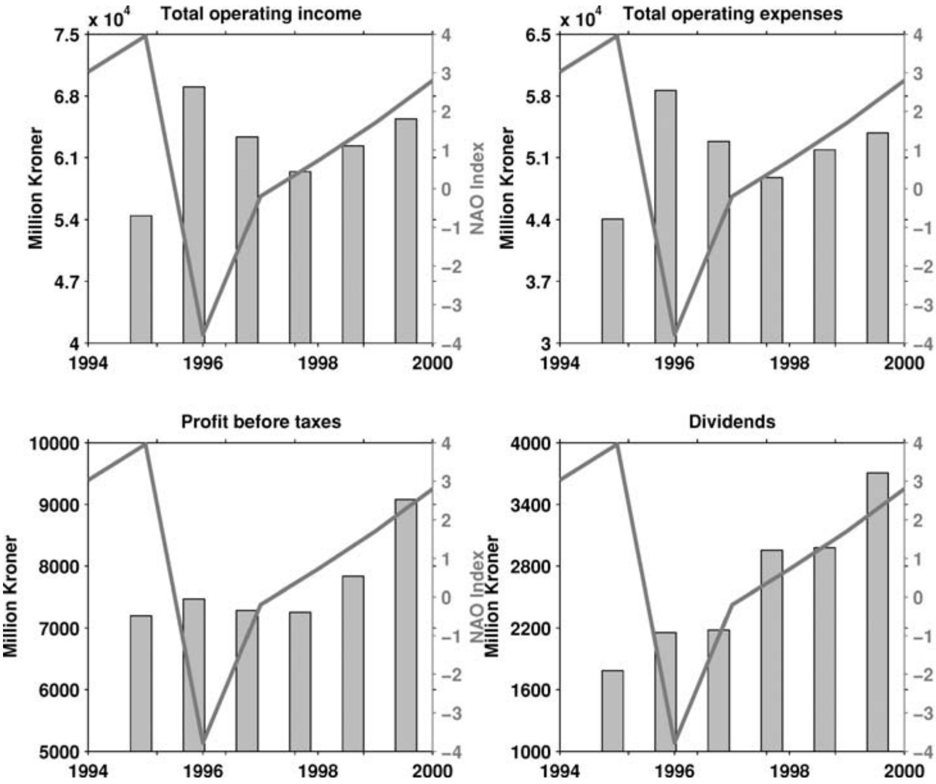

Figure 10. Financial figures for the hydropower sector in Norway plotted against the NAO index. Data are from Statistics Norway.

1999; Gillet *et al*., 2002), it could also be the expression of random atmospheric variability. If it is true that atmospheric forcing by anthropogenic emissions causes the NAO to prefer a strong positive phase, there are long-term consequences for hydropower generation. On the other hand, several strong negative phase NAO index events occurred during the late 20th century, suggesting the relationship between increased CO_2 and a preferred phase of the NAO is not straight-forward.

5. Conclusions

While the NAO index is not a perfect predictor of Norwegian climate, it is the primary mode of variability of climate there, making it a useful climate paradigm for the energy sector. There are currently models of moderate skill for predicting the phase of the NAO a few months ahead (Rodwell and Folland, 2002; Saunders and Qian, 2002). It is likely that the skill of prediction models will improve in time. Skill in predicting other climate phenomena, such as ENSO, is increasing and has provided a framework to study the dissemination and social implications of long-term climate forecasts (Ropelewski and Lyon, 2002).

The impact of the NAO on the electricity market is complex; not only are the influences of the supply and demand for hydropower in Norway involved, but also the state of supply and demand for power in the countries with which Norway trades. Then add movements in the market for substitutes for hydropower, such as fossil fuels and nuclear power. Finally, there are the elements of anticipation and expectation of what supply and demand will be on each of those markets.

Electricity forecasting in Norway has been key for the planning and management of hydropower projects (Lunde and Midttun, 1987). The institutional framework of the forecasting process continued to evolve throughout the 1980s and in 1990 deregulation and privatization began. Now growing concern over the dependence on hydropower in Norway, supported by the experience of the NAO event of 1996, has led the Norwegian government to seek diversification in the nation's power supply. Electricity generated by new gas-fired power stations will be used to meet trade contracts since Norway has a carbon tax on domestically consumed power. This policy is also one of Norway's strategies in meeting its targets of carbon emissions reduction under the Framework Convention on Climate Change. Uncovering linkages between the NAO and energy consumption in Northern Europe is only one part of a larger human–climate interaction.

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