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Characterizing and Reconstructing 500 years of Climate in the Baltic Sea Basin

Christin Eriksson

University of Gothenburg
Department of Earth Sciences
Box 460
SE-405 30 Göteborg
Sweden

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Department of Earth Sciences
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To Daniel, Vilda and Leo.

The roots of education are bitter, but the fruit is sweet.
- Aristotle

Abstract

Climate has always attracted considerable interest, and climate observations have been made in various ways for most of human history. Regional climate and how it varies is of particular interest, as it sets the scene for our everyday life. This thesis analyses the past climate of the Baltic Sea Basin and relates ice coverage and river runoff to changes in atmospheric circulation.

The regional climate of the Baltic Sea Basin has been analysed using relevant climatic time series for the past 100–500 years. The time series used in the thesis describe parameters such as station-based and gridded air temperature, sea level, ice cover extent, river ice break-up dates, and river runoff. To describe the atmospheric circulation over the area, gridded sea level pressure data have been used to construct time series describing the occurrence of high- and low-pressure systems as well as westerly and northerly winds.

The definition of climate was analysed and a proper climate averaging time was found to be 15 years, corresponding to a loss of variability of 90 %. The analysis used annual averages and revealed positive trends in high-pressure activity and air temperature, possibly indicating a north-ward shift of the low-pressure tracks.

The winter climate of the past five centuries was examined through a comprehensive analysis of the longest time series, describing winter severity, available for the Baltic Sea Basin. The covariation of several climatic variables was examined using new statistical techniques. Over the last 500 years, 15 time periods stood out, giving a climatic imprint with respect to winter severity, circulation patterns, and interannual variability. Both warm and cold periods were identified in the past Baltic Sea climate; their onset was probably caused by perturbations of the system, although correspondences with solar and volcanic activity can be identified for certain of them. On the interannual timescale, describing year-to-year variability, warm periods are associated with less variability while cold periods are associated with more.

Two reconstructions have also been made, describing the past evolution of maximal ice cover extent in the Baltic Sea and river runoff from the Baltic Sea drainage area. Statistical modelling was used to link atmospheric circulation parameters to changes in ice and river runoff. High ice coverage in the Baltic Sea was demonstrated to be closely associated with high-pressure circulation and easterly winds, while low ice coverage was associated with westerly winds and low-pressure circulation. Runoff information was developed from three different models, each formulated to describe one of the three subdomains (north, south, and Gulf of Finland) using atmospheric circulation and temperature. The northern part was sensitive to changes in temperature and circulation characteristics, while the southern model was less affected by temperature. Correlation with observations is satisfactory, indicating that the derived statistical relationships are highly credible. The past 500 years of river runoff display no significant trend, but regional and temporal variability is large.

Key words: Climate, Baltic Sea, Atmospheric circulation, Statistical modelling, Wavelet, Sea Ice, River runoff,

Preface

This thesis consists of a summary (Part I) and the following appended papers (Part II), which are referred to by their roman numerals. Paper I was written before my marriage, and was published under my maiden name Pettersen.

Paper I:
Omstedt, A., C. Pettersen, J. Rodhe, P. Winsor, 2004: Baltic Sea climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation, *Climate Research*, 25, 205-216.

Paper II:
Eriksson, C., A. Omstedt, J. E. Overland, D. P. Percival, H.O. Mofjeld, 2007: Characterizing the European Sub-Arctic winter climate since 1500 using ice, temperature, and atmospheric circulation time series, *Journal of Climate*, 20, 5316–5334.

Paper III:
Eriksson C., 2009: Reconstruction the annual maximal ice cover extent in the Baltic Sea (MIB) during the 16th and 17th century. Submitted to *Climatic Change*

Paper IV:
Hansson, D., C. Eriksson, A. Omstedt, D. Chen, 2009: Reconstruction of river runoff to the Baltic Sea, Submitted to *International Journal of Climatology*

In Paper I, the ideas are the result of several discussions among the authors. All the statistical analyses were conducted by Eriksson. The results were jointly interpreted by Omstedt and Eriksson, while Omstedt did most of the writing.

Paper II is also the result of several discussions among the authors. Percival computed the statistical relationships while Eriksson did most of the interpretation, wrote the paper, and handled the final revisions.

Paper IV was initiated by Omstedt and analyses were carried out by Eriksson. Eriksson and Hansson worked together to interpret the results of different approaches to formulating the regression model. Eriksson wrote a first draft, published in GEWEX newsletter. Hansson continued and expanded the analyses, and wrote the final paper while Eriksson was on maternity leave.

Contents

Part I

Summary

The trouble with weather forecasting is that it's right too often for us to ignore it and wrong too often for us to rely on it.

- Patrick Young

1 Introduction

Ongoing concern regarding the present state of the climate and where it is heading accompanies us in our everyday lives, beginning with a quick glance at the morning newspaper, and continuing via billboards seen on our way to work, discussions over lunch, our children’s homework, and finally the late-night TV news. Policy makers and the community are demanding straight answers from the scientific community on how to adapt to a changing climate. But can researchers deliver such answers?

Although concern over the global climate is important, the regional climate affects people the most. The regional climate is influenced by many processes over a wide range of spatial scales. While the basic climate processes are the same in all parts of the world, the interaction between these processes are complex and varies between different regions of the world. What processes govern the climate in a specific region are determined, for example, by latitude, elevation, vicinity to warm (or cold) ocean currents, and land use. Depending on the combination of these variables, a great variety of climate types exist simultaneously on the Earth, all of which react differently to variations in their forcing.

As a marginal sea the Baltic Sea is strongly influenced by the conditions in the North Sea and the North Atlantic Ocean. Slowly varying variables such as salinity and sea surface temperatures are easily exported into the Baltic Sea, while rapid changes are effectively damped by the narrow and shallow straits. The atmosphere is free of the limitations imposed by narrow and shallow straits, so circulation over the area is largely affected by large-scale atmospheric patterns. The variability in atmospheric circulation therefore has a strong impact on surface climate in northern Europe. For example, the warm and wet winters of the 1990s resulted from the more frequent incursion of maritime air masses, which contributed to both record-breaking low ice coverage and a deeper halocline in the Baltic Sea.

The Baltic Sea system is a unique and special environment that currently are undergoing large changes due to eutrophication, pollution and over fishing. With about 85 million people living in the Baltic Sea drainage area, in 14 different countries, the future of the Baltic Sea is depending on political collaboration. How to protect the Baltic Sea in the best possible way is based on knowledge gained from the past and on future projections. On the whole, the air temperature changes over the Baltic Sea are projected to be 0.9°C larger than the global average (e.g. The BACC author team 2008 for review). However, the relative uncertainty in the regional warming is also larger than that in the global mean warming. Future projections also call for increased river runoff to the Baltic Sea Basin, in particular, possibly increased river runoff in the northern parts of the Basin (Andréasson et al. 2004, Graham 2004). Identifying seasonally specific variations and associated patterns of temperature, precipitation and circulation variability is very much needed in order to evaluate present and past climate (see Jones et al. 2009, for a review).

Currently much effort is put on understanding the past climate of the Baltic Sea region and to relate it to the present climate (e.g. Zwiers 2005, Zorita et al. 2008). Historical documents are being revisited and time series are being homogenized, all for gaining more knowledge on the dynamics of our region. To assess how the Baltic Sea climate has been affected by the ongoing rise in levels of greenhouse gases, it is important to study the range in which circulation varies naturally. It is interesting for both scientists and society if the typical spring situation of the Baltic Sea region, seen in Figure 1, also was typical for the past and if it also will be typical for the future. In the Netherlands the likelihood of holding outdoor skating marathons has been vividly used by the politicians to communicate climate change (Visser & Petersen 2009). As Sea ice is a sensitive indicator for climate change, this parameter has been used in this thesis to identify and explain some of the important climate change signals driving the Baltic Sea climate.

Figure 1: Baltic Sea seen from space on 22 March 2002. From NASA Earth Observatory Collection. White areas can be snow, Ice or clouds. Sea ice is still present in the Bothnian Bay and the inner parts of the Gulf of Finland. Snow is covering more than half of Sweden and all of Finland.

This thesis has used the best available datasets compiled for the vicinity of the Baltic Sea to investigate whether there is a common climate change signal in our region and, if so, whether this signal can be explained. In Paper I, we investigate how the statistical properties of the last 200 years of relevant climatic parameters have changed. We found that the timescale of climate in our region is approximately 15 years, and used this as the climate averaging time in the statistical analysis. In Paper II, we extend the time period over which we look for climate signals to 500 years; we identify several important periods with different climate characteristics by using long-term combined proxy and instrumental data from around the Baltic Sea. Papers III and IV use large-scale atmospheric circulation indices and statistical relationships derived from a regression model to reconstruct the maximal ice cover extent and river runoff in the Baltic Sea. Reconstructions of past climate are important in providing a historical context for evaluating the nature of twentieth-century climate change. They also give suggestions as to how the climate may have varied in the past, information that can be used to increase our understanding of past history.

2 Baltic Sea

The Baltic Sea is one of the largest brackish water bodies in the world. Due to its geographical extent, the Baltic Sea region contains great internal differences. In the north-eastern part, the climate is said to be subarctic and very continentally influenced, while the southern and western parts are more maritime with milder and wetter conditions. The climate displays very strong seasonality, summers and winters differing greatly in temperature. The Baltic Sea region, due to its proximity to both a great land mass and the outer branch of the North Atlantic Current, can experience both mild maritime conditions and locked-up continental conditions, such as persistent high-pressure circulation, in the same locales. The Baltic Sea is situated in mid-latitudes with strong weather variability due to westerlies with low-pressure systems passing through the region.

2.1 Geology

Over the last 100,000 years, the Scandinavian Peninsula and the Baltic Sea Basin have experienced repeated glaciations, marked by the growth of the Scandinavian Ice Sheet. The last deglaciation of the area started only approximately 15,000–17,000 calibrated years before present (cal yr BP) and is the starting point of a new and warmer phase in the Baltic Sea region.

The not-so-long history of the Baltic Sea starts about fifteen thousand years ago with the formation of the Baltic Ice Lake, 15,000–11,600 cal yr BP (The BACC author team 2008). Large ice sheets that had been dominating the region for several thousand years were now retreating rapidly, leaving behind suppressed land and discharging large amounts of freshwater. The Baltic Ice Lake was soon replaced by the Yoldia Sea, which lasted for approximately 900 years. At this stage, a connection with the outside ocean was established near Närke and Vänern, situated just south of the retreating ice sheet. The connection with the ocean later closed as the Yoldia Sea was replaced by the Ancylus Lake, and a freshwater system now came into being. The Littorina Sea later followed, when a connection with the outside ocean was reopened approximately 8500 cal yr BP, due to the great sea level rise resulting from melting ice sheets. The wide and deep straits in the south allowed for extensive water exchange with the North Atlantic, and the salinity of the Littorina Sea was higher than the Baltic Sea as we know it today. The transgression phase of the Littorina Sea continued for approximately 3000 years in its southern parts, caused by a rapid sea level change that dominated the isostatic uplift. When the sea level rise ended, the land uplift in Sweden and areas north of Lithuania caused regression of the Baltic Sea, resulting in shallower sills and thereby reduced Atlantic inflows. Even today, the land is still recovering from the last glaciation, and isostatic maps indicate that Sweden is experiencing isostatic uplift in the north and isostatic depression in the south.

TABLE 1: BALTIC SEA DATA

Population of Baltic Sea drainage area.	*85 million*	Mean depth	*55 m*
Area (including Kattegat)	*415,000 km²*	Maximum depth	*460 m*
Volume	*21,000 km³*	Maximum ice extent	*420, 000 km²*
Shoreline	*8,000 km*	Minimum ice extent	*50 km²*
Drainage area	*1.6 million km²*	Net precipitation	*1,500 m^3s^{-1}*
River discharge	*14,000 $m^3\ s^{-1}$*	Net outflow to the North Sea	*15,500 m^3s^{-1}*

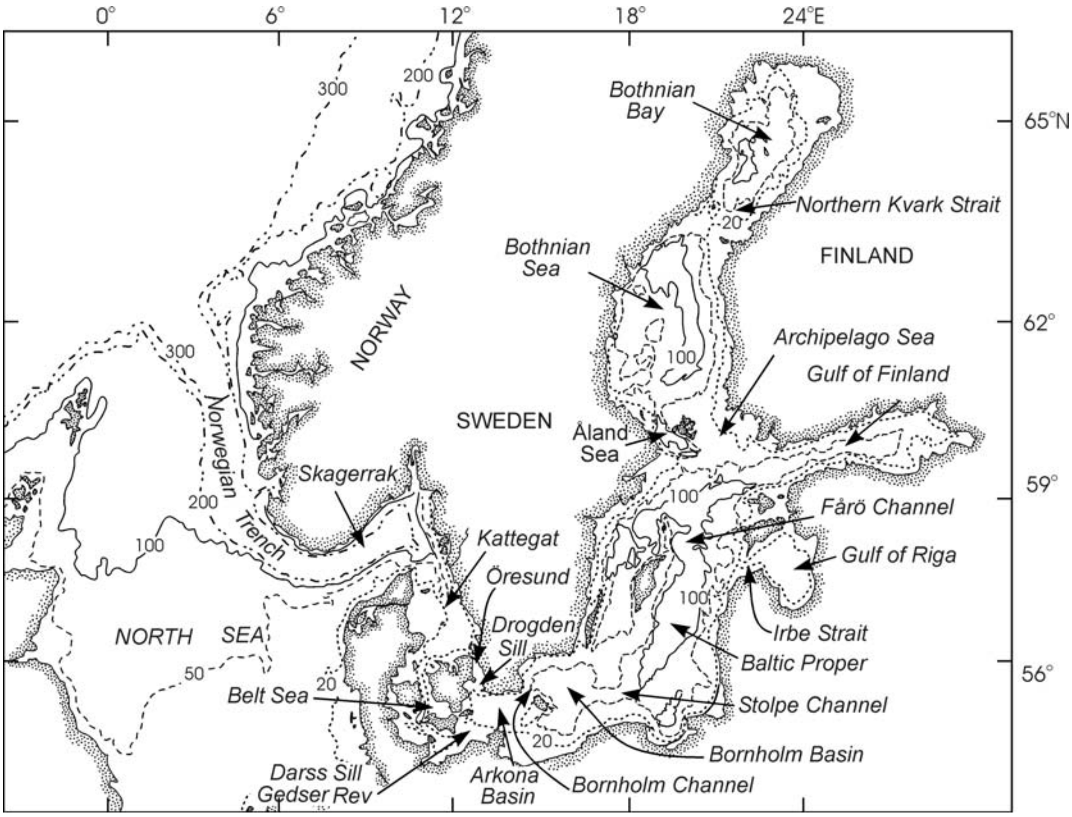

Figure 2: The Baltic Sea Basin, with depth contours indicated. In Table 1 Baltic Sea data is gathered. From (Omstedt et al. 2004a)

2.2 Oceanographic description

The Baltic Sea and its many sub-basins (Figure 2) are best described beginning in the entrance area and going north. The inlet area consists of narrow straits (i.e., Little Belt, Great Belt, and Öresund, with channel widths of 0.8, 16, and 4 km) and shallow sills (i.e., the Darss and Drogden sills, with maximum depths of 18 and 8 m, respectively). Inside these sills are the Arkona and Bornholm basins, which are connected to the Baltic Proper. Moving north, the gulfs of Riga and Finland lie on the eastern side of the basin, while farther north is the Bothnian Sea and finally the Bothnian Bay. Water exchange with the North Sea is restricted by the narrow and shallow straits, and the estuarine circulation in the Baltic Sea is driven by the large freshwater input to the basin. The added water volume is trapped above the permanent halocline, resulting in a higher sea level relative to that at Kattegat, creating an outflow of surface water. On its way out of the Baltic Sea, the outflowing water entrains additional water, making the outflowing volume greater than the freshwater input. A counterflow of more saline Kattegat water into the Baltic Sea is needed, and most of the Kattegat water that enters the Baltic Sea passes through the Great Belt. On average, the flow over the sills is balanced by the net freshwater supply. Adding to the estuarine circulation are the large fluctuations caused by changing winds and water level variations, the frequency and amplitude of which in Kattegat are responsible for pumping waters through the Great and Little belts and Öresund. Sea level differences can create momentary flows 10 times or more larger than the mean flow. Owing to the shallowness of the sills, much of the inflowing water never reaches the inner Baltic Sea, but instead flows back and forth over the sills. These water exchange characteristics, together with substantial vertical mixing in the interior, lead to a permanent halocline at a depth of approximately 60 meters in the Baltic Proper, where the upper layer has a salinity of approximately 6–8 practical salt units (psu) and the lower layer of approximately 10–14 psu. The mixed-layer depth varies with the seasonal thermocline. In winter, the water column is well mixed by the wind all the way down to the permanent halocline. Small inflows recur quite regularly, but typically penetrate only to a depth just below the permanent halocline, leaving the deep waters stagnant. Deep water replenishment is a complicated process in which several conditions must be met to allow major inflows of saline and oxygenated water. Inflows generated by sea level variations in the Kattegat are also modulated by the total supply of freshwater to the Baltic Sea, which tends to enhance outflows and suppress inflows (Stigebrandt & Gustafsson 2003, 2007). Time series of major Baltic inflows indicate that these inflows have been less frequent over the past 30 years than earlier in the twentieth century (Matthäus & Franck 1992).

2.3 Climate

The location of the Baltic Sea between the 50th and 70th parallels determines the large influence of atmospheric circulation on Baltic Sea conditions. Variable weather conditions are typical of high and middle latitudes and are associated with fluctuations in the location and the intensity of the polar front. The polar front is the boundary between the warm tropical and cold polar air masses, and is generally located poleward of 30° latitude in both hemispheres. On the day-to-day scale the polar front feeds the area with cyclonic and anticyclonic pressure systems; fronts that develop there and air masses of different origins are transported over Scandinavia. Strong westerly air flow brings maritime humid air masses to the south-western and southern parts of the region. When the humid westerly air masses are transported eastward and northward over the region, they weaken due to friction and drying processes, yielding a more continental climate over those parts. The relevant great circulation patterns, such as the Icelandic Low, Azores High, and Siberian High, largely determine the climate of this region on both the synoptic[1] and longer timescales. As a result, these unstable weather conditions make the climate of this region vary greatly on both a day-to-day and yearly basis. The variability is greatest in winter, when solar radiation is weak and atmospheric circulation is strong.

Recurring and persistent large-scale patterns of circulation and pressure anomalies covering a vast geographic area are often referred to as teleconnection patterns. Different teleconnection patterns influence different parts of the atmosphere and are often named accordingly. The annual and decadal climate variability in Europe is strongly influenced by atmospheric circulation and the North Atlantic, whose primary mode (i.e., pattern) is the North Atlantic Oscillation (NAO), see Figure 3. This refers to the oscillation in air masses between the Icelandic Low in the north and the Azores High in the south (e.g. Walker & Bliss 1932, van Loon & Rogers 1978). The NAO index is calculated as the difference of normalized pressure between the Azores subtropical high and the Icelandic subpolar low (Hurrell 1995). This pressure difference gives rise to variations in the meridional pressure gradients and thereby the strength of the zonal flow, which is imposed by the geostrophic wind balance. The greatest pressure differences are found in winter, also when the “skill” of this index is highest, explaining the variability in both temperatures and precipitation. The NAO varies between two phases: a positive phase associated with milder and wetter winter conditions, and a negative phase in which drier and colder winter conditions are expected (see Figure 3). Long-term NAO index series have been constructed extending far back in time (Jones et al. 1997, Luterbacher et al. 1999, Trouet et al. 2009). NAO has proven also to be a good indicator of the Baltic Sea climate over the past century in terms of both temperature (Chen & Hellström 1999) and Baltic Sea ice conditions (Koslowski & Loewe 1994, Tinz 1998, Jevrejeva & Moore 2001, Omstedt & Chen 2001, Jevrejeva et al. 2003). Positive NAO conditions have also been coupled to weakened haline stratification and decreased salt content in the Baltic Sea (Schrum 2001), and wintertime sea level in the Baltic (Andersson 2002). The coupling between the NAO and the climate in the Baltic Sea region, however, is not always supported; several studies have demonstrated that the nineteenth-century Baltic Sea climate was uncoupled from the NAO, indicating the non-stationarities in the circulation and temperature connection (Omstedt & Chen 2001, Slonosky & Yiou 2002, Jacobeit et al. 2003, Omstedt et al. 2004b, Vicente-Serrano & Lopez-Moreno 2008). A weakness of the NAO index is that it is interpreted as indicating zonal flow strength, while in practice it also captures the meridional flow to some extent. Meridional flow situations caused by easterly cyclones in the Atlantic also produce a positive NAO index, although these situations are uncoupled from the zonal winds. The information gained on the regional scale of a teleconnection pattern is only somewhat valid, and does not provide any detailed information for the region. With the rapidly increasing number of European station pressure data, the construction of gridded data

[1] “Synoptic scale = Spanning smaller distances, a few hundred to a few thousand kilometres, and possessing shorter lifetimes, a few to several days, this class contains the migrating cyclones and anticyclones that control day-to-day weather changes.” From “climate.” Encyclopædia Britannica. 2009. Encyclopædia Britannica Online. 24 Apr. 2009 <http://search.eb.com/eb/article-53292>.

for the European region has replaced the use for crude indices such as the NAO when analysing regional data (Luterbacher et al. 2002, Luterbacher et al. 2004, Pauling et al. 2006).

Questions have been raised whether it is statistically justifiable to analyse long-term climate variability using monthly or seasonally averaged indices such as the NAO, given that the timescale of most teleconnection patterns is approximately 10 days (Franzke 2009). It cannot be ruled out that part of the observed climate variability on monthly and seasonal timescales stems from the fast weather fluctuations resulting from the averaging. Such variations are the climate noise of the time series and should preferably be uncoupled on timescales related to forcing originating from outside the atmosphere (e.g., solar variability and Sea Surface Temperatures (SST) variations). Analyses of interannual and decadal variations of the NAO indicate that only the decadal variations differ from white noise (Stephenson et al. 2000).

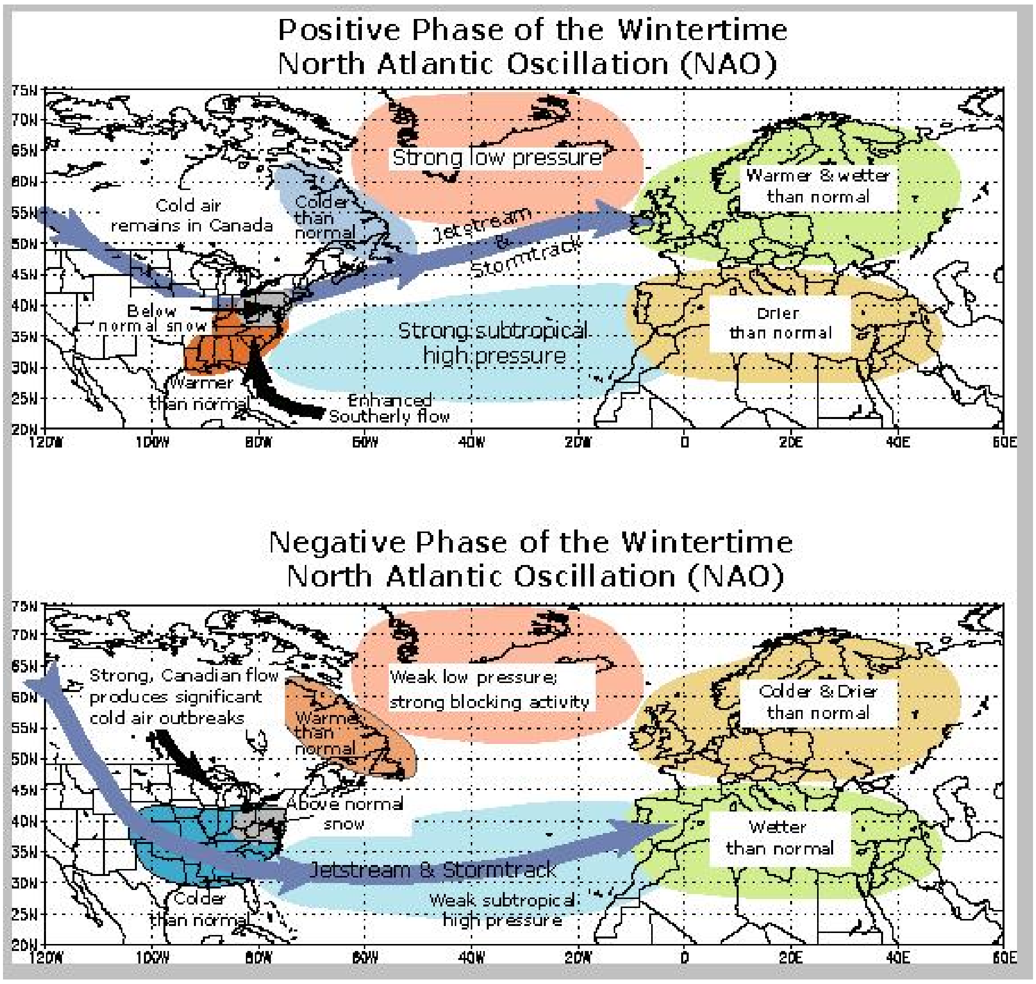

Figure 3: Phases of positive and negative NAO. Upper panel show pressure situation associated with positive NAO, giving warm and wet winters in Scandinavia. Lower panel are associated with negative NAO, giving colder and drier winters in Scandinavia. Images from NOAA, Lamont-Doherty Earth Observatory (http://www.ncdc.noaa.gov/paleo/ctl/clisci100.html)

2.4 River runoff

Despite the location of the Scandinavian mountain range in the west, a great deal of precipitation makes its way into the region and supplies the Baltic Sea with freshwater. Adding also to the hydrological cycle is a great drainage area that covers 1.74 million km^2, including approximately 250 rivers supplying the Baltic Sea with freshwater. The catchment area drained by these rivers is about four times as large as the sea itself. Two of Europe's largest lakes are situated in the catchment area, lakes Ladoga and Onega, which damp the river flow before it reaches the Baltic Sea. The five largest rivers are the Neva, Vistula, Daugava, Neman, and Oder. Owing to the large contribution of freshwater to the system, the Baltic Sea exports approximately 15,000 $m^3\ s^{-1}$ to the North Sea through its narrow straits. Like other basins in humid landlocked regions, the Baltic Sea has a positive water balance, indicated by its low salinity (e.g. Matthäus & Schinke 1999, Omstedt et al. 2004a). The freshwater surplus to the Baltic Sea is nearly balanced by the highly saline inflows from the North Sea. Precipitation and evaporation are fairly balanced in the Baltic Sea, which leaves the total freshwater budget dominated by the river runoff. The water budget components of the Baltic Sea, taken from (Omstedt et al. 2004a, Omstedt & Nohr 2004), are river discharge of 14,000 $m^3\ s^{-1}$ and net precipitation (i.e., precipitation – evaporation) of 1500 $m^3\ s^{-1}$. The runoff regime is the result of complex interactions, being subject to precipitation, evaporation, changes in water storage, vegetation, and land use in the drainage area. The seasonal differences are great and vary from maximal discharge during snowmelt in late spring and early summer to minimum freshwater discharge in winter. Changes in the runoff characteristics are currently occurring on the seasonal scale due to hydropower production (e.g. Graham 2000). Large man-made reservoirs store water in seasons with high runoff in order to generate electricity from the outflowing waters during seasons when runoff is low. In the northern parts of the basin, this feature is most pronounced in the form of increased winter flows and reduced spring flows, but the annual runoff remains unchanged. Questions have been raised whether this modulation of the natural runoff could change the water exchange characteristics of the Baltic Sea (Matthäus & Schinke 1999). Baltic Sea deep water could be sensitive to high runoff, in that a larger volume outflowing in the surface layer could lower the salinity further down in the water column, by mixing and entrainment that would increase the dilution of the inflowing salty waters. In such a case, the inflowing waters would be unable to penetrate to the deepest parts of the basin. By increasing the runoff in periods when conditions are most favourable for deep water renewal, deep water inflows may be reduced. The importance of this mechanism, however, has not been fully evaluated, but calculations incorporating altered seasonal runoff characteristics seem to indicate that this effect is of minor importance for timescales greater than a few years (Erik Gustafsson, personal communication). Large runoff combined with sufficient wind mixing could instead improve oxygen conditions for the bulk of the deep water, since they would deepen the permanent halocline, allowing inflowing waters to penetrate further down in the water column (Stigebrandt & Gustafsson 2003, 2007).

2.5 Sea Ice cover

Due to the elongated shape of the Baltic Sea, the prerequisites for ice formation in it are quite diverse. Most of the southern parts seldom experience ice formation, while the northern parts are always ice covered for large parts of the year. An average ice season starts in November when ice forms in the northern parts of the Gulf of Bothnia. The ice cover expands over the following months, usually peaking in February–March, when it covers nearly half the area of the Baltic Sea in a normal winter. The ice-covered parts of the Baltic Sea are the shores and gulfs, while the open sea rarely freezes. Only in rare severe ice winters is the total area of the Baltic Sea ice covered all the way to the Skagerrak. Variations in sea ice conditions are highly sensitive to climate perturbations, as only a very slight change in meridional heat transport affects the sea ice extent (e.g., Paper III). In the Baltic Sea this is demonstrated by the fact that growth of only approximately 5% in the cold sum[2] can be followed by a 50% increase in the ice extent (Jurva 1952).

The sensitivity of the ice to changes in winter mean temperatures has been modelled (Omstedt & Hansson 2006a, b). The results indicate that the Baltic Sea would be ice free only if the mean winter air temperatures over the Baltic Sea exceed +2°C; similarly, when the mean winter air temperatures are less than or equal to –6°C, the Baltic Sea would be completely ice covered. Information about the past severity of winter ice in the Baltic Sea was compiled by (Seinä & Palosuo 1996), who summarized and described the winter ice conditions from 1720 onwards;

Figure 4 depicts the ice coverage for winters graded by their severity (Seinä & Palosuo 1996). It has been demonstrated that the ice winter severity has decreased from a higher mean state in the nineteenth century, when there was a higher frequency of severe ice winters, to a lower mean state in which severe ice winters have occurred less frequently (Omstedt & Chen 2001, Eriksson et al. 2007, Hansson & Omstedt 2008). The changing between states in terms of the occurrence of severe ice winters is not extraordinary, in Paper II (Eriksson et al. 2007) it is shown that the early 18th century also was in a state with less frequent severe ice winters.

[2] The cold sum is the sum of all observations of negative air temperatures after the ice has formed.

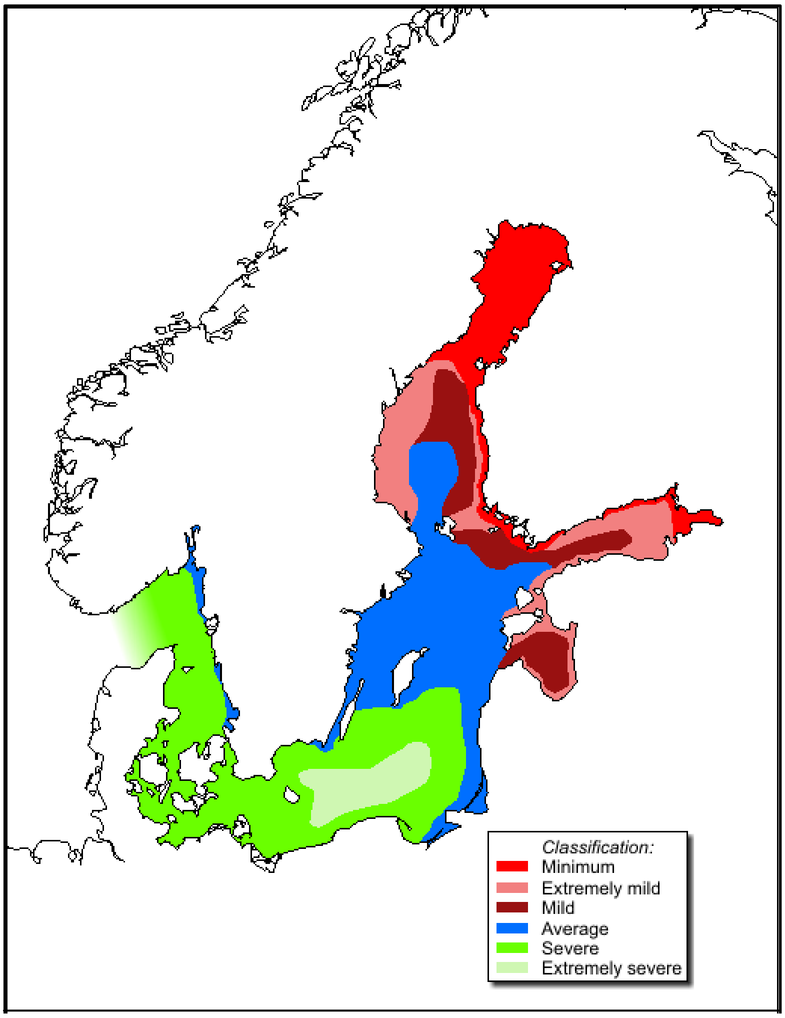

Figure 4: The Baltic Sea Basin. The categories of winter ice severity are shown in different colours. Maximal ice extent is reached only in extremely severe winters when the ice covers Skagerrak. In extremely mild winters, only the bright red areas are ice covered; the last time this occurred was the winter of 2007–2008. Based on Figure 3 in Seinä and Palosuo (1996), redrawn by Daniel Hansson

3 Data and Methods

This thesis uses several well-documented time series of climatic variables to study the climate of the past. Statistical methods were used to analyse the variability of our time series. TABLE 2 lists the different datasets and their sources. The period studied in Paper I spans the 200 years of the nineteenth and twentieth centuries; data for this period are fairly reliable and are thought to representatively capture past changes in the Baltic Sea climate. Papers II–IV use data covering the past half millennium; for obvious reasons, the data for the first part of this period are less reliable. The studies reported in Papers II and III are confined to winter data. Winter data are used because the largest year-to-year variability is found in winter, and information about climate signals is probably best defined in this season. The most reliable gridded pressure data for the Baltic Sea region are also those for winter (Luterbacher et al. 2002).

TABLE 2: TIME SERIES AND GRIDDED DATA USED IN THE THESIS

Climate variable	Region	Time span	Resolution	Main Reference
Air temperature (°C)	Uppsala	1722–1998	Monthly	(Bergström & Moberg 2002)
Air temperature (°C)	Stockholm	1756–2000	Monthly	(Moberg et al. 2002)
Sea level	Stockholm	1825–2000	Monthly	(Ekman 1999)
Circulation types	Northern Europe	1775–2000	Monthly	(Chen 2000)
Max ice cover in the Baltic Sea (MIB)	Baltic Sea	1720–2000	Annual	(Seinä & Palosuo 1996)
Ice in the western Baltic Sea (IWB)	Baltic Sea	1500–1999	Annual	(Koslowski & Glaser 1999)
Ice breakup (d.y.)	Mälaren	1712–1997	Annual	(Eklund 1999)
Ice breakup (d.y.)	Torneå	1693–2002	Annual	(Kajander 1993)
Ice breakup (d.y.)	Riga	1529–1988	Annual	(Jevrejeva 2001)
Ice breakup (d.y.)	Tallinn	1500–2000	Annual	(Tarand & Nordli 2001)
Winter air temperature (°C)	Tallinn	1500–2000	Annual	(Tarand & Nordli 2001)
Sea level pressure (hPa)	Northern Europe	1500–1995	Seasonal	(Luterbacher et al. 2002)
Air temperature (°C)	Northern Europe	1500–2002	Seasonal	(Luterbacher et al. 2004)
River runoff	Baltic Sea	1901–1949	Monthly	(Mikulski 1986, Cyberski & Wróblewski 2000)
River runoff	Baltic Sea Sub-basins	1950–1995	Monthly	BALTEX Hydrological Data Centre

3.1 Synoptic climatology: now and then

Synoptic climatology examines the relationship between local and regional climatic conditions and atmospheric circulation (Barry & Carleton 2001). Synoptic observations typically comprise the temperature and pressure at a given station at certain times. Nowadays, standard weather observations include instrumental measurements of air temperature, dewpoint temperature, air pressure (adjusted to mean sea level), wind speed and direction, pressure change over the last three hours, and pressure tendency; as well, visual observations are made of cloud amount, cloud type, and cloud base height (for low, middle, and high cloud layers), visibility, and current weather. In addition, precipitation amounts are recorded every six hours and snow depth once a day. With all this information, it is possible to follow a weather system from early development, through its peak, until it breaks down. Such information is essential to making good weather forecasts, since advanced computer models require great deal of input data.

Historically, the field of surface observations started in the late seventeenth century when several European cities began to keep records of regular meteorological observations (see Camuffo & Jones 2002, Jones & Briffa 2006). In Sweden, the earliest regular such observations were initiated in the early eighteenth century in Uppsala (Bergström & Moberg 2002), Stockholm (Moberg et al. 2002), and Lund (Bärring et al. 1999), concerning properties such as air temperature, air pressure, cloudiness, and weather type. Such measurements were often made and initiated by astronomers and interested laymen. Before records of instrumental measurements were kept, most information used in climate research is journals of different kinds, often kept by people who in one way or another were dependent on the weather. Documentary data is a general term that include all forms of written historical information about past climate and weather (see Brazdil et al. 2005, for a review). The typical weather-related information available from the early parts of the last millennium consists of harvest reports telling whether the harvest was good or bad, which gives a hint of the kind of growing season experienced (e.g. Meier et al. 2007). Travel reports are also a source of climate knowledge. In the Baltic Sea area, where the presence of sea ice could impede or enable otherwise possible or impossible journeys, this is of particular interest (e.g. Retsö 2002). A compilation of historical surface information into maps for a specific area gives a good understanding of how pressure systems and storm tracks have been situated over time (Lamb 1995). When pressure maps have been constructed, it is possible to project the information onto a grid covering the region of interest.

This thesis uses circulation data from a 1° × 1° gridded dataset (Luterbacher et al. 2002). The data is a reconstruction of monthly sea level pressure (SLP) fields back to 1659 and seasonal reconstructions from 1500—1658 for the Eastern North Atlantic region, i.e., 30°W to 40°E, 30°N to 70°N. The SLP grids have been reconstructed by means of principal component regression analysis with predictors comprising all available early instrumental time series (i.e., pressure, temperature and precipitation) as well as several climatic indices based on documentary proxy data. Subsequently the SLP reconstruction was used for an empirical orthogonal function (EOF) analysis. The SLP reconstructions assume stationarity in the statistical relationships derived during the modern calibration period (i.e., 1901—1960).

Owing to the short calibration period, the reconstruction is also entirely based on high-frequency relationships. The SLP reconstruction was tested, and it was found that the best model performance was obtained for the winter data (Luterbacher et al. 2002). The authors concluded that this indicates of greater spatial coherence between the atmospheric circulation and climate variables in the cold season. By compiling a gridded dataset regional information is much better captured, hence, if all information would have been combined into a mean much of the variability would have been evened out. The gridding allow for high amplitudes from documentary sources to impact the reconstruction in an area close to the collected information.

3.2 Geostrophic wind components

The atmospheric circulation over an area is complex and could be described by a wide range of parameters, although direction and strength are the most frequently used. In the climate community, long-term measurements of wind direction and speed are scarce; on the centennial timescale they are almost non-existent. A common way of calculating wind speed and direction over longer time periods is therefore to calculate the geostrophic wind from the pressure field. The geostrophic wind describes the wind field in terms of its strength in the east–west and north–south directions. From the pressure field it is also possible to construct additional indices that describe the rotational components of the flow. These rotational components describe the circulation in terms of low-pressure (cyclonic) or high-pressure (anticyclonic) systems. Taken together, the geostrophic wind components and rotational terms form a set of circulation indices that quantify atmospheric motions in terms of zonal (east/west), meridional (north/south), and rotational (cyclonic/anticyclonic, expansion/contraction, and deformation) flow components. They are fairly easy to derive from gridded air pressure datasets, and allow good physical interpretation, making them very appropriate for our purposes.

The classification used in this thesis was based on SLP data on a 5° latitude by 10° longitude grid-point basis. The pressure grid used, with the 16 points depicted as stars, in calculating the circulation indices, is depicted in Figure 5. Paper I used monthly climatology, while Papers II—IV used seasonal climatology together with reconstructed seasonal SLP data (Luterbacher et al. 2002) to calculate the geostrophic velocity field. In Paper I the geostrophic components were calculated using a classification scheme originally developed for the British Isles (Briffa 1995), a scheme later adapted to the Baltic Sea (Chen 2000); however, in the ensuing papers (i.e., Papers II—IV), the geostrophic velocity field was decomposed into its five basic flow fields.

3.2.1 Circulation classification in weather types

In Paper I we used the Lamb classification of weather types (Lamb 1950) to describe the atmospheric circulation over the Baltic Sea. The Lamb weather type classification is an objective scheme that determines the strength and vorticity of the geostrophic wind components, thereby determining the weather type. The scheme produces 27 different weather types: eight directional types: N (north), NE (north-east), E (east), SE (south-east), S (south), SW (south-west), W (west), NW (north-west); anticyclonic (A) and cyclonic (C); 16 hybrids (e.g., CN, CNE, AN, and ANE); and one unclassified type (U). The frequency of the calculated weather types is summarized for each month. A weather type classification is a descriptive way to describe the atmospheric circulation. The name of the weather type makes it easy to visualize the dominant circulation pattern and gain understanding of the underlying forcing mechanisms. The frequency of a certain weather type is useful for interpreting the variability of other climate variables (e.g., air temperature) strongly dependent on atmospheric circulation. In Paper I we conclude that four weather types dominate, namely, the westerly (W), south-westerly (SW), anticyclonic (A), and cyclonic (C) types. Taken together, these account for 59.2 % of the studied period. These estimates are in line with those of (Chen 2000).

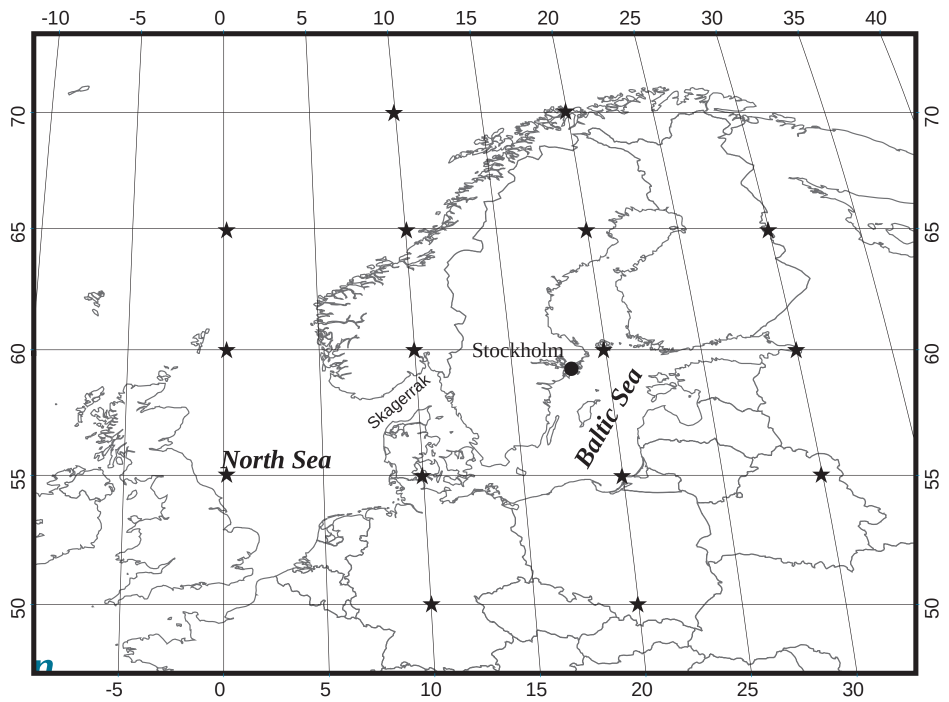

Figure 5 The sea level pressure (SLP) grid (shown as stars) used to calculate the circulation indices that describe circulation over the Baltic Sea region; used in Papers I—IV.

3.2.2 Circulation indices from the geostrophic velocity field

In Papers II-IV, a set of circulation indices was calculated on a seasonal basis using the grid of pressure data presented in Figure 5. Instead of using the classification scheme, the focus is on determining the relative importance of the different parts of the velocity field. The geostrophic velocity field $\mathbf{V}_h$, was divided into its five basic flow fields, as follows (see Paper II for details).

$$\mathbf{V}_h = \underbrace{\mathbf{V_0}}_{location} + \underbrace{\mathbf{R}}_{orientation} + \underbrace{\mathbf{E}}_{area} + \underbrace{\mathbf{D_1} + \mathbf{D_2}}_{shape} \qquad (1)$$

The first term, $\mathbf{V_0}$, is *translation*, which describes change in location induced by zonal and meridional winds. The four following term are the kinematic properties of fluid flow. The second term, $\mathbf{R}$, is *vorticity*, a rotational component describing the orientation and represents the strength of the circular movement of air masses. Positive values are associated with cyclonic rotation (low-pressure systems) and negative values with anticyclonic circulation (high-pressure systems). The third term, $\mathbf{E}$, is *expansion* or *convergence/divergence*, giving the change in area of the flow. The two deformation velocities fields represent the torque put on the velocity field, giving a change in shape, due to *shear*, $\mathbf{D_1}$, and *stretching* due to normal deformation, $\mathbf{D_2}$.

3.3 Stepwise multiple linear regression

The atmospheric circulation indices calculated in the previous section are used in Papers III and IV to create statistical models of maximal ice extent (MIB) and river runoff in the Baltic Sea based on stepwise multiple linear regression. By formulating a model based on components of the atmospheric circulation it is possible to relate variations in ice and runoff to circulation characteristics. The circulation indices are used as predictors and comprise the basis of the statistical model. The statistical model is formulated to inspect the atmospheric circulation indices to identify the predictors that significantly contribute to variation in the time series analysed. This inspection was made possible by using the stepwise regression method. The stepwise regression routine chooses predictors whose importance is assessed in terms of an F-test; predictors that pass the 90% significance level are considered. The most important predictor is determined in the first step, the remaining predictors are considered and the second most important predictor is chosen in the next step, and so on. The previously chosen predictors are subjected to the F-test after each step, to see whether they have become less important after the latest choice of predictor. If this is the case, the predictors are discarded from the regression equation. The predictors are added to the regression equation after each step and the best fit is computed. The multiple linear regression model takes the form

$$Model = A_0 + \sum_{i=1}^{6} A_i X_i \tag{2}$$

where A_i, i = 0 … 6 are the coefficients determined by regression and X_i, i = 1 … 6 are the predictors calculated from the velocity field and shown in Eq. 1. A value of the sought variable, ice or runoff in this case, is produced from the model in Eq. 2. To determine the confidence of the statistical relationship produced using the above method, the model must be validated. In most cases when statistical models are developed from multiple linear regression methods, the series are divided into two different subsets, one used for calibration and the other for validation. A practical way of doing this is to cut the series in half and use the first half of the series for validation and the second half for calibration. Since most time series of data are more accurate in the latter part, this is usually considered to ensure better model “skill”. The disadvantage of cutting the series in half is that only variations associated with the scale of the calibration period can be resolved. In paper III, another way of dividing the series into subsets was considered, namely, dividing the series by odd or even years. This way of constructing the calibration subset may train the model so that it captures variations associated with greater scales.

3.4 Matching pursuit

The matching pursuit (MP) technique in combination with a complementary wavelet analysis provides a powerful method for examining time series (Percival et al. 2004a). As discussed in (Percival & Walden 2000) and (Percival et al. 2004a), the idea underlying MP is to approximate a time series in terms of a small number of vectors selected from a large collection of vectors called a dictionary. The efficiency of the approximation depends critically on the contents of the dictionary. As originally formulated by (Mallat & Zhang 1993), the dictionary contained vectors that allowed the time/frequency decomposition of a time series. In this case, we formulated the dictionary to allow episodic events also to be selected, along with sinusoidal and square wave oscillations.

In Figure 6 an example of the different types of vectors associated with the dictionary is shown. Episodic events are handled by “groups” — sequential observations of the same sign (Figure 6a) and a Haar wavelet shape, which are adjacent “groups” of the opposite sign (Figure 6b). We also included sinusoidal (Figure 6c) and square wave oscillations (Figure 6d) because of our interest in describing climate variability in terms of sudden regime-like shifts. With the dictionary so defined, MP is potentially useful for picking out abrupt changes or events in climate time series.

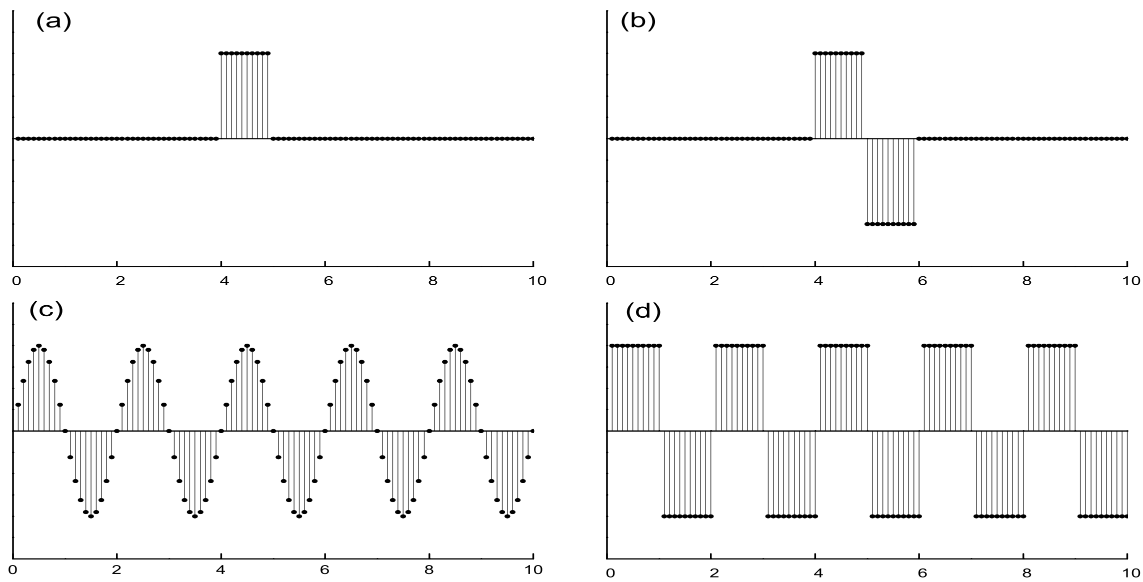

Figure 6: Examples of dictionary elements used in matching pursuit analyses of a time series. (a) A vector that describes a grouping of 10. (b) A vector created from a discretized Haar wavelet function associated with changes on a scale of 10. (c) A vector containing a sinusoidal oscillation, with a period of 20. (d) A vector containing a square wave oscillation with a period of 20 time steps in the time series.

Details of the method are provided in Paper II. MP provides an additive decomposition of a time series and guarantees a decrease in the sum of squares of the residuals at each successive step of the sequential fitting of a time series. By successively comparing the residuals at a given step with the vectors in the dictionary, we build up a picture of what constitutes the important components of a time series. MP is a valuable tool for exploratory data analysis because it provides an objective method of exploring a time series in terms of a collection of possible explanatory patterns, both periodic and episodic. In addition, some of the first vectors picked out by MP might also serve as the starting points of more formal statistical models. The periods singled out in the MP analysis can be further examined using wavelet analysis.

3.5 Wavelets

It is well known from Fourier theory that a signal can be expressed as the sum of a series of sines and cosines, a sum also referred to as a Fourier expansion. Fourier analysis has been widely used in climate and oceanographic research to resolve signals on certain timescales. The great disadvantage of Fourier expansion, however, is that it has only frequency resolution, but no time resolution. This means that, although we might be able to determine all the frequencies present in a signal, we will not know *when* they are present. To overcome this problem, solutions have been developed that can represent a signal in the time and frequency domain at the same time.

Wavelet analysis is a useful method for analysing climate time series (Percival et al. 2004a, Percival et al. 2004b) and complements our use of matching pursuit. A wavelet (i.e., small wave) is defined over a specific interval, unlike a standard wave, which is defined over the entire axis. A wavelet analysis is the result of an integration of the resulting function when a time series, $x(u)$, is multiplied by a wavelet. For function ψ to be a wavelet, it has to fulfill the following conditions:

- ψ must integrate to 0, i.e., $\int_{-\infty}^{\infty} \psi(u)du = 0$; and
- ψ^2 must integrate to 1, i.e., $\int_{-\infty}^{\infty} \psi^2(u)du = 1$.

The first condition tells us that the wave must be balanced around zero. The second condition tells us that the fluctuations of the wavelet must be contained within an interval of finite width. The simplest form of wavelet is the Haar wavelet. The Haar wavelet has the form of two adjacent groups, and has the form of the vector presented in Figure 6b. The Haar wavelet can be defined as

$$\psi_{\lambda,t}{}^{(H)}(u) \equiv \frac{1}{\sqrt{\lambda}}\psi^{(H)}\left(\frac{u-t}{\lambda}\right) = \begin{cases} -\frac{1}{\sqrt{2\lambda}}, & t-\lambda < u \le t; \\ \frac{1}{\sqrt{2\lambda}}, & t < u \le t+\lambda; \\ 0, & \textit{otherwise.} \end{cases} \tag{3}$$

Variable λ is the scale and *t* is the point where the wavelet is centred. To define the wavelet for different scales, the wavelet must be stretched or shrunk to conserve its properties. Similarly, the wavelet needs to be relocated to be defined for different times *t*. The above expression allows us to form different wavelets according to the choice of scale and position. It is seen that:

- $\frac{u-t}{\lambda}$ does the stretching/shrinking and relocation, and
- $\frac{1}{\sqrt{\lambda}}$ is needed so that Eq.3 has unit energy.

The continuous wavelet transform (CWT) of time series *x(u)* with respect to wavelet ψ is a function of scale and location and is defined as

$$W(\lambda,t) = \int_{-\infty}^{\infty} \psi_{\lambda,t}(u)x(u)du \tag{4}$$

A value for a given scale and location, $W(\lambda,t)$, is called the wavelet coefficient. To visualize what the wavelet coefficient describes, it is useful to rewrite Eq. 4 using the definition of the Haar wavelet in Eq. 3. For a wavelet scale $\lambda=1$ at $t=0$ which centres the wavelet at the origin, we get

$$W^{(H)}(1,0) = -\frac{1}{\sqrt{2}}\int_{-1}^{0} x(u)du + \frac{1}{\sqrt{2}}\int_{0}^{1} x(u)du. \tag{5}$$

This equation tells us that the Haar wavelet coefficient, $W^{(H)}$, is proportional to the difference between two adjacent averages for equal intervals. These intervals are referred to as the scale of the wavelet. Thus, if $|W^{(H)}|$ is large, these averages differ substantially; on the other hand, if

$W^{(H)}$ is near zero, there is little difference between the two averages. More generally, it can be stated that the wavelet coefficient, $W^{(H)}(\lambda,t)$, is the difference in averages over a certain scale λ before and after time t. Similarly, other wavelet transforms can be deduced, and by looking at the basic wavelet, one can interpret the meaning of the wavelet coefficients.

In practical applications, CWT cannot be computed exactly, because x is only recorded at selected times. So, in place of CWT we use the discrete wavelet transform (DWT), which is specifically designed to work with time series sampled at equal intervals (irregular sampling is typically handled by interpolating the data). DWT can be regarded as approximating CWT over a so-called dyadic grid of scales and is computed by a wavelet filter instead of a wavelet function. Each row is usually set to the largest integer less than or equal to $\log_2(N)$; N represents the sample size. DWT also requires the discretization of the continuous time variable. In Papers II—IV, the maximal overlap DWT (MODWT) is used, which is a version of DWT. MODWT is a decomposition of a time series giving localized coefficients that can be compared with those of other time series to ascertain the correlation structure on a scale by scale basis (Karlöf et al. 2006). Unlike DWT, MODWT is well defined for all sample sizes and also gives N wavelet coefficients for each dyadic scale. Although MODWT is not an orthogonal transform, it can be used to construct a multiresolution analysis and an analysis of variance similar to those given by the orthogonal DWT (Percival & Walden 2000).

4 Characterizing climate

The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things (IPCC 2007). To analyse the past climate in a proper way, one must distinguish between natural and unnatural forcing mechanisms. This is not easy at the present time, since we know that anthropogenic influence has been substantial over the past 150 years. We know that, since the industrial revolution, the amounts of aerosols and greenhouse gas concentrations have increased in the atmosphere; we also know that land use and population have changed immensely.

Climate is a broad field of research in which most research focuses on various statistical properties, including maximum, minimum, and mean temperatures. These properties can in many ways be seen as conserved over time if nothing in the driving parameters is changed. Variability is also a statistical property of climate, and its changes could often be coupled to a change in forcing. The forcing variables of climate can be related to many different timescales: long timescales are typically associated with orbital parameters of the Earth such as the precession, obliquity, and eccentricity, shorter timescales include solar irradiance and the NAO signal, while very short timescales are weather and the daily cycle.

A common pitfall when analysing climate variables on longer timescales is data reliability. Regarding station data, the data quality in a dataset, for obvious reasons, gradually decreases moving back in time. This is of course because, as we move further away in time from the point when the data were collected, we are less confident that the data have been collected in the same way as is done today. Even unavoidable and seemingly insignificant incidents, such as changing the person collecting the data, could have large effects on data quality. Other things to be aware of regarding station data are that the locations of weather stations could, over time, have been affected by urban heating or major improvements in instruments. Old weather monitoring sites located in places that we know are now affected by urban heating must be treated carefully. Thermometer exposure issues have been found to affect the Stockholm air temperature series in the late nineteenth century, which probably resulted in too high summer temperatures (Moberg et al. 2003). Looking for climate change in a series that is clearly inhomogeneous is not very useful, since real signals could be masked by the changed conditions. To avoid such pitfalls, the meteorological time series used today are checked for homogeneity (Alexandersson & Moberg 1997, Moberg & Bergström 1997, Bärring et al. 1999, von Storch & Zwiers 1999). Performing these tests on a time series identifies years when conditions changed. One must, however, bear in mind that a homogeneity check could identify the years that do not signify changed instrumental conditions, but rather changes in forcing. Therefore, such years should, when possible, be validated against other information, such as journals kept by observers or similar records. A problem with European documentary data is that when instruments came into use it was the death knell for many types of documentary sources as the observers quickly moved to using the new instruments. For that reason, it is very hard to verify the early measurement records (Brazdil et al. 2005, Jones et al. 2009, and references therein).

Old collections of station data, however, are not the only way to gain knowledge of the past climate; a vast community of researchers collecting proxy data has grown substantially in recent years. Proxy data are indirect sources of information regarding past climate, which currently include ocean and lake sediments, pollen grains, corals, ice cores, tree rings, and historical documents.

4.1 Time scales in climate

The synthesis of weather is often said to be the definition of climate. A climate timescale is the period over which a given climatic variable is averaged. How this averaging is done, and over what period, are often treated differently depending on the question one is working with and the resolution of the time series to be used. A common definition of climate is a period of thirty years. Almost all current weather data are presented as anomalies compared with the latest standard meteorological period of 30 years, currently the 1961—1990 period. If, for example, daily temperature is measured, it is related to the average daily temperatures over the latest standard meteorological period. Remember yesterday's weather report? Surely the meteorologist reported that the expected temperatures and rainfall were above or below normal, normal in this case being the 1961–1990 average.

In Paper I (Omstedt et al. 2004b) we looked more closely into the definition of climate timescale and analysed how the variance of different climatic time series differed. The studied time series were air temperature and sea level from Stockholm, a seasonal index calculated as

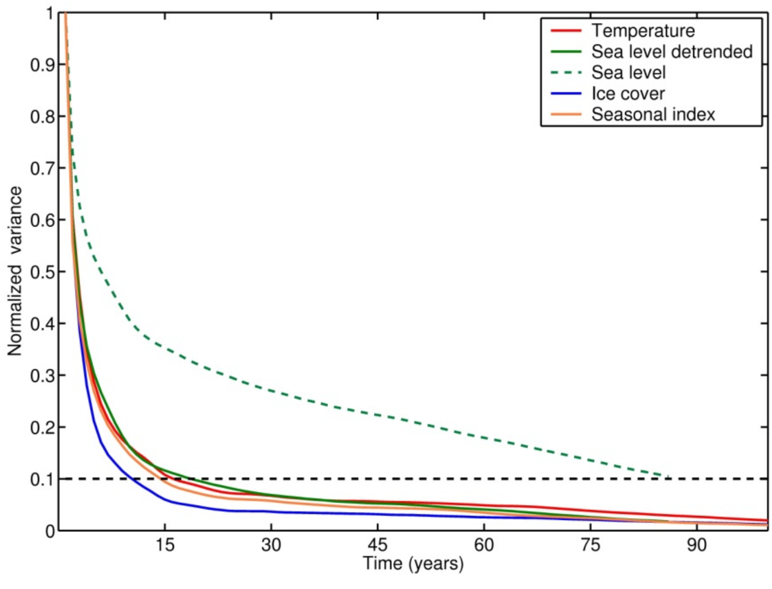

Figure 7: Normalized variance of the studied time series. At a time scale of approximately 15 years, 90% of the variance is captured (the dotted line is at the 10% level). When the sea level curve is detrended equal to a sea level rise of 1 mm per year for the period 1900—2000 period, it displays the same characteristics as do the other variables. From (Paper I Omstedt et al. 2004b).

the difference between the summer (JJA) and winter (DJF) seasonal temperatures, and ice cover (see TABLE 2). By computing the variance of the time series over different averaging times, we found that 90% of the variance is found within timescales shorter than 15 years. To compare the different variables, the variance was normalized such that variance is 1 for a resolution of one year. In Figure 7 it is apparent that the different variables behave similarly, except for sea level observations. The similarities between the time series could probably be explained by close interrelationship on short timescales, and by the fact that their variations could be related to variations in the same forcing. It is also indicated that their internal response time is shorter than or as large as the timescale of the variation of the forcing. The question was raised as to why sea level does not follow the same curve as do the other variables. It is probable that sea level in the Baltic Sea is externally driven by a forcing that does not affect the other variables. This forcing could very well be the ongoing global sea level change, estimated to be 1.7 ± 0.5 mm year^{-1} (IPPC 2007, p. 387). A trend of 1 mm year^{-1} over the last century is in line with the results of (Ekman 1988, 1999); when this trend is removed, the sea level curve falls into line with all the other variables. An accelerated sea level rise over recent decades with enhanced greenhouse gas forcing, however, is not apparent in the Stockholm sea level series (Ekman 2000).

In Paper I we divided the time series of the different variables into 15-year intervals and examined how these intervals had changed over the instrumental period. For each variable, we examined the variability related to the sub-periods by examining mean values, maximum values, minimum values, variance, and trends. From the mean values one can observe that there have been, and will probably continue to be, changes between different 15-year periods. This illustrates the limitations of using the term *normal* in climatology. By examining the mean values (Figure 8a), a positive trend in air temperature was found, while closer inspection of the maximum and minimum values (Figure 8b,d) revealed that both high and low temperatures have occurred in both centuries.

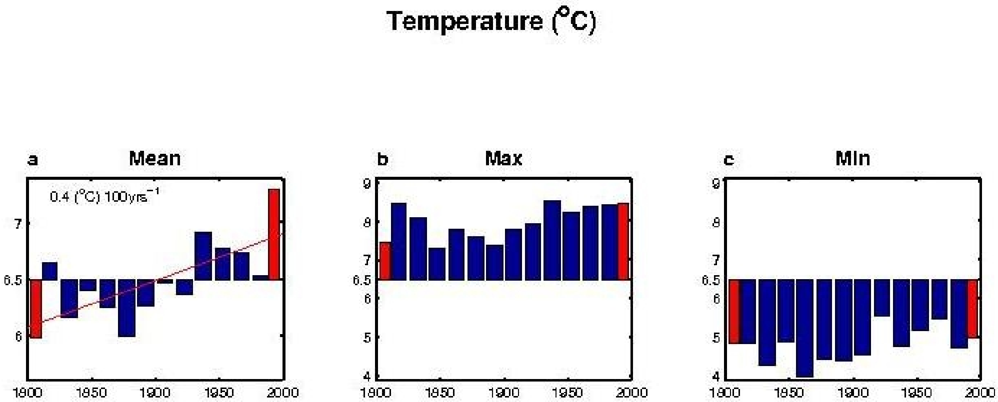

Figure 8: Climate statistics for the Stockholm air temperature using a 15-year climate period, shown as anomalies from the 1800—2000 mean. a) mean temperatures and trend; b)maximum temperatures and c) minimum temperatures From (Paper I Omstedt et al. 2004b).

Information about the maximum and minimum values is highly relevant, not only to researchers but to society. Adaptation to a possibly changing climate must consider both extreme events and change in the mean state. By studying the extremes, one can, for example, determine whether a shift to a warmer mean state eliminates the possibility of extreme cold years. Figure 8b and c illustrates that, over a 15-year period, at least one year with exceptionally warm and another with exceptionally cold temperatures would occur. What is also apparent from such an inspection is that the two centuries differ markedly in behaviour, displaying an increase in mean and maximum temperatures beginning at the end of the nineteenth century. More information from the Stockholm record is given by the seasonal index, which gives the magnitude of the annual temperature cycle. This index displays a negative trend, which could be interpreted as a more maritime-influenced climate; the maximum and minimum values, however, indicate that the variability is still stable, giving no clear trends (see Paper I).

To relate these properties to circulation changes, information about the atmospheric circulation over the same time period was taken from a gridded pressure dataset. The four most common circulation types were calculated from this grid, which accounted for 59.2% of the total weather types. In addition, it is evident from the weather frequencies that the centuries behaved differently, the frequency of westerly winds and anticyclonic being much higher in the twentieth than the nineteenth century.

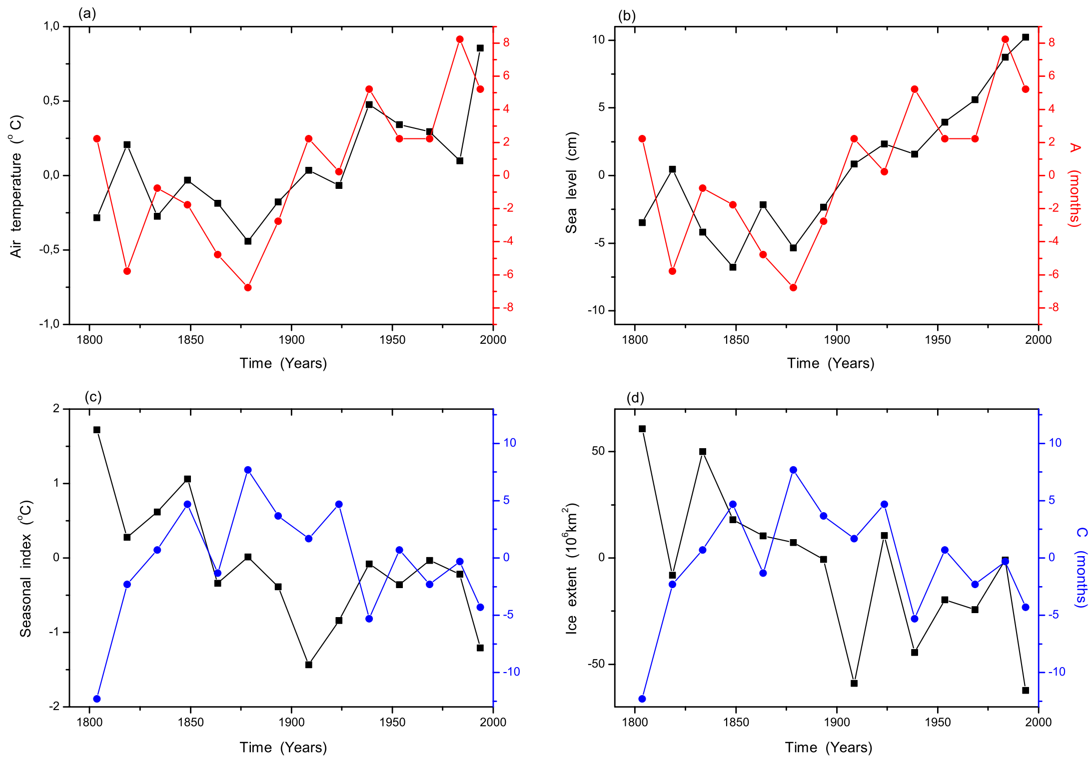

Figure 9: Anomalies in the climate records together with the circulation types that describe the rotation of the atmospheric circulation. Red indicates anti-cyclonic and blue cyclonic circulation. From (Paper I Omstedt et al. 2004b).

It is also noticeable that the highest frequencies of cyclonic circulation are found in the transition between the two centuries, which could have triggered the ending of the Little Ice Age. Comparison of weather frequencies and the other variables indicates that, starting in the mid nineteenth century, the air temperature in Stockholm is closely related to the frequency of high-pressure circulation (Figure 9a). Similarly, examining the interrelationships after the mid nineteenth century reveals a close connection between ice extent and low-pressure circulation (Figure 9d).

The study covering the past two centuries demonstrates that the climate has been largely influenced by high-pressure circulation and westerly winds, which could be due to a northward shift in the low-pressure tracks. A northward shift in the low-pressure tracks would explain the increased frequency of high-pressure circulation and is consistent with the upward trend in the NAO index (Jacobeit et al. 2003) and its associated sea level rise (Andersson 2002). This work therefore supports the hypothesis that climate change over the region could at least partly be attributed to circulation changes.

In Paper I, we divided the past two centuries into 15-year climatic periods for which we investigated different climatic variables. In Paper II, we took a slightly different approach, in order to gain an understanding of the past climate. Instead of examining the climate of preset time periods we tried to find time periods in the time series that displayed similar characteristics – essentially the opposite of what was done in Paper I. Instead of focusing on the variance we looked for patterns in the time series. These patterns were identified by an MP analysis and ranged from several years to centuries.

4.2 Regimes in climate

Climate is far from well organized in terms of well-defined oscillations and trends. Climate variability could be organized as pending between different states, some more stable and long-lasting than others. Even though the best-known way of looking at climate change is to study some kind of gradually increasing or decreasing variable, this is far from capturing the complexity that the climate of our planet is demonstrating, due to its non-linear nature. It is well known that, in the past, the Earth's climate has experienced rapid shifts from one state to another, resulting, for example, in glaciations and deglaciations. Climate reconstructions based on borehole data clearly indicate the great range of climate change and the great number of timescales on which the climate operates (see chapter 6 in IPCC 2007). One problem in detecting climate change is that the tools one uses for detection often determine the results one gets. More explicitly, this means that most methods are good at finding one type of change, which could be trends, regime shifts, or oscillations. Using the MP technique, described in section 3.4, it was possible to look at the time series with fresh eyes. Since the MP method can detect different types of changes, we found it to be a good tool for our analysis. The dictionary used in the MP analyses was constructed so that it contained dictionary vectors describing all sorts of climate change patterns one could expect to find. Patterns associated with climate change are discrete events of both short duration, such as volcanic eruptions, and long duration, such as a change in mean state. The dictionary also contains vectors that describe oscillations, to allow the resolution of NAO-like phenomenon. The objective of using the MP technique was also to compare series containing different information and different variables with each other. Figure 10 presents the 10 first steps in the MP analysis of MIB. Strikingly, the first mode identified is the cold phase occurring between the mid eighteenth and latter nineteenth century. The vector chosen in step 1 yields the highest explained variability of all the vectors in the dictionary, in this case 6.9%. In step 2, the cold winters of World War II are identified as the second most important feature, raising the explained variability to 11.1%. In each consecutive step, the vector that increases the explained variability the most is added, and by advancing further in the analysis, more and more variability is explained.

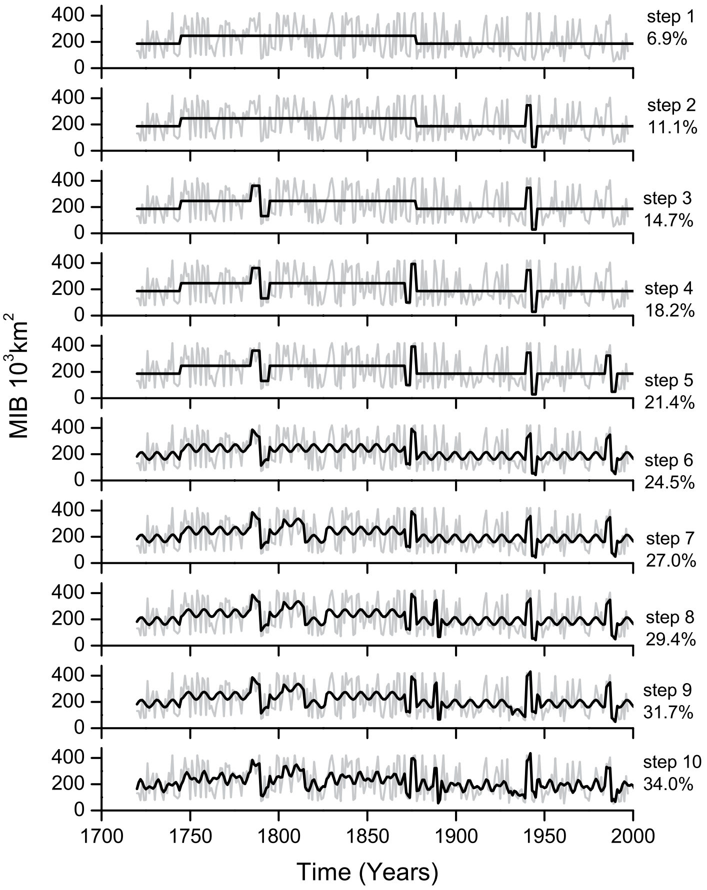

Figure 10: Matching pursuit analysis of MIB. The top panel shows the first event (black line) identified by the MP analysis, together with the observational time series (gray line). The succeeding panels show the results of the next steps as black lines, added to the previous steps. At each step, the percentage of the explained total variance is indicated, From Paper II.

From analysing all the time series using MP, we were able to determine that warm and cold periods of varying durations were common features of several climatic parameters and locations. We selected a total of 15 periods with different characteristics (TABLE 3); a comprehensive description of the 15 periods is given in Paper II, where the MP periods are carefully investigated and explained with reference to several mechanisms. To further explore the MP periods, a wavelet analysis was performed on the time series. By looking at the MP periods in terms of variability on different timescales, we succeeded in explaining uncommon characteristics of warm and cold periods. By analysing the shorter timescales in the series, we found that, on short timescales, warm periods have low variability while cold periods have high variability. Mild periods could have reduced variability on short timescales because these are periods of increased climate stability. Cold regimes, on the other hand, display greater variability on interannual timescales and thereby yield a more diverse climate. Centennial-scale variability was found with obvious changes between the nineteenth and twentieth centuries, changes in the decadal signal being apparent. From the longer-term perspective of interannual and decadal timescales, we found that modulations of these scales are often accompanied by rapid shifts. It is impossible to find any clear periodicities in the analysis, so we concluded that the Baltic Sea climate is better described by discrete events. The periods singled out were also compared with circulation indices and winter temperatures derived from gridded data (Luterbacher et al. 2002, Luterbacher et al. 2004). Much of the behaviour of the temperature and ice time series could be explained by the atmospheric circulation, in particular, by wind direction and rotation. A recent study of spring temperatures in south-western Finland (Holopainen et al. 2009) concluded that the late eighteenth and early nineteenth century (coinciding with MP8) experienced high variability on the year-to-year scale, which is in line with our result of higher interannual variability during cold periods.

TABLE 3: CLASSIFICATION OF BALTIC SEA WINTER CLIMATE (FROM PAPER II).

MP 1	1522–1536	Mild
MP 2	1562–1576	Cool
MP 3	1577–1591	Mild
MP 4	1597–1629	Cool
MP 5	1630–1662	Mild
MP 6	1663–1706	Cool
MP 7	1707–1750	Mild
MP 8	1750–1877	Cool
MP 9	1803–1820	Cool
MP 10	1878–2000	Mild
MP 11	1930–1939	Mild
MP 12	1940–1942	Cool
MP 13	1971–1975	Mild
MP 14	1985–1987	Cool
MP 15	1988–1993	Mild

5 Reconstructing the past

Reconstructions of past climate are important for providing a historical context within which to evaluate the nature of twentieth century climate change. A number of reconstructions of millennial-scale climate variability have been carried out (Figure 11) in order to understand patterns of natural climate variability, on decade to century timescales, and the role of anthropogenic forcing (Jones et al. 2009). Reconstructions are of great use as they also provide tests of the response of large-scale climate to a variety of climate forcings which occurred during the last millennium. Many reconstructions have used mainly tree-ring data and other datasets of annual to decadal resolution. Lake and ocean sediments have a lower time resolution, but provide climate information on multicentennial timescales that may not be captured by tree-ring data. Recently, Northern Hemisphere temperatures over the past 2000 years were reconstructed by combining low-resolution proxies with tree-ring data (Moberg et al. 2005). This study, (Moberg et al. 2005), suggests that natural multicentennial climate variability may be greater than usually thought (see e.g. Mann et al. 1998), and that much of this variability could result from a response to natural changes in radiative forcing. By applying wavelet methods to the time series used, they were able to extract signals in the time-scale domain. This does not imply that the global warming of the last few decades was caused by natural forcing factors alone, but underscores a need to improve scenarios for future climate change by also including forced natural variability, which could either amplify or attenuate anthropogenic climate change significantly.

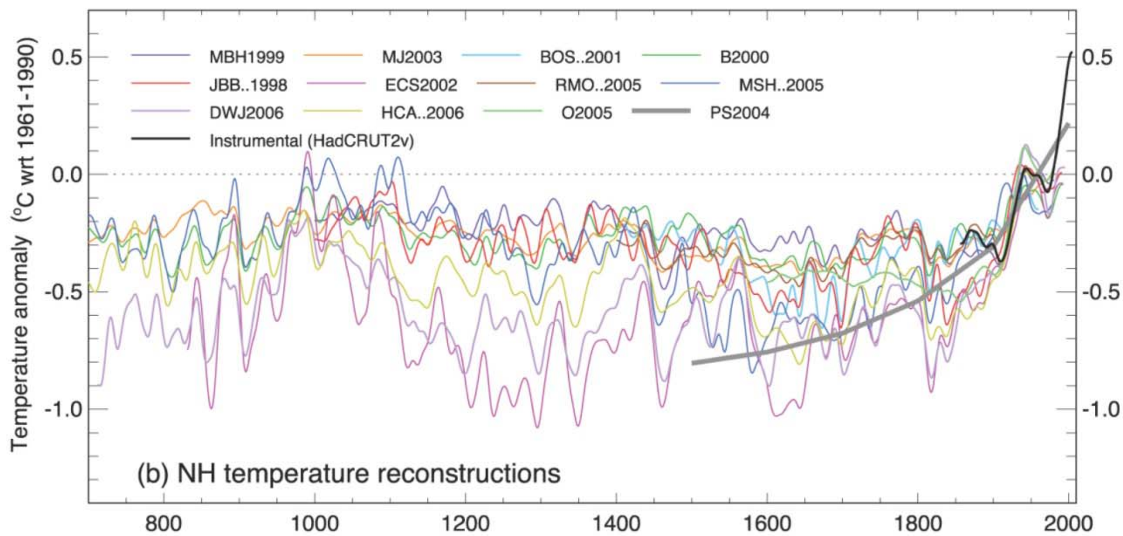

Figure 11: Reconstructions of Northern Hemisphere temperature. Anomalies are related to the 1961—1990 mean. From (IPCC 2007,middle panel of graph 6.10 p. 467)

The existence of great past climate variability is more problematic than less past climate variability would be for interpreting future climate change. This is because climate sensitivity is much larger in a climate simulation tuned to a varying climate, which then projects a larger range of future climate temperature increase (e.g. Tett et al. 2007).

5.1 Reconstruction of regional climate variables

Reconstructions of Northern Hemisphere mean temperatures are good at giving an integrated view of climate variations over a vast area; they do not, however, reveal anything about the regional climate. Regional variability is evened out when a hemispheric mean is constructed from many different and diverse regions. There is always a clear need for more local and regional reconstructions from diverse proxies in as many parts of the world as possible (e.g. Jones et al. 2009). The aim of Papers III–IV was to gain a better understanding of the regional climate and the variability associated with it. Investigating the regional climate in greater detail calls for more detailed information about the regional scale. Throughout the thesis, regional information about the surface climate is used in the form of locally calculated atmospheric indices. Previous studies have often cited the NAO index; however, its explanatory ability has proven to be very unstable over time, and little insight into the regional pressure pattern has been gained from this index (Slonosky & Yiou 2002, van Ulden & van Oldenborgh 2005, Bouwer et al. 2008). By constructing regional information about the circulation, one can better assess how atmospheric mechanisms control ice extent and river runoff in the Baltic Sea. In both reconstructions, a model is made using circulation indices for the Baltic Sea region; in addition, air temperature is included in the river runoff model.

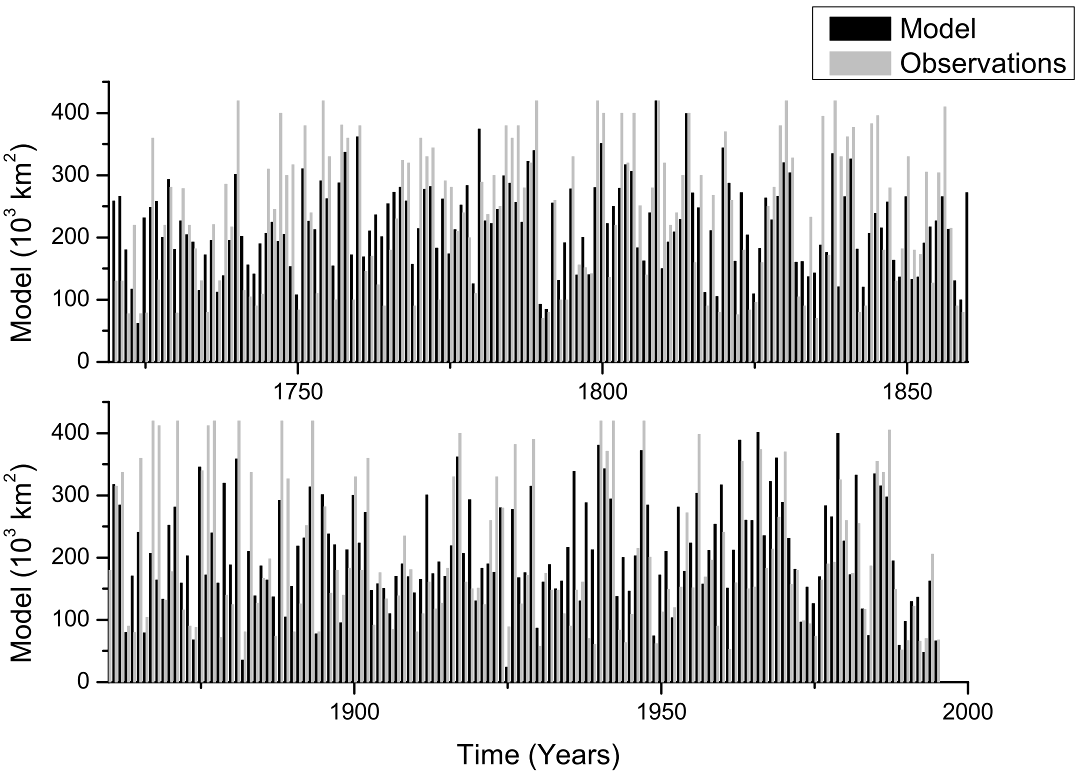

Figure 12: Maximal Sea ice extent in the Baltic Sea (MIB); modelled (black), and observed (gray). From Paper III.

5.1.1 Maximal ice cover extent in the Baltic Sea over the last 500 years

In Paper III, the MIB is related to atmospheric circulation indices over the period for which observational information is available. In this way, a model is formed that describes the most important factors determining the ice extent. When the model is formulated, it is possible to create a new series of ice data for the period before the observational record, in this case, the 1500–1719 period for which we have pressure information. To evaluate whether the model is performing well, a validation period is needed that is outside the calibration period; in this model formulation, the even years in the time series served as the calibration time and the odd years the validation time (Figure 12). Two other model formulations were also tested but not shown here; more information on these is found in Paper III. Encouragingly, the model performs well over the calibration period in terms of correlation coefficient ($R = 0.69$).

The model formulation is shown in Eq. 6 in terms of standardized predictors, allowing for immediate evaluation of how great an influence the ingoing predictors have. When using standardized predictors, the first term of the regression model equation is the mean of the observational data for the calibration period, which is also the mean for the model during this time. The following terms of the regression model equation describe how much the model would change in relation to the mean and standard deviation (std) of the ingoing predictors. If all the predictors simultaneously assumed values near their mean values, the model would produce a value near the mean of the observations for the calibration period. Similarly, those terms that assumed values near a standard deviation of ±1 would contribute to the model according to the size of the preceding coefficient.

$$MIB = 213 - 101u - 49v - 14\zeta - 29\delta_1 \tag{6}$$

It is obvious from the model formulation that zonal wind is the most important factor creating a large ice extent. Westerly flows, associated with positive values of u, cause the advection of warm air masses from the Atlantic and thereby a reduction in ice formation. Easterly flows, associated with negative values of u, favour ice growth. Second, the model states that positive meridional flows, v, limit ice growth; hence, importing air masses from the south is associated with warmer winters. A negative sign in front of the rotation term, ζ, indicates that low-pressure circulation diminishes the ice growth. Finally, the term δ_1 describes the shear deformation, which when positive is associated with precipitation. Precipitation thus limits the ice growth; this is probably because precipitation is associated with mild temperatures and, if precipitation comes as snow, it will insulate the ice, limiting its growth. Taken together, this means that a well-developed Russian high, which brings cold from the north-east, is most favourable for ice growth. A closer inspection of the predictors reveals that over the last 500 years, the strength of the zonal wind was greater than ±1 std in 136 years, 50 years being positive and 86 negative. Compared with the meridional flow, which only exceeded ±1 std in 17 years (9 positive and 8 negative), the zonal flow stands out as the most important factor.

5.1.2 River runoff

In Paper IV, the river runoff to the Baltic Sea Basin is modelled and reconstructed back to 1500 (Figure 13). To model the river runoff from the Baltic Sea Drainage Basin it is necessary to acknowledge the differences *within* the region. As the greatest factors that contribute to river runoff are precipitation and the drainage area, we assumed that the model had to be formulated to resolve these features. In the Northern and Eastern parts of the Baltic Sea drainage area, more continental air masses are dominant, while the southern parts are generally more affected by humid North Atlantic air masses. Considering the drainage area as a whole, the greatest impact on river runoff comes from lakes Ladoga and Onega in the eastern part of the drainage area discharging in the Gulf of Finland. A northern, southern, and eastern model formulation were therefore considered appropriate.

Candidate predictors in the model are the mean seasonal Baltic Sea air temperature and circulation indices developed from gridded data over the region (Luterbacher et al. 2002, Luterbacher et al. 2004). As additional predictors, two-season lags of the air temperature and circulation are included in the model formulation. A lag is desirable, since not all precipitation enters the Baltic Sea in the same season in which it is precipitated; damping factors occur naturally in the system, snowmelt being an obvious one.

The model produces the highest correlation coefficients for the calibration period for the northern and southern model. The correlation for the Gulf of Finland is weaker and is probably associated with difficulties resolving the effects of the big lakes Ladoga and Onega. From the model formulation it is clear that no overall atmospheric circulation feature is common to all seasons and regions; this, however, merely reveals that resolving the runoff to the Baltic Sea calls for regionally developed models. The somewhat different characteristics of the three sub-regions can be detected by the model equations. Over all seasons, the most important atmospheric circulation indices for the southern region are the rotational and deformation components. Physically, this means that the strength and torque of the cyclonic or anticyclonic pressure systems are important to the freshwater discharge. Precipitation in almost all regions of Sweden is favoured by cyclonic activity (Hellström et al. 2001), and powerful cyclonic systems bring more precipitation than do less powerful ones. In southern Sweden this has been most evident in autumn, and is probably related to high SST values leading to more unstable conditions and higher atmospheric moisture content (Linderson et al. 2004). The rotational, zonal, and meridional wind components, together with temperature, are the most important factors for the northern region, while temperature and wind primarily influence the runoff in the Gulf of Finland. This is expected, as zonal and meridional wind produce different rainfall responses. Westerly winds are often associated with humid air from the North Atlantic, while northerly winds tend to advect dry air into the region. The rotational components (i.e., the strength of the cyclonic or anticyclonic systems) are major influences on freshwater discharge in the northern region. In the Gulf of Finland, the strength of the cyclonic activity is only included in the summer. Lag and damping from the large lakes probably lessen the input from the rotational components. For southern Sweden, the strength of vorticity in autumn is reportedly an important factor controlling the amount of precipitation (Linderson et al. 2004).

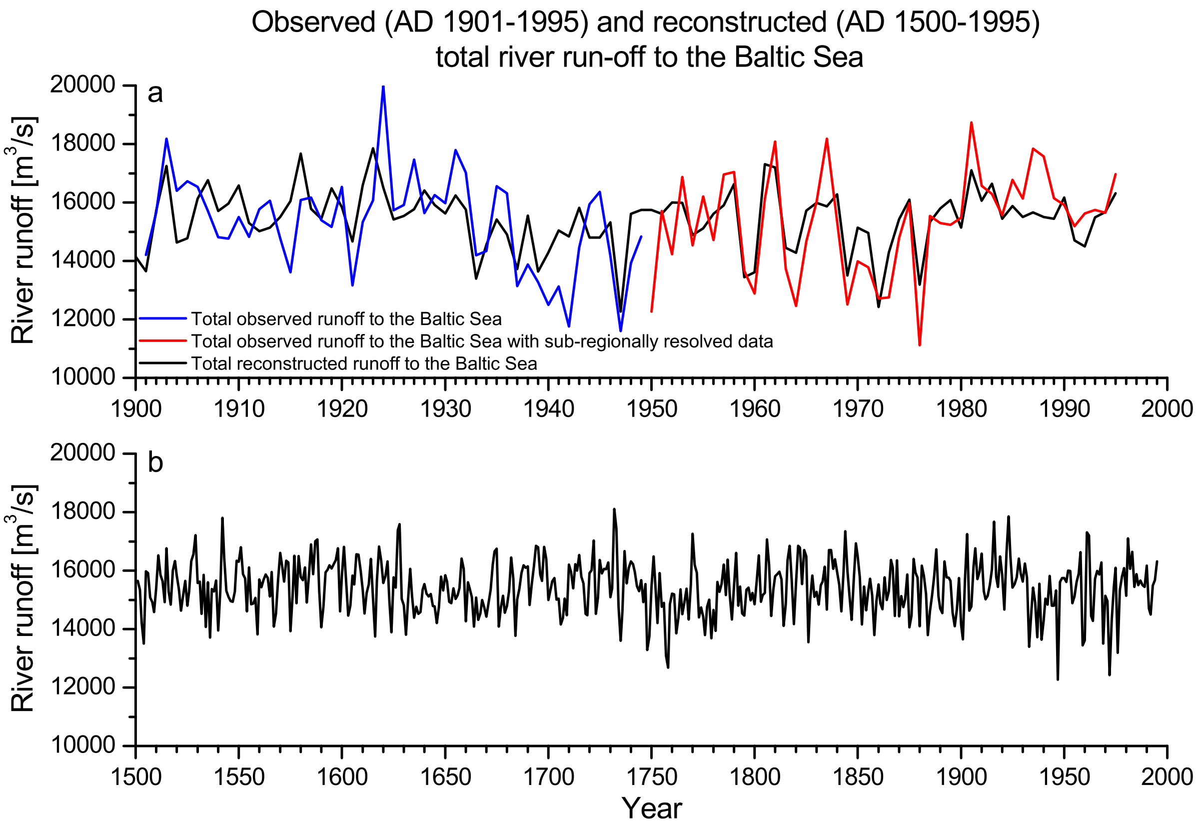

Figure 13: Reconstructed (black line) and observed (blue and red lines) annual river runoff over the twentieth century (upper panel). For the 1901–1949 period, only data on estimated total runoff to the Baltic Sea are available (blue line). From 1950 onwards, observations from all three sub-regions are available (red line). The full reconstructed annual river runoff to the Baltic Sea over the full 1500–1995 period is seen in the lower panel. From Paper IV.

From a modelling point of view, natural river discharge is preferable to observed regulated river discharge. For the analysis undertaken in this paper, we have neglected the input of the hydropower that changes the distribution of the river runoff over the year. However, our model was developed during a period when river discharges are being heavily modulated by large water reservoirs (Matthäus & Schinke 1999, Graham 2000).

5.2 Validation work

Validating long reconstructions of climate variables is far from trivial. The most challenging aspect of this field of research is the fact that, to create the best model, all available information should be incorporated in the model. This model construction method, however, leaves no information for generating a validation series. To get around these problems, many researchers have tried to link different variables and in this way validate their models. Historical data have also proven to be useful in climate analysis, and great efforts are currently underway in the field of historical climatology (Brazdil et al. 2005, Leijonhufvud et al. 2008, Jones et al. 2009).

If no source of additional information is to be found, a time series can be subjected to signal processing to build trust in a reconstruction. In this thesis, wavelet analysis is used to validate the reconstructions of ice and river runoff. Considering that the variability in a time series should remain fairly stable over time, it is useful to investigate whether this is indeed the case. Wavelet analysis allows us to examine a time series in the time-scale domain and can thus be used to determine whether there are any instationarities in the reconstruction over different scales and where they are located. This makes it possible to see whether the reconstructed series captures similar variability over the different scales.

5.2.1 Maximal ice cover extent in the Baltic Sea over the last 500 years

To evaluate the model over the early period that lies outside the observational period, information was gathered from various historical sources. A time series was constructed based on historical information from England, Holland, Poland, Sweden, Finland, Estonia, and Denmark. This time series uses a wide range of sources graded as more or less credible according to their proximity to the Baltic Sea basin. The types of information used often concern how society reacted to unusual winters. Such information generally concerns winters that were in many ways extraordinarily severe.

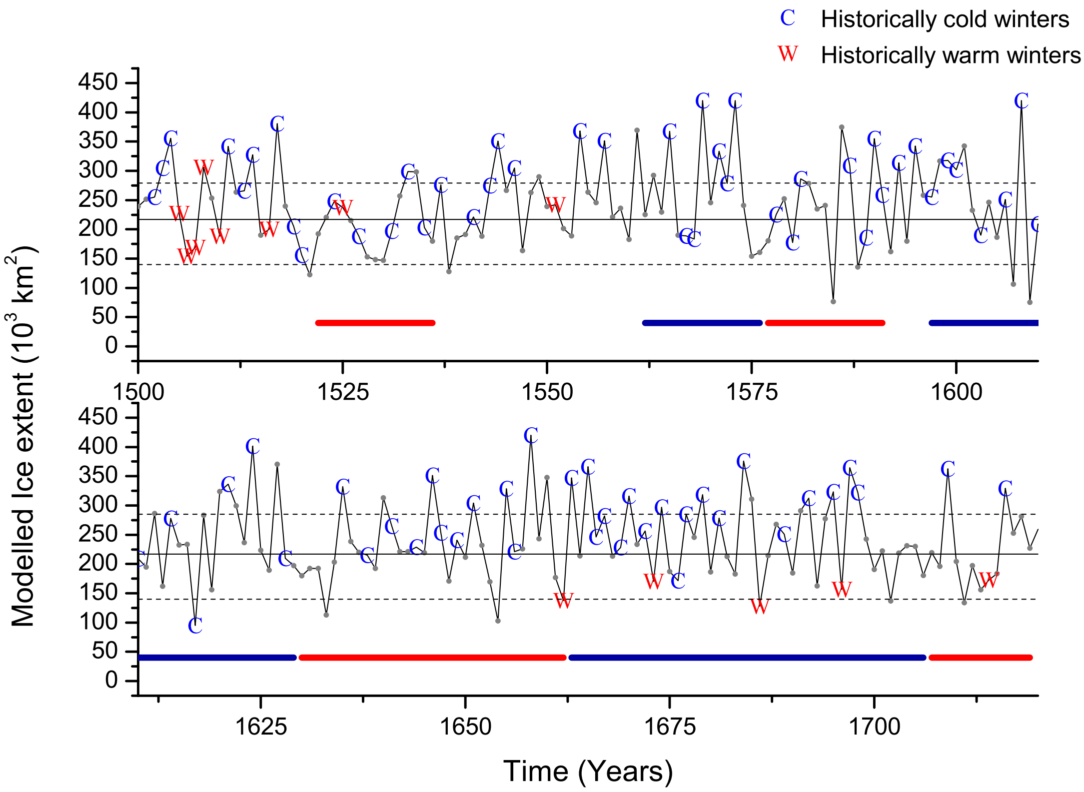

Figure 14: Modelled ice extent in the Baltic Sea. The blue Cs indicate the historically cold winters and the red Ws the historically warm winters. The black line indicates the mean ice extent, the dashed lines the upper and lower limits of normal winters according to the winters of 1720–1995 (Seinä & Palosuo 1996), and the red and blue lines the MP periods, red being warm and blue being cold.

Most reports cite extremely cold winters while fewer mention unusually warm ones, probably reflecting how vulnerable society was to winters with persistent cold. Great famines were reported in Finland and Estonia during the harsh winters of 1695 and 1697 (Neumann & Lindgren 1979). Military reports are also popular archives for people searching history for climatologically relevant information; in the present study they were also consulted in determining the credibility of our model (Neumann 1978, Lindgren & Neumann 1983). The most spectacular extraordinary winter climate event was probably the march led by Swedish king Charles X over the frozen Little and Great Belt in 1658. Records of means of transportation used also shed some light on the Swedish winter climate (Retsö 2002).

Figure 14 shows the model results for the 1500—1719 period. Where historical information is found, the years are marked with a blue C if the documents indicate that the winter was cold and with a red W if the winters are indicated to have been warm. The second panel covers 1610—1720, the period when the model agrees best with the historical data, as only two winters fall outside the model. From the lower panel it is readily seen that the model allow Charles X to march over Little and Great Belt. The year 1658 clearly stands out as well above the mean and is even the year with most ice coverage of all years in the lower panel. In Figure 14, the MP periods identified in Paper II are plotted as blue and red lines beneath the model. A closer examination of the mean values for the modelled ice extent during the MP periods reveals that the periods marked as cool in Paper II have a higher mean than the overall mean for the 1500—1720 period; similarly, periods marked as warm have a lower mean. Compared with the mean for the 1720—1995 observation period, however, MP3 and MP5 have higher means. It is in no way contradictory to suggest that the model is performing well; the results merely indicates that there was a higher mean state during this period, albeit interrupted by warmer than average periods.

Besides the information gained from the documentary data, a wavelet analysis was carried out on the reconstructed MIB series. It was found that the correlation was high on most examined scales, except the 16 year scale (see Paper III). Wavelet variance was also examined and found to display good results for the reconstructed period; however, less variance was evident during the early period on all scales. Given the results of this analysis on different scales, it is reasonable to think that the model is performing well, even for the early period outside the calibration period.

5.2.2 River runoff

For this reconstruction there is little information regarding historical river flow that could serve to validate the early part of the reconstruction period. We tested how well the model captured the variability associated with different timescales by both cross-correlation and a multi-resolution analysis (MRA) of the maximum overlap discrete wavelet transform (MODWT) see section 3.5. High cross-correlation values were obtained for all scales, lending credibility to the reconstruction (see Paper IV). In Figure 15, the MRA for the full period of the reconstructed river runoff is shown together with the observations for the past century. The MRA is an additive decomposition, based on the MODWT coefficients that express the original time series as the sum of several new series, each associated with variations on a particular scale. The bottom panel in Figure 15 shows the reconstructed series together with the observations for the last century. The first attribute of the series one probably notices is that the reconstructed series has less variability than do the observations. This problem of reduced variability occurs in all statistical models, since the models cannot incorporate all variables that affect the variability and use them as predictors. Only in theory it is possible to construct a statistical model that fits the data perfectly. A perfect fit would imply that the statistical relationships between runoff and circulation remained constant over time and that all relevant predictors had been measured exactly. Since in this case we are dealing with data projected onto a grid and then transformed into differences that are supposed to yield the derivatives of the velocity field, it is not plausible that the fit would be perfect. However, when the observations and reconstructed data are compared, it is noticeable that the reconstruction captures much of the variability. The second panel from the bottom shows the variability associated with one-year averages, and from which it is apparent that the observations display more variability in the 1950s than does the reconstruction. The variability is modulated over the first centuries included in the model, the lowest amplitudes being found in the late seventeenth century. The third panel from the bottom shows the variability associated with changes in two-year averages. In this panel, the fit with the observations is very good; as for the rest of the reconstruction, it is apparent that the mid eighteenth century has the highest variability. The fourth and fifth panels from the bottom show the variability associated with changes in the four- and eight-year averages. For the early part of the reconstruction, great variability is found in the four-year scale. However, the amplitudes associated with the scales corresponding to the four- and eight-year averages are somewhat smaller in the reconstruction than those of the twentieth century observations. The top panel in Figure 15 can be interpreted as indicating what is left of the reconstructed runoff series in the bottom panel when the variability associated with scales 1—8 is removed. Consequently, this panel shows the variability associated with averages of 16 years or longer. The “loss” in amplitudes (i.e., variability) in the smaller scales of the reconstruction is evident here, resulting in slightly higher amplitude in the “smooth” series ($\tilde{S}_4$) for the reconstruction. All in all, the reconstruction captures much of the variability on the different scales; variability on all the different timescales is sustained throughout the reconstructed period, though somewhat modulated over the centuries.

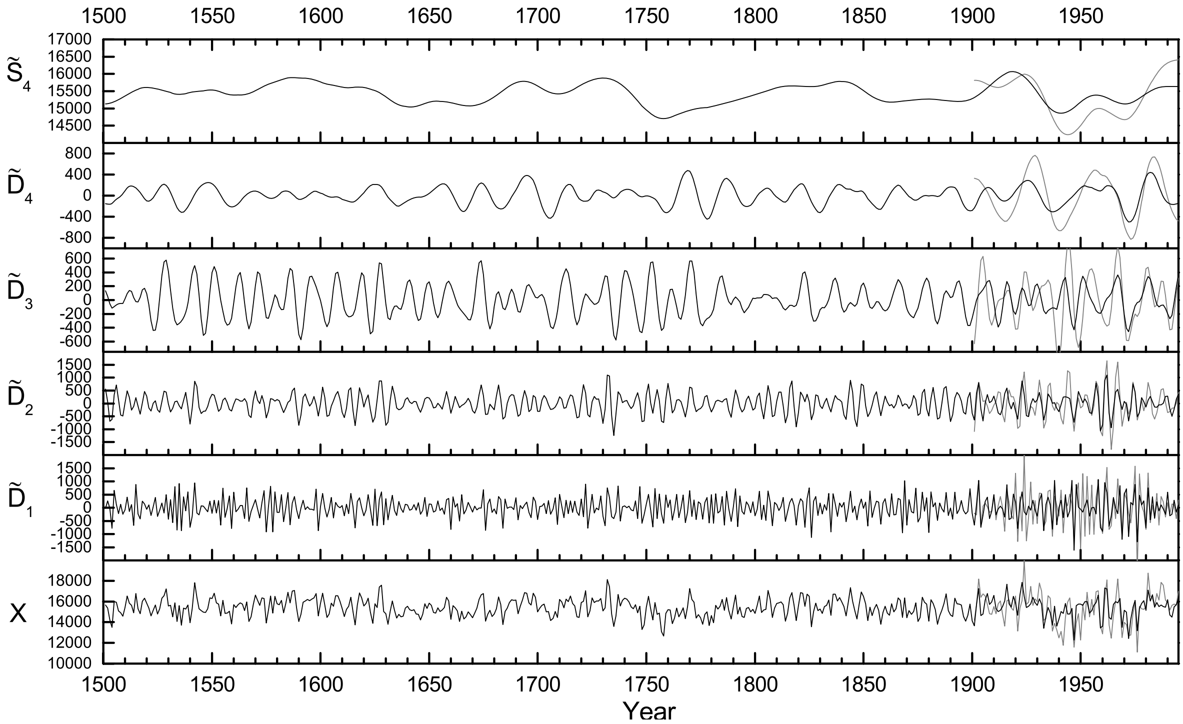

Figure 15: MRA of the reconstructed runoff (black) together with the observed runoff (gray). The MRA is based on a maximal overlap discrete wavelet transform using a D(4) wavelet with reflection boundary conditions. The bottom panel shows the original time series, above which are the jth detailed series $\tilde{D}_j$ and the smooth series $\tilde{S}_4$. The jth detailed series is based on wavelet coefficients that reflect changes in averages on a scale of 2^{j-1} years, while the smooth series is associated with changes on all scales greater than 16 years. From paper IV.

6 Conclusions and Future outlook

During the course of this thesis research, several parameters of climatic significance have contributed to our understanding of the past Baltic Sea climate. During the progress of Paper I, climate was defined as a result of a search for consistency when considering climate change and how to calculate deviations from the *normal* climate. The need for an objectively defined timescale has been manifest by the vivid use of the term “climate change” in articles and reports, obviously describing changes over a wide range of timescales and with reference to different interpretations of *normal* climate. The IPCC points in the direction of decades or longer, but does not give an exact number of years over which to average.

> *Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC 2007, glossary p. 943)*

The climate timescale was defined to help clarify the meaning of climate change in the Baltic region. By comparing the climatic parameters with the climate timescale, we had a frame of reference according to which we could describe the evolution of the Baltic Sea climate.

The winter climate in the Baltic Sea Basic was characterized using two statistical techniques that proved very useful for the task. It would be very interesting to continue the study reported in Paper II by using more information; using proxy records of different kinds would be especially interesting. From tree-rings and marine sediments it is possible to gain more information regarding the past climate; it would thus be interesting to test whether these records also identify rapid shifts between cold and warmer mean states of the climate. Using proxies describing different seasons, it would be interesting to examine how the different seasons have been changing over the centuries. The seasonal index used in Paper I hinted at changing conditions, the Baltic Sea climate having shifted from a climate with larger seasonal differences to a climate with a less pronounced seasonal cycle.

Great effort is now being put into developing climate models that can reproduce the past climate. Earlier problems in the models have been the poor resolution and description of general features of the Baltic Sea region. These problems are now being taken care of by the extensive use of large-capacity computers, and global simulations of the regional Baltic Sea climate are now more realistic. A future challenge would be to test whether the models also display features present in the observational series, and this could possibly be done using MP analysis.

Wavelet analysis has, in this thesis, proven itself useful in examining the change in variability over past centuries. Wavelet methods have illuminated differences between continuing warm and cold winters and identified changing variability between these two states.

The reconstructed ice and river runoff series describe the intricate connection with atmospheric circulation and reveal the dominant contributions. The ice series reconstruction was evaluated using regional historical information, when this was to be found, but also using information from places further away. To verify this study in an even better way than was done in Paper III, a more comprehensive study of the regional historical information available around the Baltic shores would have to be undertaken. This was to some extent done in (Leijonhufvud et al. 2008), with the use of tolags and other shipping documents and recorded port activity gathered, which suggests that the same approach could productively be applied to more ports around the Baltic coast.

It is not equally straightforward to verify the reconstructed river runoff data, given that river runoff to the Baltic is influenced by many parameters. River runoff is not directly related to the amount of precipitation over an area, as it also is related to the temperature and dampness of the ground that receives the precipitation and vegetation processes. Recent investigations of European winter precipitation reveals trends for the last 500 years (Matti et al. 2009). It might be interesting to test whether the gridded datasets that exist for precipitation over 500 years could in some way be linked by transfer functions to the river runoff.

Future investigations that aim to build our understanding of the Baltic Sea water cycle should analyse the total freshwater input to the Baltic. A limitation of the existing precipitation dataset is that it only covers land, i.e., all grid points over sea are set to zero. This factor is omitted from the study reported in Paper IV, since that study only considers the amount of freshwater gained from rivers, not the freshwater input from precipitation over the Baltic Sea. Even though the freshwater input received from precipitation over sea is only 10% of the total freshwater input to the Baltic Sea, this factor might alter the salt balance in the sea. Future projections of precipitation made by dynamic models suggest a change in the water cycle, and implications of such changes must therefore be investigated.

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