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Ocean Climate Variability over Recent Centuries Explored by Modelling the Baltic Sea

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Abstract

Natural variability and anthropogenic factors both contribute to changes in the ocean climate of the Baltic Sea. Observations over the past century indicate that changes in environmental settings and ocean climate have taken place, attracting considerable media attention and building public awareness of climate and environmental issues related to the Baltic Sea. These changes need to be seen in the context of a longer-term perspective to evaluate whether current conditions lie outside the expected boundaries of natural variability. Using a time-dependent, process-oriented, coupled basin model, this thesis examines the sensitivity of the Baltic Sea water and heat balance, investigating the variability of water temperature, ice cover, river runoff, salinity, and oxygen concentrations over long time scales, in particular, the past 500 years.

Models are influenced by initial conditions over a certain amount of time before the system has spun up and the lateral boundary conditions become dominant. Spin-up experiments demonstrate that the Baltic Sea operates on two time scales: a 33-year time scale for the water balance and a one-year time scale for the heat balance. These time scales are associated with the exchange of salt through a small cross section in the entrance area and with the flux of heat through a large surface area. It was also found that the maximum ice extent is strongly sensitive to the mean winter air temperature. A mean winter air temperature of –6°C produces full ice cover, while a mean temperature of +2°C produces minimal ice cover.

The vertically and horizontally averaged water temperatures display great variability, with both cold and warm periods occurring over the past 500 years. The warmest century was the twentieth century, but on decadal time scales, the 1730s, 1930s, and 1990s were equally warm. The coldest century was the nineteenth century, and the 1690s was the coldest decade since 1500. These temperature variations are also reflected in the maximum ice extent. The Baltic Sea has been at least partly ice covered every winter over the past 500 years, and the winter 2008 ice cover was the smallest ever observed.

River runoff from 1500 to 1995 was reconstructed using atmospheric circulation indices. It was found that river runoff to the northern Baltic Sea and the Gulf of Finland is sensitive to changes in temperature, wind, and the strength of cyclonic activity. Runoff to the southern Baltic Sea, on the other hand, is more sensitive to the strength of cyclonic activity and changes in temperature. Even though there is some variability on annual and decadal time scales, no statistically significant change in the total Baltic Sea river runoff has occurred since 1500.

Reconstructed river runoff was used as forcing to model the variability of the salinity and oxygen concentrations of the Baltic Sea. The salinity was found to have increased since 1500, peaking in the mid nineteenth century. Oxygen concentration is closely related to salinity; conditions were found to have been hypoxic once or twice per century until the mid-twentieth century, when the deep water became constantly hypoxic. This large change in oxygen conditions is probably due to the increase in nutrients released from anthropogenic sources, leading to the eutrophication of the Baltic Sea.

Key words: Baltic Sea, ocean climate, modelling, reconstruction, water temperature, sea ice, river runoff, salinity, oxygen concentration, long-term.

Preface

This thesis consists of a summary (Part I) and four appended papers (Part II). In the summary, the papers are referred to by their Roman numerals. Note that Paper I is divided into the original paper (Ia) and the corresponding corrigendum (Ib).

Paper Ia:
Omstedt A, Hansson D (2006) The Baltic Sea ocean climate system memory and response to changes in the water and heat balance components. Continental Shelf Research 26, 236–251, doi:10.1016/j.csr.2005.11.003.

Paper Ib:
Omstedt A, Hansson D (2006) Erratum to: "The Baltic Sea ocean climate system memory and response to changes in the water and heat balance components" [Continental Shelf Research 26(2) (2006) 236–251]. Continental Shelf Research 26, 1685–1687, doi:10.1016/j.csr.2006.05.011.

Paper II:
Hansson D, Omstedt A (2008) Modelling the Baltic Sea ocean climate on centennial time scale: temperature and sea ice. Climate Dynamics 30, 763–778, doi:10.1007/s00382-007-0321-2.

Paper III:
Hansson D, Eriksson C, Omstedt A, Chen D (2009) Reconstruction of river runoff to the Baltic Sea, AD 1500–1995. Submitted to International Journal of Climatology.

Paper IV:
Hansson D, Gustafsson E (2009) Salinity and hypoxia in the Baltic Sea since AD 1500. Submitted to Journal of Geophysical Research – Oceans.

Omstedt initiated Paper I and Hansson conducted the modelling. The results were jointly interpreted and Omstedt did most of the writing. After publication, Hansson found a model error in the analysis programs, and re-computed the analysis. Omstedt wrote the corrigendum.

The idea for Paper II came from Omstedt. Forcing field compilations, model runs, and analysis were carried out by Hansson, who also did most of the writing. Omstedt contributed ideas for analyses and did some of the writing.

Omstedt initiated Paper III and Eriksson carried out the first analysis. Eriksson also wrote a first draft published in the GEWEX newsletter. Eriksson and Hansson jointly interpreted the results of different approaches to formulating the regression model. When Eriksson left for maternity leave, Hansson continued and expanded the analyses and wrote the final version of the paper.

The idea for Paper IV arose from discussion between the authors during work on Paper II. Gustafsson carried out the model computations, except for the control run conducted by Hansson. The results were analysed jointly and Hansson did most of the writing.

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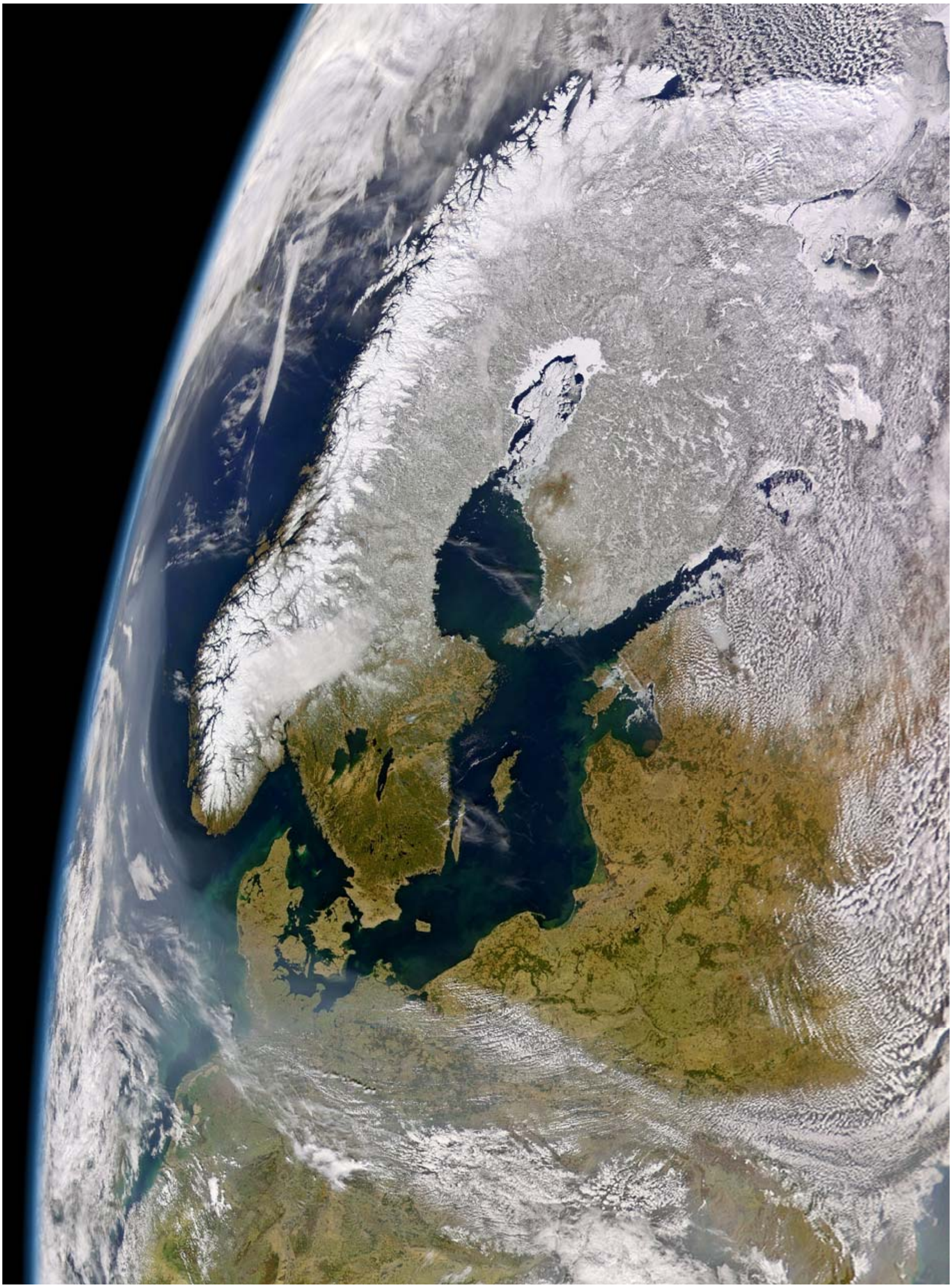
Part I

Summary

"It’s snowing still," said Eeyore gloomily.
"So it is."
"And freezing."
"Is it?"
"Yes," said Eeyore. "However," he said, brightening up a little, "we haven’t had an earthquake lately."
– Alan Alexander Milne



The Baltic Sea Basin on 1 April 2004, as seen from the SeaWiFS satellite (NASA/Goddard Space Flight Centre).

1. Introduction

Climate tells you what clothes to buy, but weather tells you what clothes to wear.
– Unknown student

Imagine travelling through space, passing one strange planet after another. Suddenly you discover a bluish planet, with white feathery stripes and a green–brown texture underneath. The sight resembles the famous "Blue Marble" photo taken during the Apollo 17 expedition in 1972. You have reached Earth, our home in space. A closer look reveals a diverse planet with abyssal dark blue oceans, large ice caps at the North and South poles, pan-continental mountain ranges, vast arid deserts, lush belts of green forests, and continents with large freshwater lakes and semi-enclosed seas. An even closer look reveals cities, roads, villages, people, animals, and plants – all at the mercy of Earth's "will". Despite humans' insignificant appearance, they have left a large global footprint in their wake – overfishing, eutrophication, deforestation, pollution, and release of greenhouse gases, to mention but a few impacts. All these have implications for the four spheres of Earth:

The atmosphere: the gaseous layer between solid earth and space
The lithosphere: the solid earth beneath our feet
The hydrosphere: all water on Earth, no matter what form it takes
The biosphere: the realm of all living organisms

One of the most important issues for the future is global warming. If it continues, it will probably have large impacts on all the above-mentioned spheres. The chemical composition of the atmosphere will be altered due to the increased concentration of greenhouse gases and aerosols. This may in turn alter the balance between the emission and absorption of heat, affecting all other spheres of Earth, resulting in anthropogenic climate change.

Climate change is something most people are aware of today. Over the past few years, several national and international reports (e.g., SOU, 2007:6; Stern, 2007; IPCC, 2007) have had a huge impact on the public and lawmakers. A Nobel Peace Prize has even been awarded for the work of the Intergovernmental Panel on Climate Change and to the former American vice-president Al Gore for his well-known book and film, both entitled *An Inconvenient Truth*, about the issue. Not a day goes by without climate-related news being reported in the mainstream media. Although most people today are aware of the problem, most do not understand the mechanisms of climate change to any great extent.

1.1 Climate and climate change

So, what *exactly* is climate and what do we mean by climate change? This topic is rarely addressed, which is probably why there are so many misconceptions of the issue. To discuss climate and climate change, we first need simple, yet proper, definitions of the terms used. For example, climate is often confused with weather, and vice versa. What happens over short time scales is not climate, only the manifestation of variability in weather. Instead, climate can be regarded as the statistics describing weather over a long period. Therefore, for the purposes of this thesis, I will define climate as "the statistical description of weather in terms of the long-term mean and variability of extremes on global, regional, or local scales".

Defining climate change is a bit trickier. This is partly because definitions of climate change differ between authorities, organizations, and even scientists. There are two widely used definitions of climate change. The parties to the United Nation's Framework Convention on Climate Change (UNFCCC) agreed to define climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (UNFCCC, 1992). At the same time, the Intergovernmental Panel on Climate Change (IPCC) chose, in their fourth assessment report (IPCC, 2007), to define climate change as "a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use". Choosing the appropriate definition is essential in seeking to understand the concept. Most of the time when dealing with climate change, the change is unknown in origin, that is, we usually do not know whether the change can be attributed to human activities, natural variations, or a combination of both. For that reason, this thesis will adopt the IPCC definition. If necessary for clarification, the term "anthropogenic" will be added to "climate change" when human activity can be attributed specifically, and "climate variability" will be used when referring to variations unrelated to anthropogenic influences. The same convention is used by the BACC Author Team (2008), hereafter BACC (2008).

The study of climate change is not a new science, and there have been many attempts to describe parts of the climate system over the centuries. However, it was not until 1824 that French physicist Joseph Fourier discovered what is now known as the greenhouse effect (Fourier, 1824). Swedish physicist Svante Arrhenius later attributed large swings in global temperatures to atmospheric carbon dioxide (Arrhenius, 1896). Later, Serbian geophysicist Milutin Milanković proposed a theory about long-term changes in solar insolation due to orbital variations, which he argued pushed the Earth in and out of glacials (Macdougall, 2006). These theories are now more or less unanimously accepted, and climate science has come a long way since. Today, several thousand scientists from a wide range of disciplines are engaged in building our understanding of our climate system and climate change on all spatial scales, from micro to global. Every sixth year since 1990, the IPCC has released an assessment report summarizing current knowledge of climate change. These reports help policymakers formulate proper legislation to minimize possible anthropogenic climate change.

The Earth's climate system is extremely complex. Our atmosphere reacts in one way, the oceans in another, and the biosphere in yet another, all depending on the initial state and processes affected. To make things even more complicated, these systems are all coupled non-linearly, resulting in an intricate web of feedback mechanisms on all temporal and spatial scales. Some of these feedbacks are positive, such that specific processes may be reinforced and amplified; other feedbacks are negative, and suppress ongoing processes.

Despite being a complex system, scientists can attribute at least some of the ongoing climate change to human activity, mostly due to the release of heat-trapping greenhouse gases and cooling aerosols. Over the last century (1906 to 2005), global temperature rose by 0.56–0.92°C, for a mean rise of 0.74°C (IPCC, 2007). This has led to, among many phenomena, a sharp decrease in Arctic sea ice coverage and thickness, thinner snow cover in many regions, retreating glaciers, rising sea levels, persistent and intense droughts and heat waves in some regions, higher frequency of heavy rain in other regions, fewer cold spells, longer growing seasons, and thawing of permafrost at higher latitudes. These concerns were some of the factors that led the IPCC (2007), in their fourth assessment report, to conclude that most of the observed increase in global average temperatures since the mid twentieth century was very likely (with more than 90% certainty) due to observed increases in anthropogenic greenhouse gas concentrations.

1.2 Climate and oceans

One might think that the atmosphere is the most important factor when considering climate change. In one way it is. It is the part of the climate system that we come in contact with every day. On a global scale, however, the effect of the atmosphere is surpassed by that of the oceans. The Earth's oceans are immense. The mass of the hydrosphere is 1.4×10^{21} kilograms, of which approximately 97% comprises ocean water, while the atmosphere weighs just 5.1×10^{18} kilograms (Nordling and Österman, 1999). This also indicates that the heat capacity (i.e., the amount of heat required to increase the temperature of a material by one degree Kelvin) of water is greater than that of air. Gill (1982) explains that, per unit area, a depth of 2.5 metres of a given area of water contains the same amount of heat as the whole atmosphere immediately above that area. As 71% of the Earth's surface is covered with oceans, we can roughly estimate that the top 3.5 metres of the world's oceans contain the same amount of heat as does the whole atmosphere. Added to this, the average depth of the world ocean is approximately 3700 metres, making the amount of energy stored in the oceans almost beyond comprehension. If you think that raging weather systems, with devastating hurricanes, huge fronts with thunder and lightning, torrential rain, and fierce hailstorms are powerful, think of what the oceans could theoretically stir up if all their energy were unleashed. The oceans truly are a very large piece of the climate system puzzle. Due to surface heat flux, incoming solar radiation is absorbed as heat by the ocean and vertically mixed into the interior where it is stored. If the oceans only absorbed heat, the temperature would soon rise high enough for the oceans to boil. Luckily, this is not the case. Instead, some of the stored heat is re-emitted. The released heat passes into the atmosphere where it may be absorbed, or escape and enter space. Heat can be released by latent heat flux, which is essentially the same as evaporation: water vapour is exported to the atmosphere, giving rise to clouds and rainfall, mostly in a near-equatorial region known as the Intertropical Convergence Zone (ITCZ). The ocean can also release heat in the form of sensible heat, which is the kind of heat you feel. This heat is conducted to the atmosphere and sets the air masses in motion due to convection and advection toward the poles where heat is in deficit. The resulting winds help drive the ocean currents. These currents transport massive quantities of water, redistributing stored heat around the globe from the tropics to the high latitudes. Estimates of maximum poleward transport are on the order of 5 and 1–1.5 petawatts for the atmospheric and oceanic parts, respectively (Ganachaud and Wunsch, 2000; Trenberth and Caron, 2001; Wunsch, 2005; Polonskii and Krasheninnikova, 2007). Oceanic transport is dominant at lower latitudes, while atmospheric transport is more important at higher latitudes.

Not only is the ocean responsible for storing and redistributing heat; it also stores large quantities of added atmospheric carbon dioxide. The oceans soak up approximately 40% of net carbon dioxide emissions (i.e., emissions from fossil fuel burning, cement production, land use change, and terrestrial biosphere response) from the atmosphere via biological (primary production) and physical (dissolves) processes. Here again, we have the three spheres – the oceans, atmosphere, and biosphere – in collaboration. Most carbon on Earth is not stored in the atmosphere, as one may think at first. Actually, the atmosphere contains the smallest amount of carbon; the terrestrial biosphere contains more, but the oceans and marine sediments contain most, and completely dominate the carbon cycle (IPCC, 2007). The time scale of the oceans is on the order of 1000 years and may have a profound effect on the Earth's climate over millennia. Of course, there are many more ways than the above-mentioned that the ocean helps continuously change the climate, for example, albedo variations due to ice and cloud formation and impact on the biogeochemical cycle. Space limitations and the scope of this thesis preclude exhaustive discussion of ocean effects; nevertheless, the above-mentioned processes are sufficient for a basic understanding of global ocean–climate interaction.

1.3 Structure of the thesis

In this thesis, I will focus on a very small portion of the world's oceans, the Baltic Sea. Indeed, compared with the great widths and depths of the world's oceans, the Baltic Sea is a dwarf. This semi-enclosed sea in Northern Europe comprises only 0.12% of the surface and 0.0017% of the volume of the world's oceans. Though it seems quite insignificant, it plays an important role in the lives of some 85 million people living in the Baltic Sea drainage basin. One can regard the Baltic Sea as a laboratory, as it is known for having an almost unequalled marine monitoring system. Few other sea areas can match the intensity and density of the Baltic's observation grid. Furthermore, there is a long tradition of land-based observations in the area. Since the mid eighteenth century, meteorological, sea level, and ice observations have been made almost uninterrupted on a daily basis. Studying the Baltic Sea lets us better understand the kinds of variability to be expected from internal variations in the climate system and the kinds of changes human activities may evoke. All this knowledge can be applied in developing better climate models, giving us better projections of future climate change, whether due to internal variability or anthropogenic factors.

This thesis is based on four papers I have co-written and that have been published in or submitted to peer-reviewed journals. These papers follow a clear conceptual path. Paper I sets out to investigate the sensitivity of the Baltic Sea ocean climate. Paper II uses the findings presented in Paper I and extends the investigation of water temperature and sea ice to cover the past 500 years. Paper III reconstructs and examines the river runoff over the same period. These results are then used in Paper IV in exploring the long-term variability of salinity and oxygen conditions in the Baltic Sea. These papers are available directly after the summarizing chapters. Complete details regarding my research are available in those papers. Therefore, I have written the summarizing chapters in such a way that a person with general scientific knowledge can understand the basic significance of my results, and gain a comprehensive overview of the state of the science in this research area. It is my opinion that science must be communicated in comprehensible terms to people outside the scientific community to enhance scientific debate.

The coming chapters are structured as follows. First, I will focus on the Baltic Sea as a system: how it came into being, how it works, and how it can be represented in climate models. This forms a solid foundation for the studies on which I have collaborated. Next, the Baltic Sea ocean climate and its response to climate change will be studied. Most of my work deals with ocean climate change over recent centuries. Accordingly, I will review how water temperatures, ice extent, river runoff, salinity, and oxygen concentrations in the Baltic have changed since 1500. Insight into the historical evidence supporting the results will also be presented. I conclude these summarizing chapters by giving my outlook of what I see as important areas for future research.

2. The Baltic Sea system

Our planet is invested with two great oceans; one visible, the other invisible; one underfoot, the other overhead; one entirely envelopes it, the other covers about two thirds of its surface.
– Matthew F. Maury

The Baltic Sea was first mentioned by its present name by Adam of Bremen in the eleventh century. The name has since become well established, although the equivalent name in Scandinavia and Germany is the East Sea and in Estonia, the West Sea. There has been frequent raging discussion of where the Baltic Sea starts and ends. Some regard the Baltic Sea as the whole sea area from Kattegat to the Gulf of Finland and Bothnian Bay. Others claim that the Baltic Sea starts inside the Danish straits, or that it applies only to the Baltic Proper in the central Baltic. In this thesis, the Baltic Sea is used comprehensively to denote the sea areas of the Kattegat, Belt Sea, Öresund, Arkona Basin, Bornholm Basin, Baltic Proper, Gulf of Riga, Gulf of Finland, Archipelago Sea, Åland Sea, Bothnian Sea, and Bothnian Bay (see Figure 2.1).

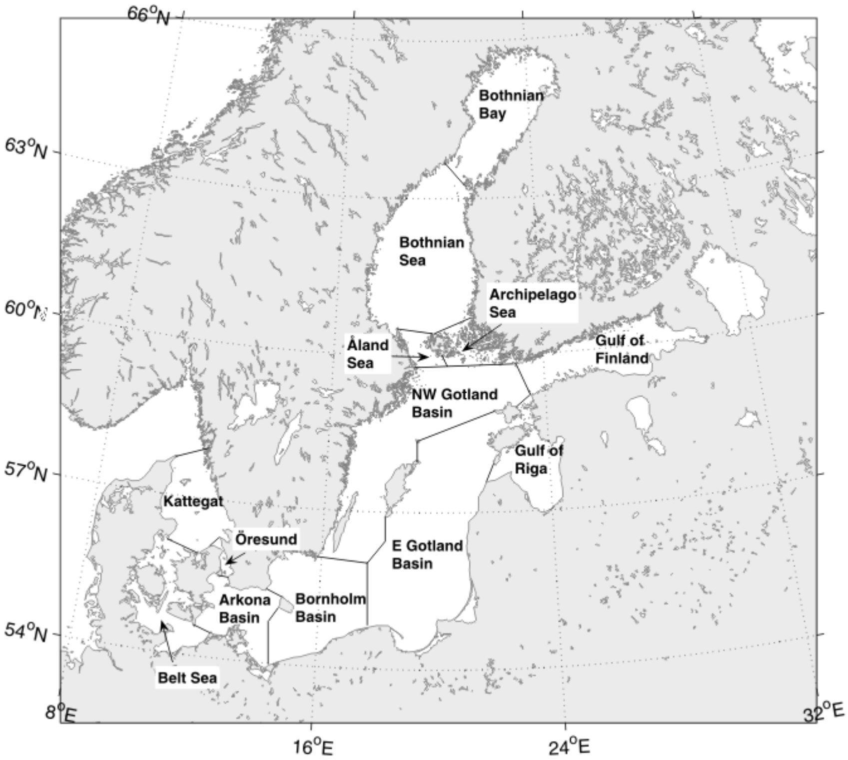


Figure 2.1: *The Baltic Sea includes all the sea areas from Kattegat in the west to Bothnian Bay in the north and the Gulf of Finland in the east (courtesy of E. Gustafsson).*

The Baltic Sea is dwarfed by the world's oceans. It has an average depth of only 55 metres, and a maximum depth of 459 metres at the Landsort Deep between the island of Gotland and Nynäshamn in mainland Sweden. This semi-enclosed sea is one of the world's largest brackish water bodies with an area of almost 420,000 km^2 and a volume of 21,700 km^3 (BACC, 2008). All freshwater entering the Baltic Sea comes from the Baltic drainage basin, which has an area of approximately 1.74 million km^2 and covers all or much of Sweden, Finland, Poland, Estonia, Latvia, Lithuania, Poland, and Denmark, as well as minor parts of the Czech Republic, Slovakia, Ukraine, Belarus, and Russia. The potential for anthropogenic impact is clearly huge.

2.1 An overview of Baltic geological history

This thesis does not focus on the geological history of the Baltic Sea, so I will only briefly summarize how the post-glacial Baltic came to be. This history is important in understanding the Baltic's present state and why it is a brackish inland sea and not a freshwater lake or saline ocean bay. It all started when the last glacial ended some 12,000 years BP, creating the Baltic Sea basin more or less as we know it today. However, the characteristics of the Baltic Sea have undergone many transformations since then. It has alternated between being a freshwater lake and an ocean bay. At other times it has also settled into a brackish state, much as it is now.

When the Scandinavian ice cap started to melt approximately 17,000–15,000 years BP, large amounts of freshwater accumulated in the *Baltic Ice Lake* south of the retreating ice sheet. The global sea level was much lower than today, so the Baltic Ice Lake was located higher than the outside ocean and had no exchange of water with it. The only outlet was approximately where the Öresund strait is located today. A few times the water masses succeeded in penetrating what is present-day central Sweden, creating a new massive outlet. Later, this outlet became permanent as the post-glacial rebound cut off the outlet in Öresund and formed a land bridge between south Sweden and Denmark (Björck, 1995; Andrén, 2003a).

The new outlet setup pushed the Baltic Ice Lake into a new phase known as the *Yoldia Sea*. In this phase, the outlet through central Sweden was widened and saline water from the ocean could for the first time enter the Baltic Sea. Periods of hypoxic conditions (i.e., depletion of dissolved oxygen) in central and south Baltic are known from this phase (BACC, 2008). The Yoldia Sea phase only lasted for approximately 900 years, and came to an end when post-glacial rebound prevented the inflow of saline water. Rapid land uplift resulted in the outlet being reduced to the Göta Älv in west Sweden and the Otteid–Steinselva strait in Norway (Björck, 1995; Andrén, 2003b). This marks the starting point of *Ancylus Lake* some 10,700 years BP.

The water level of Ancylus Lake continued to rise. Its two outlets became increasingly shallow and narrow, making it difficult for outflowing water to escape to the ocean, and the maximum water level was reached 10,200 years BP. What happened next is shrouded in mystery. It is known that the water level dropped to that of the global ocean over a few centuries, but it is unknown where the outlet was located. The most probable location is somewhere in the south Baltic (Björck, 1995; Andrén, 2003c; BACC, 2008). The water could have found a way out through the present Great Belt, where the Dana River was located, as northern and southern Sweden were united in a single landmass, as we know it today, approximately 10,000 years BP.

Shortly after, saline water again made its way into the Baltic Sea and a new phase began, that of the *Littorina Sea*. The Danish Straits became deeper and wider, and approximately 8000 years BP the Öresund strait was more or less the same as today. This transformation let large quantities of saline water enter, making the salinity of the Littorina Sea significantly higher than that of the Baltic today (Andrén, 2004). In addition, the climate had changed and the climate of northern Sweden was almost equal to that of modern southern Sweden. As the climate started to cool, glaciers around the globe started to expand, lowering the global sea level. In combination with continued post-glacial rebound, less saline water managed to enter the Baltic Sea. Approximately 3000 years BP, the salinity had decreased and the brackish Baltic Sea assumed its present form and shape. In practice, this means that the Baltic Sea as we know it today is younger than the pyramids of Egypt.

2.2 How does the Baltic Sea work?

The topography formed on geological time scales is one of four factors governing the physical state of the Baltic Sea; the other three are meteorological, hydrological, and oceanographic factors. Changes in any of these factors may have a large impact on the dynamics of the sea, and together these four form, control, and sustain the semi-enclosed, brackish Baltic Sea and its unique marine environment. The processes are similar to those in a two-layered estuary, which are determined by freshwater surplus from river runoff and net precipitation, and by inflow and outflow of saline and brackish water through the entrance area.

The freshwater component is divided into freshwater runoff from surrounding land and net precipitation (defined as precipitation minus evaporation) over the sea. In an average year, 15,000 $m^3 s^{-1}$ of river runoff drawn from the drainage basin enters the Baltic Sea. However, seasonal variations are large (see Figure 2.2; solid line). In winter, much of the precipitation, especially in the Northern Baltic Sea region, comes as snow and is not released as liquid water until spring or early summer when temperatures rise above freezing. The river runoff through winter and early spring is therefore low, but increases heavily during snowmelt and spring flood. Humans have also influenced river runoff, mostly through regulating river flows by building dams and hydroelectric power plants. Although the annual mean river runoff is not influenced by such activities, the seasonal distribution has been artificially changed, more water being released in winter and less in late spring and summer. In addition to river runoff, net precipitation contributes an average of 1500 $m^3 s^{-1}$. This input is also subject to large seasonal variation (Figure 2.2; dashed line) and can be related to river runoff and sea ice extent (Rutgersson et al., 2002). Excess brackish water escapes the system in a northbound flow via the Danish straits and Kattegat.

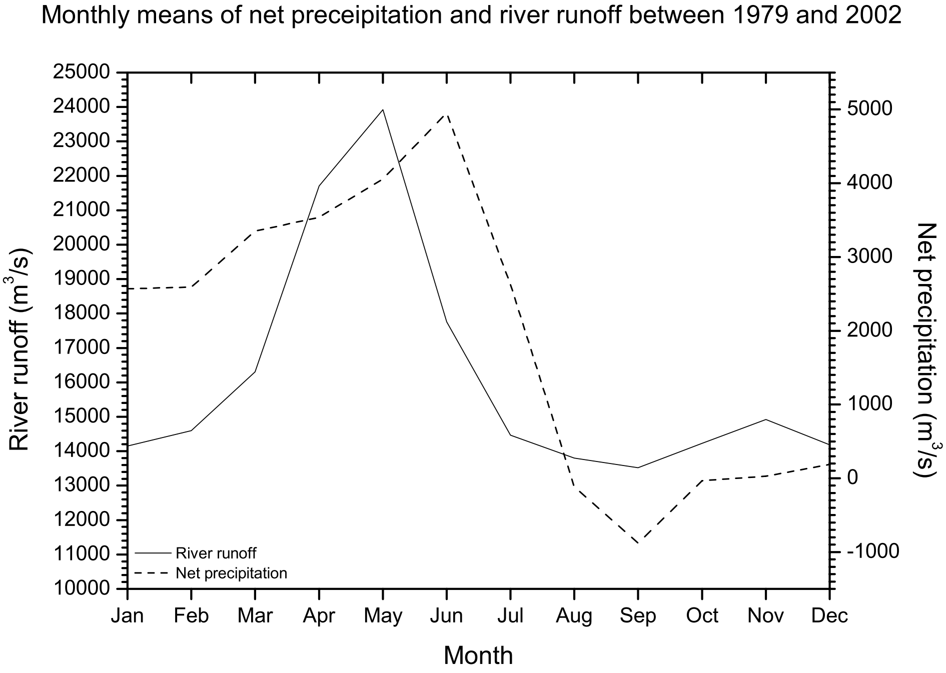


Figure 2.2: *Monthly distribution of river runoff (solid line) and net precipitation (dashed line). Long-term means over the 1979–2002 period are used. Please note that the 1980s was an unusually wet decade.*

Water exchange between the North Sea and the Baltic Sea is barotropically driven, determined by the frequency and amplitude of the sea level in Kattegat versus inside the Danish straits. The sea level in Kattegat and the Baltic Sea is tightly linked to the prevailing large-scale wind patterns over the region. However, temperature and precipitation may also substantially affect the sea level (Hünicke and Zorita, 2006). When conditions permit, saltwater enters the system along the seabed via Kattegat and the narrow and shallow Danish straits, setting up a pronounced salinity gradient. The highest salinities are found in the south while fresher water is found in the north and east where large rivers discharge. The water column is permanently stratified with a low-saline surface layer (7–8 salinity units), a halocline at a depth of approximately 60 metres, and a saline bottom layer (11–14 salinity units; e.g., Stigebrandt, 1983; Matthäus and Schinke, 1999). This feature effectively prevents the vertical mixing and ventilation of deeper layers.

The water layer beneath the halocline is dependent on inflow events for deep-water renewal. Weaker inflows (10–20 km^3) occur rather frequently. These events are usually only slightly denser than the halocline, and therefore interleave just underneath it at the level of neutral buoyancy. Stagnant conditions are consequently rare in the upper deep water. Large inflows of approximately 100–250 km^3 of high-saline (17–26 salinity units) and well-oxygenated waters, known as major Baltic inflows (MBI), occur very infrequently. MBIs flow along the seabed and are dense enough to penetrate all the way to the deepest parts of the central Baltic. This is the primary mechanism for the ventilation of deep and bottom water. Since the 1880s, a total of 113 major inflows have been identified (Matthäus and Schinke, 1999; BACC, 2008). However, for the duration of the two World Wars, expeditions were not dispatched as it was extremely dangerous to gather data at sea, so some MBIs may have been missed.

MBIs can take place under particular meteorological conditions. A long period of high sea level pressure, easterly winds, and low Baltic sea levels followed by a prolonged period of cyclonic activity and zonal winds is ideal and facilitates inflow events (Schinke and Matthäus, 1998). Such conditions are unusual, but are most likely between October and February. All MBIs since 1880 took place between August and April (Matthäus and Franck, 1992). Since the mid 1970s, the regularity and intensity of inflows have changed and only three MBIs have taken place (in 1983, 1993, and 2003). This lack of inflows has caused an unusually long stagnation period between 1977 and 1992 marked by declining salinity and anoxia (i.e., severe hypoxia, a complete lack of oxygen) in the deep water. Similar stagnant periods have also been identified in the 1920s and 1930s (Meier and Kauker, 2003) and the 1950s–1960s (Meier, 2005) and were associated with increased runoff and intensifying zonal winds.

Topography is pivotal in the Baltic Sea system. An elaborate system of several clearly defined submarine basins connected by narrow straits forms the backbone structure (Figure 2.3). These features function as barriers to inflowing water. It is easy to conceive that the Baltic Proper is poorly ventilated and that only very large MBIs have the volume and density required to penetrate to the deepest parts of the Baltic Sea. Inflowing water slowly decreases in density as it mixes with and entrains ambient water along the way, but diffusive fluxes also play a role. The archipelago surrounding Åland creates an effective barrier, as the sill depth lies above the halocline of the Baltic Proper. This limits the water exchange between the Bothnian Sea and the Baltic Proper to surface water.

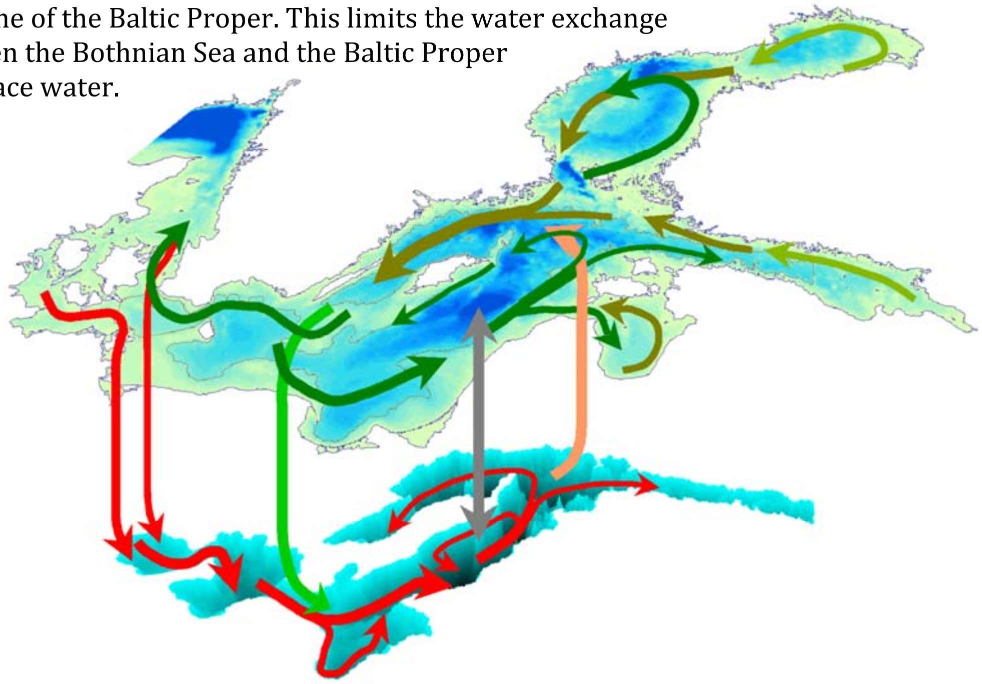


Figure 2.3: *The large-scale water circulation of the Baltic Sea above and below the halocline. Dense inflowin water (red arrows) can penetrate to the deepest parts. Meanwhile, brackish water circulation (dark green arrows) occurs at the surface. Entrainment (light green and beige arrows) and diffusion are the two mechanisms of water exchange between the surface layer and the deep water. Image from BACC (2008), courtesy of Springer Verlag and J. Elken.*

Another important aspect of the Baltic Sea system is its heat balance. Most of the water volume is contained in the upper water layers, but sea surface temperatures alone are not representative of the full heat balance, as sea surface temperatures only reflect trends in air temperature and not annual heat accumulation. Sea surface temperature differs from one point to another, but the heat of the entire water body remains constant if energy is not added or removed from the system. Additionally, the well-developed halocline of the Baltic Sea hinders the deep water from releasing its thermal energy into the atmosphere. The amount of heat in the system is known as the heat content, *H*. Changes in the heat content over time may be formulated as

$$\frac{dH}{dt} = (F_i - F_o - F_{loss})A_s, \tag{1}$$

where *H* is related to water temperature according to $H = \iint \rho c_p T dz dA$. Here, F_i and F_o are the heat fluxes associated with inflows and outflows of water, F_{loss} is the total heat loss to the atmosphere and ice, A_s is the surface area, ρ is the water density, c_p is the specific heat of water, and *T* is the water temperature. F_{loss} may in turn be described as

$$F_{loss} = (1 - A_i)(F_n + F_s^o) + A_i(F_w^i + F_s^i) - F_{ice} + F_r + F_g, \tag{2}$$

where

$$F_n = F_h + F_e + F_l + F_{prec} + F_{snow}. \tag{3}$$

The terms of the equation denote the ice concentration (A_i), net heat flux (F_n), sun radiation to the open water surface (F_s^o), heat flux from water to ice (F_w^i), sun radiation through ice (F_s^i), heat sink associated with ice advection (F_{ice}), heat flux associated with river runoff (F_r) and groundwater (F_g), sensible heat flux (F_h), latent heat flux (F_e), net long-wave radiation (F_l), and fluxes due to precipitation in the form of rain (F_{prec}) and snow (F_{snow}). Table 2.1 shows the order of magnitude of annual mean heat fluxes. The sensible heat, latent heat, net long-wave radiation, solar radiation to the open water, and heat flux between water and ice are the dominant fluxes. Note that the heat fluxes are positive when going from the water to the atmosphere.

Table 2.1: *Estimated annual heat fluxes of the Baltic Sea by order of magnitude. The fluxes are denoted as the net heat flux* (F_n)*, sun radiation to the open water surface* (F_s^o)*, heat flow from water to ice* (F_w^i)*, sun radiation through ice* (F_s^i)*, heat fluxes associated with precipitation in the form of rain* (F_{prec}) *and snow* (F_{snow})*, heat sink due to advection of ice from the Baltic Sea* (F_{ice})*, heat fluxes associated with river runoff* (F_r) *and groundwater* (F_g)*, heat fluxes related to in- and outflowing water* $(F_o - F_i)$*, and net heat loss to the atmosphere* (F_{loss})*. All units are in Wm*$^{-2}$*. From Omstedt and Nohr (2004).*

F_n	F_s^o	F_w^i	F_s^i	F_{prec}	F_{snow}	F_{ice}	F_r	F_g	$F_o - F_i$	F_{loss}
10^2	-10^2	10^0	-10^{-1}	10^{-1}	10^{-1}	-10^{-1}	10^{-1}	10^{-1}	10^{-1}	-10^0

On the seasonal scale, a net heat flux into the ocean occurs in spring and summer, increasing the heat content. In autumn and winter, the surplus heat is slowly released. About two thirds of the heat content is contained in the Baltic Proper. The Gulf of Finland contains little heat due to its small volume, while the Bothnian Sea and Bothnian Bay contain little heat due to their location at high latitudes (Schrum and Backhaus, 1999). The interannual variability in Baltic Sea net heat loss is approximately ±10 Wm^{-2}, but the long-term net heat loss has been calculated to be zero. Attempts to establish a trend in the calculated heat content of the Baltic Sea between 1958 and 2005 have failed (BACC, 2008). Omstedt and Nohr (2004) found no statistically significant increase in the vertically and horizontally averaged water temperature, which is closely related to the heat balance, of the Baltic Sea between 1970 and 2002 despite atmospheric warming of approximately 1°C. This indicates that the Baltic Sea is almost in thermodynamic balance with the atmosphere over longer time scales.

2.3 Instrumental observations and modelling of the Baltic Sea

As mentioned earlier, the oceans contain vast amounts of energy. It is crucial for our understanding of the climate system that proper monitoring of the oceans be performed. Regular monitoring at sea has been done for just over a few decades at best, and only occasional observations exist from before the mid nineteenth century. One could definitely interpret much of past climate change by studying, for example, notes from ship logs about weather events or ice-free areas in winter. However, such records are usually too few and far between to resolve extended ocean areas in detail. In the old days, a ship actually had to sail out, make the measurements, record them, and sail back home before the information could be used for anything interesting. Later, usually in the first half of the twentieth century, self-recording instruments were devised, built, packed, sailed out, and carefully lowered into the sea. There they operated for a certain amount of time, and then were carefully hoisted aboard ships, brought home, and underwent data extraction procedures. Such instruments greatly facilitated the creation of longer data series. Even today, this is usually how things are done, although the instruments have generally been further developed, incorporating more advanced technology, better precision, and the ability to withstand being in the ocean for a longer time. In addition to these semi-manual measuring techniques, satellites orbiting the Earth are also used to collect data about the oceans by remote sensing, often measuring sea surface temperatures, currents and eddies, salinity, phytoplankton blooms, waves, ice extent, etc. Satellites are primarily useful in measuring the surface, but not the subsurface, ocean, and can be regarded as providing valuable supplementary data in deep-sea research.

Fortunately, the Baltic Sea has a very long tradition of marine monitoring, covering the entire twentieth century and going even further back in some respects. The first known oceanographic measurements were made by Wilcke (1771) in Öresund using a water sampler of his own design. Several other pioneers followed him over the following century, measuring temperature, salinity, density, and currents along Swedish coasts and onboard light ships (Fonselius, 2001). Sea level has been observed since 1774 in Stockholm, making the longest sea level record in the world (Ekman, 1988). Germany and Sweden embarked on two separate deep-sea expeditions in 1871 and 1877, respectively (Meyer et al., 1873; Pettersson, 1893). In the 1890s, it was agreed that the countries and territories bordering the Baltic Sea would cooperate in a joint effort to monitor the sea. Prof. Otto Pettersson and Dr. Gustaf Ekman also proposed that only a few offshore stations were needed to track the state of the Baltic Sea (Fonselius, 2001; Fonselius and Valderrama, 2003), and these stations, with some additions, are still used today. Consequently, there are well-kept records of deep sea water starting from the 1890s. The expeditions carried out before 1958 were usually dispatched once per year, and almost exclusively in the summer months; few measurements were made in the coldest months of January through March (Fonselius and Valderrama, 2003; see Figure 2.4).

This temporal resolution may be sufficient for salinity, which displays minimal seasonal variability, especially in the deep water. On the other hand, one measurement per year is too crude for resolving seasonal variability in temperature, oxygen, nutrients, and other biogeochemical components. Starting in the 1950s, the number of stations and sampling intensity and frequency increased.

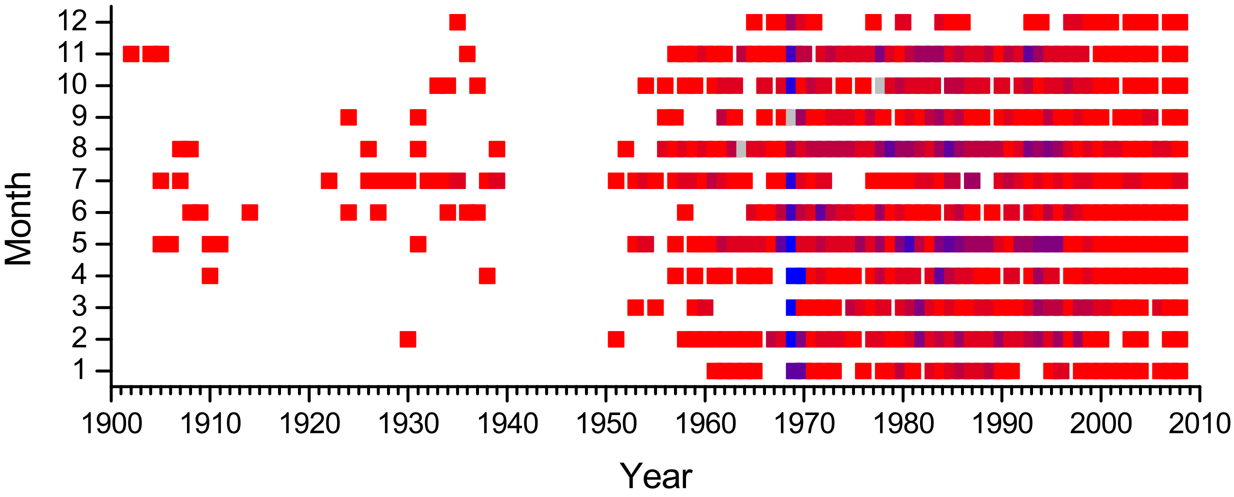


Figure 2.4: *The frequency of observations made at the Eastern Gotland Basin station BY15 is regular after 1960, but irregular before that. Large data gaps exist during the two World Wars. The intensity of the measurements is colour coded, red indicating fewer and blue more measurements. Data provided by the Baltic Environmental Database and SMHI.*

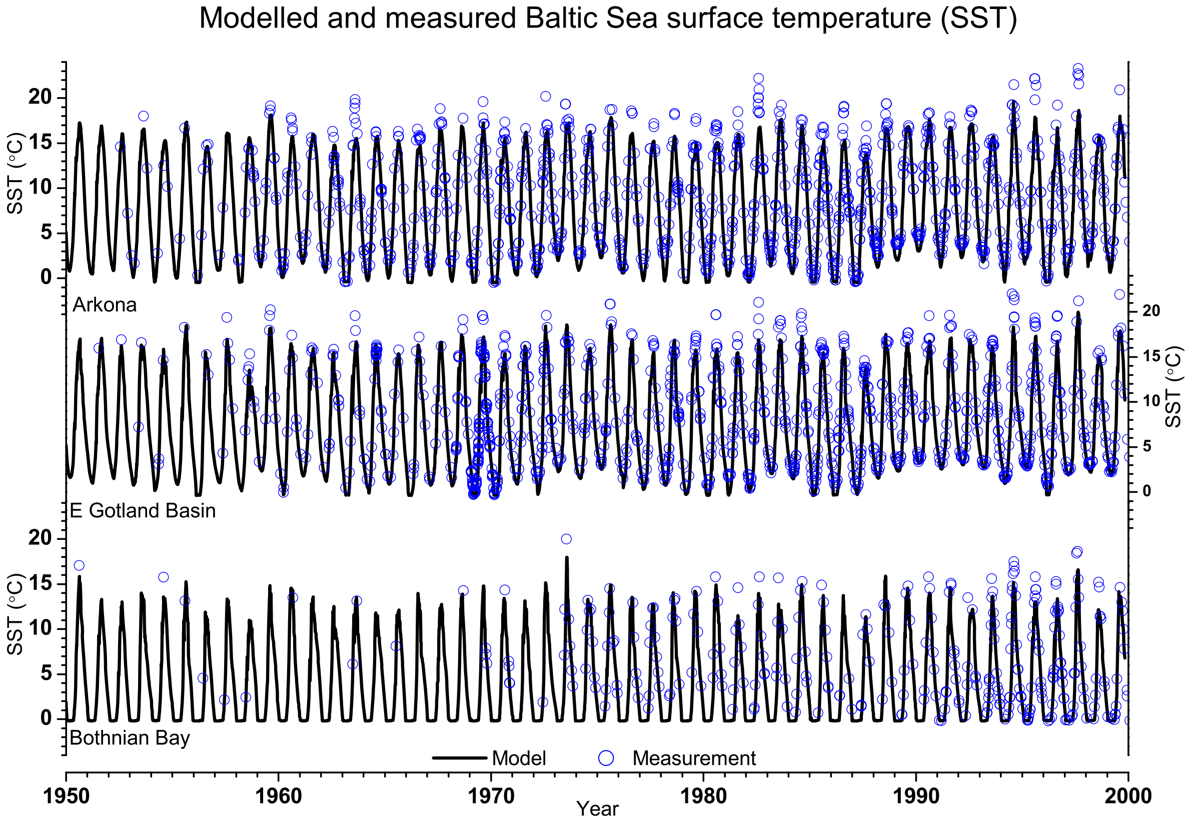


Figure 2.5: *Modelled (line) and measured (dots) sea surface temperatures at three different locations in the Baltic Sea between 1950 and 2000. Modelling allows better time resolution of the dynamics, even though real data might be lacking.*

Unlike routine measurements of meteorological parameters, observations of the ocean are rarely carried out at set intervals. Time series may include gaps when measurements could not be made (e.g., the World Wars and severe winters) and display inhomogeneities due to changes in techniques (e.g., use of better instruments) or station relocation and changes in other parameters affecting data integrity. Guesses have to be made as to what happens between data points. Combining instrumental observations and models may be the answer to the problem, providing a good way to achieve higher temporal resolution. At the same time, we gain more confidence in our models if they can reproduce the past properly. Figure 2.5 shows modelled and observed sea surface temperatures for three Baltic Sea subbasins: Arkona Basin, Eastern Gotland Basin, and Bothnian Bay. Although the collected data are sparse over the first few decades, the model nevertheless realistically captures the interannual variability.

It is easy to get carried away with models and to regard their results as reality. One must remember that a model is only an attempt at creating a virtual reality, hence the name “model”. It tries to reflect the real world as simply, yet as representatively, as possible. The concept is depicted in Figure 2.6. A satellite image of the Baltic Sea is transformed into a simpler analogue by removing much of the detail that is unlikely to affect the general recognizability of the image. Insofar as it is still obvious what the simplified version represents, it functions perfectly well as a substitute for reality. Models are created according to essentially the same principle. Asking someone what his or her model does *not* include is a huge question, and answering it will take considerable time; it is easier to say what the model *does* include. Once these considerations are second nature, working with models poses no problems.

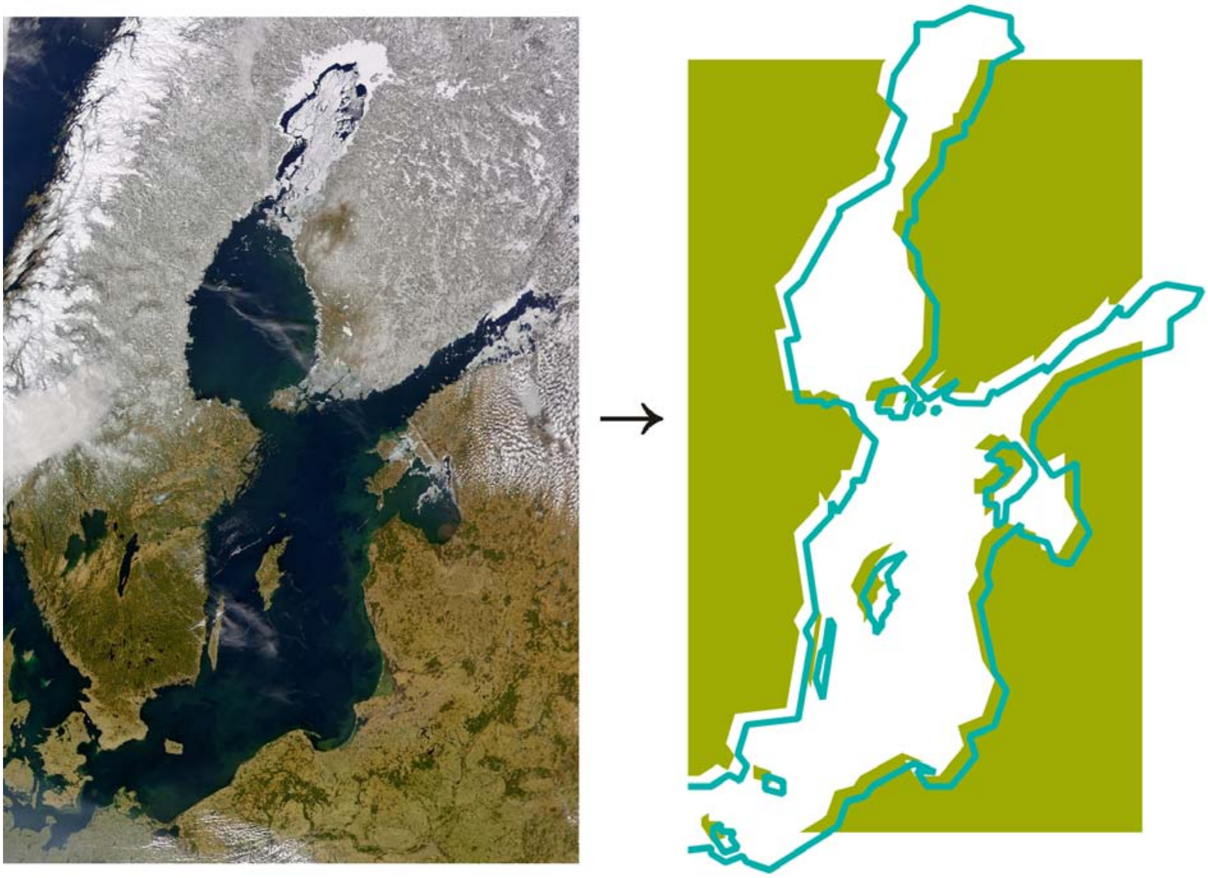


Figure 2.6: *The concept of a model. A complex and detailed reality is transformed into a simpler form. Satellite image from NASA, and simplified image courtesy of T. Jantzen.*

When choosing a model, one must consider what type to use: there are plenty of options, ranging from simple to advanced statistical models, box models, process-oriented models, coupled models, 3D models, global circulation models, etc. Depending on the chosen model, one must cope with its specific advantages and drawbacks. It is often said that one should use the latest, state-of-the-art models, but this not always so useful. One can often resort to much simpler, faster, more cost-efficient, and less CPU-demanding methods. As for the Baltic Sea, a full 3D model would surely do the trick, but there is a much simpler approach that generates essentially the same results. In my thesis, I worked with the PROBE-Baltic model. PROBE stands from Program for Boundary Layers in the Environment and is an equation solver for one-dimensional transient, or two-dimensional steady, boundary layers. PROBE-Baltic is a further development of that program, applicable to the Baltic Sea ocean climate system. It divides the Baltic Sea into 13 vertically resolved subbasins (see Figure 2.1 for subbasin layout) connected horizontally using strait-flow models. Water level in Kattegat and river runoff is used to calculate the barotropic water exchange. Baroclinic outflows are assumed to be in geostrophic balance in straits wider than the internal Rossby radius, while in narrow straits the baroclinic exchange is assumed to be at the maximum flow rate. The in- and outflowing depths are based on information on the stratification and sill depths of the subbasins.

The physical properties of each subbasin are calculated using six horizontally averaged time-dependent advective-diffusive equations for heat, salinity, momentum (two equations), and turbulence (turbulent kinetic energy and dissipation rate of turbulent kinetic energy). Gustafsson and Omstedt (2009) developed and implemented the simple oxygen concentration model used in Paper IV. Additional concentration equations may easily be added (e.g., the eight additional equations for the carbon-based ecosystem presented in Omstedt et al., 2009). In PROBE-Baltic, all conservation equations are formally written in the same way. In its one-dimensional, time-dependent form, the equation for a variable ϕ becomes

$$\frac{\partial \phi}{\partial t} + w\frac{\partial \phi}{\partial z} = \frac{\partial}{\partial z}\left(\Gamma_{\phi}\frac{\partial \phi}{\partial z}\right) + S_{\phi}, \qquad (4)$$

where t is time, z is depth, w is vertical velocity, and Γ_{ϕ} denotes an exchange coefficient. From the left, the terms represent the local time derivative, vertical advection, turbulent diffusion, and source/sink of ϕ. There are also conservation equations for volume and ice. Ice formation is assumed to begin when the surface water temperature becomes super cooled (i.e., sea surface temperature is less than the freezing temperature) and the heat deficit is regarded as the ice thickness. Furthermore, the ice concentration is calculated using a one-dimensional ice-front model developed by Omstedt (1990). The model has been validated (Omstedt and Axell, 2003) and applied in climate sensitivity studies (Paper I) and climate reconstructions (Papers II and IV; Gustafsson and Omstedt, 2009). A full description of PROBE-Baltic is presented in Omstedt and Axell (2003).

PROBE-Baltic uses temperature, zonal and meridional wind components, relative humidity, and cloudiness at a sub-daily resolution as forcing. Additional forcing is daily sea level from Kattegat and monthly resolved river runoff and precipitation. Forcing data are individually chosen for the length of the model run. This thesis examines three different periods: in Paper I, 1958–2004; in Paper II, 1893–1999 as well as 1500–2001; and in Papers III and IV, 1500–1995. This requires three sets of forcing data to deal with the different time scales, i.e., the 50-, 100-, and 500-year time scales. These forcing fields are discussed in more detail in section 2.4.

All models must be initialized to be able to run. During initialization, all initial conditions and boundary values are set. The initial conditions must be set carefully to prevent their exerting a long-term influence. In Paper I, this problem was investigated for both salinity and temperature in the Baltic Sea. The purpose was to examine on what time scales the boundary values and initial conditions dominate. Intuitively, one understands that model runs on longer time scales will be less dominated by initial conditions and more governed by the quality of the boundary values. In the case of the Baltic Sea, these boundary values are made up of the lateral boundary conditions at the sea surface and at the outer boundary toward the North Sea. Spinup experiments in Paper I demonstrated that initial salinity conditions (starting from limnic [0 psu] or oceanic [34 psu] conditions) influence the calculations for at least 33 years. This time scale is also closely related to the residence time of water in the Baltic Sea. For temperature the time scale is one year. Depending on what one wants to study, these two time scales must be considered. The reason for the large difference in time scale between salinity and temperature is understandable: salinity is regulated by water exchange through the narrow Danish straits, while changes in temperature are associated with the heat flux across the air–sea boundary surface.

2.4 Forcing fields on different time scales

The shortest modelled period, 1958–2004, uses gridded synoptic forcing fields with high spatial and temporal resolution data. This forcing is compiled from the two gridded datasets from the ERA40 reanalysis project (conducted by the European Centre for Medium-Range Weather Forecasts) and the SMHI 1° × 1° data. Both datasets have a one-by-one–degree spatial resolution; the ERA40 data have a six-hour temporal resolution versus the three-hour resolution of the SMHI data. The ERA40 data were used for the 1958–2001 period, and the SMHI data starting in 2002. Both datasets were examined for use in Baltic Sea modelling by Omstedt et al. (2005) and can be used in numerical modelling, though the horizontal resolution is too coarse to resolve the Baltic Sea completely. A possible consequence of the coarseness in the horizontal resolution is land influence in the forcing fields, a problem corrected by Omstedt and Axell (2003) using correction formulae in PROBE-Baltic. Furthermore, the BALTEX Hydrological Data Centre provided monthly resolved river runoff data for the 13 subbasins, and sea level data were collected from daily mean sea level observations in Kattegat.

Modelling longer time scales, such as the whole twentieth century, entails coping with a less dense synoptic observational field. Land-based meteorological stations were not uncommon in the late nineteenth century, but coastal stations were. More meteorological stations that could capture marine meteorological conditions were deployed over the twentieth century. However, there are a few coastal stations that cover the studied period. In the Nordklim dataset (Tuomenvirta et al., 2001), the Vinga (57.6°N, 11.6°E), Hoburg (56.9°N, 18.2°E), Gotska Sandön (58.4°N, 19.2°E), and Holmögadd (63.4°N, 20.8°E) stations cover the 1890–1999 period with monthly observations of temperature, cloudiness, and relative humidity. All these stations are located on islands inside or outside the outermost part of the archipelago along the Swedish coast, thus limiting the land bias. The zonal and meridional wind components are calculated via geostrophic winds based on pressure series collected in the Wasa project (Schmith et al., 1997). The pressure series comprise mean barometer readings at a six-hour resolution from the stations of Potsdam, Nordby, Lund, Göteborg, Visby, Stockholm, Helsinki, Härnösand, and Haparanda. Meanwhile, daily sea level has been measured in the Danish town of Hornbæk on the Kattegat coast of Zealand since the end of the nineteenth century. Existing gaps have been filled with linear regression data from the Kattegat sea level stations of Varberg and Viken. As the land uplift rate is assumed to be roughly the same at all sea level stations, this effect is negligible at the time scales considered. Finally, the river runoff was compiled using data from Cyberski and Wroblewski (2000) for 1901–1920, from Mikulski (1986) for 1921–1949, and from the BALTEX Hydrological Data Centre for 1950 and after.

Very few instrumental meteorological series exist before the late eighteenth century. The earliest series from the Baltic Sea region is that of Uppsala, starting in 1722. To overcome this problem, reconstructions based on proxy data (e.g., documents, tree rings, sediments, and ice cores) can instead be used for model forcing. This technique was used in Papers II–IV, where a 500-year perspective was taken spanning the 1500–2001 period. For this a gridded sea level pressure (Luterbacher et al., 2002) and a gridded temperature (Luterbacher et al., 2004) reconstruction was used. A simple downscaling of seasonal reconstructed temperature and sea level pressure to six-hour resolution was applied according to

$$\Phi = \Phi^{season} - \Phi_{ERA40}^{season} + \Phi_{ERA40}, \qquad (5)$$

where Φ is the downscaled forcing, Φ^{season} is the gridded reconstructed seasonal data, and Φ_{ERA40} and Φ_{ERA40}^{season} are the mean ERA40 data on six-hour and seasonal resolution, respectively. The represented short-term (less than a season) variability is drawn from the variability of

ERA40 data between 1 January 1971 and 31 December 2000. An assumption is made that the variability over this period is stationary and valid throughout the last 500 years. For temperature, Equation 5 is quite straightforward, as Φ^{season} is the selected grid points in the Luterbacher et al. (2004) reconstruction. For zonal and meridional wind, total cloudiness, relative humidity, and river runoff a stepwise regression method was employed to generate these parameters. This method formulates statistical relationships between large-scale circulation indices for Northern Europe developed by Eriksson et al. (2007) based on sea level pressure data from Luterbacher et al. (2002). The circulation indices characterize the zonal and meridional wind flow, vorticity, divergence/convergence, shear, and normal deformation. The indices are selected individually and added to the regression equation if they pass an F-test at the 95% level. Thus, stepwise regression methods will only include those predictors that are most important to the forcing field. The general equation for this method can be written as

$$\Phi^{season} = B_0 + \sum_{n=1}^{6} B_n \Phi_i^{season} , \qquad (6)$$

where B_0 and B_n are the regression coefficients and Φ_i^{season} is the circulation indices. Sea level change in Kattegat over the past 500 years was calculated using the north–south pressure gradient across the North Sea between Oksøy, Norway, and De Bilt, the Netherlands. Although based on a simple model, this approach proved to be well suited to examining sea level changes in Kattegat and salt exchange in the Baltic Sea, according to Gustafsson and Andersson (2001). The pressure gradient was set up by the sea level pressure reconstruction of Luterbacher et al. (2002).

Water temperature and ice extent are not very sensitive to freshwater forcing but are more sensitive to changes in large-scale meteorological forcing. On the other hand, modelling salinity and oxygen requires higher confidence in the water balance. River runoff and sea level have an extensive impact on salinity levels and, consequently, on the available oxygen in the Baltic Sea. Paper III developed an improved version of river runoff over the past 500 years, which is discussed in detail in section 3.3.

3. Climate and the Baltic Sea

How inappropriate to call this planet Earth, when clearly it is Ocean.
– Arthur C. Clarke

The Baltic Sea region extends across 20 latitudes (approximately 49°N to 69°N) and roughly 30 longitudes (approximately 8°E to 37°E). The climate of the region varies greatly from southwest to northeast, as the large-scale circulation pattern of the region is influenced by two air masses: maritime from the North Atlantic and continental from the east. The maritime influence from the North Atlantic is closely associated with prevailing westerly winds in the Baltic Sea region. These advect mild (cool) and humid air in winter (summer) and are largely governed by the sea level pressure gradient between the Azores subtropical high and the Icelandic subpolar low. The strength of the North Atlantic influence varies on shorter time scales (weeks), and the mechanism is described using an index known as the North Atlantic Oscillation (NAO; van Loon and Rogers, 1978). A positive (negative) index indicates strong (weak) North Atlantic influence. The effect of NAO is most prominent on winter temperatures, winters with a positive NAO being approximately 2°C warmer than winters with a negative NAO (Vihma and Haapala, 2009). During negative NAO conditions, westerlies are weakened or blocked as the continental influence increases in strength. This influence is governed by the strengthening or weakening of the Russian high (low), allowing cold (warm) and dry airflow into the region in winter (summer). Due to these mechanisms, there is often a pronounced temperature gradient in the region, with maritime conditions in the southwest and subarctic in the northeast. Figures 3.1 and 3.2 show monthly long-term mean air temperature and precipitation from six different meteorological stations, representing temperature variability in all parts of the Baltic Sea region. Lindenberg in Germany and Sodankylä in Finland are inland stations, while Göteborg, Stockholm, Visby (temperature only), Gotska Sandön (precipitation only) – all in Sweden – and St. Petersburg in Russia are located on the shores of the Baltic Sea. The long-term mean (black line) is based on the normal 1961–1990 period, widely used as a climatic reference period. However, large variability is evident even in this period, as indicated by the shaded grey areas denoting maximum and minimum monthly means. It could therefore be argued, playfully, that the only thing normal in climate is that nothing is really normal.

As mentioned in Chapter 1.1, the global mean temperature rose by 0.74°C over the past century (IPCC, 2007). This has also strongly affected the temperature trends in the Baltic Sea region over the past century. As a whole, the region has warmed slightly more than the global average, but with large spatial and temporal differences. The decadal surface air temperature trends between 1871 and 2004 for the south and north (above 60°N) are presented in Table 3.1. The most warming occurred above 60°N, where the annual long-term trend amounts to 0.10°C per decade. There are also large differences in warming between the four seasons: spring and winter have warmed substantially, while summer and autumn warming is less pronounced.

Table 3.1: *Annual and seasonal decadal air temperature trend in the Baltic Sea region above and below 60°N between 1871 and 2004. The northern region has warmed more than the south, while spring and winter are the seasons displaying the most pronounced changes. Values written in bold are significant at a 95% level.*

Geographical Region	Annual	Winter	Spring	Summer	Autumn
North (above 60N)	**0.10°C**	0.09°C	**0.15°C**	**0.06°C**	**0.08°C**
South (below 60N)	**0.07°C**	**0.10°C**	**0.11°C**	0.03°C	**0.06°C**

Source: BACC (2008)

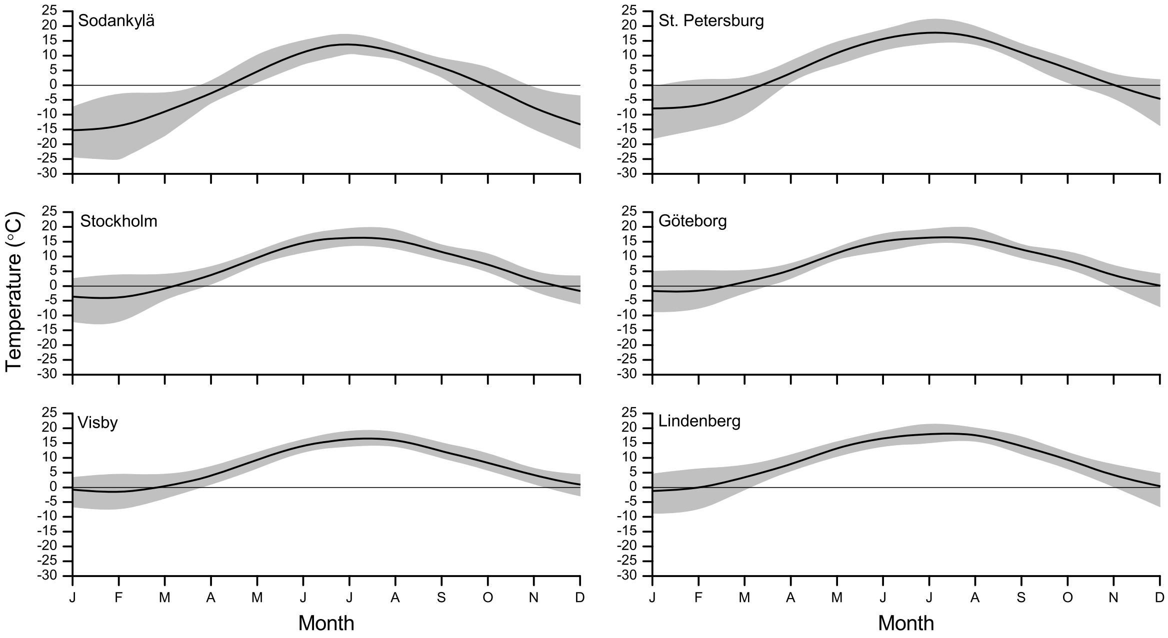


Figure 3.1: *Monthly mean temperature for Lindenberg (Germany), Göteborg (Sweden), Stockholm (Sweden), Visby (Sweden), St. Petersburg (Russia), and Sodankylä (Finland) based on the normal 1961–1990 period. The grey shaded region indicates the minimum and maximum temperatures in the normal period. All locations are situated in the Baltic Sea drainage basin.*

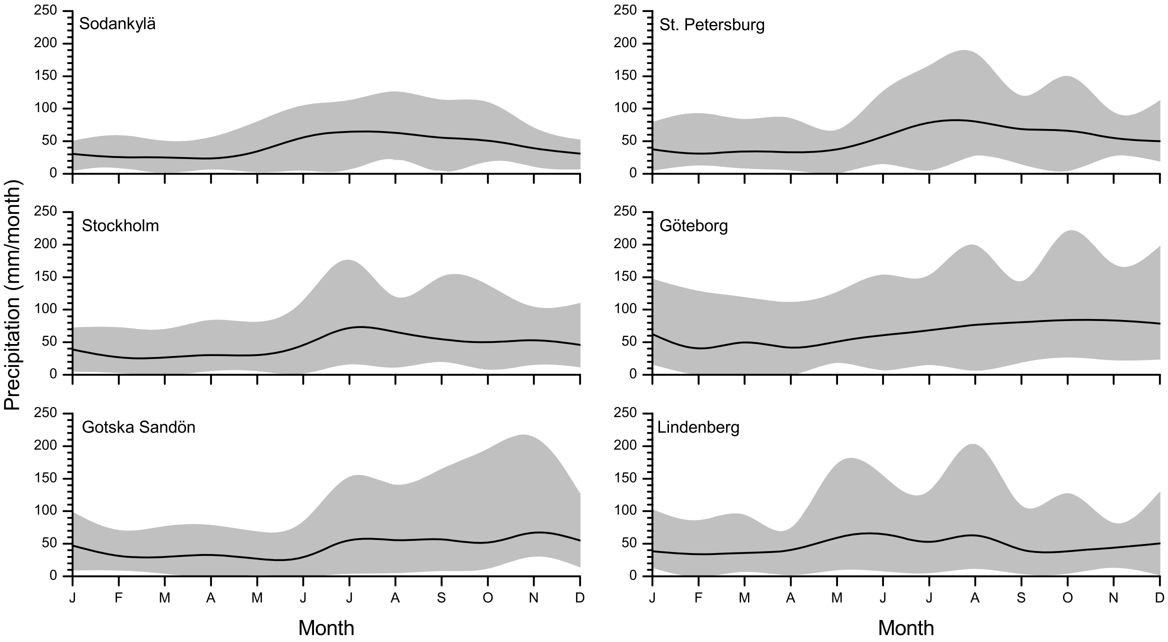


Figure 3.2: *Same as Figure 3.1, except it shows precipitation. Visby has been replaced with Gotska Sandön, located approximately 90 kilometres northeast of Visby.*

The temperature rise in the region in the late nineteenth and twentieth century was not uniform or constant over time. There is large inherent inter-decadal variability in the region and two warm maxima with approximately the same annual temperature have taken place over the past century, in the 1930s and the 1990s. A warming due to natural causes ended the so-called Little Ice Age in 1877 (Omstedt and Chen, 2001) and culminated in the 1930s. Thereafter a cooling period started in the 1940s and lasted until the 1970s. Through the late 1980s and early 1990s temperatures once again reached elevated levels, this time possibly partly linked to anthropogenic causes, such as greenhouse gas emissions, although a robust link has yet to be established (BACC, 2008). Understanding the climate system requires looking at time scales of several decades, centuries, or even millennia. Studying short periods risks underestimating the full internal variability of the climate. Gaps, inhomogeneity, and short time series make it difficult to carry out proper detection and attribution studies. There is also the risk that changes unrelated to climate change, such as eutrophication, over-fishing, or land usage, may be incorrectly attributed to anthropogenic climate change. The work conducted in Papers II, III, and IV supplies needed context, putting the twentieth century into a long-term perspective.

3.1 Water temperatures over past centuries

While the air temperature typically changes quickly, within weeks, days, or even hours, water temperature changes more slowly. As demonstrated in Paper I, the time scale for water temperature change is about one year, indicating the water temperature has some kind of long-term memory property. As described in section 2.2, most of the Baltic Sea's water volume is contained in the upper water layers, but sea surface temperatures alone are not representative of the full heat balance of the Baltic. Sea surface temperatures mirror air temperatures and not the annual heat accumulation. For that reason, sea surface temperatures may differ from one point to another, even though the heat of the water body remains constant, provided that energy is not added or removed from the system. In this thesis, the heat balance is taken into account by horizontally and vertically integrating the water temperature. This temperature property, $\overline{T}_w$, is defined as

$$\overline{T}_w = \frac{1}{V} \iint T_w dz dA, \qquad (7)$$

where V and T_w are the volume and temperature, respectively, of each vertical layer. Several PROBE-Baltic simulations using different forcing fields were carried out and the water temperature was calculated according to Equation 7. To determine the success of the model, we must compare the results with real observations. Fortunately, an estimate of the mean water temperature of the Baltic Sea can be constructed based on observations. Omstedt and Nohr (2004) used 1744 measured profiles from the major subbasins to compile an observed water temperature dataset covering the 1970–2001 period. Using this dataset, the modelled water temperature in Papers I and II can be directly compared with observations after simple conversion to anomalies, which is done in Figure 3.3. Expressing the temperature as anomalies has the advantage of easing comparison, since the derived forcing fields for PROBE-Baltic are compiled from different datasets and therefore differ somewhat in absolute modelled temperatures. It is noticeable that the modelled water temperatures capture the variability and trend of the observed temperature. We can conclude that the model results agree well with observations over the later twentieth century no matter what forcing is used. As we only have observed water temperature from 1970 to the present, we can only assume that the model results stay within reasonable error limits before that. It can be argued that the forcings comprising pure meteorological observations (i.e., those starting in 1893 and 1958) model the water temperature more trustworthily, while reconstructed forcing (i.e., that starting in 1500) is probably less reliable in early centuries due to decreased variability owing to noisy data (von Storch et al., 2004).

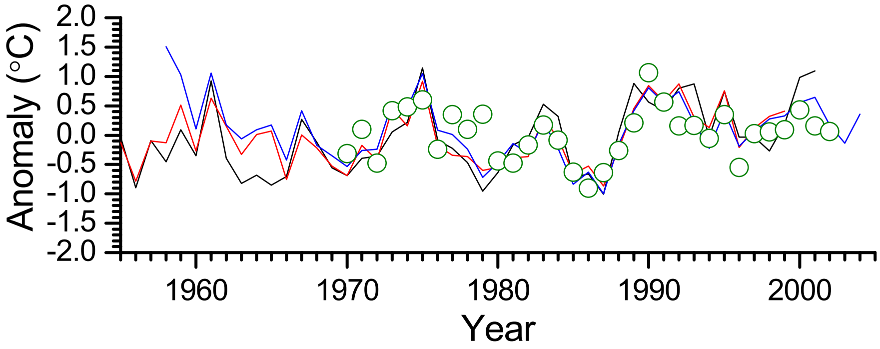


Figure 3.3: *Modelled water temperature anomalies from 1500 to 2001 (black line), 1893 to 1999 (red line), and 1958 to 2004 (blue line), and observations between 1970 and 2001 (olive green circles) from Omstedt and Nohr (2004). The modelled water temperature captures the variability of the observed counterpart. Redrawn from Paper II.*

3.1.1 Long-term variability since AD 1500

So what does the water temperature tell us about the long-term variability of the Baltic Sea climate? Looking at Figure 3.4, it is apparent that the water temperature has been associated with large decadal and centennial variability over the past 500 years. The recent warming in air temperatures over the twentieth century is reflected in the water temperature as well. A significant, and still ongoing, warming has taken place since the 1980s, culminating in the 1990s. Another prominent warming also took place in the early twentieth century, peaking in the 1930s. One should not focus only on warming, since cooling also has taken place in recent times. The extremely cold winters of the early 1940s appear as a marked cold pulse in annual water temperatures (these years were actually among the coldest of the past half millennium). There was another colder period from the 1960s to mid 1980s, with annual water temperatures mostly below the long-term average of the twentieth century. Before 1900, the temperature was mainly below the long-term mean of the twentieth century. The increase from 1877 to 1935 probably reflects the ending of the Little Ice Age (Omstedt and Chen, 2001), and indicates that it had a significant impact on water temperatures. The Little Ice Age was a climatic period that began in the fourteenth or fifteenth century (exact dating is still debated) and lasted until the end of the nineteenth century (e.g., Wanner et al., 2008). As the name indicates, this was a period of colder temperatures than we are used to today, and it probably left a long-lasting impression on the people of the time (Fagan, 2000). Two cold peaks stand out in the modelled water temperature as exceptionally cold: the end of the seventeenth century and the late eighteenth century. These coincide with the Maunder Minimum (approximately 1645–1715) and the Dalton Minimum (approximately 1790–1830), periods of unusually low solar activity and large volcanic eruptions (Luterbacher et al., 2001; Wagner and Zorita, 2005).

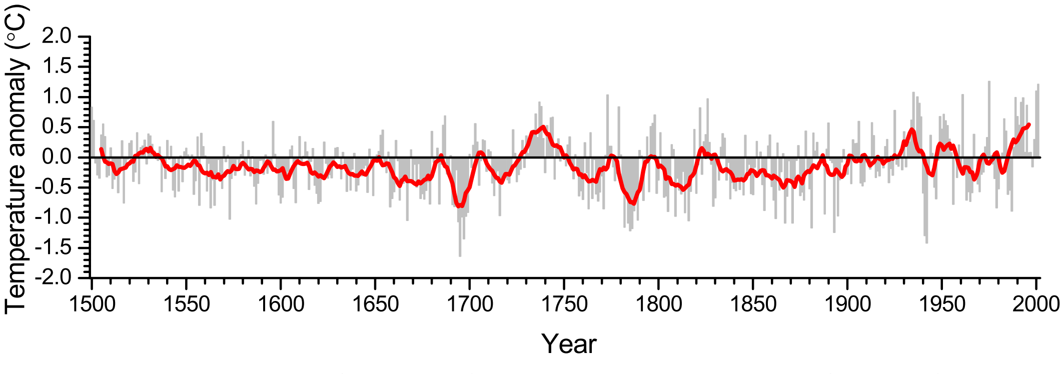


Figure 3.4: *Modelled annual (grey bars) and decadal smoothed (red line) mean annual (horizontally and vertically averaged) water temperature over the past 500 years. Anomalies are expressed with reference to the 1900–1999 period. Redrawn from Paper II.*

There is dispute as to whether the Little Ice Age occurred globally or was primarily restricted to the North Atlantic sector, and whether it affected annual or seasonal scales (e.g., Lamb, 1995; Matthews and Briffa, 2005). A tabular overview by Ljungqvist (2009) of available quantitative temperature proxy records suggests that the Little Ice Age affected most parts of the Northern Hemisphere. However, the Little Ice Age was evidently not homogenously cold in the Baltic Sea region, as is also apparent from Figure 3.4. A major warm period occurred between 1720 and 1740, consistent with the findings of Eriksson et al. (2007), Grudd (2008), and Leijonhufvud et al. (2009). The amplitude and rate of warming at that time was almost identical to the warming of the late twentieth century (Paper II). Jones and Briffa (2006) also discussed this warm period in the context of northwest Europe as a broader geographical area. Long instrumental records of temperature from northwestern Europe indicate a pronounced warm period in the early eighteenth century, only interrupted by the extremely cold winter of 1740. This warm period seemed to have been restricted to the British Isles, the Low Countries, and Scandinavia, and temperature observations from Berlin, Germany, do not indicate the same warming. However, one must be cautious when interpreting these trends, due to the very small number of available contemporary temperature records. National and pan-European meteorological observation networks did not start until the second half of the eighteenth century. There are other sources (i.e., proxies) that suggest that the early eighteenth century was unusually mild. Although it seems contradictory at first, glaciers in southern Norway advanced rapidly during the period. The culprit seems to have been a prevailing positive mode of the North Atlantic Oscillation index (Nesje and Dahl, 2003), associated with westerly wind direction that advects moist air into Northern Europe, resulting in wet winters and cool summers in Northern Europe. Thus, increased rainfall in winter accompanied by milder temperatures significantly contributed to the advancing glaciers. At the same time, storm activity in the English Channel seems to have been lower than in preceding decades. Weather observations between 1685 and 1750 extracted from Royal Navy logbooks indicate the 1730s as the most quiescent decade in terms of storminess in the study period (Wheeler et al., 2009). Newly published papers suggest that storminess may be more related to periods of colder temperatures than the opposite in the North Sea and Baltic Sea domain (Björck and Clemmensen, 2004; Bärring and Krzysztof, 2009). These independent observations may therefore serve as concurring evidence that the early eighteenth century was warmer than the preceding decades.

For the Baltic Sea, there is only one instrumental time series covering the warm period between 1720 and 1740 that continues up to this day, and that is the Uppsala temperature record commencing in 1722 (Bergström, 1990; Moberg and Bergström, 1997; Bergström and Moberg, 2002). Other series exist but do not cover the full period or are reconstructed from documentary data and dates of ice break-up, such as the Tallinn winter air temperature series (Tarand and Nordli, 2001) and the Stockholm January–April air temperature series (Leijonhufvud et al., 2008). The newly published Stockholm winter and spring air temperature reconstruction by Leijonhufvud et al. (2009) spanning the past 500 years may therefore be very important in addressing this lack. Interestingly enough, the Uppsala record, used as forcing by PROBE-Baltic to model the past 500 years, is introduced into the reconstructions at the point in time when a significant warming appears in the water temperature. The Uppsala air temperature record indicates a pronounced warming from 1722 to 1739, and a declining temperature thereafter, just as the modelled water temperature does. There are some known problems with the observed temperature record for this period. First, the Uppsala temperature record is incomplete before July 1773. Bergström (1990) interpolated observations from nearby stations to fill in the missing periods. Second, the temperature was measured indoors in an unheated and well-ventilated room. The thermometer was moved outside for the first time in 1739. It is obvious that measuring the indoor temperature, as a proxy for outside temperature, may produce different values, and that moving the thermometer outdoors may result in inhomogeneous data. This matter has been addressed through careful homogenization testing of the series (Moberg and Bergström, 1997), though there remain some doubts about the series in its first years before 1739 and it should be used with caution (Moberg et al., 2006). Finally, it must be stressed that the importance of the Uppsala air temperature record in the reconstructed forcing decreased over the eighteenth and nineteenth centuries as more and more instrumental series were incorporated into the reconstructed European temperature by Luterbacher et al. (2004). As we will see in section 3.2.4, the warm period early in the instrumental Uppsala temperature series can be discussed with regard to winter conditions, giving additional clues to the warm bias puzzle.

3.2 Ice conditions in the Baltic Sea

Changes in the ice extent have large consequences for physical, biological, and human interaction with the Baltic Sea. For example, ice acts as a lid on the ocean water, effectively preventing it from evaporating; thus, increasing and decreasing ice extent helps regulate the net precipitation over the Baltic Sea (Rutgersson et al., 2002). Ice is important for the survival of some of the organisms in the region, for example, the Baltic ringed seal that requires ice for its breeding habitat. A decrease in ice extent could rapidly damage the already fragile population of this species (Meier et al., 2004). For humans, ice extent plays a vital role not only for occasional ice skaters, but also for imports to and exports from the Nordic and Baltic countries, some of which come over the sea (e.g., 80% of Finland's international trade is transported via the sea, Vihma and Haapala, 2009). Therefore, well-functioning ice services are needed in winters to ensure that ships travel safely through ice-covered areas.

The maximum ice extent in the Baltic Sea (MIB) usually occurs in late February or March. It can be regarded as an integrated property, reflecting the intensity of the cooling period and the position of the freezing temperature isotherm. Ice formation takes place every winter, beginning along the coasts of northern Bothnian Bay and the eastern Gulf of Finland where the air temperature always falls well below freezing for an extended period. Therefore, these parts are usually already partially ice covered in December and become ice-free as late as May or even June when winters have been severe.

3.2.1 Sensitivity of the Baltic Sea ice extent

Paper I examined the response and sensitivity of MIB as a function of air temperature, finding that, in general, ice extent is highly sensitive to even minor changes in air temperature. If the mean winter air temperature over the Baltic Sea is −6°C or lower, the whole Baltic Sea is ice covered. Winters with mean temperatures above +2°C experience a much reduced ice extent. This threshold has been surpassed only once, in 2008, in what was the mildest ice winter of the past 290 years, with an MIB of 49,000 km^2 (see Figure 3.5). Five of the ten mildest ice winters since 1720 have occurred in the past 20 years, clustered in the early 1990s. This is a clear indication that maritime circulation patterns are strengthening their position in winter at the expense of continental circulation patterns. If maritime conditions similar to those in the Kattegat were prevalent throughout the Baltic Sea region, ice-free conditions would occur in approximately 25–50% of winters (Paper I). The long-term trend since 1720 displays a significant trend toward decreasing ice extent (Haapala and Leppäranta, 1997). However, when computing the long-term trend since 1900, up to and including the most recent winter (2008–2009), a slight decreasing trend is observed, though it is not significant at the 90% level. Most of the decrease in ice extent therefore took place over the last decades of the nineteenth century (Vihma and Haapala, 2009), probably directly associated with the end of the Little Ice Age in the Baltic Sea region in 1877, as pointed out by Omstedt and Chen (2001). At that time, air temperatures increased rapidly and reduced ice extent and growth in winter. This continued until the early twentieth century, when a minimum was reached in the 1930s; a similar minimum was reached again in the 1990s.

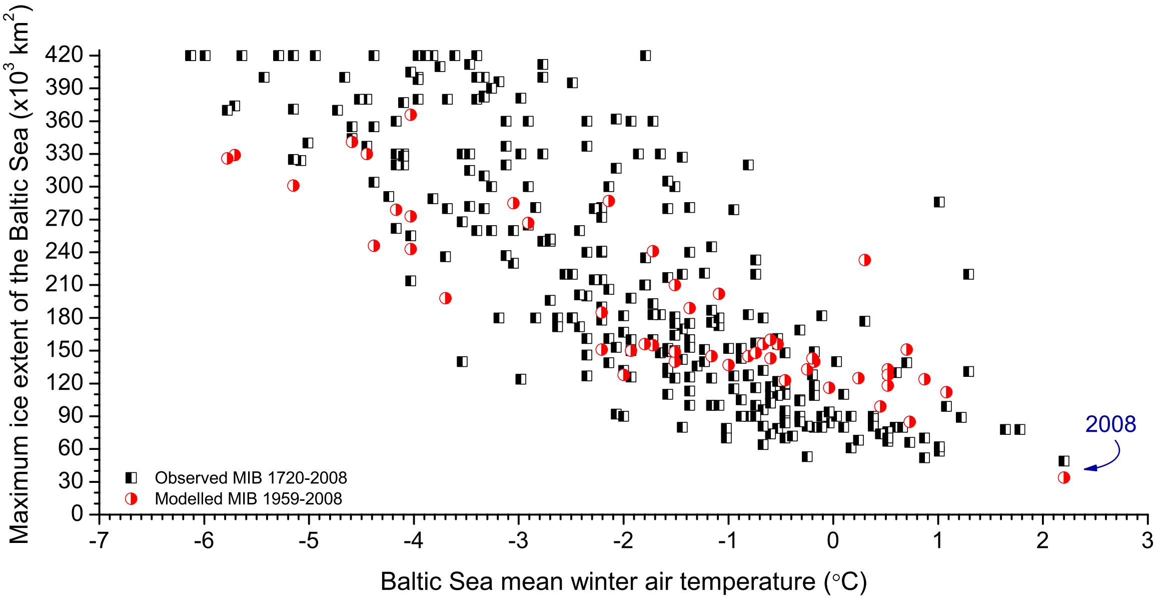


Figure 3.5: *Observed and modelled MIB related to mean winter air temperature over the Baltic Sea. MIB is highly sensitive to even small changes in mean temperature. The record low MIB in 2008 is specifically indicated. Updated and redrawn from Paper I.*

3.2.2 Observations and classifications of ice extent

The late Prof. Risto Jurva of Finland collected observations of historical ice extent in the Baltic Sea over past centuries, starting in 1720. The observations comprise ice conditions reported in newspapers, lighthouse records, shipping records, travel journals, ice charts, accounts of ice in Danish waters collected by Speerschneider (1915), and correlations with temperature observations from Finnish stations (mostly from Mariehamn on the Åland islands and from Helsinki). Although all the pre-nineteenth century material was destroyed during the bombings of Helsinki in 1944, Prof. Jurva fortunately managed to compile the observations into maximum ice extent estimates in the early 1940s, and the published histogram was subsequently digitized. The early part of Prof. Jurva's estimates is associated with a level of uncertainty, as those observations rely more on personal accounts in newspapers, journals, and similar sources. Not until the 1880s does the estimated MIB become more reliable as more data are available from ships travelling through the Baltic Sea (Jurva, 1952). New methods have come into play over time. The Finnish Institute of Marine Research, now part of the Finnish Meteorological Institute, has made observations of ice extent and thickness since the early twentieth century, though the methodologies have changed over time. Initially, sea ice extent was observed by the Finnish Institute of Marine Research Ice Service onboard its vessels. In the 1930s, air-based reconnaissance was initiated, increasing the accuracy of the ice charts. Even more precise ice charts were obtained when satellites became available in the late 1960s. Obviously, one must be aware of technological improvement when assessing long-term trends and variability in the data. Regarding the ice extent before 1880, this thesis uses the maximum estimated MIB from 1720 onward. This may overestimate the ice extent early in the period but, as the correlation with air temperatures is high, one might assume that the error is not too large. According to Vihma and Haapala (2009), the uncertainty is greatest for extremely severe winters, when the minimum and maximum estimated MIB differ by up to 20%. However, estimated MIB during the mild decade of the 1760s is also associated with similar uncertainties. Based on the estimated and observed MIB between 1720 and 1995, Seinä and Palosuo (1996) constructed an ice winter classification (see Figure 3.6 and Table 3.2). It should be stressed that the probability of a given ice classification occurring changes if another period is considered, due to climate non-stationarity. The absolute long-term mean of MIB is 217,000 km², which corresponds to approximately 52% ice cover.

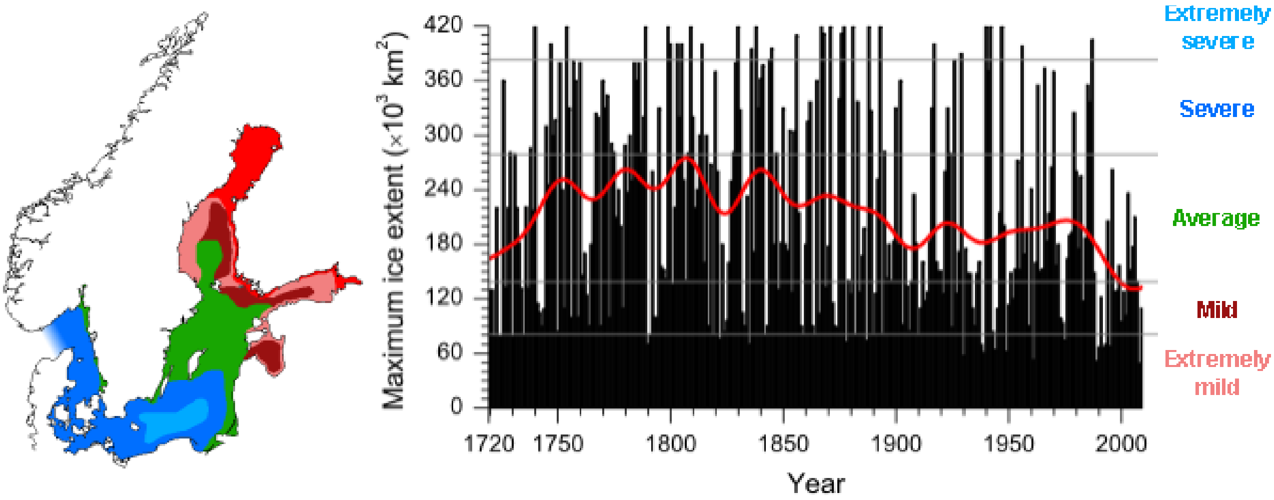


Figure 3.6: Left: *Maximum ice extent in mild, average, and severe ice winters, based on the ice winters between 1720 and 1995. Note that Bothnian Bay is always ice covered while part of the Baltic Proper is rarely ice covered. Redrawn from Seinä and Palosuo (1996).* Right: *Reconstructed and observed MIB 1720 to 2009 and the according classifications. The red line is the decadal variability enhanced using decadal smoothing.*

Table 3.2: *Ice winter classifications according to Seinä and Palosuo (1996), based on ice winters between 1720 and 1995. The long-term mean of MIB during this period was 217,000 km^2.*

Classification	From	To
Extremely mild		81,000 km^2
Mild	81,001 km^2	139,000 km^2
Average	139,001 km^2	279,000 km^2
Severe	279,001 km^2	383,000 km^2
Extremely severe	383,001 km^2	

Jevrejeva et al. (2004) investigated changes in ice seasonality over the twentieth century; they found strong indications that the ice season length had decreased by 14–44 days over the century, associated with large regional variability. Much of this seasonal shortening is attributable to earlier ice break-up, which can be explained by the earlier arrival of spring. Trend analysis indicates a tendency toward increasing and decreasing occurrences of extremely mild and mild ice winters, respectively, since 1720. Neither of these trends is statistically significant at the 95% level. However, the number of average ice winters has increased over time and is significant at the 95% level. At the same time, there has been a statistically significant decrease in the number of severe ice winters. There has also been a slight, but insignificant, decreasing trend of extremely severe ice winters over the same period, indicating long-term warming in the region. However, even though the warming continues, very cold winters will happen in the future as well, but with reduced frequency; the last extremely severe ice winter occurred in 1986–1987 with an MIB of 405,000 km^2.

3.2.3 Reconstructing and validating past ice extent

In Paper II, MIB was reconstructed by modelling and was analysed for all winters since 1500. Large multi-decadal variability was found, and periods of limited ice formation occurred even in the midst of the Little Ice Age. Periods of mild ice winters took place in the early sixteenth century and in the early and mid eighteenth century. As discussed above and demonstrated in

Paper I, this was a direct effect of increased air temperatures (see Figure 3.7). After the end of the Little Ice Age in 1877, air temperatures slowly increased, peaking in the 1990s, diminishing ice extent being a consequence. At the same time, the nineteenth century stands out as the coldest and most ice-covered century.

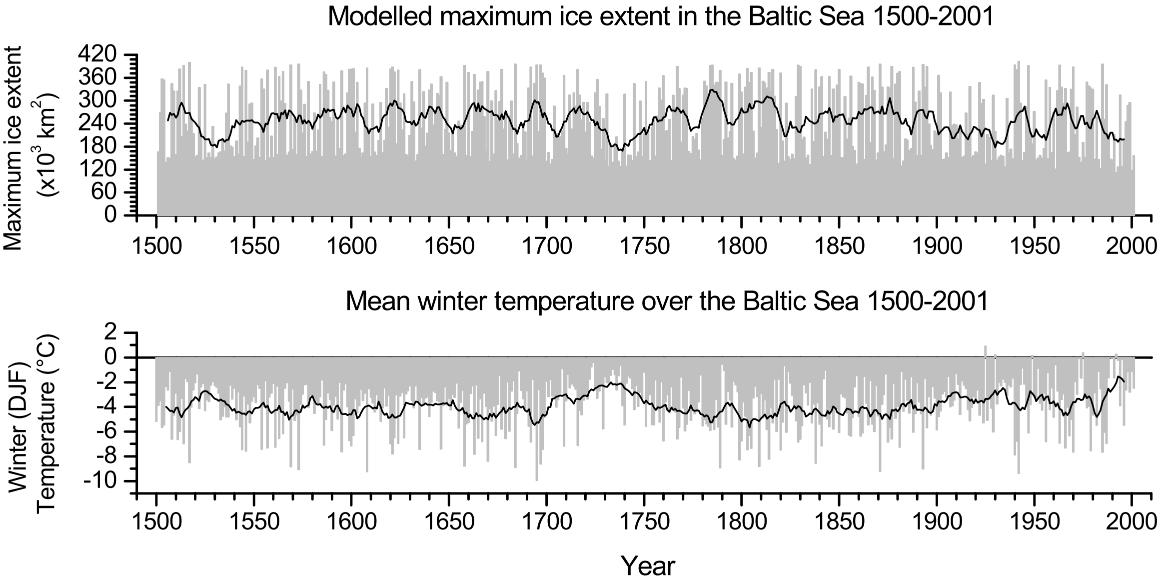


Figure 3.7: Top: *Annual MIB as modelled by PROBE-Baltic between 1500 and 2001. Large multi-decadal variability is visible. The mid 1500s and early and mid 1700s display low MIB values similar to those of the late twentieth century.* Bottom: *Mean winter air temperature used as forcing. Winter is defined as the months of December through February. It is evident that the periods corresponding to mild winter temperatures also reflect low MIB values. From Paper II.*

As mentioned previously in this chapter, there are estimates of ice extent since 1720, covering just over half the modelled period. One can therefore directly compare modelled, estimated, and observed MIB with each other for this period, obtaining a measure of modelling accuracy. The first years, covering the winters of 1501 to 1719, are not as easy to validate as measurements are lacking. To overcome this, documentary data are used. These data comprise independent observations in the form of historical accounts of winter events related to the Baltic Sea region. These accounts describe how the harsh or mild winters significantly impacted contemporary society via, for example, travels across the ice in central Sweden (Retsö, 2002), military campaigns that succeeded or failed due to the presence or lack of ice (Neumann, 1978; Lindgrén and Neumann, 1983), and famines during harsh winters (Neumann and Lindgrén, 1979). There is also documentary evidence regarding Polish winter conditions enhanced with tree-ring chronologies (Przybylak et al., 2005) together with some information on British winter conditions, mostly regarding severe winters that allowed the Thames to freeze (Lamb, 1995). Although the distance between the United Kingdom and Scandinavia is relatively great, both areas usually simultaneously experience similar divergences in climate. The Central England Temperature series is fairly well correlated with MIB and explains 27% of the variance (Eriksson, 2009).

Searching the scientific literature yielded 150 independent accounts of ice conditions spread over 100 of the 219 years between the winters of 1501 and 1719. The information is sometimes contradictory, i.e., indicating that winter was simultaneously mild and cold in different parts of the region. When that happens, conditions in the location nearest the Baltic Sea are taken as correct. Many winters are indicated as extremes, either as very mild or severely cold. Most sources describe cold winters, indicating that coldness had a more significant impact on society, or that mild winters were uncommon. It is imperative that one use truly independent sources to avoid a type of circular validation. For example, Speerschneider's (1915) great compilation of accounts of ice conditions in Danish waters cannot be used, as it was used when constructing the winter severity index for the western Baltic Sea (Koslowski and Glaser, 1999). This was in turn used by Luterbacher et al. (2004) in the reconstruction of Northern European winter temperatures later used in Papers II–IV to provide meteorological forcing for the PROBE-Baltic model. This eliminates many of the well-known records and series that could have been used in validating the modelled MIB.

The upper two panels of Figure 3.8 show the modelled MIB with indications of historical accounts of the individual ice winters, blue triangles for cold and red squares for mild winters identified from the literature. For a modelled winter to be classified as validated, a small set of criteria must be met. The annual anomaly of the modelled MIB must be calculated and compared with the long-term mean of estimated and observed MIB between 1720 and 2001. If a winter is above (below) the long-term mean, it is regarded as validated if a historically documented winter backs up the claim as a cold (mild) winter. In the years for which documentary sources are available, 68% of the modelled annual ice extent is deemed validated. Interestingly, there are differences between cold and mild winters in the amount of successful validation. While 71% of winters with a cold indication are confirmed accurate, only 57% of the mild winters pass the check. Similarly, more winters in the second half of the period are validated than in the earlier period: between 1501 and 1609, the validation rate is 65% versus 73% between 1610 and 1719. This is mostly an effect of a greater number of validated cold (63% to 81%) rather than mild winters (64% to 44%). The mild winters score badly in the second half of the period, as the modelled MIB is biased toward colder conditions. Therefore, the modelled MIB is generally higher than the observed one, which is unfavourable for winters with a small ice cover. If the long-term mean of the modelled MIB were instead used to validate winters, significant improvement would be seen in the mild winters, with an increase to 79% and 89% validation rates in the early and later periods, respectively. The score for cold winters would be slightly lower, and the overall analysis and conclusions would be unaffected.

The lower three panels of Figure 3.8, covering the period starting in 1720, show the modelled and observed MIB. Although the annual absolute values differ, the long-term variability is well captured. The absolute value is not the main goal of this modelling exercise; instead, it is the long-term trends and variability over time that are interesting. Periods with observed cold or mild conditions are also indicated as cold or mild according to the model. As pointed out earlier, there is a risk of indirectly validating a series against itself. Starting in 1829, the Helsinki air temperature record is incorporated in the Luterbacher et al. (2004) reconstruction, and thus in the model forcing. Prof. Jurva used the Helsinki air temperature record to perform correlation analysis with his estimated MIB series. However, as many other temperature records are available for the time, it can be assumed that the Helsinki climate signal is restricted to the eastern Baltic Sea region and degraded enough by noise in other regions not to affect the comparison presented in Figure 3.8. Thus, one can regard the modelled ice extent in the eighteenth and early nineteenth centuries as independent of the estimated ice extent. From the mid nineteenth century and onward, the risk of dependence increases, but still remains low.

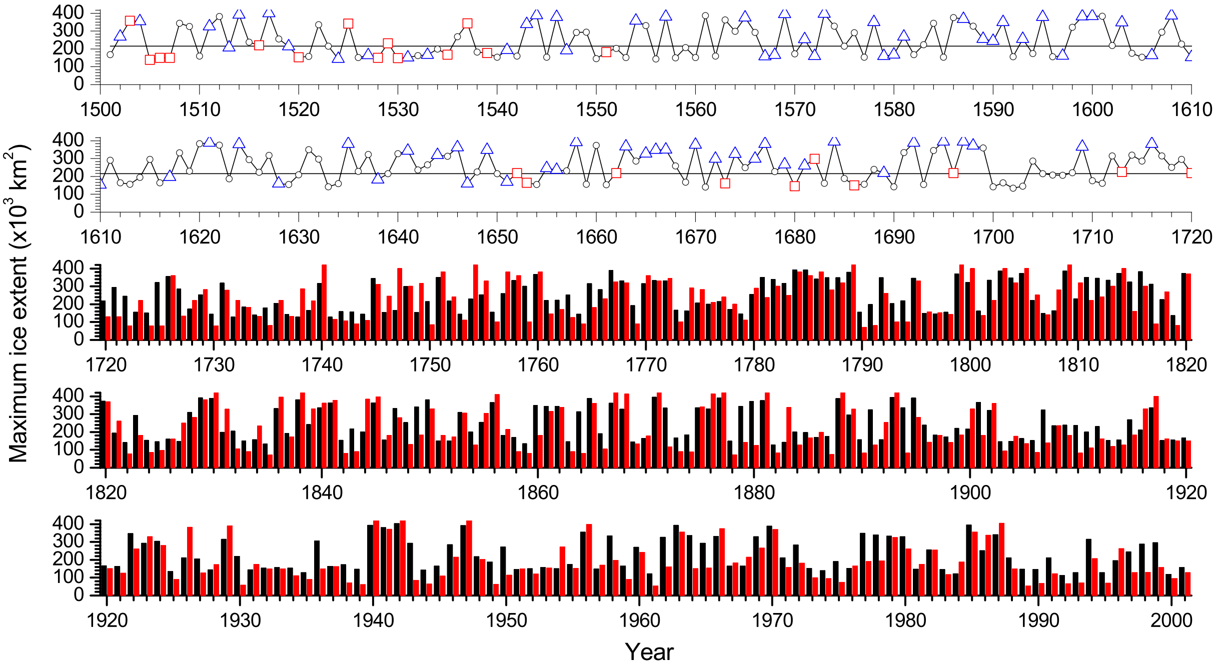


Figure 3.8: *The upper two panels show modelled MIB between the winters of 1501 and 1719. Circles denote winters for which no documentary evidence regarding ice severity has been found, blue triangles represent winters for which evidence regarding severe ice conditions has been found, and red squares indicate winters historically known as mild. The lower three panels show modelled and estimated/observed MIB between 1720 and 2001. Black columns are model results and red columns are observations. From Paper II.*

The results of Paper II can be directly compared with those of another study that reconstructed MIB over the past 500 years. Eriksson et al. (2007) and Eriksson (2009) used the same Luterbacher et al. (2002, 2004) temperature and sea level pressure reconstructions as are used in Papers II–IV, though instead of numerical modelling, statistical modelling was used as the method. Unlike in numerical modelling, a direct physical interpretation can be made from the statistical relationships established. Eriksson (2009) found that the ice cover is primarily determined by the zonal and meridional wind flow in the region. This is clearly in agreement with the sensitivity analysis presented in Paper I (see Figure 3.5). Other factors affecting ice growth are the type of circulation (i.e., cyclonic or anti-cyclonic) and precipitation. Cyclonic systems are more associated with zonal wind flows, and thus bring both warmer air temperatures and precipitation, which also reduces the ice growth. By examining long instrumental series of temperature and ice conditions, Eriksson et al. (2007) managed to identify 15 climatic periods of cold and mild winter conditions over the past five centuries. Cold periods were found to be associated with high climatic instability, i.e., larger interannual variability than in mild periods when smaller annual variability was found. This is specifically evident in recent decades with their persistent mild conditions.

The reconstruction of MIB in Paper II and in Eriksson (2009) may be regarded as an independent series from the observed series compiled by Jurva (1952) and Seinä and Palosuo (1996).

3.2.4 Observational air temperature series examined using ice records

Revisiting the issue of a possible warm bias in the mid eighteenth century, as discussed in Section 3.1.1, Hansson and Söderberg (2009) investigated the warm bias in the early Uppsala record from January through April by using ice records from the Baltic Sea. They found a warm bias of up to 1°C between 1722 and 1738. However, despite removing such a large warming, the 1722–1740 period remains as warm as the 1930s, though slightly colder than the 1990s. This is strong evidence that a problem still exists in the early Uppsala temperature record, which may be transferred to the reconstructed meteorological forcing used in PROBE-Baltic. However, the MIB series constructed by Seinä and Palosuo (1996) indicates a decrease in ice extent over the 1720s and 1730s similar to that of the late twentieth century (see Figure 3.9), and Leijonhufvud et al. (2009) concluded that the 1730s was the second warmest decade since AD 1500 in terms of Stockholm winter and spring air temperatures.

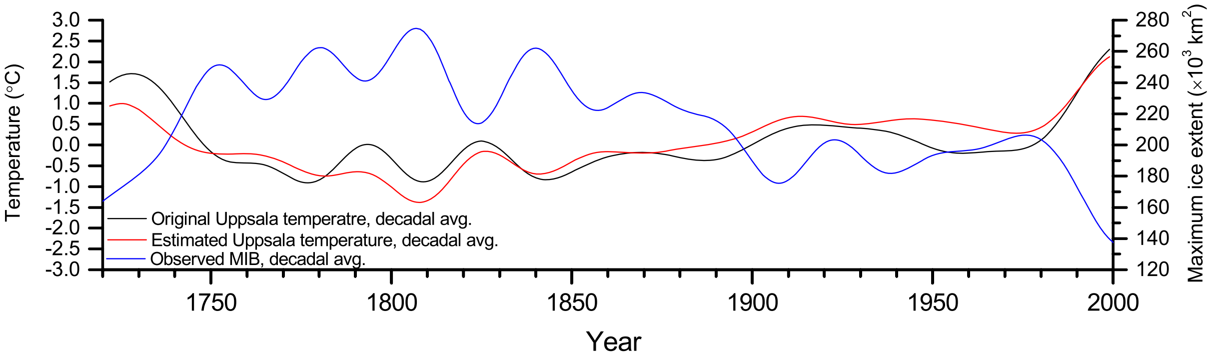


Figure 3.9: *Decadal smoothing has been applied to the measured (red) and re-estimated (black) Uppsala air temperature and to the MIB (blue). In the first half of the eighteenth century, the MIB values indicate low ice extent as the same time as Uppsala has mild winters. Nineteenth century temperatures are generally low and MIB values high, while the twentieth century displays increasing temperatures and decreasing ice extent.*

The conclusion from this exercise is that the incorporation of the Uppsala air temperature record into the PROBE-Baltic forcing data probably elevates the modelled water temperatures and reduces the ice extent modelled in Paper II. The modelled MIB is therefore probably lower than it should be over that period, though it does still reflect the actual mild winter conditions.

3.2.5 Ice thickness

Sea ice may cover a fairly large area even in mild winters, as seen in Figure 3.5. Ice thickness data may therefore reveal large changes in ice volume over time, which cannot be seen from above the ice. For example, Bothnian Bay has been completely ice covered every winter since 1720, and almost certainly since 1500 (Paper II). Even if the air temperature rises in the northern Baltic Sea region, it will not rise above the freezing point (see Figure 3.1) in the foreseeable future. However, increased temperatures, despite being below the freezing point, will reduce ice growth and consequently the ice thickness. A good example can be found by studying long-term changes in ice thickness along the Swedish coast. Östman (1937) and Wallén and Ahlmann (1954) investigated this for the late nineteenth and early twentieth centuries. Figure 3.10 shows ice thickness and the number of days with ice in ports along the coast of Bothnian Bay. Over time, the ice thickness decreased, as did the length of the ice season. This hints that something happened to the large-scale atmospheric circulation, and that milder air masses prevailed more frequently in the north. The changes coincide with the end of the Little Ice Age and the warming that culminated in the 1930s (when increasing temperatures were referred to as “climate improvement”; e.g., Ahlmann, 1948). If ice *extent* in Bothnian Bay were the only factor considered, change would not be detected, since the entire area was ice covered every winter.

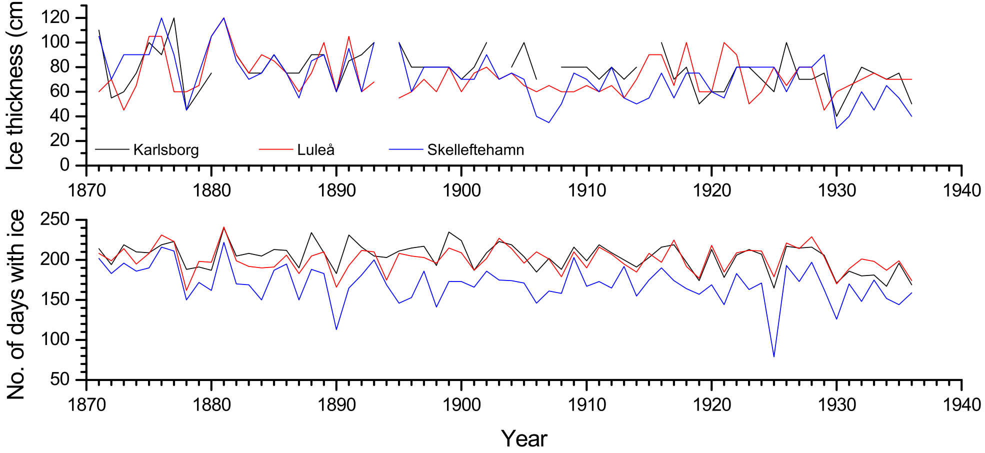


Figure 3.10: *Ice thickness and number of days with ice in three Swedish ports – Karlsborg, Luleå, and Skelleftehamn – all located in Bothnian Bay. A thinner ice cover and shorter ice season are seen between 1871 and 1936. Data from Östman (1937).*

A great advantage of using a model like PROBE-Baltic is that ice thickness can be calculated as well. The model can be used to make a rough estimate of the amount of ice in particular areas and at particular times when ice thickness was pivotal. One such time was the invasion of Denmark in mid-winter 1658, when the Swedish King, Charles X Gustav, and his army crossed the frozen Belt Sea. According to Speerschneider (1915), the Belt Sea seldom froze enough to permit people to walk across the ice: the Belt Sea froze once per decade and could be crossed on foot approximately once every twenty years. Figure 3.11 shows the modelled ice extent and thickness in the winter of 1658 (Paper II). At the time of the first crossing on 30 January, the Belt Sea was 97% ice covered to a thickness of 17 centimetres; during the second crossing on 6 February, the Belt Sea was 96% ice covered to a thickness of 21 centimetres. Was this enough to permit an army of at least 3000 men and horses, together with all their followers, carriages, and cannons, to walk across the ice? Ericson (2008) discussed the contemporary military requirements for travelling across ice. As no contemporary sources have survived, Ericson had to rely on the latest published Swedish military instructions on how cavalry should safely cross ice. In 1956, it was recommended that foot soldiers cross only where the ice is at least five centimetres thick, while soldiers with horses need ice at least ten centimetres thick. Ericson also mentions that Swedish provision carriages were driven across the frozen Kvarken, separating the Bothinan Sea from Bothnian Bay, during winter warfare in 1939 and 1940. For the ice to hold up, a thickness of at least 15 centimetres was required and thickness measurements were made at least every 50 metres. Present-day recommendations call for five-centimetre-thick ice for soldiers weighing up to 100 kilograms, ten centimetres for weights up to 500 kilograms, 14 centimetres for one tonne, and so on. The required spacing is also dependent on weight, five-metre spacing needed between soldiers weighing up to 100 kilograms, ten metres for weights up to 500 kilograms, and 50 metres for units weighing of one tonne or more (Försvarsmakten, 2007). It can only be assumed that soldiers in 1658 applied approximately the same standards as today's armies. The ice thickness calculated by PROBE-Baltic was thick enough to permit an ice march across the Belts on 30 January and 6 February 1658, and the soldiers probably had enough space between them during the crossings. Though most of the soldiers had no problem managing the crossing, the ice did sag beneath their feet and they had to walk with icy cold water up their legs. A few were unlucky, walking where the ice was incapable of sustaining their weight, and fell through (Ericson, 2008). However, as history has shown, the Swedish army managed to cross the Belt Sea and conquer about one third of Danish territory.

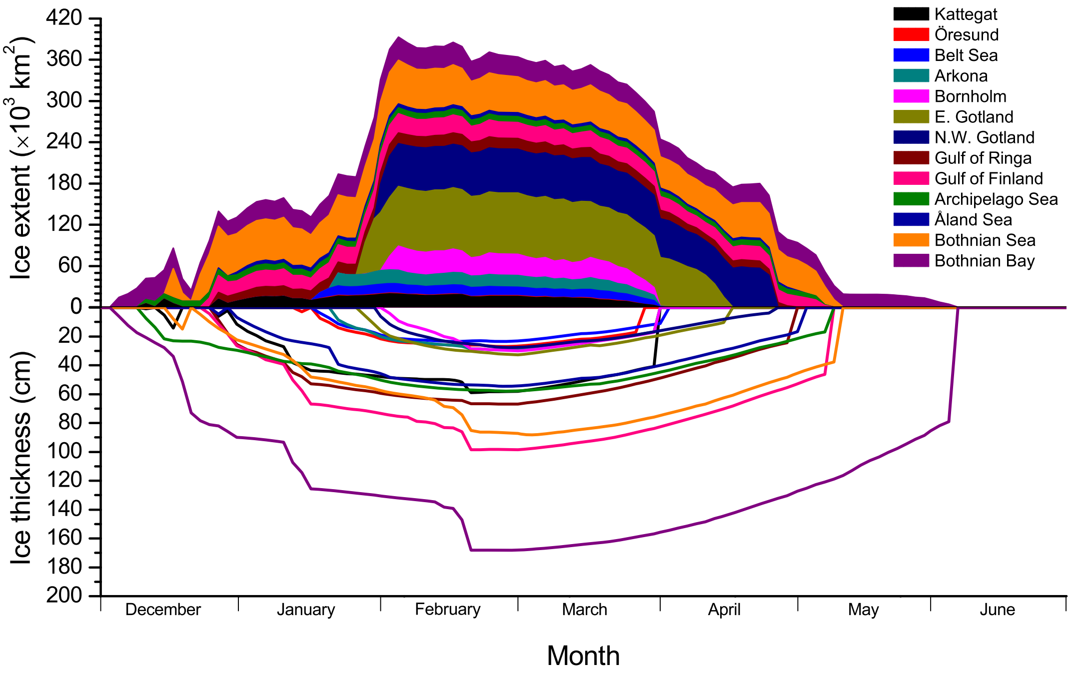


Figure 3.11: *Ice extent (upper panel) and thickness (lower panel) in the winter of 1658. The passage across the Belt Sea took place on 30 January and 6 February, when ice was at least 15–20 centimetres thick.*

3.3 River runoff

The low salinity of the Baltic Sea arises from freshwater added by river runoff and precipitation, and from inflowing saline bottom water and outflowing low-saline surface water through the Danish straits. The amount of runoff is determined by a series of complex processes of precipitation, evaporation, vegetation growth and maintenance, soil moisture, lake overflow dynamics, land use, and anthropogenic water uptake and storage. A change in river runoff is a potent factor that may affect the water balance, and thus the salinity and ecosystems of the sea. Approximately 15,000 m^3s^{-1} of freshwater is added via river runoff, while net precipitation adds another 1500 m^3s^{-1}. The yearly and decadal variability of river runoff is great. According to BACC (2008), the wettest year of the twentieth century was 1924, with mean runoff of 18,167 m^3s^{-1}, while the 1990s was the wettest decade, with mean runoff of 14,582 m^3s^{-1}, excluding Kattegat and the Danish Straits. Similarly, the driest year of the century was 1976, when mean runoff was 10,553 m^3s^{-1}, while the 1970s was the driest decade, when mean runoff was 12,735 m^3s^{-1}. Figure 3.12 shows the monthly river runoff to the Baltic Sea based on observations; this was the forcing used in PROBE-Baltic in Papers I and II for shorter time scale modelling (from 1900 onward).

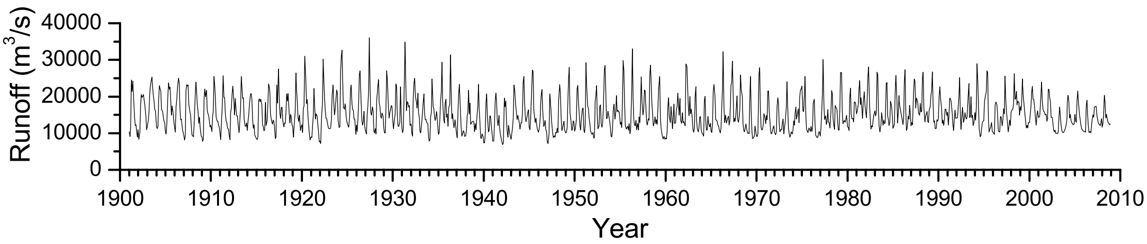


Figure 3.12: *Monthly river runoff to the Baltic Sea between January 1901 and December 2008. From 2005 to 2008 only data from a large-scale hydrological model are available.*

Lindström and Bergström (2004) found an 8% increase in river runoff, albeit not statistically significant, over the twentieth century when analysing the longest available river runoff records in Sweden; a similar increase occurred also in the 1920s. They also found indications that the runoff might have been even higher in the nineteenth century than at present despite cooler temperatures. Changes have also occurred elsewhere in the Baltic Sea region, especially in winter when increased runoff was observed in Finland, Russia, and Estonia (BACC, 2008). Analysing the total river runoff, based on the data in Figure 3.12, one finds no long-term trend in *annual* means since 1901, though large seasonal changes have occurred. Winter and spring runoff have increased significantly, while summer runoff has decreased; autumn runoff, however, displays no trend. It is unclear whether these changes are due to river flow regulation or to climate change; they are most likely a combination of both. An increase in precipitation has been observed in the Baltic Sea region over recent decades, but it is not spatially or temporally uniform. Winter and spring have seen increased precipitation, while summer has seen increased precipitation in the northern Baltic Sea basin and decreased precipitation in the south (BACC, 2008). Meanwhile, the construction of hydroelectric power plants since the 1950s has redistributed some of the seasonal river flow (Graham, 2000). Storing water from peak flows, usually occurring in late spring and early summer when snowmelt has set in, and releasing it again in winter when electricity demand is high, artificially changes the river runoff seasonality, although the annual mean remains the same. This has occurred at the same time as climate change may be changing precipitation patterns. It is therefore difficult to sort out how large a part climate change and hydropower development may be playing in the changes observed in river runoff. In this context it is noteworthy that, while more than 200 rivers discharge into the Baltic Sea, the ten largest account for about half the volume flow (BACC, 2008), and most of these have been exploited for hydropower.

Hydropower development has been debated with respect to the water exchange between the Baltic Sea and North Sea. Matthäus and Schinke (1999) suggested that an artificial change in river runoff seasonality might hinder proper water exchange between the Baltic Sea and Kattegat in winter, when deep water is usually renewed. They found indications that artificially increased river runoff in winter freshens the outflowing surface water, which in turn lowers the salinity of the inflowing water through mixing processes and entrainment with the saltier Kattegat water. This mechanism would restrict the inflow from penetrating to the deepest parts of the Baltic Sea, where frequent water renewal is vital to keeping oxygen at an appropriate level to sustain marine life. A model study by Meier and Kauker (2003) found that regulating river flows had a negligible effect on the Baltic Sea water exchange mechanism.

Long-term changes in river runoff are important, as they affect salinity and deep-water renewal. These were essentially the main focus of Papers III and IV. In Paper III, the runoff to the Baltic Sea since 1500 was reconstructed; this reconstruction was later used in Paper IV as runoff forcing in PROBE-Baltic to permit more realistic modelling of long-term changes in salinity and oxygen conditions.

3.3.1 Reconstructing river runoff since AD 1500

Reconstructing river runoff to the Baltic Sea by means of statistical modelling requires that the model domain be clearly defined. In Paper III, three domains were set up, as meteorological conditions are known to differ between them. Bothnian Bay and the Bothnian Sea constitute the northern model region, which is mostly governed by dry continental air masses. This is also the case for the Gulf of Finland, a subbasin that constitutes its own model domain, as the large lakes Ladoga and Onega modulate river runoff in a complex manner. The remaining subbasins, from the Åland and Archipelago Sea to Kattegat, constitute the southern model region, which is mostly governed by humid North Atlantic air.

As described in Section 2.4 concerning the construction of forcing fields (see Equation 6), a stepwise regression analysis was conducted using the large-scale atmospheric circulation indices developed by Eriksson et al. (2007) as predictors. Derived from the sea level pressure reconstruction of Luterbacher et al. (2002), these indices describe zonal and meridional wind flow, vorticity, divergence/convergence, and normal and shear deformation. In addition, Baltic Sea air temperature is also included as a predictor. This is the same temperature used as forcing in Paper II and derived from the gridded European temperature reconstruction of Luterbacher et al. (2004). Finally, a two-season lag was introduced such that all the predictors, including both temperature and circulation indices, from the two previous seasons could also be considered in the regression analysis. This approach was deemed appropriate, as much of the precipitation that finally arrives in the Baltic Sea as river runoff, does not enter rivers and streams directly due to complex interactions that delay the precipitation-to-runoff response. In the stepwise regression analysis, the predictors are chosen and individually added to the regression equation if they pass an F-test at the 90% significance level. If the F-test fails, the predictor will be rejected and not included in the equation. In that way, this method will only construct statistical relationships when the pre-set significance level is maintained, creating an equation with the most important predictors.

The statistical relationships obtained from the above procedure indicate that Baltic Sea runoff has no uniform response to the large-scale atmospheric circulation pattern. The three basins each have their own distinct atmospheric circulation characteristics, which confirm the need to develop sub-regional models. Runoff from the southern region depends mostly on the rotational and deformation components of atmospheric circulation, while the rotational components and zonal and meridional wind flows are important for runoff in the northern region. In the Gulf of Finland, on the other hand, temperature and wind components are important for describing the runoff. That the rotational component is important is understandable, as it describes the intensity of the cyclonic activity. Intense systems are generally associated with more precipitation than are weaker systems. Autumns are often stormy in the Baltic Sea region, possibly due to high sea surface temperatures feeding the atmosphere with moisture, resulting in unstable conditions and increased precipitation, at least in southern Sweden (Linderson et al., 2004). That the rotational component is not as pronounced for the Gulf of Finland may indicate that lakes Onega and Ladoga reduce this effect. Zonal and meridional wind flows produce different responses in the runoff. Zonal winds bring more humid air from the North Atlantic, increasing the risk of precipitation, while meridional winds tend to advect dry air into the region, thus reducing the risk of precipitation.

The reconstructed total river runoff to the Baltic Sea indicates good reconstructive skill over the calibration (1950 to 1995) and validation (1901 to 1949) periods, and there is no long-term trend over the past 500 years on an annual scale (see Figure 3.13). Dry periods with low runoff occurred in the mid eighteenth and mid twentieth centuries, and runoff was slightly above present levels over most of the past 500 years.

Annual variability on the sub-regional scale differs considerably. Most variability is found in the southern and northern region, and less in the Gulf of Finland. In the last case, this is probably due to modulation by lakes Onega and Ladoga, which dampens the annual variability. In the northern region, most seasons have very distinct characteristics due to the strong influence of continental air masses. Winters are mostly below freezing, and springs and early summers, when spring flooding occurs, are generally well above freezing, generating less interannual variability. In the southern region, on the other hand, one year differs greatly from the next in terms of cyclonic activity and temperature.

Decadal changes are perhaps even more interesting when it comes to climate change. Notably, the response in terms of runoff characteristics of the southern Baltic Sea region is almost opposite to that of the northern region and the Gulf of Finland: wet periods in the north and the Gulf of Finland generally coincide with drier periods in the south. This is most markedly so around the 1720s and 1730s, and in the twentieth century when persistent high runoff occurs in the north and the Gulf of Finland, and runoff in the south is low. Annual variability is also larger in the south region, and wet periods occurred there in the decade centred on 1694 and in the first three decades of the twentieth century. None of the three regions displays any statistically significant trend over the past 500 years.

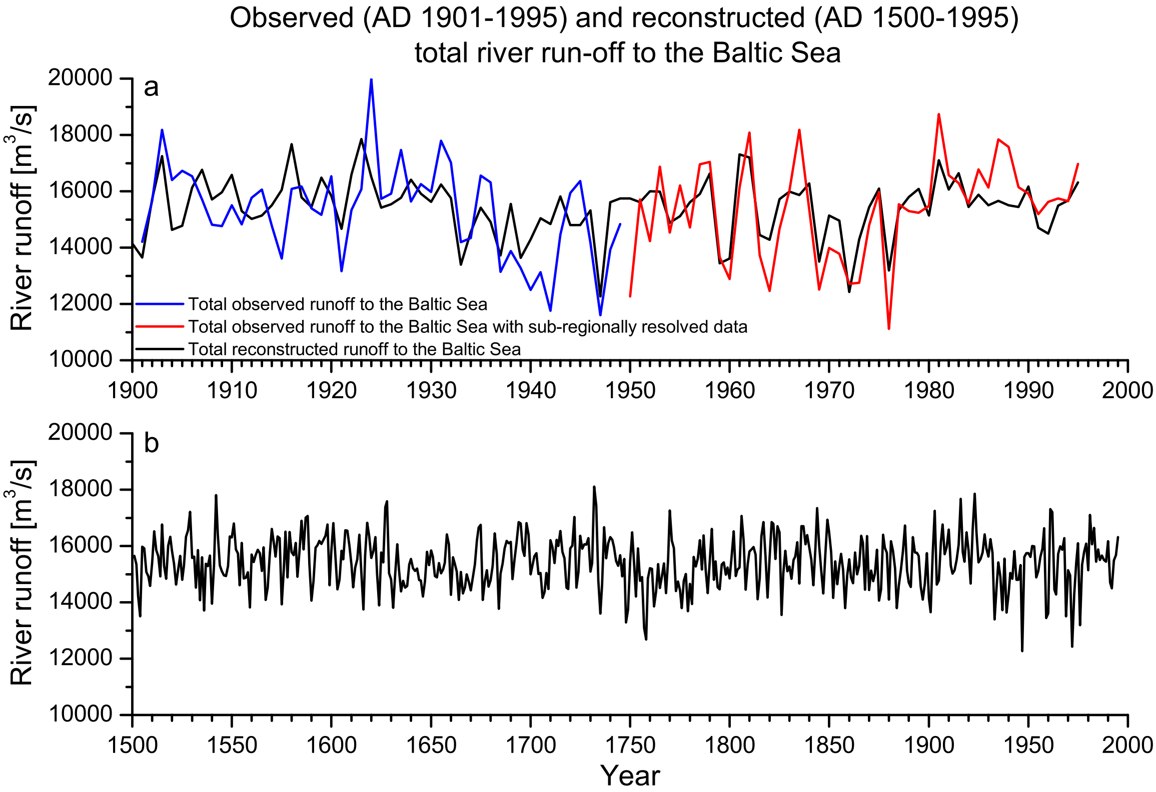


Figure 3.13: a. *Reconstructed (black line) and observed (blue and red lines) annual river runoff over the twentieth century. Data used for the calibration period, 1950–1995 (red line), comprise sub-regionally resolved observations, while data for the validation period, 1901–1949 (blue line), comprise observations of total runoff to the Baltic Sea.* b. *Annual reconstructed river runoff, 1500–1995. From Paper III.*

3.3.2 Validating reconstructed river runoff

Validating the reconstructed runoff series is not as straightforward as validating, for example, ice and temperature, for which good proxy records exist. Observed and reconstructed precipitation records can be used as part of a validation process (e.g., Mitchell et al., 2004; Linderholm and Chen, 2005; Pauling et al., 2006), but runoff and precipitation are not that closely related. Many different mechanisms act on the water on its way from the atmosphere, across land, via rivers, and finally to the Baltic Sea. There is also the possibility of estimating the thickness of annual clay deposits from rivers, i.e., varve thickness, using this as a proxy for maximum river runoff (Sander et al., 2002), but this is not representative of mean annual flow as reconstructed in Paper III. Validating the reconstructed river runoff in Paper III instead made use of a theoretical approach to investigate the long-term retention of variability using multi-resolution analysis (MRA) of the maximum overlap discrete wavelet transform (MODWT). MRA is an additive method that lets us decompose the reconstructed and observed river runoff into several new time series, operating on specific time scales, in which the sum of all series makes up the original one. By using this method on reconstructed and observed river runoff data, localized coefficients are computed for both datasets, allowing comparison of the variability and correlation structure on a scale-by-scale basis (Karlöf et al., 2006). The computed wavelet coefficients are associated with a scale of 2^{j-1} years, where j denotes the jth series of the MRA. A cross-correlation analysis between the series indicates high correlation on all wavelet time scales, confirming that the reconstruction has some reconstructive skill (Paper III). Looking at the bottom panel in Figure 3.14, which shows the original data series, reveals that the reconstruction does not capture all the variability of the observations. This is logical, as the reconstructed river runoff is based only on reconstructed sea level pressure and temperature and completely omits soil and other runoff mechanisms and processes. In addition, climate is not stationary; therefore, the statistical relationships established for the second half of the twentieth century will not have been the same over the previous 500 years. However, given these caveats, one must be very satisfied with the results and the amount of variability captured. The $\tilde{D}_1$ panel (Figure 3.14), which shows annual scale variability, indicates good agreement between the series over most of the twentieth century, except in the 1920s and 1950s when variability is underestimated by the reconstruction. In $\tilde{D}_2$, where a time scale of two years is shown, the reconstruction and observations agree very well. The general features of variability associated with time scales of four and eight years ($\tilde{D}_3$ and $\tilde{D}_4$, respectively) are well captured by the reconstruction, though the amplitude is underestimated on these scales. The top panel, denoted $\tilde{S}_4$, captures all time scales of 16 years or longer. In a sense, one may regard this as long-term variability added to the annual mean river runoff. The approximate contribution on these long time scales is between 15,000 and 15,500 m^3s^{-1}, which is of the same order of magnitude as the long-term mean. Shorter time scales contribute on the order of one twentieth or one thirtieth of that, but it is these scales that modulate the annual amount of river runoff. As the MRA analysis demonstrated, most of the variability of the observed series is captured by the reconstructed series on all time scales.

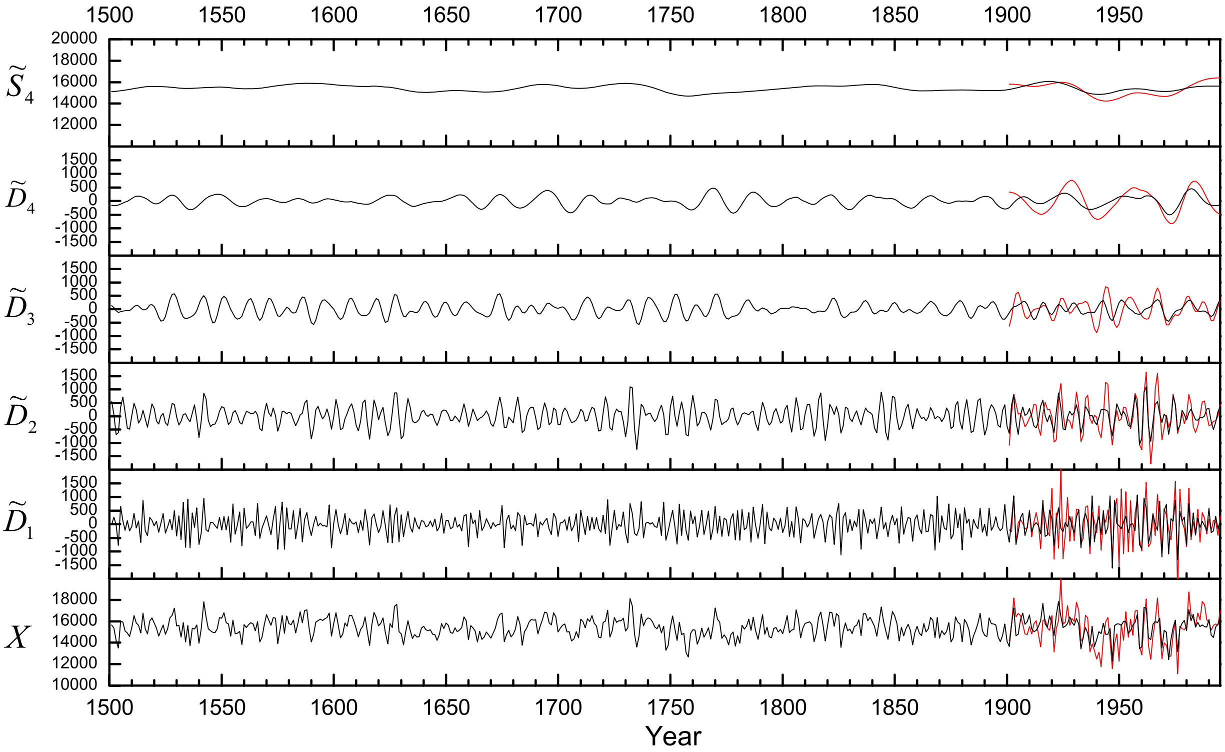


Figure 3.14: *Multiple resolution analysis (MRA) of the reconstructed (black) and observed (red) runoff. The MRA uses a maximal overlap discrete wavelet transform with reflection boundary conditions. The bottom panel shows the original series, while the four middle panels show the* j*th series,* $\tilde{D}_j$*. The* j*th series is based on wavelet coefficients that reflect changes in averages over a scale of* 2^{j-1} *years. The upper panel shows the smoothed series,* $\tilde{S}_4$*, capturing changes on all scales of 16 years or longer. From Paper III.*

3.3.3 Future river runoff and response on salinity levels

Runoff over the past five centuries has been sensitive to changes in temperature. In general, warming of the Baltic Sea region is associated with increased runoff in the northern region and the Gulf of Finland, and a decrease in the southern region (Paper III). This relationship is also likely to hold for future runoff, as state-of-the-art regional climate models find the same behaviour (BACC, 2008). In total, however, runoff has decreased as temperature has risen, as the decrease in the south is dominant (Paper III). Climate models suggest a 3–5°C temperature increase in the Baltic Sea region over the twenty-first century. Using the estimated salinity-runoff response scheme presented in Paper I, we can assume a decrease in runoff on the order of 1500 to 2000 m^3s^{-1}, which would lead to an increase in Baltic Sea salinity of 2–3 PSU. This experiment is not without its limitations and should not be taken as a proper projection of future runoff or salinity levels. Extrapolating and taking only temperature into account when estimating future runoff is not very realistic, since precipitation is dependent not only on temperature, and the estimation ignores many other changes in general circulation over the region. The properties of the established statistical relationships will also change over time, as climate is not stationary. In addition, the experiment ignores all the dynamics, processes, and interactions occurring in the soil, on the ground, in rivers, and involving vegetation. There are also large uncertainties related to the sea level pressure and temperature reconstructions (Luterbacher et al., 2002, 2004) used in formulating the circulation indices used in the river runoff reconstruction. Despite all this, the experiment may tell us something about the future climate, namely, that the future is full of unknowns and is hard to predict. This is also the message of climate model scenarios in which projected runoff ranges from a slight decrease to a substantial increase (e.g., Graham, 2004; BACC, 2008). The wide range of future runoff projections may be due to the uncertainty associated with changes in evapotranspiration. Graham et al. (2009) discusses the matter, arguing that evapotranspiration due to increasing temperatures in regions with high water surface-to-land ratios may significantly affect the runoff.

Given that the potential impact of hydropower development on runoff seasonality was neglected, and that only atmospheric circulation indices were used, ignoring all land, soil, and vegetation processes, it is impressive how well the river runoff over the past 500 years can be reconstructed by the model.

3.4 Salinity and oxygen concentrations in the Baltic Sea

The low salinity of the Baltic Sea is unique, making this part of the world ocean home to a very fragile ecosystem. In the Baltic Sea, both marine and freshwater species share the same habitat. Due to pronounced horizontal and vertical salinity gradients, the number of species decreases toward the interior of the Baltic Sea. Due to the salt stress, individuals of Baltic species tend to be smaller than individuals in surrounding marine areas. A change in salinity is therefore very challenging for the ecosystem, as it causes the expansion or retreat of habitats. As discussed in Paper I, increased (decreased) river runoff leads to a decrease (increase) in Baltic Sea mean salinity, operating on a time scale of about three decades. Closely associated with salinity is available oxygen. Major Baltic inflows usually bring oxygenated, salty water that is dense enough to penetrate to the deepest parts of the Baltic Sea. The deep water is thus ventilated, lifting the old and often hypoxic water upward, replacing it with new, oxygen-rich water. Major inflows have almost been completely absent from the Baltic Sea since the 1970s (Matthäus and Schinke, 1999), leading to a long stagnation period of increasing hypoxia, in some cases even anoxia, covering vast areas of the Baltic Sea bed. One factor contributing to this long stagnation period may have been prevailing high river runoff between the late 1970s and mid 1990s (Stigebrandt and Gustafsson, 2007). Only a few inflow events took place, but these were not large or dense enough to ventilate the water in the deepest parts. The absence of major inflow events, and the anomalous high runoff, gradually weakened the halocline. When windy conditions set in during the winters of the 1990s, the halocline was further weakened and eroded to a greater depth. Consequently, the well-mixed upper layer became thicker, improving the oxygen conditions in a larger water volume. Although the hypoxic conditions continued in the deepest parts of the Baltic Sea, the area of hypoxic seabed was only half that of the past three decades.

3.4.1 Long-term variability of salinity and oxygen concentrations

Large, long-term changes in salinity are manifested on geological time scales. The first saline water inflow occurred as early as the Yoldia Sea phase, approximately 11,000 years ago. Although the Yoldia Sea only lasted a few hundred years, its water became brackish enough to create a strongly stratified water column that temporarily favoured anoxic bottom conditions in some places (BACC, 2008). When the Danish straits opened up and became wider and deeper approximately 8500 years ago, saline water started to pour into the Baltic Sea, making salinity levels higher than at present (Westman et al., 1999; Gustafsson and Westman, 2002), peaking 5000–6000 years ago. Eventually, the salinity level decreased when post-glacial uplift made the straits shallower (Figure 3.15, upper panel). There are, however, opposing views suggesting that the present salinity levels are equal to or higher than those of 5000–6000 years ago (Emeis et al., 2003). On short time scales, when examining daily and monthly measurements from lightships and cruise ship data, long-term variability in salinity can be detected over the twentieth century (Winsor et al., 2001, 2003; Madsen and Højerslev, 2009). Over a few decades, the total salinity of the Baltic Sea varies by up to 1 PSU. As geological processes are negligible over such short time scales, changes in river runoff and precipitation must be the main culprits. For example, the decline in salinity in the 1980s (Figure 3.15, lower panel) is known to be associated with an anomalously wet decade. A similar decrease took place in the 1930s. Due to the large variability on decadal scales, there is no significant long-term trend in salinity levels, neither in the entrance area nor in the Baltic Sea as a whole.

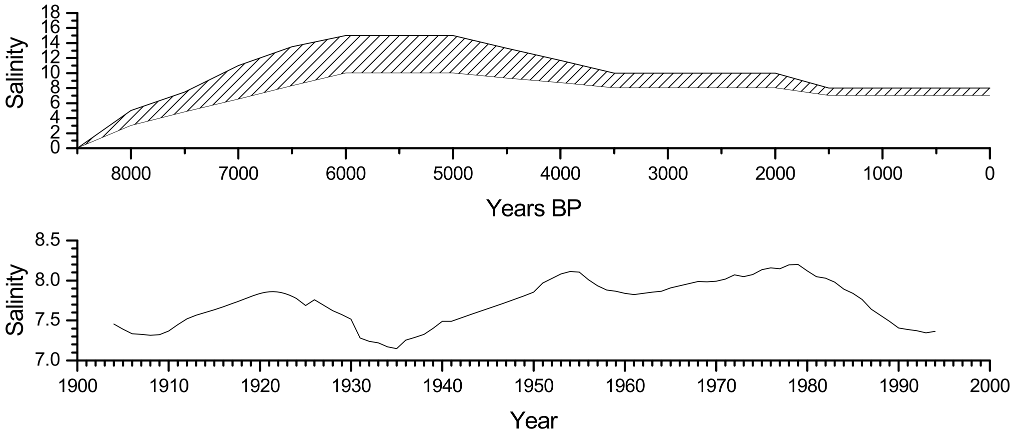


Figure 3.15: *The upper panel shows the long-term variability of estimated salinity in the Baltic Sea on a geological time scale, based on proxy data from Gustafsson and Westman (2002). The shaded area denotes the uncertainty related to these estimates. Note that the* x-*axis reads years before present and not actual years. The lower panel shows estimated total annual salinity of the Baltic Sea over the twentieth century, based on daily lightship and monthly cruise data.*

The deep water of the Baltic Sea often suffers from hypoxic conditions, which are improved when saline oxygenated water is allowed to ventilate the deep water. Hypoxia is lethal to higher aquatic life forms, especially for benthic organisms, which often become trapped and cannot escape to shallower, more oxygenated water. Hypoxia arises when the oxygen consumption rate exceeds the supply rate. The supply comes from deep-water renewal and from mixing. Consumption, on the other hand, depends on the supply of organic matter, which is closely related to the eutrophication of the Baltic Sea. Increased anthropogenic emissions of nutrients (i.e., nitrogen and phosphorous) from untreated waste and agricultural fertilizers reach the Baltic Sea via rivers and increase the nutrient load in the water column. This has created enhanced primary production in the surface layer. When plankton die, they slowly sink to the bottom where they decay in an oxygen-consuming process. If not regularly ventilated, the already low level of oxygen in the deep water then becomes anoxic and hydrogen sulphide (H_2S) is formed, which is toxic and has a distinctive smell of rotten eggs. Dead seabeds are not unique to the Baltic Sea, but appear in coastal waters worldwide, usually in connection with heavy anthropogenic impact (Diaz and Rosenberg, 2008).

Layers of sedimentation in marine sediment cores have proven to be a valuable information source for detecting periods of hypoxic conditions in the Baltic Sea over the past few thousand years, and have been shown to be well correlated with warm climatic periods (Zillén et al., 2008; Conley et al., 2009). During the Holocene Thermal Optimum (approximately 9000 to 5000 years before present) and the Medieval Warm Period (approximately AD 750 to AD 1200) air temperatures were similar to or higher than present temperatures in the Baltic Sea region. Warm climatic periods often involve great advances in the development of civilization. For example, in the Medieval Warm Period, the population of the Baltic Sea region increased and agriculture expanded greatly, resulting in large-scale deforestation and increased nutrient leakage. The warmer climate and increased anthropogenic nutrient load probably worked together to impair oxygen conditions in the Baltic Sea. Improvement occurred over the Little Ice Age, but conditions again deteriorated when the present warm period began and the industrial revolution spread in the Baltic Sea region, resulting in a rapid socioeconomic development, population growth, rapid expanding forestry, and new agricultural technologies. These factors contributed significantly to increased nutrient release and once again caused prolonged hypoxia in the deep water of the Baltic Sea.

3.4.2 Modelling salinity and oxygen over the past 500 years

Managing and securing the Baltic Sea as a resource for future generations entails understanding long-term changes in its salinity and oxygen conditions. Sediment cores may give the "big picture" on longer time scales, but seldom explain the causative mechanisms. Modelling the salinity and oxygen conditions represents the perfect compromise, giving us very high temporally resolved data covering long time scales. This was done using the PROBE-Baltic model in Paper IV, following the implementation of the meteorological data used in Paper II and reconstructed river runoff data from Paper III. The results of Paper IV focus on the Eastern Gotland Basin, the largest subbasin of the Baltic Sea and affected by widespread severe hypoxia. The Eastern Gotland Basin is assumed to be relatively representative of the Baltic Proper, which is the region of the Baltic Sea where hypoxic conditions frequently prevail. The model results are expressed as volume weighted in three depth intervals: a surface layer comprising water from the surface to 60 metres depth, containing 63% of the water volume; an upper deep-water layer, 60–125 metres depth, containing 31% of the volume; and a deeper deep-water layer, 125–250 metres depth, containing the final 6% of the water volume (Gustafsson and Omstedt, 2009).

As shown in Figure 3.16, there has been large variability in salinity in all three layers over the past 500 years. Peaks of high salinity took place in the mid sixteenth century, at the end of the eighteenth century, and in the mid twentieth century. Salinity also decreased in some periods, particularly in the last decades of the seventeenth and twentieth centuries. The late twentieth century is well-known for its protracted stagnant period, but even the late seventeenth century was stagnant for a long time. Although the long-term variability in salinity is about the same in all three layers, shorter-term variability is more pronounced in the two deep-water layers. The salinity in these two layers is heavily influenced by inflow events, bringing new saline water beneath the halocline. The absence of such events leads to a freshening of the deep water more quickly than the surface water. This reduces the stability of the halocline and increases the diffusive fluxes (Stigebrandt and Gustafsson, 2007), mostly over decadal scales. A new inflow of saline water re-establishes a stronger halocline, and more saline deep water. Throughout this process, the surface layer continues to be well mixed.

Results for the first half of the sixteenth century may be uncertain, as initial conditions may affect the model outcome. As discussed in Paper I, the initial conditions influence the results over at least the first 33 years of the model run. Analysing the long-term trend over the whole period, omitting the first 50 years of the model run, reveals a small, but statistically significant, positive trend. The salinity has thus increased slightly, by approximately 0.5 PSU, in the Baltic Sea since 1550. Salinity peaked in the late eighteenth century and in the late 1930s and early

1940s. Salinity has declined slightly since then, which is obvious in both the observed (Figure 3.15, lower panel) and modelled (Figure 3.16) salinity.

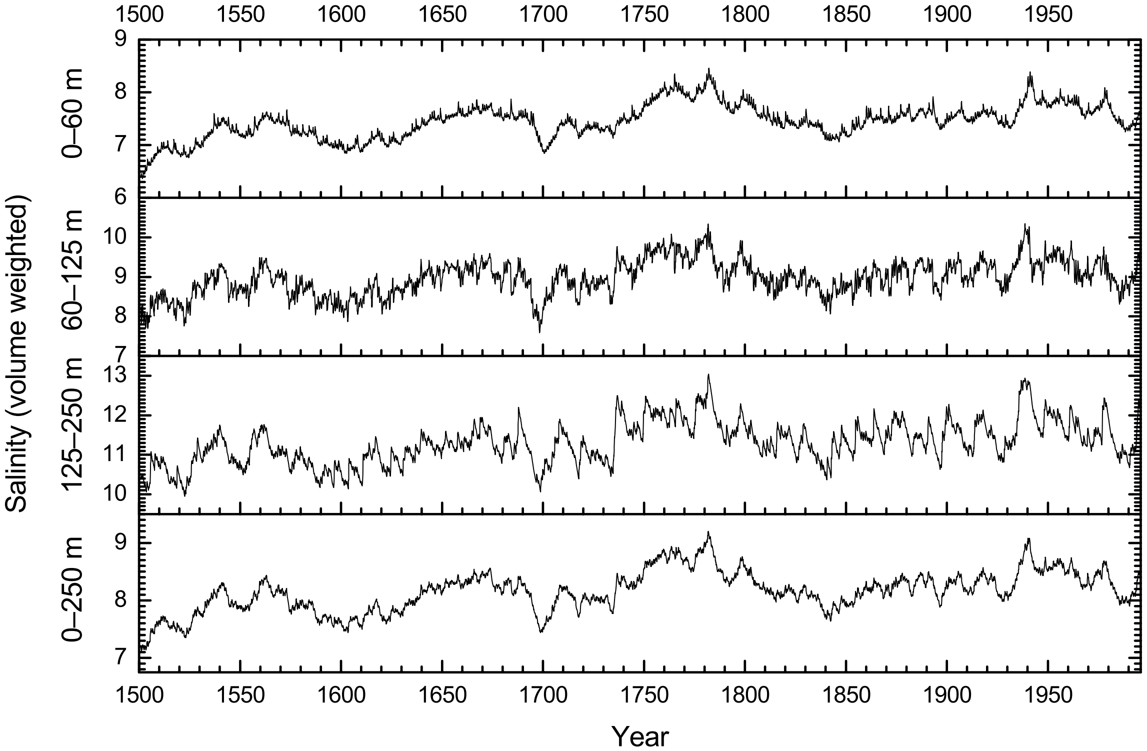


Figure 3.16: *Volume-weighted modelled salinity of the Eastern Gotland Basin. The long-term changes in salinity have been great over the past 500 years. Less variability is found in the surface layer than in the deeper layers. From Paper IV.*

The oxygen modelling in Paper IV builds on the efforts of Gustafsson and Omstedt (2009), who implemented a simplified oxygen module in PROBE-Baltic. Achieving reasonable levels of available oxygen when modelling the Baltic Sea entails some assumptions. First, one can assume that the water entering the Baltic Sea through the Danish straits becomes oxygenated due to the shallowness of the sills. Therefore, any potentially oxygen-consuming processes in Kattegat do not significantly affect the incoming oxygen concentration. Large quantities of Baltic Sea water are entrained with the inflowing water when it enters the Baltic Sea (Stigebrandt and Gustafsson, 2003). The oxygen concentration reaching the Baltic Sea deep water via dense bottom currents is hence determined by the temperature and salinity of the inflowing water, and by the properties of the entrained water.

Second, the added nutrient load over the past century has increased the oxygen consumption rates. In Paper IV it was therefore assumed that the oxygen consumption rate from 1500 to 1949 was half the contemporary one. This assumption was based on vertical flux estimates of organic matter to Baltic Proper deep water in the late 1930s made by Eilola (1998). Added anthropogenic nutrients have increased substantially over the twentieth century (Savchuck et al., 2008), particularly since the 1950s and 1960s when fertilizers came into large-scale use (Andrén et al., 2000). The break point in 1950 for increased oxygen consumption is therefore justified, although the increase was probably not as abrupt, occurring from one year to the next, but built up over a few decades. As we suspect that increased population and large land use changes have affected nutrient loads since medieval times, this division of oxygen consumption rates may not be optimal, but works well enough as a preliminary approximation.

From Figure 3.17 it is very clear that the doubled oxygen consumption rates have had a profound effect on oxygen conditions. The deep water plunges to a chronic state of hypoxia after 1950, with a mean oxygen concentration of only 0.4 mL O_2 L^{-1} versus 4.1 mL O_2 L^{-1} between

1500 and 1949. The upper deep water is also significantly affected, having a mean oxygen level of 6.4 mL O_2 L^{-1} between 1500 and 1949, but of only 4.1 mL O_2 L^{-1} after 1950. On the other hand, the surface layer is not greatly affected by changing oxygen consumption rates, as it is well mixed and oxygenated.

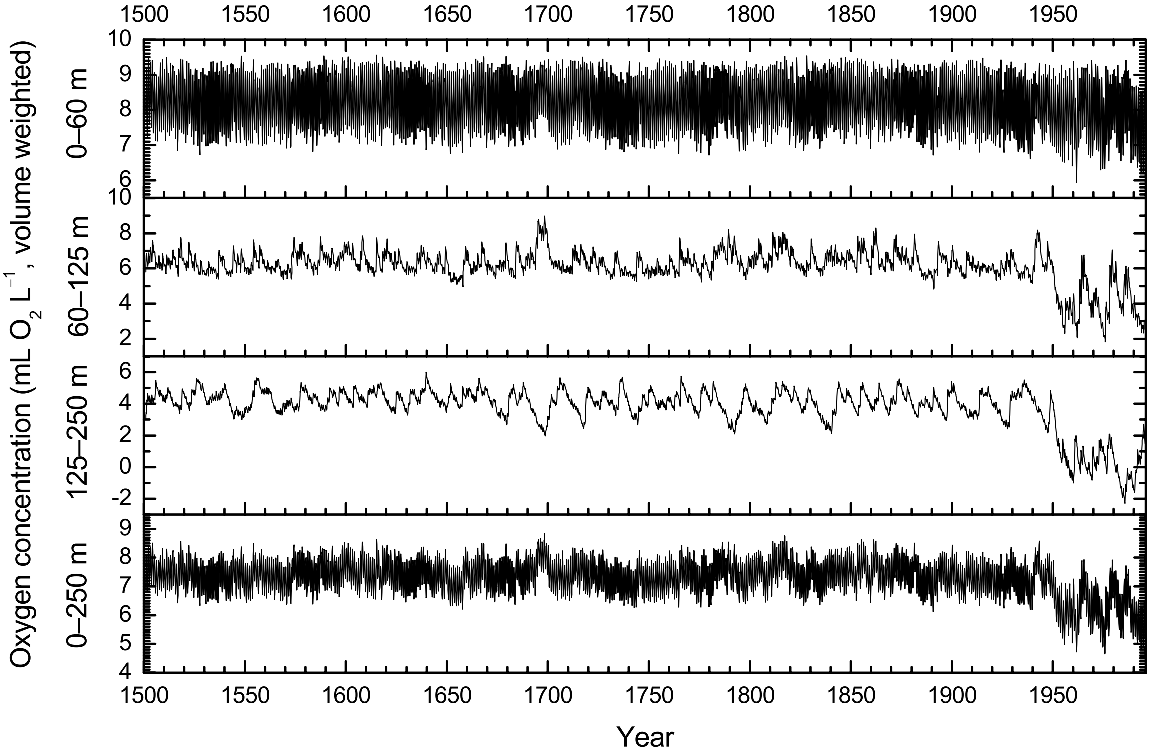


Figure 3.17: *Volume-weighted modelled oxygen of the Eastern Gotland Basin. The upper layer is well oxygenated throughout the past 500 years, but the two deep-water layers are seriously affected by an increase in anthropogenic nutrients after 1950. From Paper IV.*

The mean oxygen concentrations of the deeper deep water decrease by approximately 0.1 mL O_2 L^{-1} per century between 1500 and 1949. Leaving the oxygen consumption rates unchanged at 1950 would indicate that the decrease continues until 1995. This implies that changes in large-scale atmospheric circulation patterns have not, at least not over the second half of the twentieth century, contributed significantly to deteriorating oxygen conditions in the Baltic Sea.

3.4.3 Validating modelled salinity and oxygen concentrations

As with river runoff, there are very few long-term observations of salinity and oxygen conditions usable in validating the modelled oxygen concentrations. Some marine sediment cores reveal historically large-scale salinity variations and oxygen concentrations (Zillén et al., 2008, and references therein); unfortunately, it is seldom possible to obtain annually resolved salinity and oxygen concentrations from them. In addition, when bottom water ventilation takes place and oxygen returns to sustain higher aquatic life, many benthic organisms that mix and homogenize the sediment return. Depending on the sedimentation rate and length of the hypoxic period, such bioturbidity destroys much of the lamination created in anaerobic environments by sedimenting clay particles and dead material.

The Swedish scientist Johan Carl Wilcke made one of the earliest salinity measurements in the Baltic Sea region in the late eighteenth century. He constructed his own water sampler, collected water from various depths, evaporated the water, and weighed the remaining salt. In this way, Wilcke could prove the existence of both horizontal and vertical salinity gradients (Wilcke, 1771). Such measurements are of great historical value, but do not serve as good validation data, as measurements at that time were made extremely infrequently. Since the early twentieth century, cruise ships have been measuring salinity at the BY15 station in central Eastern Gotland Basin. As seen in Figure 2.4, it would take until the late 1950s for regular measuring routines to be established. Therefore, the model results presented in Paper IV are validated against observed data spanning the 1958–1995 period.

Figures 3.18 and 3.19 show the modelled and observed salinity and oxygen, respectively. Both parameters are modelled realistically over the validation period, capturing the large-scale variability. The well-known stagnant conditions of the 1980s are well modelled, appearing as a decline in salinity and oxygen concentrations over the period. There are differences in amplitude and frequency between observed and modelled salinity and oxygen, especially in the case of oxygen, but the long-term variability is captured. Given the very simplified oxygen model, without any plankton module, and the assumption of constant oxygen consumption rates, the results are reasonably close to observations.

The above salinity and oxygen concentration behaviour tells us that stagnant conditions have occurred frequently in the Baltic Sea over the past 500 years, but that the current deep-water hypoxia has severely worsened since the mid twentieth century beyond the levels expected of naturally occurring hypoxia in the Baltic Sea. The cause is most likely the increased use of fertilizers and discharge of untreated waste.

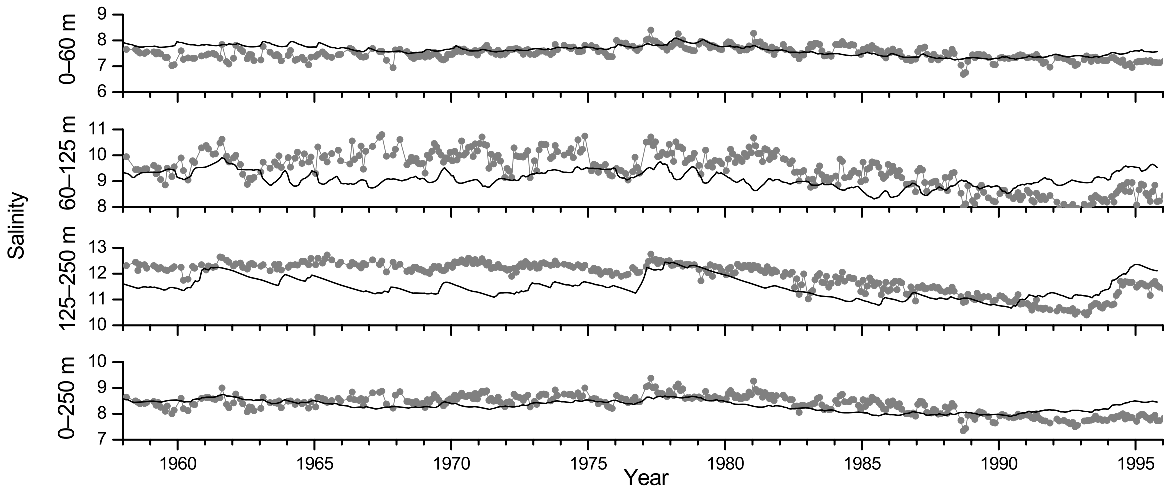


Figure 3.18: *Comparison of modelled (black lines) and observed (grey circles) salinity in the surface, upper deep, and deeper deep water. From Paper IV.*

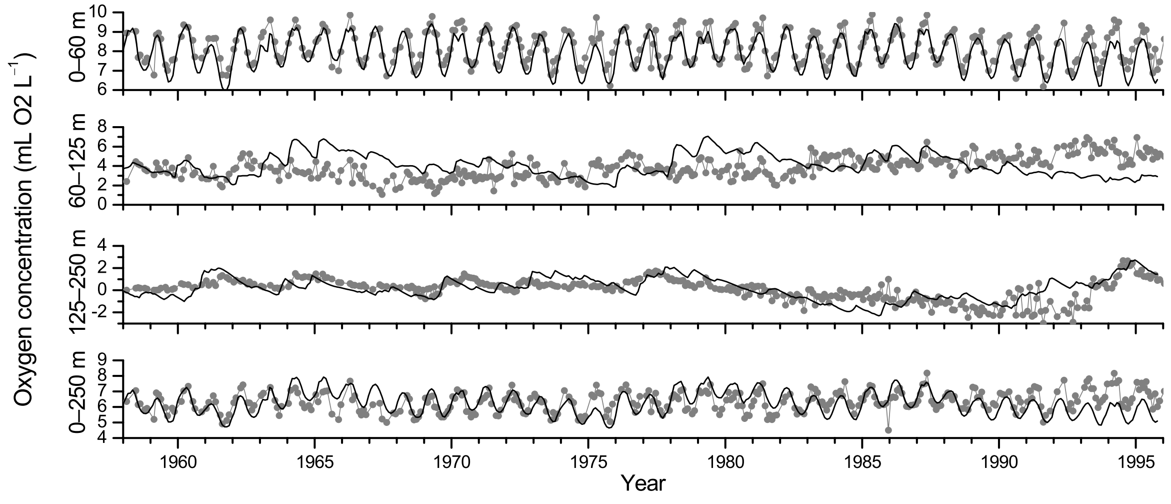


Figure 3.19: *Comparison of modelled (black line) and observed (grey circles) oxygen concentrations in the surface, upper deep, and deeper deep water. From Paper IV.*

4. Future outlook

Canute set his throne by the seashore and commanded the tide to halt and not wet his feet and robes; but the tide failed to stop.
– Henry of Huntingdon

In much of this thesis I have used reconstructed meteorological forcing when modelling the Baltic Sea. It is truly amazing that we can derive considerable new knowledge of integrated properties, such as water temperature, ice conditions, river runoff, salinity, and oxygen concentration, just from these reconstructions. This work is pioneering and demonstrates that modelling is a powerful tool, and that reconstructing past climate variability is important for improving our understanding of our planet as a system. The model used can quite easily be set up for any sea or ocean, permitting quick and efficient investigation. The possibilities are endless. The knowledge gained from this thesis may be used in future model studies aiming to propose future scenarios.

Besides producing new answers, a thesis also always raises new questions and considerations. I have come across several matters I would like to examine further in future research. Most of these concern applying my research to historical conditions, or developing the methods further. There is still a lot to be done, and the ocean climate over the past 500 years in the Baltic, or any other sea area, is still far from being fully understood. Several approaches will be described in this chapter, all of which yield insight into new ideas that can be fully explored using this thesis as starting material. The keyword in all this is interdisciplinarity.

Historical approach. Documentary sources tell a vivid story of life in our region centuries ago. The oldest documentary sources usually consist of sporadic information about the weather, usually weather extremes (e.g., drought, floods, heat waves, severe winters, and storms). Such information is crucial to understanding both climate variability and change. Changes in climate will manifest themselves primarily as changes in extreme events rather than changes in the mean state. As time progress, more and better sources will become available and climate can be reconstructed in finer temporal resolution (seasonal and monthly, and in some cases even better).

The church has long played an important role in people's lives, and many notes on weather and climate can be found in parish registers. Nordahl (2003) made a popular summary of notes from parish registers in Scania on the severe winter of 1740. These notes reveal how agriculture was impacted by severe cold, and provide information about ice conditions. Such data from several locations may help build a detailed picture of how weather in particular years, and climate on longer time scales, affected the public. Speerschneider (1915) collected information regarding sea ice in Danish waters from AD 690 until the early twentieth century. There are almost yearly accounts of ice conditions starting from the seventeenth century. Again, this outlines long-term changes in ice seasons over time. However, he also demonstrated how one must take care when interpreting old sources. A good example from Speerschneider (1915) is that of a chronicler who writes, "the winter began in September and lasted until May. The German rivers were ice covered in October. On 6th to 8th January the cold was intolerable. Birds fell down from the sky, hens dropped their combs, people lost their noses and eyes or died, and the cows' udders froze". Obviously, he experienced the winter of 1740 as very harsh and cold, although he did exaggerate. The winter air temperature in Uppsala in 1740 was in fact near the long-term average of the twentieth century.

Information reflecting ice conditions is often found in historical documents. Information on ice, tolls, port activity, and port administration has been used to estimate ice conditions in the inlet of the port of Stockholm. This method allowed Leijonhufvud et al. (2008, 2009) to reconstruct the late winter and early spring temperature in Stockholm over the past 500 years. Similarly, Glaser and Riemann (2009) were able to combine several documentary sources from Germany and Central Europe, using them to reconstruct the annual air temperature in that region. This reconstruction is crucial for the Baltic Sea as well, due to its proximity to Germany and Central Europe.

Methods like the above could be applied in regions where measurements span only limited periods or are lacking completely. Kattegat and Skagerrak make up a geographical region I believe is particularly suitable for further investigations based on old archived documents. On the eastern shores of this area there has been lively historical development over the past millennium: alliances were forged and dissolved, trading and fisheries were extensive, great areas of land were conquered, and cities were founded. The port of Göteborg played an important role in the Swedish kingdom as its only port on the west coast, surrounded by the archenemies of Denmark in the south and Norway in the north. The port ledgers have survived until today, covering the mid-seventeenth century up to the mid-nineteenth century, but also a few years in the sixteenth century (Lenart Palm, personal communication). These reveal the dates of arriving ships, which may reflect ice conditions in the harbour, as theorized by Leijonhufvud et al. (2008, 2009). Using these sources, the ice conditions and length of ice season for the Göta River could possibly be reconstructed for many of the past 500 years, though I have not investigated the possibility myself. Surely other data exist that can be used as well (e.g., chronicles, city reports, and parish registers). In addition, archives in Norway and Denmark may supply even more information. If it were possible to use all these archives, and patch them together, crucial progress could be made toward understanding winter climate variability on long time scales in the Kattegat and Skagerrak region.

Lilja (2008) conducted an extensive investigation of environmental conditions along the shores of the Baltic Sea since AD 800. Combining archaeological excavations with agrarian history, oceanographic research, and fisheries data gives a detailed description of how the population on the shores of the Baltic Sea made use of the sea, how they lived, and how the environment and climate have changed over time. That provides important insight into what it has been like to live by the Baltic Sea. A future research project would be to make a similar compilation for the Kattegat and Skagerrak region. Maybe it would be possible to investigate and evaluate large-scale environmental, climatological, archaeological, and historical conditions of the past 10,000 years, when the first settlers, of the Hensbacka culture, came (Schmitt et al., 2006). It is also possible to assess long-term climate change by using natural archives (see Brázdil et al., 2005 for a comprehensive review). In the greater Baltic Sea region, tree rings (e.g., Linderholm and Chen, 2005; Grudd, 2008), pollen (e.g., Antonsson and Seppä, 2007), marine sediments (Andrén et al., 2000; Zillén et al., 2008), and a combination of proxies (e.g., Luterbacher et al., 2002, 2004; Holopainen et al., 2009) have been very useful in the quest to reconstruct past climatic and environmental conditions. There is no reason to doubt that similar data sources and methods in combination with historical documents could also be used for a sub-region, such as the Kattegat and Skagerrak region.

Effort put into reconstructing past climate using historical documents and natural archives will benefit studies like those in Papers II through IV, as they will complement and build on ocean climate modelling. More information on river runoff, ice conditions, storms, temperature, and other climatic variability could then be better understood. This is a future research area in which I see great potential, especially with interdisciplinary work focusing on regions lacking long time series of vital environmental, climatological, and anthropological parameters.

Fisheries approach. Closely related to the historical approach is the fisheries approach. One might argue that this approach should be included in the previous category, but it is an important enough factor in Baltic Sea history to be singled out.

Coastal communities in the Baltic Sea region have experienced large changes in their way of life over past centuries. For a long time, fishing was the primary source of income. Cod was an extremely important commodity for the coastal communities of the North and Baltic seas, and its fishery has a history of at least 1500 years. The Norse developed techniques for catching, salting, and drying large quantities of stockfish, which they used as a staple during their long journeys at sea from Norway, Denmark, and England to Iceland, Greenland, and even Vinland in present-day Newfoundland. Northern European fisheries and fish-processing techniques were widely known throughout coastal Europe, and large portions of the catch were sold on the continent (Fagan, 2006). Later, medieval coastal communities of the Baltic Sea developed their own technique for curing herring. Trade in this commodity also achieved wide recognition, and the Hanseatic League eventually took control of the Baltic herring trade. Cod and herring remained key catches in the region for a long time, and still are today. Ship records of fishery activity and fish landings may serve as good documents of coastal development. These may give clues as to when a coastal community was settled or expanded, when it rose to power, and how its people interacted with neighbouring communities and other countries. It is also known that climate change may affect these fisheries, for example, through changed salinities and temperatures. The low-saline conditions of the Baltic Sea cause the eggs of Baltic cod sink to the halocline region before achieving neutral buoyancy, so occurrences of hypoxia in this region may threaten the survival of cod eggs (Wieland and Jarre-Teichmann, 1997). Information regarding cod catch in the Baltic Sea has been collected from the mid sixteenth century to the present (MacKenzie et al., 2007a). In the long run, these records may help us understand when and why cod stocks increased or decreased, and whether this was due to an external factor, the environmental setting, or climatic conditions in the region.

Maps from the 1720s indicate that fish were scarce in the Sannäs Fjord in central Bohuslän, Sweden. At that time, the fishermen had to sail one nautical mile outside the fjord to catch fish. In the twentieth century, the fjord was again teeming with fish and fishing boats, until fish once again disappeared late in the century (Kjell Nordberg, personal communication). History has repeated itself. Why is that? We cannot know for sure, but the current disappearance may be due to the same sort of environmental problem (e.g., hypoxia) the fjord suffered from a few centuries ago. Fish and other catch will move if the required environmental conditions deteriorate, and that is reflected in fishing records. Similarly, the classical Bohuslän herring periods, which were extremely important for the growth of the coastal communities of western Sweden, may have resulted from unusually strong negative NAO phases and persistent easterly winds in autumn (Corten, 1999). Such information is valuable and can also be used to reconstruct past climate variability and environmental settings.

As the climate has changed, attention has been paid to what the future of commercial fishing holds. A newly published paper by Cheung et al. (2009) reports that climate change will alter marine biodiversity. In some regions, this will have a negative impact on fisheries, while in others the effect will be positive, either due to the strengthening of current catch species or the invasion of new ones. For the Baltic Sea it basically comes down to what will happen to the salinity. Decreasing salinity will affect the marine species, forcing them to retreat toward the North Sea, and few new species will be able to establish permanent residence in the Baltic Sea. The fishing fleet will therefore either have to find new fishing grounds closer to the inlet, or target freshwater fish species instead (e.g., MacKenzie et al., 2007b). On the other hand, as pointed out in Paper III, the uncertainty related to river runoff during a warming period is great and the salinity response unknown. I would therefore argue that more research be directed toward this problem, in combination with more intense investigation of past changes in Baltic Sea fish communities and ecosystems.

Data from such sources may supply considerable information about long-term climate change and environmental problems, and yield great insight into the development of coastal communities and how they managed to adapt to these changing conditions. This would also serve as a good basis for interdisciplinary study of how coastal communities shifted from fishing as their main industry to the more contemporary tourism industry, and what role these communities may play in the future.

Modelling approach. As demonstrated throughout this thesis, modelling is a great complement to reconstructive work. It can focus our attention on understanding the mechanisms underlying extremes or long-term changes, and also supply missing values in reconstructions where sources are lacking. Modelling can also be used to validate a reconstruction, and vice versa. In future research, reconstructions can help improve modelling efforts by further improving the forcing fields, for example, by infusion into existing gridded reconstructions (e.g., Luterbacher et al., 2002, 2004). This would increase the certainty and confidence of the model results over the earliest centuries, for which data availability has been low for the Baltic Sea region. It is hoped that including reconstructions will let us model even further back in time.

A more independent modelling project would be to couple ocean climate models with global or regional circulation models. These already exist mainly for 3D models, but with ocean parts that are rarely well resolved. A similar solution for process-oriented models, such as PROBE-Baltic, would be very useful. Not only would it save a lot of time, but it would also produce realistic results specifically for the Baltic Sea system. This would be useful when computing future Baltic Sea scenarios, in particular when investigating changes in the Baltic Sea heat content.

Figure 3.11 shows the ice thickness and extent in different subbasins of the Baltic Sea for the winter of 1658. Investigating changes in the ice volumes using modelling is another field of research in which I see great potential. Measurements of ice thickness are limited to the coastal areas, and lacking in the open sea. Using a model like PROBE-Baltic would give a good estimate of the amount of ice throughout the Baltic Sea. By calculating the annual maximum volume, changes in the ice regime could be detected and attributed to climate change or other factors.

Hypoxia of the Baltic Sea over the past five centuries was investigated in Paper IV; a good way forward would be to improve the oxygen model used in that paper. There remain many sediment mechanisms to be explored and a plankton module has yet to be implemented. Though the assumption of constant oxygen consumption rates may serve us well when using a simplified model, to achieve even more realistic results, these consumption rates must be investigated and reconstructed. I suspect that the oxygen consumption rates were affected as early as AD 1500, and that the early twentieth century rates experienced a slower transition than the abrupt change used in Paper IV. The modelling of oxygen concentrations in the Baltic Sea would probably improve if these issues were resolved.

If the oxygen model of the Baltic Sea were improved, then it could be used in combination with marine sediment data. As demonstrated in Paper IV, many of the stagnant periods over the past 500 years have been very short. By helping to date stagnant periods and detect stagnant conditions whose laminae have been disrupted by bioturbation, modelling may fulfil an important function and work constructively with marine sediment data. This would open up new possibilities to reconstruct salinity variability and oxygen concentrations in the Baltic Sea over long time scales.

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As a simple novice, I started out on an adventurous quest in pursuit of knowledge. Finally, I have reached the end of that road, only to discover a crossroad offering almost endless opportunities to venture on. I would not have come this far without the time, effort, and patience invested in my journey by my supervisor Anders Omstedt. His guidance throughout these five years of study has meant everything in times of both adversity and progress. No matter what, he always managed to turn setbacks into possibilities, and kept despair and gloominess at bay by spreading cheerfulness and laughter. It has been a delight to cooperate with you, thanks to your deep commitment to the project and encouragement that I should find my own way. I really thank you for the years of support, and truly hope that we will continue to combine forces in the future.

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