Baltic Sea Environment Proceedings No. 137

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Published by:

Helsinki Commission
Katajanokanlaituri 6 B
FI-00160 Helsinki
Finland
http://www.helcom.fi

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The report is a result of collaboration between HELCOM and the BALTEX community. From the BALTEX community, Marcus Reckermann, Hans von Storch and Anders Omstedt are acknowledged for their dedicated work for this report.

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For bibliographic purposes this document should be cited as:
HELCOM, 2013
Climate change in the Baltic Sea Area: HELCOM thematic assessment in 2013. Balt. Sea Environ. Proc. No. 137.

Design and layout: Leena Närhi, Bitdesign, Vantaa, Finland

Photo credits:
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Page 53, Martin Karlsson / SLU Aqua. Page 55, Metsähallitus NHS / Essi Keskinen.
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Number of pages: 66
Printed by: Erweko Oy, Finland
ISSN 0357 - 2994

Executive Summary

This report is based on the Baltic Assessment of Climate Change II (BACC II) and provides an update to the Climate Change in the Baltic Sea Area: HELCOM Thematic Assessment in 2007. Both reports are a result of close collaboration between HELCOM and BALTEX, the Baltic Sea Experiment.

This assessment provides recent information on past and projected future climate change in the Baltic Sea Area and potential impacts of climate change on the Baltic Sea ecosystem. As used here, "climate change" is a neutral term because changes in the climate may result from internal dynamics, natural external factors, or anthropogenic pressures.

Surface air temperatures have overall shown a significant increase in the Baltic Sea region over the past 140 years. Since 1871, the annual mean temperature trends show an increase of 0.11 °C per decade north of 60°N and 0.08 °C south of 60°N, while the trend of the global mean temperature was about 0.05 °C per decade for the period 1861 to 2000. The daily temperature cycle is also changing and there has been an increase in temperature extremes. These changes are resulting in changes in the seasons: the length of the growing season has increased, whereas the length of the cold season has decreased.

Model simulations of a potential future climate project an increase in temperatures in the Baltic Sea area over time and the increase will generally continue to be larger than the corresponding increase in global mean temperature. The largest warming was projected for the north in winter. The increase in winter daily mean temperatures will be most pronounced in the coldest periods, while warm extremes in summer are also expected to become more pronounced than at present.

Surface waters in the Baltic Sea have warmed in all seasons since 1985. The annual mean sea-surface temperature has been estimated to have increased by up to 1 °C/decade from 1990 to 2008, with the greatest increase in the northern Bothnian Bay and with large increases also in the Gulf of Finland, the Gulf of Riga, and the northern Baltic Proper. In the northern areas, the recent decrease in the extent and duration of sea-ice cover has strongly influenced the seawater temperatures, although these changes appear to be within the range of variability during the past 500 years.

There has been a significant decreasing trend in the annual maximum ice extent of the Baltic Sea, amounting to a decrease of 20% over the past 100 years. There has also been a large change in the length of the ice season during the past century. In the Bothnian Bay, which has the longest ice season, the trend is –18 days/century. In the eastern Gulf of Finland, where ice also forms every winter, the length of the ice season decreased by 41 days over the past century, while in the past 50 years the rate decreased by 62 days/century.

In a future climate, the largest changes in sea-surface temperature are projected to occur in the Bothnian Bay and Bothnian Sea during summer and in the Gulf of Finland in the spring. The summer sea-surface temperature increase is likely to be about 2 °C in the southern parts of the Baltic Sea and about 4 °C in the northern parts near the end of this century. The surface water layer is projected to warm more than the deep water in all sub-basins of the Baltic Sea. New scenario simulations indicate that there will also be a drastic decrease in the sea-ice cover in the Baltic Sea in the future.

The amount of precipitation in the Baltic Sea area during the past century has varied between regions and seasons, with both increasing and decreasing precipitation. A tendency of increasing precipitation in winter and spring has been detected during the second half of the 20th century. However, patterns for single seasons were rather different. Precipitation influences river runoff. Analyses of river runoff over the past century have shown that there has been a decrease in annual discharges from southern catchments of the Baltic Sea indicating that the southern regions of the Baltic Sea Basin may become drier with rising air temperatures. In contrast, trends in the north and around the Gulf of Finland indicate increased annual stream flows under warmer temperatures.

Model projections indicate that precipitation will increase in the entire Baltic Sea runoff region during winter, while in the summer increases in precipitation are mainly projected only for the northern half of the basin. In a future warmer climate, extremes of precipitation are projected to increase, implying a greater risk of urban flooding, among other impacts.

Generally the volume of snow in the region will decrease in the future, with the southern half of the Baltic catchment area projected to experience significant reductions in the amount of snow. The annual cycle of river runoff will tend to change considerably. The late spring maximum observed under the present climate could shift earlier, possibly even into February or January. This results from the increasing temperatures and an earlier onset of the melt season as well as from changes in the annual cycle of precipitation and increased evaporation. The melting season floods in the future will generally occur earlier and be smaller.

There is considerable uncertainty in projections of sea-level rise over the 21st century, and disagreement over the level of confidence assigned to different modeling approaches. An assessment of process models and uncertainties yielded mid-range and high-end scenarios which project 0.6 m and 1.1 m sea-level rise, respectively, for the Baltic Sea over the 21st century. This local sea level rise is partly compensated by vertical land movement which varies between 0 m/century in Denmark and 0.8 m/century in the Bay of Bothnia.

A decrease in sea-surface salinity may be largest in the region of the Danish straits, especially in the Belt Sea, and small in the northern and eastern Baltic, with the smallest change in the Bothnian Bay. In more weakly stratified basins, such as the Gulf of Finland and the Bothnian Bay, larger differences in salinity changes in the surface and bottom layers are projected, causing a reduction in the vertical stability.

Rising concentrations of anthropogenic CO_2 in the atmosphere cause enhanced dissolution of CO_2 and decrease the pH in seawater. The large-scale distribution of total CO_2 in the Baltic Sea is widely controlled by the alkalinity, which arises from limestone dissolution in the catchment area and arrives in riverine discharges to the Gulf of Finland and the eastern Gotland Sea. The increase in alkalinity in the central parts of the Baltic Sea over the past 60 years has resulted in the decrease in pH, i.e., acidification, owing to enhanced dissolved CO_2 concentrations being slightly less than expected. Increased biological production associated with eutrophication may also dampen the acidification effect of atmospheric CO_2.

The impact that future changes in climate and other anthropogenic drivers together will have on the biogeochemical cycles of the Baltic Sea is unclear. Changes in precipitation and runoff patterns will influence the inputs of nutrients to the Baltic Sea. Future warming is expected to increase hypoxia given that temperature controls the stratification of the water column, the respiration of organisms, and the solubility of oxygen. However, the effects of climate change on stratification and vertical ventilation of the water column remain unclear. Increasing areas of hypoxia and anoxia are anticipated owing to the increased nutrient inputs due to increased runoff, the reduced oxygen flux from the atmosphere due to higher temperatures, and the intensified biogeochemical cycling including mineralization of organic matter. These projected changes in biogeochemical fluxes indicate that, even if nutrient loads are reduced according to the Baltic Sea Action Plan, it will only stabilize the Baltic ecosystem close to its present state.

In addition to the climate-related changes, human-induced pressures including overfishing and eutrophication may erode the resilience of the ecosystem, making it more vulnerable to changes in the climate.

A temperature increase is expected to result in a change in the species composition and length of the spring phytoplankton bloom season. Changes in the composition of the spring bloom community will also influence the benthos. The projected changes in temperature and particularly salinity are likely to influence the zooplankton community composition, with potential negative consequences for the food conditions and growth of the main plankton-eating fish, Baltic herring and sprat. Climate change may also differentially influence the seasonal succession of both phytoplankton and zooplankton and potentially increase the temporal mismatch between these groups in the spring.
A potential climate-induced decrease in salinity would also have a negative influence on cod, the main fish-eating fish in the Baltic. It is clear that cod stocks are influenced by climate and that cod stocks influence their prey, sprat and herring, which in turn probably also influence zooplankton stocks. A projected continued decrease in salinity in the future will have a major effect on the distribution of benthic species, with a continued retreat of marine species towards the south. The projected

Over the past two centuries, human activities have had an increasing influence in the Baltic Sea area and its environment. Photo: Metsähallitus NHS / Jan Ekebom.

salinity decline will result in geographical shifts in the distribution of species in both deep-water and shallow-water communities. However, it must be emphasized that there is currently no scientific consensus on the impact of climate change on future river runoff and future salinity in the Baltic Sea.

Oxygen deficiency is the single most important environmental factor causing habitat loss and reducing the biodiversity of benthic invertebrates. Model simulations of scenarios concerning the future biogeochemistry of the Baltic Sea have estimated that, taking into account climate change, the implementation of the Baltic Sea Action Plan will result in a slight decrease in the area covered with hypoxic and anoxic waters. In contrast, the 'business-as-usual' nutrient input scenario yielded an increase of the anoxic area by more than a factor of two, while a moderate increase of about 30% was obtained for the hypoxic area.

In the littoral zone, the potential decrease in salinity may affect key species such as seagrasses. Some species such as the eelgrass *Zostera marina* may disappear from areas such as the Gulf of Finland that could have a lower future salinity. By affecting habitat-forming species, climate-induced changes in hydrography will also influence their associated flora and fauna. A potential climate-change induced decline in salinity is also expected to decrease the growth rate and shift the northern limits of the blue mussel community further to the south, with potential effects on associated flora and fauna. Nonetheless, some aspects of climate change may have positive effects on littoral vegetation. Milder winters with less coastal sea ice will reduce the scraping of ice in the uppermost part of the algal belt that removes key species.

In addition to the information on past and projected future climate change in the Baltic Sea Area, this report also provides proposals to the HELCOM decision-makers for actions related to counteracting climate change impacts in the Baltic Sea. These proposals are based on the Conclusions of the HELCOM Workshop on Baltic Sea region climate change and its implications held on 5–6 February 2013 in Warnemünde, Germany.

This assessment of Climate Change in the Baltic Sea Area: HELCOM Thematic Assessment in 2013 will serve as background material for the HELCOM 2013 Ministerial Meeting.

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Foreword

This report is based on the Baltic Assessment of Climate Change II (BACC II) report, which contains more detailed explanations and all references associated with the statements contained in this brief reflection of the full report. The few references included in this report relate to the diagrams or to very specific studies.

The report provides an update to the Climate Change in the Baltic Sea Area: HELCOM Thematic Assessment in 2007 report published by HELCOM (HELCOM, 2007) on the basis of the first BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC) report (BACC Author Team, 2008). Both reports are a result of close collaboration between HELCOM and BALTEX, the Baltic Sea Experiment.

Regarding the current level of knowledge on climate change in the Baltic Sea region, the scientific efforts undertaken to understand past changes in the climate of the Baltic Sea region have progressed especially in the past two decades. Future changes and effects of change have also been intensively addressed recently. Increasing effort is being expended to detect changes that go beyond natural variability, although the attribution to causes is still in its infancy. The current levels of knowledge and understanding are rather good with regard to the physical aspects of climate change, and scenarios of regional change are routinely constructed. The largest shortcomings in scientific understanding are in relation to biological and ecological effects and socio-economic impacts resulting from climate change. Furthermore, the Baltic marine ecosystem responds to the combined influence of all pressures that impact it, and thus it is a challenge to discriminate between the impacts that result from the various human pressures and those that arise as a result of climate change. In many cases this may not be possible.

HELCOM is the organization for cooperation and coordination related to the actions and activities of its Contracting Parties to ensure the protection of the marine environment of the Baltic Sea. Adaptation to climate change is a central question for HELCOM. From HELCOM's perspective, adaptation means adjustment and development of the necessary new measures to protect the Baltic Sea marine environment so as to allow for reaching the vision of a healthy Baltic Sea even in a changing climate.

In 2007 and 2010, HELCOM ministerial meetings noted that climate change will have impacts and this should ultimately be reflected in HELCOM policies. In the 2007 Baltic Sea Action Plan, the text reads: "We are… fully aware that climate change will have a significant impact on the Baltic Sea ecosystem requiring even ***more stringent actions*** in the future", while the 2010 HELCOM Moscow Ministerial Meeting Declaration reads: "We agree… on the need for ***supplementary actions*** and admit that climate change may have profound consequences both for the environmental status of the Baltic Sea as well as for the scope of the measures adopted by the Contracting Parties until now." Specifying these more stringent and supplementary actions requires a basis of scientific knowledge.

Uncertainty is an inherent part of climate scenarios. Uncertainty increases when scaling up from greenhouse gas emissions to projecting global and regional warming and ultimately to presenting scenarios on ecosystem changes in the Baltic Sea. Variability and uncertainty in climate projections are greater for smaller geographical scales and hence the simulations for the Baltic Sea region have poorer certainty than those for the global level. In particular, the impacts of climate change on river runoff, salinity as well as stratification and vertical ventilation of the water column remain contested due to large uncertainties in the models and will require more research in the near future.

This assessment report presents up-to-date information on the past and projected future climate change in the Baltic Sea Area and impacts of climate change on the Baltic Sea ecosystem. In Chapter 7, the report also provides proposals to the HELCOM decision makers for actions related to counteracting climate change impacts in the Baltic Sea. The report is mainly based on the Second BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC II). Chapter 7 is based on the Conclusions of the HELCOM Workshop on Baltic Sea region climate change and its implications held on 5-6 February 2013, Warnemünde, Germany.

Unless a region of the Baltic Sea is mentioned specifically below, this report covers general conditions in the Baltic Sea area; however, there are great differences in climate and environmental conditions from north to south and east to west in the Baltic Sea Basin. More detailed information on the individual regions can be found in the BACC II report together with references to the literature that has been used in the report.

1 Introduction

Climate change in the Baltic Sea Area: HELCOM thematic assessment in 2013

The Baltic Sea is a young sea in a region that has experienced large natural variations in conditions since the melting of the glaciers that covered this area ended about 10,000 years ago. During this historical period, long-term natural changes in the climate have occurred owing to changes in the orbital configuration of the Earth that influence the amount of the sun's energy that is received on Earth. The climate of the Baltic Sea Basin has also been affected by increases in atmospheric particles caused by volcanic activity, changes in the reflection of sunlight from the sea and surrounding land, and natural changes in the concentrations of greenhouse gases in the atmosphere. However, over about the past two centuries, human activities have had an increasing influence on the Baltic Sea area and its environment, with a growing population and an intensification of agricultural and industrial activities. The Baltic Sea area is also influenced by wider regional and global conditions, including the increasing global emissions of greenhouse gases, mainly carbon dioxide and methane, which are impacting the global climate. Owing to natural variability and the complexity of environmental processes, it is difficult to separate natural changes in climate from those related to human pressures; it is even more difficult to project future climate change based on models that cannot completely describe natural conditions and processes and their variability or predict how they will develop in the future and scenarios of the development of future human activities that result in emissions of greenhouse gases.

Building on the 2007 HELCOM Thematic Assessment of Climate Change in the Baltic Sea Area, this report provides an overview of some of the new knowledge and understanding that have developed during the past five years, based on the second BALTEX Assessment of Climate Change for the Baltic Sea Area, as well as some proposals for mitigation measures based on the HELCOM workshop in February 2013. However, while our understanding of recent and ongoing environmental conditions and processes is improving, projections of future conditions remain uncertain. As in the 2007 report, the term "climate change" does not refer only to anthropogenic climate change, but is a broader term, including changes due to internal dynamics and natural external factors, as well as anthropogenic pressures. This HELCOM assessment summarizes the changes observed thus far but does not attempt to attribute their causes.

Wider regional and global conditions, including the increasing global emissions of greenhouse gases, impact the global climate hence also influence the Baltic Sea. Photo: Metsähallitus NHS / Lari Järvinen.

2 The Baltic Sea Climate: A Historical Perspective

The Baltic Sea is a young sea. It was formed after the glaciers that covered this area for over 100,000 years began to recede about 18,000 years ago mainly as a result of changes in the orbital configuration of the Earth around the sun. In the Baltic Sea area, this Last Ice Age ended about 11,000 calendar years Before Present (cal yr BP), which was followed by a warmer period, the Holocene. During the Holocene, the Baltic Sea Basin underwent many different phases owing to the gradual melting of the Fennoscandian ice sheet, which caused a rise in sea level, and the slow isostatic uplift of the land readjusting to the disappearance of the heavy ice sheet, thus decreasing the relative sea level. The interplay between these two processes led to a series of transitions of the Baltic Sea Basin, varying between a freshwater lake, during periods of isolation from the North Sea, and a brackish sea, when water mass exchange with the saline North Sea occurred.

Regional and global climatic factors also exerted strong influences on this area during the Holocene. The melting of the ice sheets in North America had an influence on oceanic circulation, and it is believed that large volumes of cold water from the melting ice sheets entering the North Atlantic Ocean exerted an abrupt cooling around 8200 years ago that lasted several centuries in the Baltic Sea area (Figure 1). Changes in the orbital configuration of the Earth also modulated the incoming solar insolation (solar radiation energy received on Earth) of the boreal high latitudes and thus strongly influenced the energy balance of the Baltic Sea area. The summer solar insolation peaked at around 10,000 years ago and subsequently decreased. After the melting of the remnants of the Fennoscandian ice sheet, a relatively stable period occurred around 7,000 years ago, with summer temperatures of 1 to 2 °C higher than at present (Figure 1). Its effects were shown in proxy records such as fossil insects and pollen, fossils of which show an extended vegetation cover at that time. Thereafter, continued decreased summer solar insolation resulted in a more unstable climate and a progressive millennial cooling.

Other external and internal factors influencing the climate of the Baltic Sea Basin during the Holocene include variations in the concentrations of stratospheric aerosols caused by volcanic activity, changes in the concentrations of greenhouse gases in the atmosphere due to natural factors, changes in the surface albedo (reflection of sunlight) of the sea and changes in the vegetation on the surrounding land, and salinity-induced changes in the intensity and type of circulation in the sea.

The modern configuration of the Baltic Sea was established around 4500 years ago. The climate during the past 4500 years has been characterized by increased instability in the entire Baltic Sea

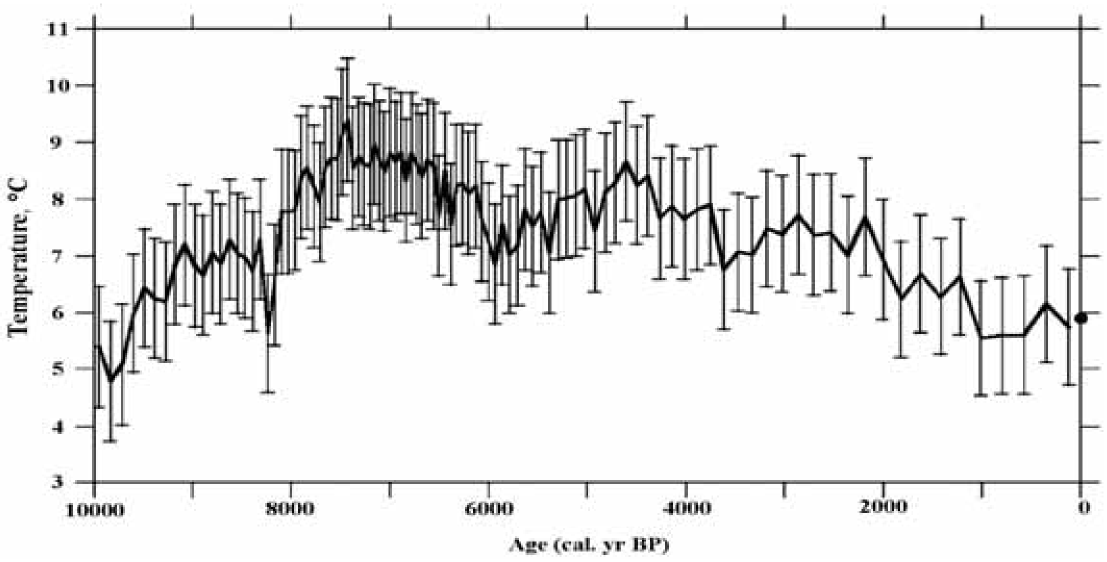


Figure 1. **Mean annual temperature reconstructed from pollen data of Lake Flarken (south-central Sweden) during the past 10,000 years (black line) (Seppä et al., 2005). Present-day annual temperature (5.9 °C) is marked by the point.**

Basin, with alternating warm and cold periods superimposed on a general cooling trend. The general cooling trend is considered to be related to decreased summer radiation due to astronomical factors, but the causes of the shorter-term variations are unclear.

Over the past millennium, four different climate periods are apparent in the Northern Hemisphere (Figure 2): 1) Medieval Warm Period (MWP, 900 to 1350 AD); 2) the Transitional Period (TP, 1350 to 1550 AD); 3) the Little Ice Age (LIA, 1550 to 1850 AD); and 4) the Contemporary Warm Period (after 1850). Some shorter intervals were mainly related to changes in solar activity or large volcanic eruptions.

Temperatures decreased in the mid-14th century, beginning a two-century period of great variability of climate conditions. Large fluctuations of temperature and precipitation occurred, with some summers hot and dry and others extremely wet with flooding. Similarly, there were several decades with severe winters and a few with relatively warm

Box: Reconstruction of past climate

In the Baltic Sea Basin and surrounding parts of Europe, relatively stable climate conditions prevailed in the tenth and 11th centuries, typified by warm, dry summers. Investigations in Fennoscandia indicate that the Medieval Warm Period (MWP) occurred between 900 and 1100; at that time, warm season (May to September) temperatures exceeded the contemporary warming at the end of the 20th century by about +0.5 °C. An exceptionally warm period also occurred from 1220 to 1250 AD. A regional reconstruction of precipitation in southern Finland showed a uniquely prolonged deficit of rainfall during the MWP, with a particularly severe drought between 1000 and 1200 AD.

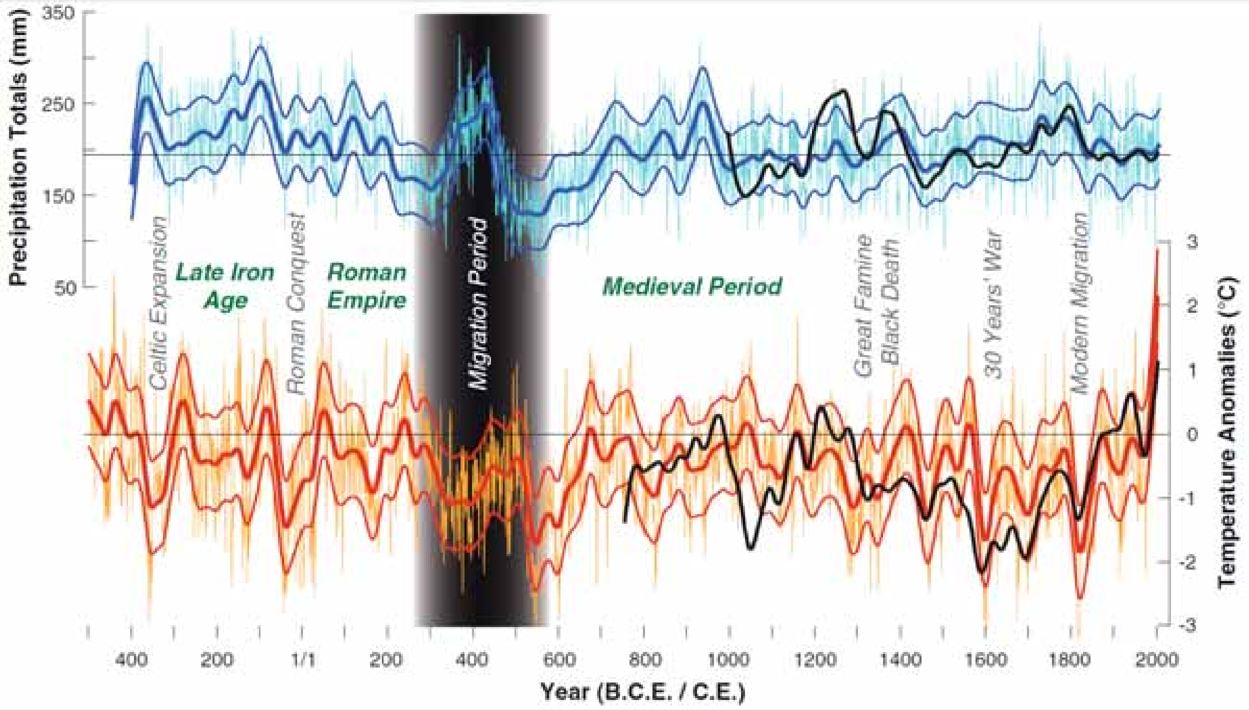


Figure 2. **Reconstructed AMJ (April, May, June) precipitation totals (top) and JJA (June, July, August) temperature anomalies (bottom) with respect to the 1901–2000 period. Error bars are ±1 root-mean-square-error (RMSE) of the calibration periods. Black lines show independent precipitation and temperature reconstructions from Germany (Büntgen et al. 2010) and Switzerland (Büntgen et al. 2006). B.C.E. = BC; C.E. = AD. Bold lines are 60-year low-pass filters. Periods of demographic expansion, economic prosperity, and societal stability are noted, as are periods of political turmoil, cultural change, and population instability (From Büntgen et al. 2011).**

winters. These large fluctuations created very unfavourable conditions for agriculture in most of Europe and Russia, particularly from 1400 to 1480.

Climate conditions in winter in the greater Baltic Sea region since 1500 AD are shown in Figure 3. This shows that the climate of the past 500 years was characterized by centennial-scale variability and the modulation of interannual and decadal signals, often accompanied by rapid shifts. There is little indication of major periodicities in the record; thus, the Baltic climate is better characterized by discrete events. The apparent random initiation and different duration of events and the lack of cycles indicate a major influence of intrinsic variability in atmospheric climate.

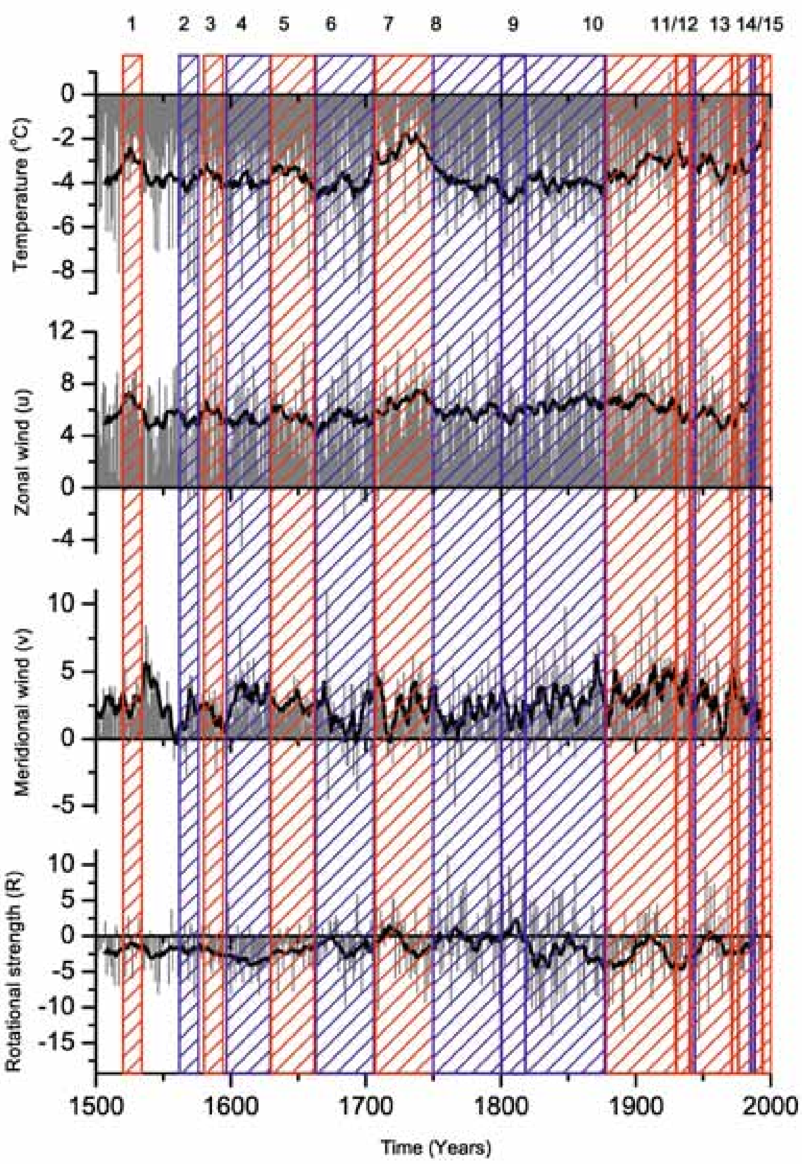


Figure 3. Winter climate conditions in the greater Baltic Sea Region since 1500 AD. The gray colour shows seasonal winter data from the two gridded datasets: (top to bottom) Baltic Sea mean winter air temperature, zonal wind component (westerly winds when positive and easterly winds when negative), meridional wind component (southerly winds when positive and northerly winds when negative), and rotational flows (cyclonic circulation when positive and anticyclonic when negative). The black line in all panels is a 15-year running mean. Blue and red fields cover time periods classified as cold and mild, respectively (From Eriksson et al. 2007) ©American Meteorological Society. Used with permission.

In the second half of the 16th century, the temperature dropped, beginning the Little Ice Age. The longest consecutive cold period occurred from the late 16th century until the middle of the 18th century, with the period from 1630 to 1700 AD the coolest during the entire past millennium in the Northern Hemisphere. The final phase of the Little Ice Age, during the first half of the 19th century, was also marked by a sequence of exceptionally cold years between 1812 and 1824. In that period, the average winter temperature in Russia and in a large part of Europe was lower than normal by as much as 10 to 12 °C.

The so-called Little Ice Age began in the second half of the 16th century. Photo: Seppo Knuuttila.

3 The Baltic Climate: Past Climate and Recent Climate Change

The previous section gave a broad overview of the historical development of conditions in the Baltic Sea Basin over past millennia based on proxy data from sources such as fossil pollen and insects and tree ring widths and density, and in the past millennium also from some written records or diaries. In the past 200 to 300 years, measurements of environmental conditions have been made with increasing accuracy. The Baltic Sea has a dense observation network covering an extended time period. Continuous time series exist since the middle of the 18th century for a few stations and a denser network of stations was developed since the middle of the 19th century. Compilations and analyses of these data can be used to provide an understanding of the climate variations over the past 200 years, as it is during the latter part of this period that recent potential anthropogenic influence can be seen. Nonetheless, data from the past 200 years must be used with care, as variations in data density and quality could be interpreted as climate trends.

3.1 Atmospheric conditions and past changes over the Baltic Sea Basin

Large-scale atmospheric circulation

The Baltic Sea Basin is embedded in the general atmospheric circulation system of the Northern Hemisphere. Climatologically, the region is controlled by two large-scale pressure systems over the Northeast Atlantic: the Icelandic Low and the Azores High, and a thermally driven pressure system over Eurasia (high pressure in winter, low pressure in summer). The climate of the Baltic Sea area is controlled to a large extent by the prevailing air masses and atmospheric parameters are controlled by the global climate as well as by regional circulation patterns. Atmospheric parameters are strongly linked together; for example, circulation influences wind, temperature, humidity, cloudiness and precipitation patterns, while solar radiation and cloudiness influence the surface temperature.

The large-scale circulation patterns in the Baltic Sea region are influenced by the North Atlantic Oscillation (NAO), which is the dominant mode of near-surface pressure variability of the North Atlantic and neighboring land masses. In its positive phase, the Icelandic Low and Azores High are strengthened, resulting in a strong westerly air flow on a more northerly tract over the eastern North Atlantic and Europe; this brings warm, wet winters to all of Europe except the southern part. When both the Icelandic Low and the Azores High are weak, termed a negative NAO, the westerly air flows are also weak, resulting in colder, drier winters in Northern Europe. The NAO shows considerable seasonal and interannual variability, with prolonged periods of domination of positive or negative phases (Figure 4).

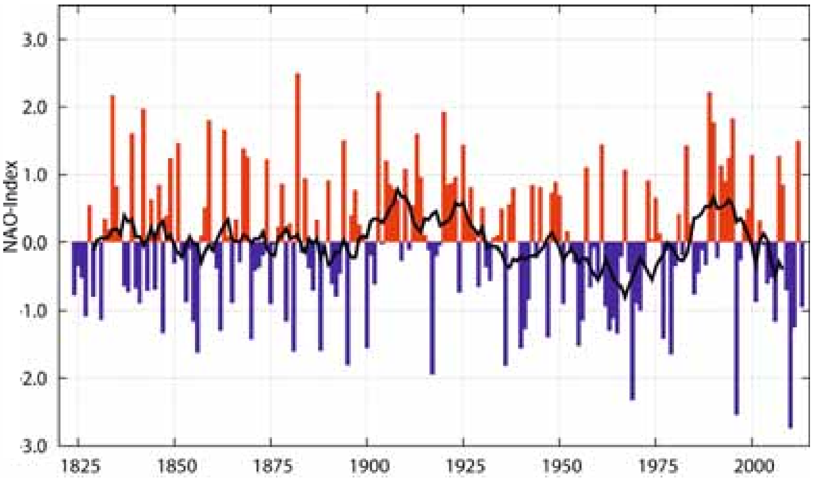


Figure 4. NAO index for boreal winter (DJFM) 1823/1824 to 2012/2013, after Jones et al. (1997) for boreal winter (DJFM), re-normalized for the period 1824-2013.

Although the behavior of the NAO in the long term is rather irregular, from the mid-1960s to the mid-1990s there was generally a positive trend, with stronger westerly winds, mild and wet winters, and increased storminess in central and Northern Europe, including the Baltic Sea area. After the mid-1990s, there was a trend toward more negative NAO indices, resulting in weak westerly air flows. Weather types appear to be more persistent than in earlier decades, which may be reflected in an increase in the occurrence of extreme events.

Recent studies suggest that during the past century the increased frequency of both anticyclonic circulation (clockwise circulation around a high pressure, in the Northern Hemisphere) and westerly wind types has resulted in a warmer climate with reduced sea-ice cover and decreased seasonal

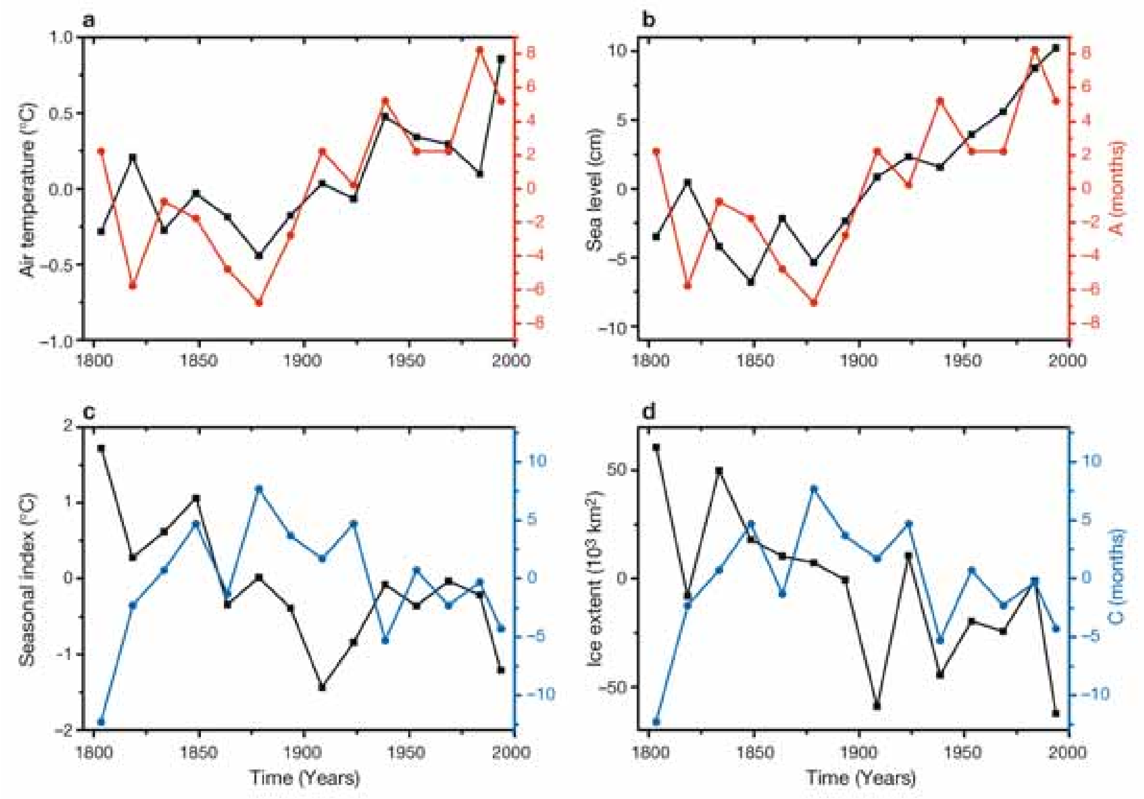


Figure 5. **Anomalies in the climate records from Stockholm together with the circulation types that describe the vorticity of the atmospheric circulation. Red indicates anticyclonic and blue cyclonic circulation, with scales given by the right y-axis: (a) air temperature and anticyclonic circulation, (b) sea level and anticyclonic circulation, (c) seasonal index, defined as the difference between summer (JJA) and winter (DJF) seasonal temperatures, and cyclonic circulation, and (d) ice cover and cyclonic circulation. Here A and C on the y-axis represent the anticyclonic and cyclonic circulation, respectively, expressed as frequency anomalies in months for the 15-year averages. From Omstedt et al. (2004).**

amplitude of temperature, indicating that multidecadal climate change in the Baltic Sea region is at least partly related to changes in the atmospheric circulation (Omstedt et al., 2004). The influence of these changes in circulation on the Baltic Sea is illustrated in a 200-year time series from Stockholm (Figure 5).

Blocking of the atmospheric flow is frequently observed in the Baltic Sea region (Figure 6). Blocking is a large-scale quasi-stationary, quasi-persistent split of the westerly air flow, which is often responsible for extreme weather events. Although a significant part of the North Atlantic blocking is not directly related to the NAO, research has

In the wind climate of Northeast Atlantic and Northern Europe, an unusually calm period occurred from 1960 to 1970. Photo: Carlo Berg.

shown that warm conditions in winter and cold conditions in summer over southwestern Greenland are related to high blocking activity and a negative phase of the NAO, while cold conditions in winter and warm conditions in summer over southwestern Greenland are related to low blocking activity and a positive phase of the NAO.

Recent studies (Bhend and von Storch, 2008, 2009) have presented a method to compare the consistency of observed trends with climate change projections, even though no estimates of natural variability exist. These studies found that anthropogenic forcing can explain a large part, but not all, of the observed changes in temperature and precipitation over the Baltic Sea region and that this correlation is unlikely to be random. This conclusion remained robust on reanalysis after removal of the NAO signal.

Wind

The near-surface wind climate exerts a strong impact on the ecosystem of the Baltic Sea. Storms are essential for the ventilation and mixing of the strongly stratified Baltic Sea and inflow events importing salt and oxygen from the North Sea are very dependent on the wind climate and pressure differences between these two seas. The wind climate is generally related to large-scale variations in the atmospheric circulation of the North Atlantic, including the NAO in winter. Overall, reconstructions over the past 200 years show that storminess in Northern Europe is dominated by large multi-decadal variations rather than long-term trends. However, during the second half of the 20th century, large changes were observed in the wind climate over the Northeast Atlantic and Northern Europe. An unusually calm period occurred from 1960 to 1970; this coincided with a period with a strongly negative NAO index and also a very high frequency of Euro-Atlantic blocking in winter, preventing or weakening westerly flow and leading to low wind speeds and fewer storms over Scandinavia. This was followed by a strong increase in annual and winter-to-spring storminess with unprecedented high winter storminess in the early 1990s, during which the NAO index reached very high values. In the first decade of the 21st century, wind speeds returned to average values again in the Baltic Sea area.

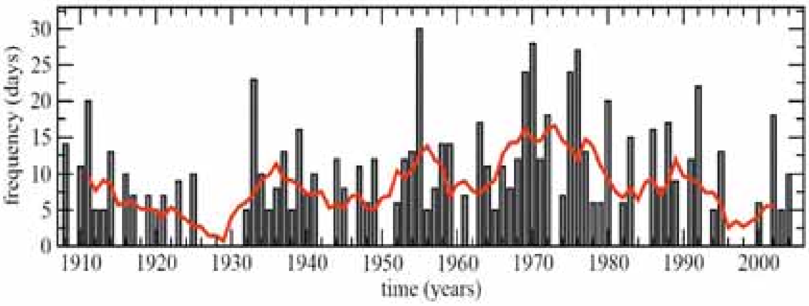


Figure 6. **Blocking index (bars) and its decadal variation (seven-year running mean; red line) for boreal winter (December to February) from 1908 to 2005. The blocking index takes into account both spatial aspects and persistence; it is defined as the number of blocked days per winter in the sector 80°W–10°W. The blocking condition must be satisfied for an interval of at least 12.5° for at least five consecutive days (persistence criteria), Rimbu and Lohmann (2011).**

Winds and storms have a significant impact on the Baltic sea ecosystem. Photo: Christof Hermann.

Temperature

There has been a significant increase in surface air temperatures in the Baltic Sea region since 1871. This has occurred with large multi-decadal variations dividing the 20th century into three phases: warming at the beginning of the century until the 1930s, then cooling until the 1960s, and another distinct warming during the last decades of the century. Linear trends of the annual mean temperature anomalies from 1871 to 2011 were 0.11

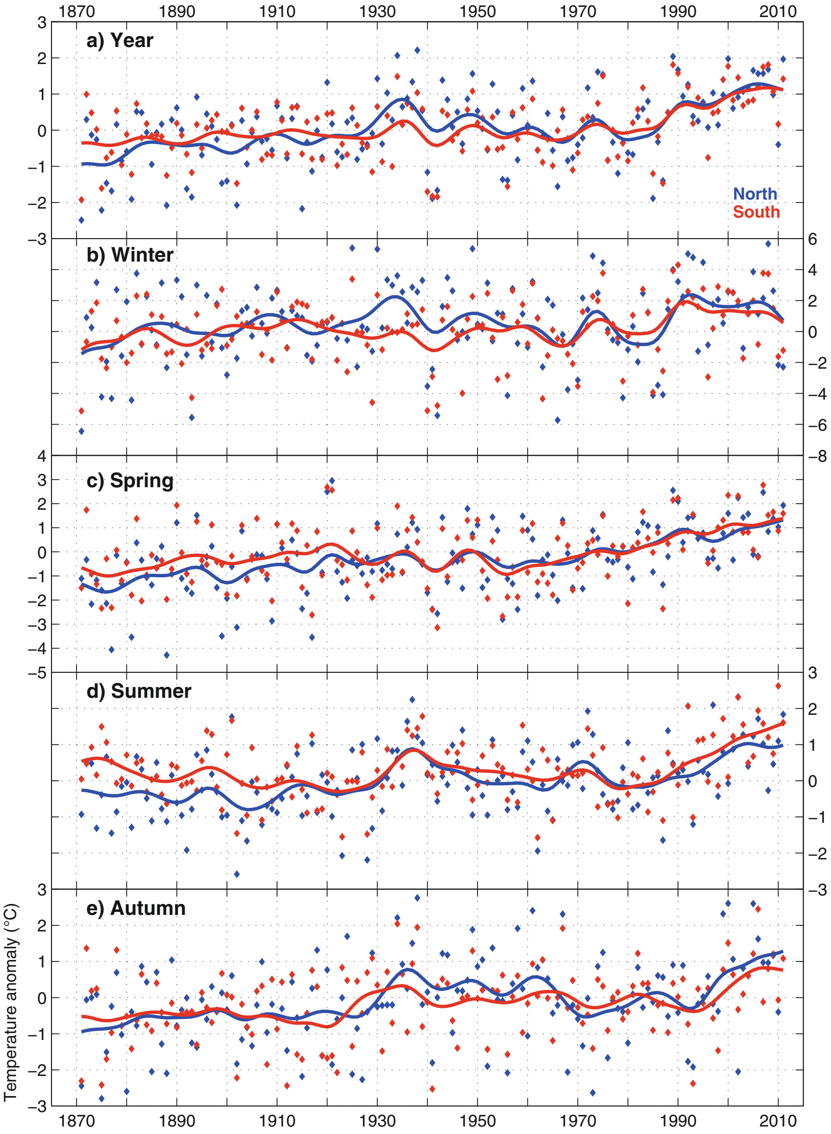


Figure 7. Annual and seasonal mean surface air temperature anomalies (compared to the 1960-1991 period) for the Baltic Sea Basin from 1871 to 2011, calculated from 5° by 5° latitude, longitude box average taken from the CRUTEM3v dataset (Brohan et al., 2006) based on land stations (from top to bottom: (a) annual, (b) winter (DJF), (c) spring (MAM), (d) summer (JJA), (e) autumn (SON)). The blue colour relates to the Baltic Sea Basin to the north of 60°N and red colour to the south of that latitude. The dots represent individual years, and the smoothed curves (Gaussian filter, σ = 3) highlight variability on time scales longer than ten years.

°C per decade north of 60°N and 0.08 °C south of 60°N, which is larger than the trend of the global mean temperature of about 0.05 °C per decade for the period 1861 to 2000 (IPCC, 2001). All seasonal trends are positive and significant except for winter temperature north of 60°N. The largest trends are observed in spring (and winter in the southern part of the area) and the smallest trends in summer. The seasonal trends are stronger in the northern area compared to the southern area. These trends are shown in Figure 7.

An analysis of temperature trends from 1970 to 2008 in the Baltic Sea area showed the strongest increase in the Gulf of Bothnia in autumn and winter (0.5 to 0.6 °C/decade), while significant changes occurred during spring and summer in the central and southern parts of the Baltic Sea area (an increase of 0.2 to 0.3 °C/decade). During the past decade, the warming has continued during spring and summer in the southern parts and during autumn and spring in the northern parts, although the winters of 2009/2010 and 2010/2011 were very cold.

The daily temperature cycle is also changing, with both the mean minimum temperature and the mean maximum temperature in the Baltic Sea area increasing over the past century. The mean maximum temperature has increased more rapidly in the latter part of spring (April and May), while the mean minimum temperature has increased in much of the winter; this has resulted in a decrease in the daily range of temperatures. In addition to an increase in mean temperatures, there has been an increase in temperature extremes. For example, in Poland a statistically significant increase in the annual number of days with daily maximum temperatures above 25 °C and 30 °C was observed for the period 1951 to 2006, while a significant decrease was observed in the length of the frost season and in the annual number of frost days (daily minimum below 0 °C) and ice days (daily maximum below 0 °C). Furthermore, the duration of extremely mild periods increased significantly in winter and the number of heat waves increased in summer.

These changes are also resulting in changes in the seasons: the length of the growing season has increased, whereas the length of the cold season has decreased. The number of days by which autumn and winter are delayed differs from south to north and east to west, but as an example in Tartu, Estonia the number of deep winter days (with snow cover) has decreased by 29 days over the past century while the growing season has increased by 13 days in this period.

Cloudiness in the region shows large long-term fluctuation. Photo: Metsähallitus NHS / Essi Keskinen.

Precipitation

The amount of precipitation in the Baltic Sea area during the past century has varied between regions and seasons, with both increasing and decreasing precipitation. A tendency of increasing precipitation in winter and spring has been detected during the second half of the 20th century. Comparing the annual mean precipitation during 1994-2008 with that of 1979-1993, less precipitation was observed in the northern and central Baltic Sea region and more precipitation in the southern region (Lehmann et al., 2011). However, patterns for single seasons were rather different (Figure 8).

The increase in precipitation in Northern Europe is also associated with an increase in the frequency and intensity of extreme precipitation events; the number of extreme precipitation days per year and the seasons in which they occur vary for the different catchment areas of the Baltic Sea.

Cloudiness

The mean cloudiness and duration of sunshine have shown large long-term fluctuations over the Baltic Sea Basin during the 20th century. From the 1950s until the 1990s, the total cloud cover decreased over Poland while the amount of low clouds increased over Estonia. These trends were reversed in the 1990s. Increasing cloud cover occurred in parts of the mountainous regions of Scandinavia and in the southeastern Gulf of Finland, mainly during winter and summer. However, over the water of the Baltic Sea, the cloud cover decreased by 1% per decade from 1970 to 2008, mainly in spring and autumn.

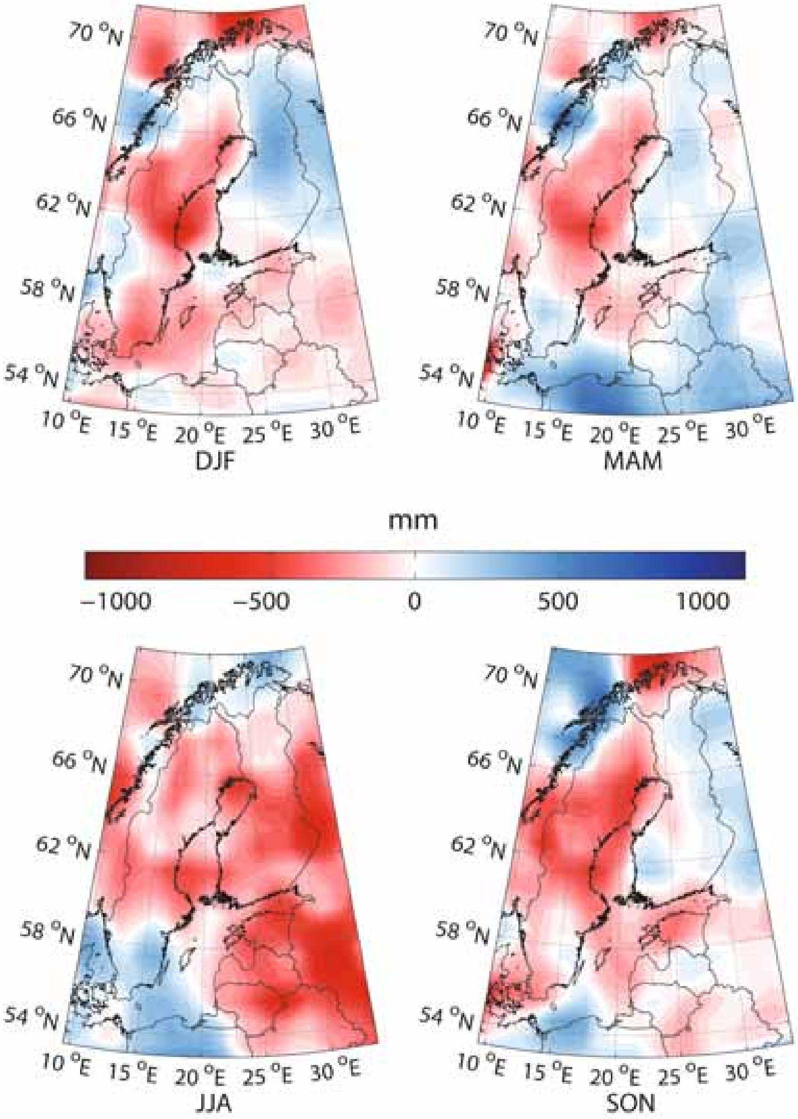


Figure 8. **Seasonal differences in 15-year totals of precipitation for the period 1994-2008 minus the period 1979-1993, based on the SMHI database (Lehmann et al., 2011).**

3.2 Past changes in the hydrology of the Baltic Sea Basin

The Baltic Sea can be considered a large, semi-enclosed brackish water estuary draining into the North Sea via the Danish Straits. The inflow from rivers to the Baltic Sea is an important variable for both the physical and ecological processes of the sea. The form of precipitation, as rain or snow, has a large impact on the annual runoff regime. In winter, much of the precipitation is stored as snow, increasingly so toward the northern part of the basin. Thus, in the north, water levels and discharges are lowest toward the end of winter before snowmelt. The highest water levels and discharges are recorded in spring or early summer owing to snowmelt. Water levels and discharges usually decrease during summer when evaporation is greatest and is normally larger than precipitation. In warm, dry summers, water levels can even drop below the winter minimum. Climate change can be expected to have a clear influence on the seasonal flow regime in response to changes in the type of precipitation and alteration of temperature-evapotranspiration regimes.

River runoff

Although decadal and regional variability is large, no significant long-term change has been detected in the total river runoff to the Baltic Sea during the past 500 years (Figure 9). An analysis of the sensitivity of runoff to temperature suggests that the southern regions of the Baltic Sea Basin may become drier with rising air temperatures, whereas in the north and around the Gulf of Finland, warmer temperatures are associated with larger river runoff. As a whole, over the past 500 years the total river runoff to the Baltic Sea has decreased by 3% per °C in response to the temperature increase (Hansson et al., 2011).

The river ice regime is considered a sensitive indicator of climate change. Photo: Piotr Debowski.

An analysis of stream flow in a large number of rivers and streams in the Nordic countries over three periods from 1920 to 2002 generally showed that trends towards increased stream flow dominated annual values as well as the winter and spring seasons, while no trend was found for autumn. An indication of earlier snowmelt floods was also apparent. Although these trends in stream flow result from changes in both temperature and precipitation, temperature was shown to have a stronger effect. As an example, Figure 10 shows anomalies and long-term variations in precipitation, temperature, water resources, and flood magnitude in Sweden for the period 1901 to 2010 in relation to the reference period 1961 to 1990.

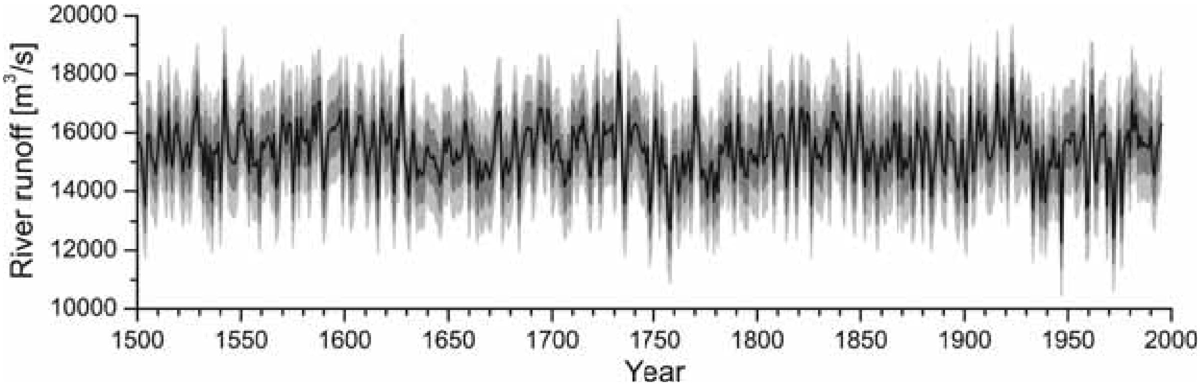


Figure 9. **Reconstructed annual river discharge to the Baltic Sea over the period 1500 to 1995. The grey shading indicates one and two standard errors of the reconstructed river discharge (Hansson et al., 2011).**

In contrast, there has been a decrease in annual discharges from southern catchments of the Baltic Sea. A decrease of about 10% in annual discharges from the rivers Nemunas (Lithuania), Neva (Russia), Vistula and Oder (Poland) has been observed over the past century. Cycles of dry and wet phases lasting about 13 years each were characteristic of these rivers.

The river ice regime is considered to be a sensitive indicator of climate change. A study of ice in the River Daugava (Latvia), which has a data series starting in 1530, showed a pronounced downward trend during the past 150 years with an even clearer trend during the past 30 years. This indicates a reduction of ice-cover duration and a shift to earlier dates of ice break-up. The ice-covered period has been declining by 2.8 to 6.3 days per decade during the past 30 years. Although regional variations exist, similar observations have been made for other rivers flowing into the Baltic Sea. In general, a shift in the river ice break-up toward earlier dates, indicating an earlier start of river flooding, can explain the increase in winter runoff of rivers to the Baltic Sea.

Both the seasonal river discharge and the ice regime are strongly influenced by large-scale atmospheric circulation processes over the North Atlantic that are closely correlated with the NAO index.

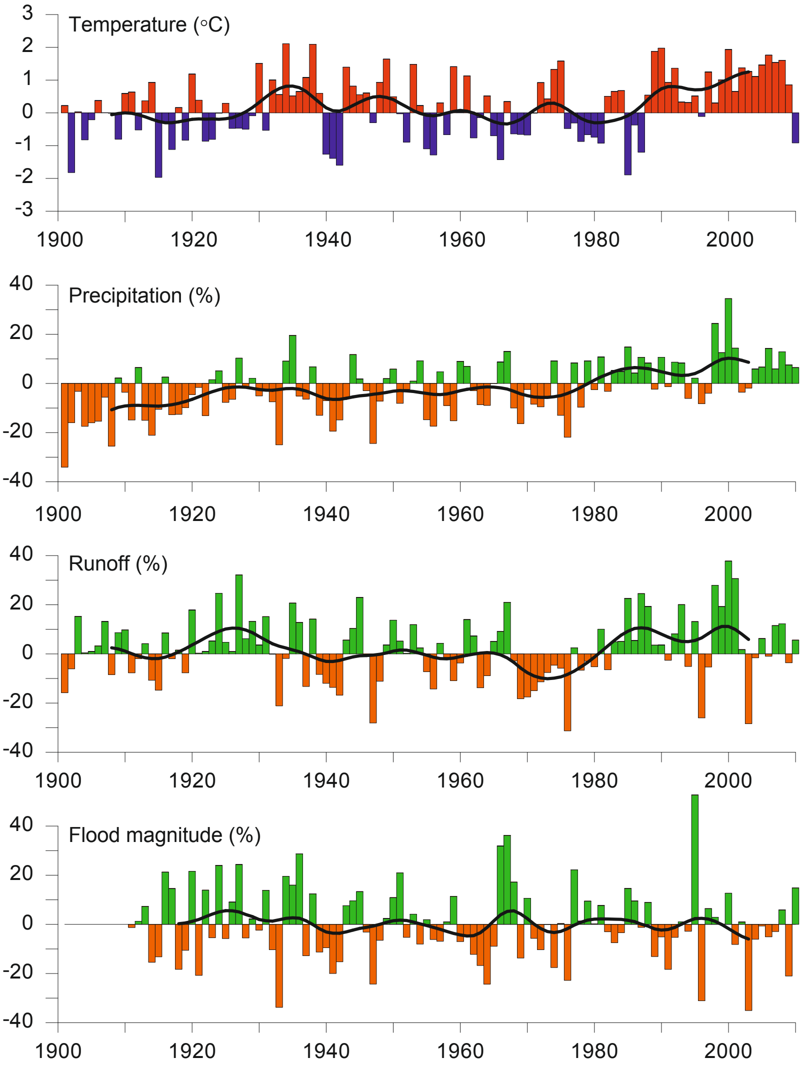


Figure 10. Annual anomalies (vs. 1961-1990) and long term variations in precipitation, temperature, water resources and flood magnitude in Sweden, for the period 1901-2010. For flood magnitude the years before 1911 were omitted due data scarcity. From Hellström and Lindström (2008), updated until 2010.

Snow

The snow cover over the drainage basin of the Baltic Sea also influences the stream flow. Snow is the origin of a significant fraction of runoff in the Baltic Sea Basin. The volume of water held by the snow cover and the spring melt rate are significant factors affecting the volume and peak of the spring floods within the area. Of all snow-cover parameters, snow-cover duration has the highest sensitivity to climate change. In the eastern part of the Baltic Sea drainage basin, the period of snow cover decreased between 1976 and 2008 in relation to the 1938 to 2008 average. The duration of annual snow cover in the Baltic Sea drainage basin in western Scandinavia and in the southwest East European plain also decreased during the past century. On the other hand, an increasing trend in the number of snow-cover days has been seen in most of Northern Eurasia. An analysis of a number of river basins in Latvia indicates a tendency toward a decrease in spring floods from 1951 to 2006 and an increase in winter flows due to changes in the snow amounts and snow season.

There is large interannual variation in the extent of snow cover in the Baltic Sea drainage area; however, there has been a decreasing trend in snow-covered area since the 1970s in Fennoscandia, with regional exceptions. The area of snow cover in the Russian part of the Baltic drainage basin also decreased during the 1970s to 1990s, but this has since ceased.

3.3 Past changes in the hydrography of the Baltic Sea

Water temperature

The thermal regime of the Baltic Sea is formed mainly by atmospheric heat fluxes, while the contribution of lateral heat advection is quite small. The seasonal cycle of water temperature is superimposed on the more or less permanent two-layer salinity stratification. Cold waters form during the winter extending down to the halocline, which has typical depths between 60 and 80 m in the Baltic Proper and somewhat less in the southern basins. During summer, when a seasonal thermocline develops at depths of about 15 to 20 m, the underlying cold intermediate layer generally keeps a 'memory' of the severity of the previous winter. Thus, the summer (July to August) temperature of the intermediate cold layer is well correlated with the surface (down to the halocline) temperature in March. Below the halocline, deeper waters are formed mainly by lateral advection of saline waters from the North Sea entraining and mixing with ambient waters. Below 100 m depth, the temperature ranges only from 3 °C to 8 °C, while the temperature in surface waters can range up to 25 °C.

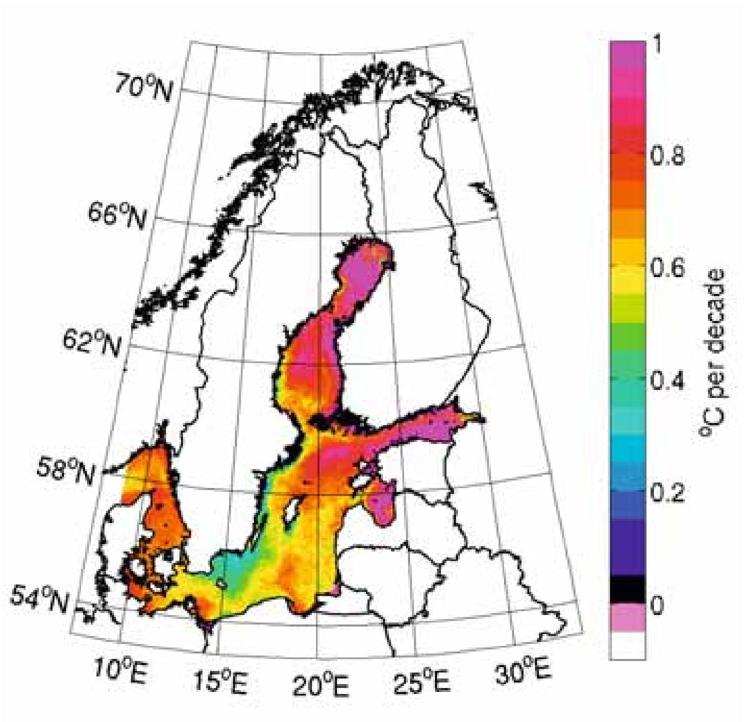


Figure 11. Linear trend of the annual mean sea-surface temperature based on infrared satellite data (1990 to 2008) provided by the Federal Maritime and Hydrographic Agency (BSH), Hamburg (Lehmann et al., 2011).

Analyses of a number of data sets of *in situ* measurements of temperature in the surface water layer, together with more recent remote sensing data, confirm a warming of surface waters in all seasons since 1985. An increase in annual mean sea-surface temperature of up to 1 °C/decade from 1990 to 2008 has been estimated based on remote sensing data, with the greatest increase in the northern Bothnian Bay and large increases also found in the Gulf of Finland, the Gulf of Riga, and the northern Baltic Proper (Figure 11). In the northern areas, the recent decrease in the extent and duration of sea-ice cover has strongly influenced the seawater temperatures. The least warming of surface waters (0.3 to 0.5 °C/decade) was found northeast of Bornholm up to and along the Swedish coast, probably owing to an increase in the frequency of coastal upwelling. Among the seasons, the largest increase is during summer.

A climate reconstruction of Baltic Sea water temperature and sea-ice conditions was modeled for the period 1500 to 2001. Annual mean water temperatures averaged over the entire sea show a number of periods of colder and warmer water, and the modeling results suggest that the current warmer temperatures are within the range of changes during the past 500 years (Figure 12). Nonetheless, the 20th century can be interpreted as the warmest, except for the warm anomaly around the 1730s.

Salinity

The overall salt content of the Baltic Sea depends to a large extent on the atmospheric net precipitation and riverine discharge, with higher salinity during dry periods and lower salinity during wet periods, and also on the regular water exchange between the North Sea and the Baltic Sea. The salinity and stratification of the deep water are strongly linked to the occurrence of Major Baltic Inflows of North Sea water, which occur sporadically and bring high-saline water to the deep layers. These major inflows are often followed by a period of stagnation during which the saline stratification decreases and oxygen deficiency develops in bottom waters. Major inflows occur normally during winter and spring; they bring relatively cold and oxygen-rich waters to the deep basins. Since 1996, several large inflows have occurred during the summer. Such baroclinic inflows have transported high-saline, but warm and low-oxygen water to the deep layers of the Baltic Sea.

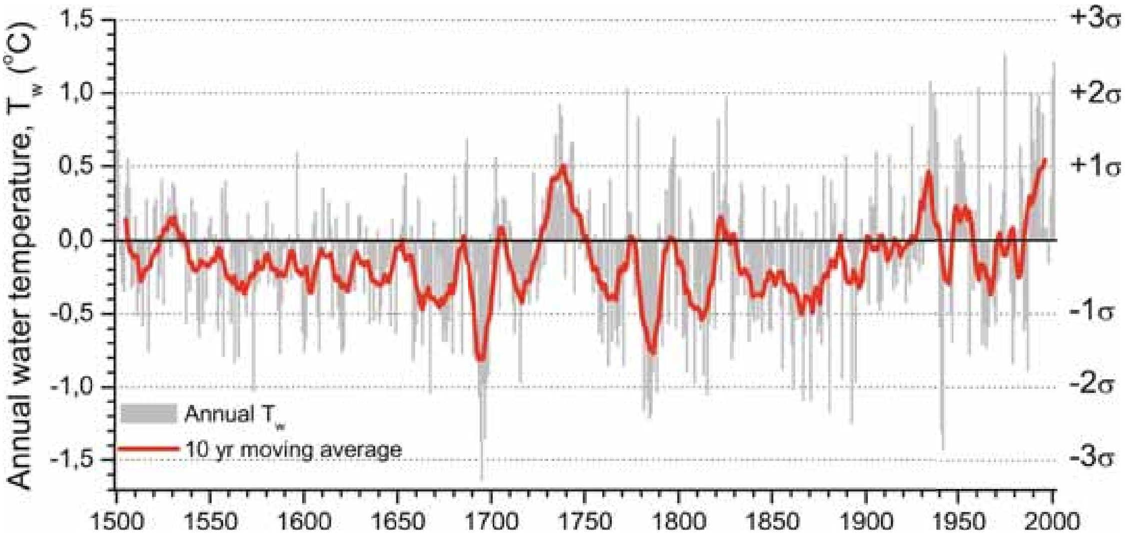


Figure 12. Anomalies of the annual and decadal moving average of the modeled Baltic Sea spatially averaged mean water temperature over the period 1500 to 2001. The dotted horizontal lines are the standard deviations of the water temperature during the standard period 1900 to 1999 (Hansson and Omstedt, 2008).

Thus, the warm-water inflows transport less oxygen to the Baltic Sea than cold-water inflows, and higher temperatures increase the rate of oxygen consumption of organic matter in the deep water and ultimately increase the production of hydrogen sulfide. Present mean salinities are estimated to be near the highest values since 1500 AD, but there have been several periods when the mean salinity of the Baltic Sea decreased from the maximum value of about 7.8 psu to about 6.5 psu.

Circulation

Results showing the mean circulation in the entire Baltic Sea as obtained by models are illustrated in Figure 13. They are in agreement with observational results and show the existence of quite stable, strong cyclonic (counter-clockwise) gyres in the Baltic Proper and the Bothnian Sea, and weaker, less-persistent currents in the Gulf of Riga, Gulf of Finland, and the Bothnian Bay. This regular circulation pattern may be interrupted for short periods when water mass movements may take alternative paths; this may occur, for example, after some Major Baltic Inflows.

Interactions between the upper and lower water layers of the Baltic Sea are quite restricted owing to the strong stratification. At the entrance to the Baltic Sea, the deep water circulation is characterized by dense bottom currents in the inflowing saline water. Processes including convection and mechanical mixing, entrainment and vertical advection of water masses result in interactions between the upper and lower layers in other parts of the Baltic Sea.

An analysis of the sensitivity of the Baltic Sea to change indicates that the average salinity of the Baltic Sea is dependent on and strongly sensitive

Major inflows of high-saline water occur normally during winter and spring, bringing oxygen-rich waters to the deep basins. Photo: Jan Ekebom.

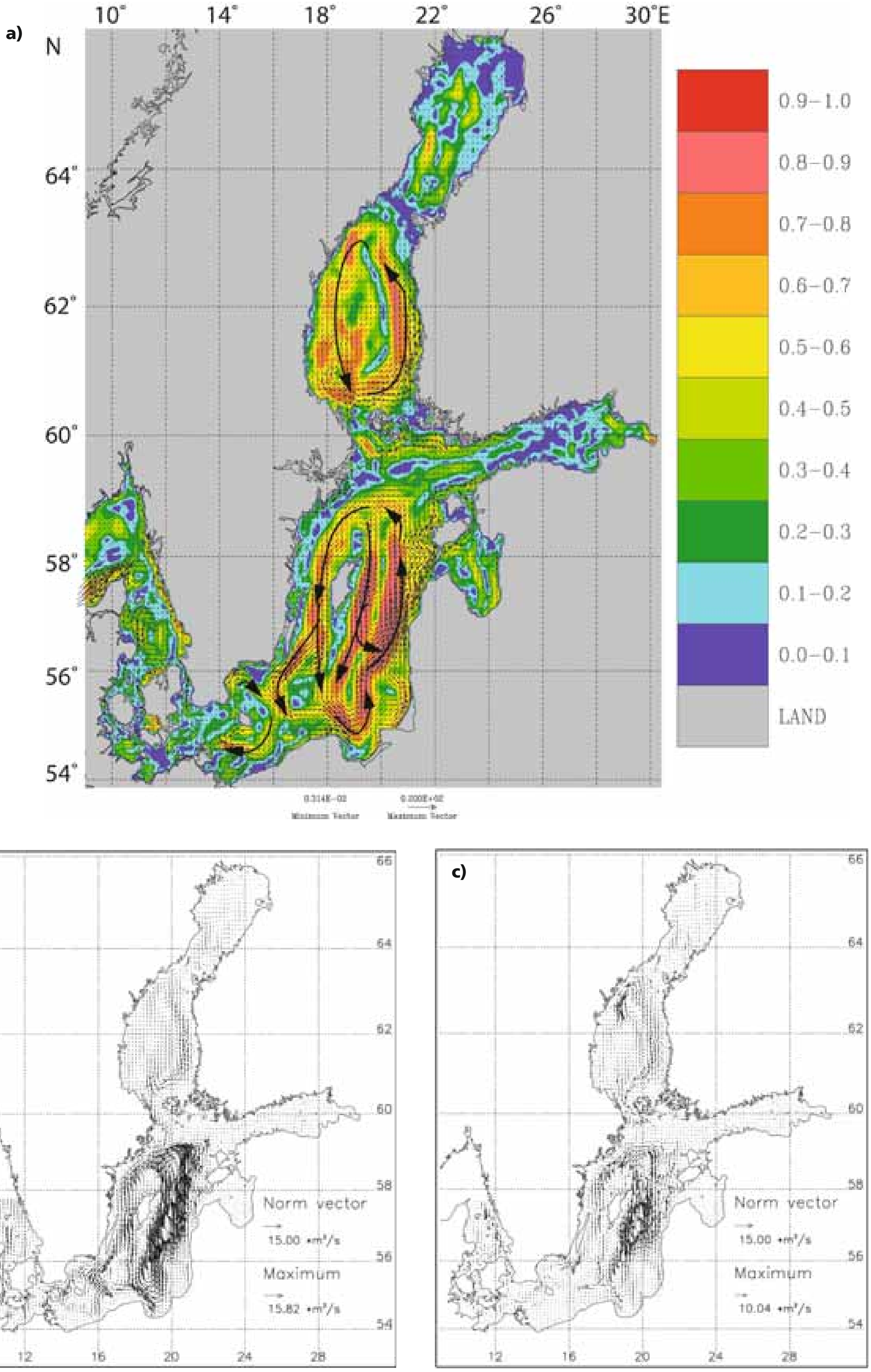


Figure 13. Baltic Sea circulation as viewed from modeling results. Average barotropic (unidirectional over the whole section) currents (a) for 1992-1995 (in cm/s) with the flow stability contours (Lehmann and Hinrichsen, 2000), and average transports per unit length (in m^2/s) for 1981-2004 above (b) and below (c) the halocline (Meier, 2007).

to changes in freshwater inflow. The annual maximum extent of ice is strongly sensitive to changes in the mean winter (DJF) air temperature over the Baltic Sea: at a mean air temperature of −6 °C the sea will become completely ice covered, whereas the ice cover will not appear at 2 °C. Changes in the annual mean water temperature are closely related to changes in the air temperature above the sea.

Sea ice

The ice season in the Baltic Sea usually begins in November when ice forms in the shallow bays of the Bothnian Bay. On average, the maximum extent of ice on the Baltic Sea occurs in March, when ice covers about 40% of the total area. The ice edge is typically located in the northern Baltic Proper and the Bothnian Bay, the Gulf of Finland, and the Gulf of Riga are covered with ice. During extremely severe winters, the entire Baltic Sea has been covered with ice, while in very mild winters ice is only formed in the Bothnian Bay and the eastern Gulf of Finland. The length of the ice season is 130 to 200 days in the Bothnian Bay, 80 to 100 days in the Gulf of Finland, and 0 to 60 days in the southern Baltic Sea.

The state of the sea ice depends on the surface energy balance, momentum flux and water flux. Some of the climate-related variables, such as ice extent or freezing date, are mainly driven by the energy balance and their variability closely reflects large-scale air temperature variability. Variables such as ice type, ice thickness, and duration of the ice-covered period are also very dependent on wind and currents and may reflect changes on a local scale. All of these variables have large interannual variability and are very closely related to large-scale atmospheric circulation.

The annual maximum ice extent of the Baltic Sea (MIB) is the most widely used indicator of sea-ice changes because it integrates winter period weather over the entire basin. A reconstruction based on various observational methods shows that the MIB displays large interannual variability owing to large-scale atmospheric circulation associated with the NAO (Figure 14). A larger MIB occurs during negative NAO phases, while a smaller MIB occurs when the NAO is in a positive phase. There has been a significant decreasing trend in the MIB, which amounted to a decrease of 20% over the past 100 years up to 2011.

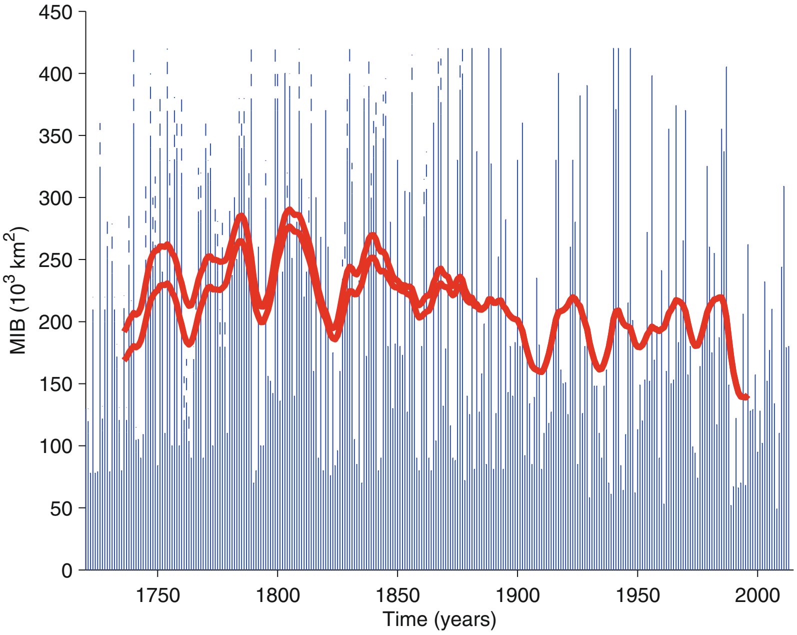


Figure 14. The maximum extent of ice cover in the Baltic Sea 1720 to 2012. The dashed bars represent the error range of the early estimates. The 30-year moving average is indicated by two lines representing the error range early in the series, converging into one line when high-quality data are available (data source: Finnish Meteorological Institute).

There has also been a large change in the length of the ice season during the past century. In the Bothnian Bay, which has the longest ice season, the trend is −18 days/century. Larger changes have been observed in the eastern Gulf of Finland, where ice also forms every winter; over the past century, the length of the ice season decreased by 41 days/century, while in the past 50 years, the rate decreased to −62 days/century. In the southern Baltic Sea, the length of the ice season decreases from east to west and from the inner waters toward the sea areas. A weak trend toward a smaller number of days with ice has been found for the last 30-year period analysed.

These changes in ice conditions are consistent with the observed increase in temperature, but some sea-ice changes could also be caused by shipping. Ship-induced waves can prevent the formation of a permanent ice cover in the autumn as well as enhance the break-up of the ice cover during spring; thus, the increase in the size of vessels and the intensity of shipping activity in the Baltic Sea could also affect local ice conditions.

Sea level

Sea-surface height is an important indicator of climate variability and long-term change. Changes in the annual mean Baltic Sea level can be seen as the sum of global, regional, and local effects. The long-term trends in global mean sea level over the past century have mainly been determined by the expansion of the water volume owing to rising ocean temperatures, by the melting of glaciers and polar ice sheets, and by the construction of reservoirs and ground water usage.

The most direct measurement of relative sea level is from tide gauges. The Baltic Sea has one of the longest running and most densely spaced tide gauge networks in the world, with many stations operating continuously since the late 19th century. As tide-gauge-derived sea-surface height records are based on local observations of relative sea level, giving the height of the sea surface relative to the sea floor and thus to land, these data include not only changes in absolute sea level but also the vertical crustal movements. In the Baltic Sea area, long-term and essentially continuous changes of the Earth's crust are caused by the Glacial Isostatic Adjustment, the vertical shift of the Earth's crust resulting from the redistribution of the Earth's crust material owing to the unloading of ice masses after the Last Ice Age.

Relative sea level is rising in the southern Baltic where the continental crust is sinking.
Photo: Christof Hermann.

Since 1978, satellite radar altimeters have measured global sea-surface height. Although these measurements allow for more accurate estimates of globally averaged and regional sea-level change, the satellite orbit constraints do not allow measurements north of 65°N. This and other characteristics of the satellite-derived data limit their use for the Baltic Sea.

The overall mean sea level change at the coasts of the Baltic Sea results from the combined effects of post-glacial rebound, the increase of the global ocean mass largely due to the melting of ice on land, thermal expansion of seawater, and the contributions of regional factors that may cause an overall change in Baltic sea level and/or a redistribution of sea level within the Baltic Sea. The Glacial Isostatic Adjustment exerts a strong influence in the Baltic Sea area, with a maximum uplift of the Earth's crust in the Gulf of Bothnia of approximately 10 mm/year (resulting in a negative trend in relative sea level) and subsidence in parts of the southern Baltic Sea coast of about 1 mm/year (resulting in a positive trend). Thus, relative sea level is decreasing in the northern Baltic where the continental crust is rising, while sea level is rising in the southern Baltic where the continental crust is sinking (Figure 15). In addition, many climate factors also influence the relative sea level, including changes in water density (temperature and salinity), changes in the total volume of the Baltic Sea, and meteorological factors.

Of the meteorological factors, wind forcing is the most important, with persistent winds from the southwest transporting water into the Baltic Sea and persistent winds from the northeast transporting water out of the sea. At interannual and decadal time scales, Baltic Sea level variations are strongly influenced by the strength of westerly winds, closely associated with the NAO. A positive NAO is associated with warm, humid winters and strong westerly winds which cause the sea level in the Baltic to rise; a negative NAO, associated with cold, dry winters causes a drop in Baltic Sea level. The correlation between the NAO and Baltic Sea level is particularly strong in winter and in the northern and eastern parts, while in the southern

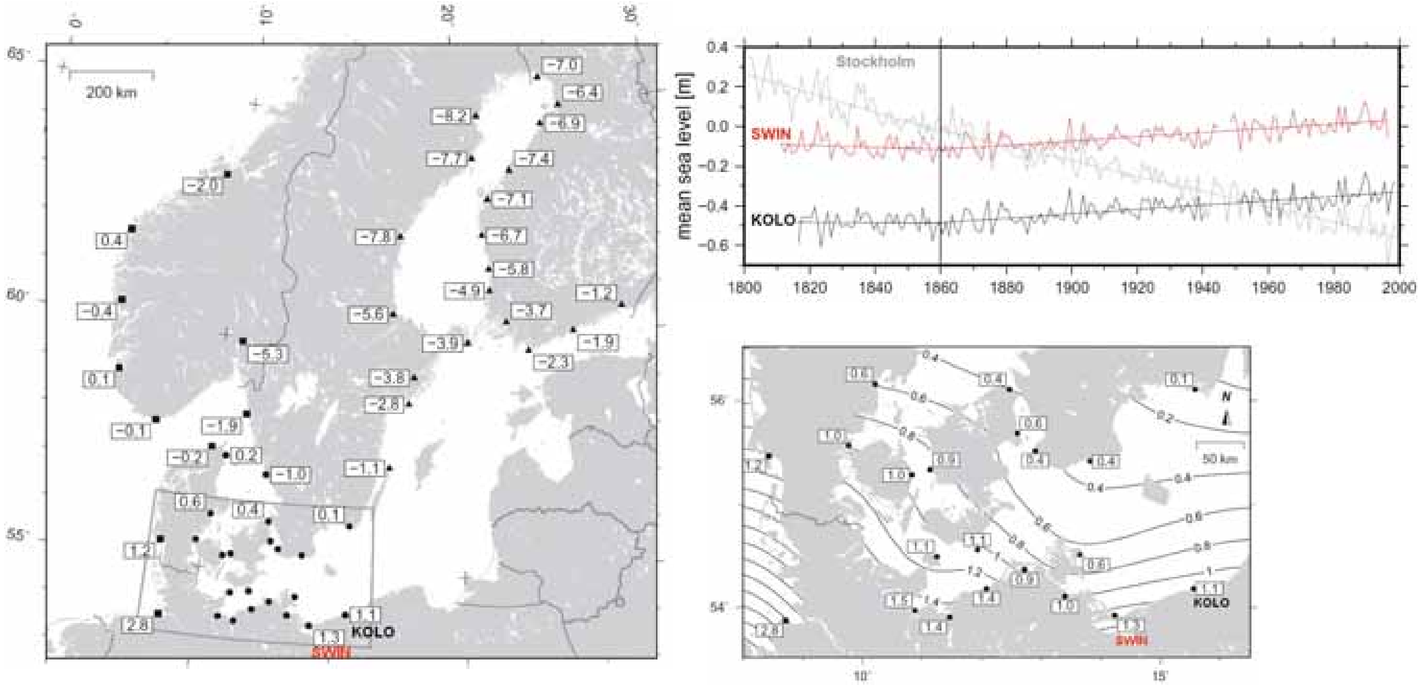


Figure 15. Maps of relative sea-level changes, based on 100-year-long tide gauge measurements, of the entire Baltic Sea region (left panel) and, in more detail, the southern Baltic coast (right panel below) together with the changes in linear trend of the (arbitrarily shifted) annual relative sea levels at Stockholm, Swinoujscie (SWIN) and Kolobrzeg (KOL) between the period before and since 1860. The symbols represent the affiliation with different reference stations (dots: Warnemünde; triangles: Stockholm; squares: Smögen) (adapted from Richter et al., 2012).

Baltic Sea the correlation is low. The strength of the correlation has changed significantly during the 20th century.

The Baltic Sea level displays considerable variability over a large range of time scales. Decadal variations in Baltic Sea level have been observed that were found to depend on season. The annual cycle of Baltic Sea level shows generally higher values during the winter months and lower values in spring, with an increase in the amplitude (winter minus spring sea level trend) during the 19th and 20th centuries.

Extreme sea levels in the Baltic Sea occur mainly due to the wind. Owing to the elongated shape, semi-enclosed configuration and the presence of shallow bays exposed to the direction of strong winds, storm surges occur every year on exposed coasts of the Baltic Sea. Winds may build up a sea level slope within the Baltic Sea, resulting in the strongest deviations at the extremities, namely, in the Belt Sea at the entrance and in the Gulfs of Finland, Riga, and Bothnia. Furthermore, when a strong persistent wind from the southwest or northeast is blowing over the Baltic Sea and its entrance, water is transported respectively into or out of the Baltic, thereby raising or lowering the sea level as a whole. Both extreme high and extreme low sea-level events tend to occur in the meteorologically more variable winter months. In general, strong westerly winds tend to raise the sea level, and strong easterly winds to lower it, in the eastern section of the sea near the coasts of Lithuania, Latvia, Estonia, Russia and Finland. The highest surges occur in the eastern part of the Gulf of Finland, particularly in bays in Estonia and eastern Finland and especially in the Neva Bay of St. Petersburg; other areas that receive major storm surges are the Gulf of Riga, particularly Pärnu Bay, and the northern part of the Bothnian Bay. At the same time, negative surges or sea level lowering occur at the coasts of Sweden, Denmark and Germany. Narrow bays in the Belt Sea and in the southwestern Baltic may receive the second highest storm surges, but also the deepest drops in water level. The higher values of relative sea level increase more rapidly or decrease more slowly in regions with isostatic uplift. This is found to be most obvious in the northern Baltic Sea, but could also be confirmed by more locally focused studies, for example, in Estonia. Finnish and Estonian tide gauges show a rise in sea level maxima of the order of 2 to 4 mm/yr.

4 Future Climate Change in the Baltic Sea Area

4.1 Introduction

Projections of future climate change make use of general circulation models (GCMs) that describe climate based on a set of grid points regularly distributed in space and time. The grid scale, i.e., the difference between two neighboring points, of present-day GCMs is in the range of 100 to 300 km. However, many important processes, such as cloud formation, convection, and precipitation, occur on much smaller spatial scales; thus, these sub-grid processes need to be approximated using simplifying algorithms termed parameterizations.

To obtain estimates of regional climate, the results of the GCMs need to be downscaled, which is a process linking large-scale variables to small-scale variables. There are two different approaches to downscaling. One uses regional climate models (RCMs) nested in GCMs. RCMs have much higher resolution and can better describe local features while still remaining able to simulate the atmospheric state in a realistic manner. The other type of downscaling method uses empirical and/or statistical relationships between the large-scale variables resulting from GCMs and small-scale variables describing regional conditions.

Climate projections are significantly different from weather forecasts. Weather forecasts cover only a few days and are based mainly on changes in the atmosphere, as the primary cause of weather changes. Climate models, on the other hand, concern statistical features of states of the atmosphere over a long time period, but they also need to take other factors into account. Climate variations are caused by changes in the environment, including the ocean, vegetation, ice, solar changes, and the composition of the atmosphere, with the strongest emphasis on the concentration of greenhouse gases (GHG) and aerosols. While some of these changes can be predicted with accuracy, others including changes in land use and greenhouse gas concentrations are not known and are very difficult to predict. Thus, scenarios are prepared of possible developments in the population and economy in the world and these are used to project how the climate may change if a particular scenario develops.

Other sources of uncertainty in model projections include limits on the amount of input data that can be used as well as the limited accuracy of such data. Models themselves are also limited because no one model can reproduce exactly the observed mean climate and its variability; an individual model may be able to describe one or a few parameters better than other models, but other models may be able to describe different parameters in a better way. No single model or method can be used for all variables and regions.

Scenarios of possible developments in the population and economy in the world are also prepared, to project factors that influence climate change. Photo: Christof Hermann.

Box: Downscaling methods

Dynamical downscaling is a methodology to obtain high-resolution climate simulations for a specific region by the application of regional climate models (RCMs). RCMs are based on limited-area versions of three-dimensional atmospheric circulation models, which in principle use the same set of dynamical equations and physical parameterizations as GCMs. They perform long-term climate change projections with an increased spatial resolution (down to about 50 to 10 km) for a specific region of interest. The main difference between RCMs and GCMs (apart from occasionally different parameterization schemes) is their lateral boundary. Because an RCM does not work globally, it does not have any information outside its modeling domain and thus needs to be provided with information on the atmospheric state at the lateral boundaries. Information on the lateral boundary conditions (LBC) is taken from the 'driving model', which can be a GCM, a global re-analysis, or from RCM output simulated on a larger domain in coarser resolution. The performance of RCMs is tested by determining whether they can reproduce the main features of the regional climate over the previous few decades when forced with realistic boundary conditions.

Statistical downscaling methods have been developed as a means to reduce the systematic biases in present climate simulations that occur with the use of RCM methodology. Statistical downscaling uses models that link simulated variables to observations. This requires that there be a strong correlation between the large-scale predictors in the GCM and the local conditions, and that these predictors are reasonably simulated by GCMs and that they capture the global warming signal. It also requires that high-quality data are available for the region for calibration. Various methods of statistical downscaling have been developed based on different calibration strategies and statistical methods.

Nonetheless, all of the techniques developed to derive regional-scale climate information are associated with uncertainties; this includes both the direct use of GCM model output as well as the use of dynamical or statistical downscaling techniques. However, uncertainties related to forcing, climate sensitivity, and natural variability can to some degree be treated by utilizing climate change information from *ensembles* that include a large number of climate change experiments. Ensembles of climate-change simulations can be constructed so that they sample different GCMs with different climate sensitivity under different emissions scenarios starting from different initial conditions. Multi-model ensemble means have been shown to outperform the single-model simulations, although for individual variables, seasons and regions single models can be found that perform better than the ensemble mean. However, different models perform better in different aspects, so there is no best model for all variables.

For global climate projections, coupled atmosphere-ocean models are now used; however, RCM climate projections are generally still conducted for the atmosphere only, using sea-surface temperature data from the driving GCM.

Natural climate variability, not related to human influences, is also an important factor in uncertainty and limitations in climate projections. It cannot be reduced but it can be described.

To determine their ability to reproduce the main features of the Baltic Sea climate over the past few decades, ten different RCMs were forced by ERA-40 reanalysis data instead of GCMs at their lateral boundaries and the ensemble of these simulations was compared to gridded observational data on seasonal mean temperature and precipitation for the Baltic Sea area. The results indicate that the temperature climate in summer is reproduced to within ±3 °C in all models in most of the region, with an exception in the southernmost part where maximum errors are above 5 °C in the warmest model. In winter, most models were too warm in parts of the northernmost basin, while in the south both over- and under-estimates were obtained. Precipitation was over-estimated in the Baltic Sea area in most models in both summer and winter, with an exception in the southern part of the basin where several models had a dry bias.

4.2 Projections of future climate change in the Baltic Sea Area

4.2.1 Projected future atmospheric changes

Temperature climate

Most regional climate change information from global models originates in recent years from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, which was used in the fourth IPCC report (IPCC, 2007). In CMIP3, about 20 different coupled atmosphere-ocean GCMs were used in a number of different experiments including simulation of the 20th century with observed forcing and with a number of scenarios from the IPCC Special Report on Emissions Scenarios (SRES) for the 21st century. In addition to GCM and scenario uncertainty, uncertainty owing to natural variability was also considered in CMIP3. Downscaling of global climate model results to the regional scale has been undertaken with a number of regional climate models including in the context of various EU-funded projects, such as ENSEMBLES. RCM climate projections are generally conducted for the atmosphere only, using sea-surface temperature data from the driving GCM. However, sea-surface temperature data taken from global models do not describe the Baltic Sea adequately. This is a major limitation, which was demonstrated in coupled Baltic Sea-RCM simulations in the EU-funded PRUDENCE project, a predecessor to ENSEMBLES.

The range of results projecting the annual cycle of temperature change for northern Sweden for 2071-2100 compared with 1961-1990 is shown in Figure 16 for 23 different CMIP3 GCM simulations and for 13 simulations in the EMSEMBLES project. Although there is a large spread between different GCMs, there is a clear increase in temperature in all seasons.

The range of differences in the temperature simulations of 13 of the RCMs from the ENSEMBLES project over the whole Baltic Sea area between 1961-1990 and 2071-2099 according to the SRES A1B scenario is shown in Figure 17. For each grid point, each of the 13 simulations were sorted and the lowest (approximate 5th percentile), median, and highest (approximate 95th percentile) were plotted for the Baltic Sea area. While the pattern of highest warming in the north in winter is similar for all models, there is a spread in the magnitude of change.

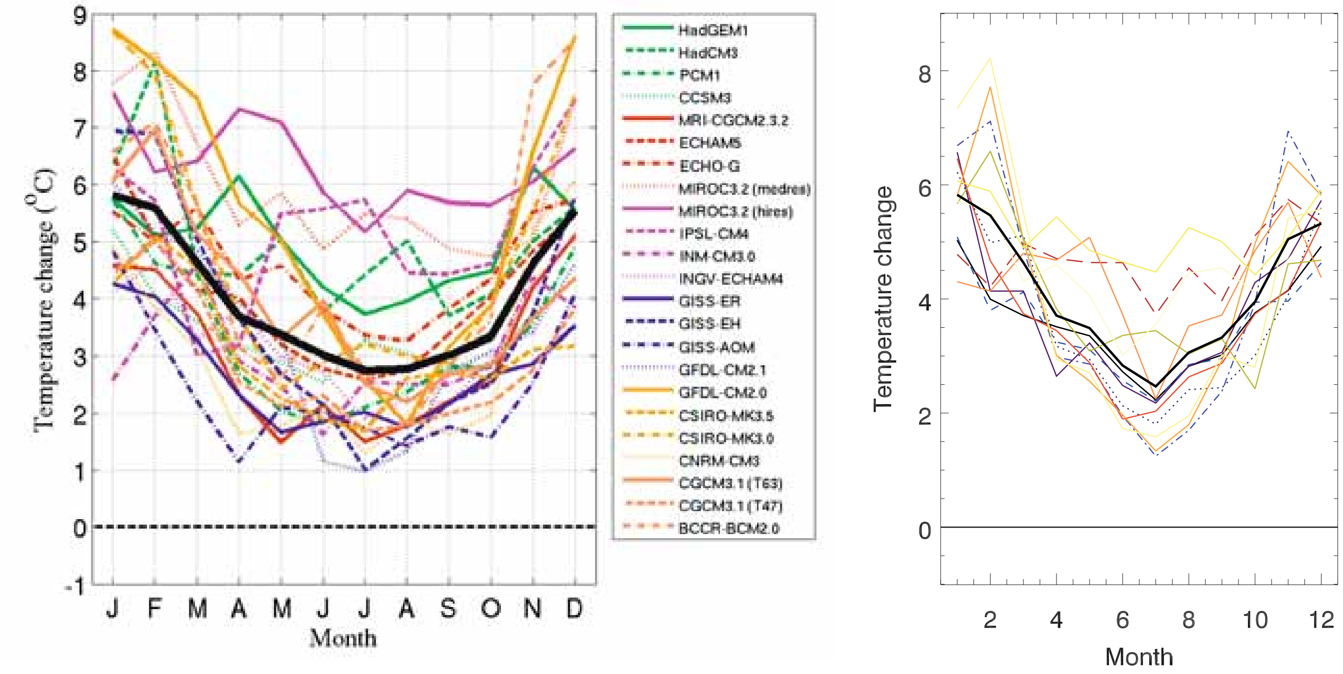


Figure 16. Projected temperature change in northern Sweden. Left panel: as calculated in 23 CMIP3 AOGCM-simulations under the SRES A1B scenario (Lind and Kjellström, 2008). 30-year averages of monthly mean data have been compared between 1961-1990 and 2071-2100. Right panel: Same quantity for 13 regional models from the ENSEMBLES project. The thick black lines are averages of the individual model results.

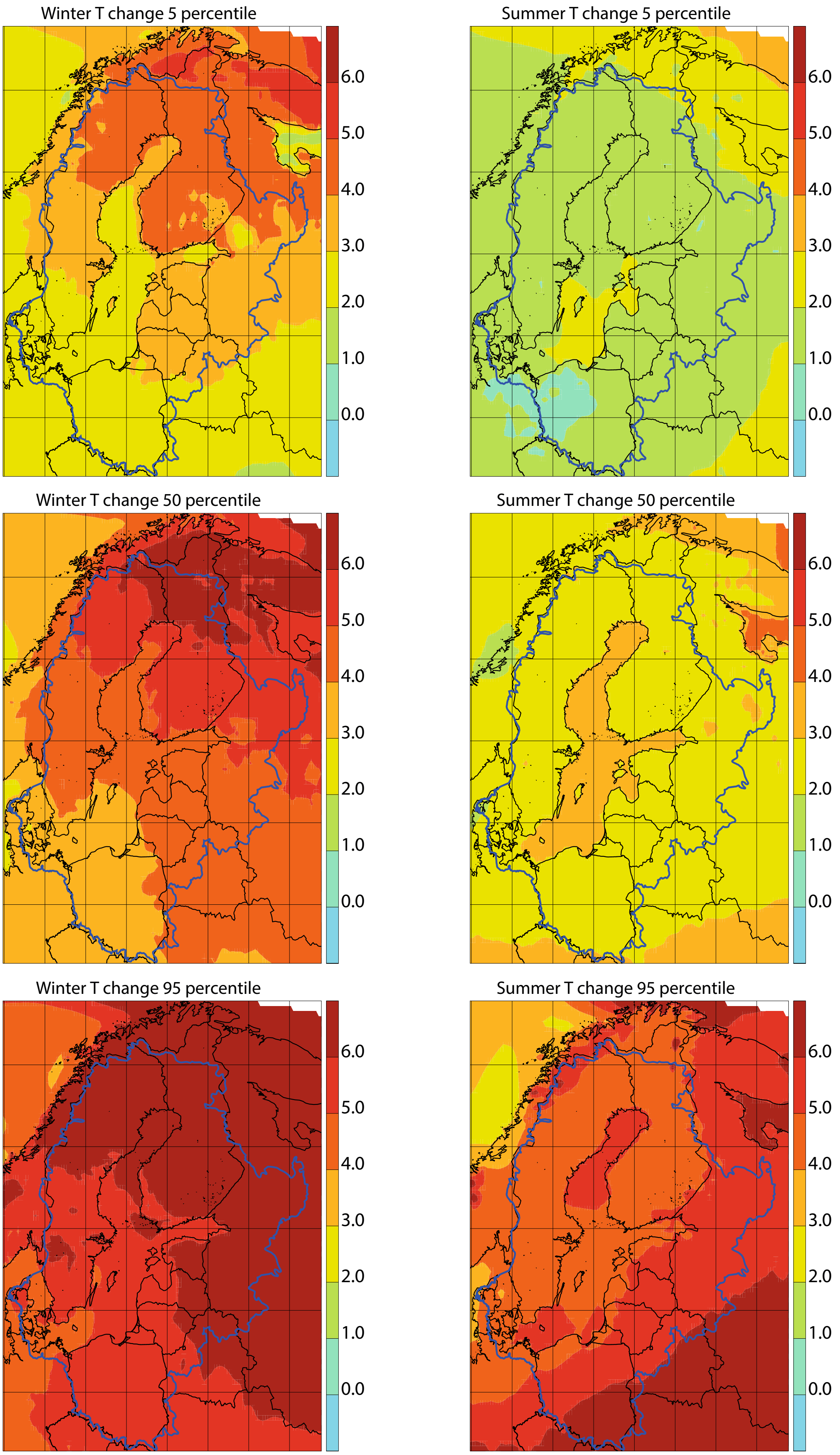


Figure 17. Surface air temperature change (°C) between 1961-1990 and 2071-2099 according to SRES A1B as simulated by 13 RCM models from the ENSEMBLES project. Left column: Winter (DJF), right column: Summer (JJA). Upper row: Point-wise smallest result (5th percentile). Middle row: Point-wise median result (50th percentile). Lower row: Point-wise largest result (95th percentile). The Baltic Sea catchment is indicated by the blue coloured line.

The overall results of these model simulations show that temperatures in the Baltic Sea area are anticipated to increase over time and the increase will generally be larger than the corresponding increase in global mean temperature. This is generally the case for the land, which will warm more quickly than the sea. It is also largely a result of the strong increase in winter temperatures resulting from feedback mechanisms associated with the retreating snow and sea-ice cover, which will enhance absorption of sunlight and increase heat storage in the soil, leading to higher temperatures. The strong increase in winter daily mean temperatures is most pronounced in the coldest periods, which is also the case for the more extreme daily maximum and minimum temperatures. Warm extremes in summer are also expected to become more pronounced than at present.

Precipitation climate

A warmer atmosphere in the future will be able to hold more moisture, thus climate models project an intensification of the global hydrological cycle. Precipitation is projected to increase in the entire Baltic Sea runoff region during winter, while in the summer increases in precipitation are mainly projected for the northern half of the basin only. For the southern part of the Baltic Sea, there is a large spread between the different models including both increases and decreases and thus little clear change in precipitation can be projected.

A similar analysis of 13 RCMs from the ENSEMBLES project as that for temperature in Figure 17 was prepared for the simulations for precipitation, as shown in Figure 18.

As the water-holding capacity of the atmosphere increases in a future warmer climate, extremes of precipitation are also projected to increase. This has implications for society as extreme precipitation is responsible for urban flooding, among other impacts. Some projections for the Baltic Sea area that show considerable decreases in average summer precipitation also show an increased likelihood of very extreme precipitation. More intense precipitation was indicated on different time scales from single rain events to long-lasting regional-scale precipitation. In addition to increased intensity of extreme precipitation events, RCM simulations also indicate an increased frequency of such precipitation extremes.

Extremes of precipitation are projected to increase. Photo: Christof Hermann.

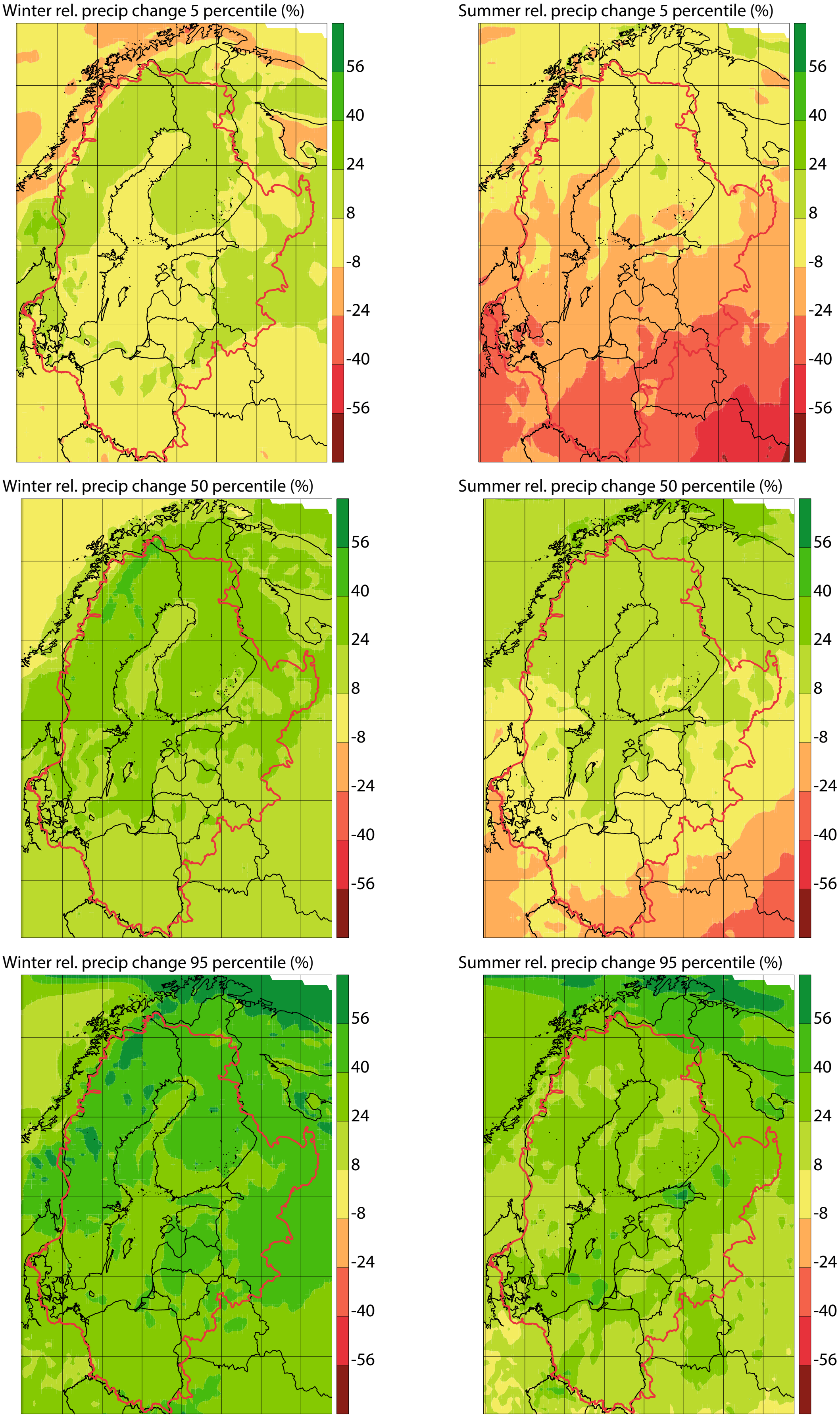


Figure 18. **Relative change in percent of average precipitation as simulated by 13 RCM models from the ENSEMBLES project. Left column: Winter (DJF), right column: Summer (JJA). Upper row: Point-wise smallest result (5th percentile). Middle row: Point-wise median result (50th percentile). Lower row: Point-wise largest result (95th percentile). The Baltic Sea catchment is indicated by the red coloured line.**

Simulations clearly show that the volume of snow will decrease in the future. Photo: Samuli Korpinen.

Snow

Simulations for the Baltic Sea area clearly show that the volume of snow in the region will decrease in the future, even though Scandinavian mountain areas may experience slight and statistically insignificant increases. However, in extreme years the maximum amount of snow could be larger than that in extreme years in the recent past climate, even if the total annual amount of snow is reduced. The southern half of the Baltic catchment area is projected to experience significant reductions in the amount of snow, with median reductions of about 75%.

The relative change in the average amount of snow in winter as simulated by 12 RCM models from the ENSEMBLES project is shown in Figure 19.

Wind climate

Projections of changes in wind climate are even more uncertain than those for precipitation climate, both in relation to seasonal mean conditions and extremes. Results for the 13 ENSEMBLES RCMs for relative change in the daily average wind speed on a seasonal basis give no clear picture, although there is a slight tendency for an increase particularly over the sea area. Simulations of extremes of wind speed show an even wider spread than those for mean wind speed, but there appear to be small median decreases in winter and small increases in summer over land areas.

4.2.2 Projected future changes in Baltic Sea hydrology

Downscaled precipitation can be used, in conjunction with temperature, to drive hydrological models and estimate changes in runoff in the future. However, the application of climate model data to drive models of climate impacts must be done with great care because climate impacts may be very sensitive not only to the simulated relative changes in climate from the present state but also to the absolute level of temperature and precipitation simulated by the climate model, which is very seldom free of bias. An analysis of the results of several regional climate models for the eastern

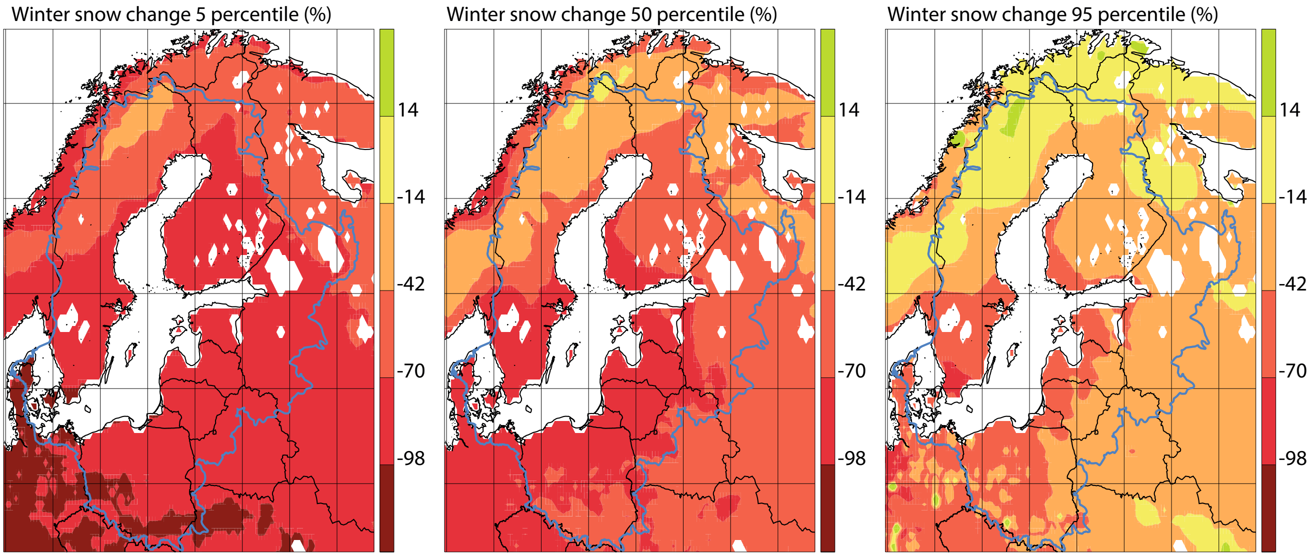

Winter snow change 5 percentile (%)
Winter snow change 50 percentile (%)
Winter snow change 95 percentile (%)

Figure 19. Relative change in percent of average winter snow amount as simulated by 12 RCM models from the ENSEMBLES project. The minimum, median, and maximum relative changes are shown.

Baltic Sea showed that the RCMs produced a reasonable cycle of temperature for this region but they clearly overestimated precipitation in winter and underestimated precipitation in summer. A bias correction method was used to bring model results much closer to observations. These corrected values of precipitation and temperature were used to estimate future changes in runoff in the eastern Baltic Sea catchment area.

Future runoff will be influenced by two factors: evaporation will tend to increase owing to higher air temperatures, but precipitation is also expected to increase in much of the Baltic Sea area. The annual cycle of runoff will also tend to change considerably, with the late spring maximum observed under the present climate shifting earlier and possibly even into February or January. This results from the increasing temperatures and an earlier onset of the melt season as well as from changes in the annual cycle of precipitation and increased evaporation. In areas that presently receive spring floods owing to the melting of snow, the floods in the future will generally occur earlier and will be smaller as there will be less snowfall and a shorter period of snow accumulation. As a result, sediment transport to the Baltic Sea will decrease as will the risk of flooding. In the southern part of the Baltic Sea, increasing precipitation in winter is expected to result in increased river discharge, while in summer decreasing precipitation and increasing temperatures and evapotranspiration will result in drying. This major shift in the annual cycle of runoff may have serious economic consequences for local societies.

4.2.3 Projected future changes in the hydrography of the Baltic Sea

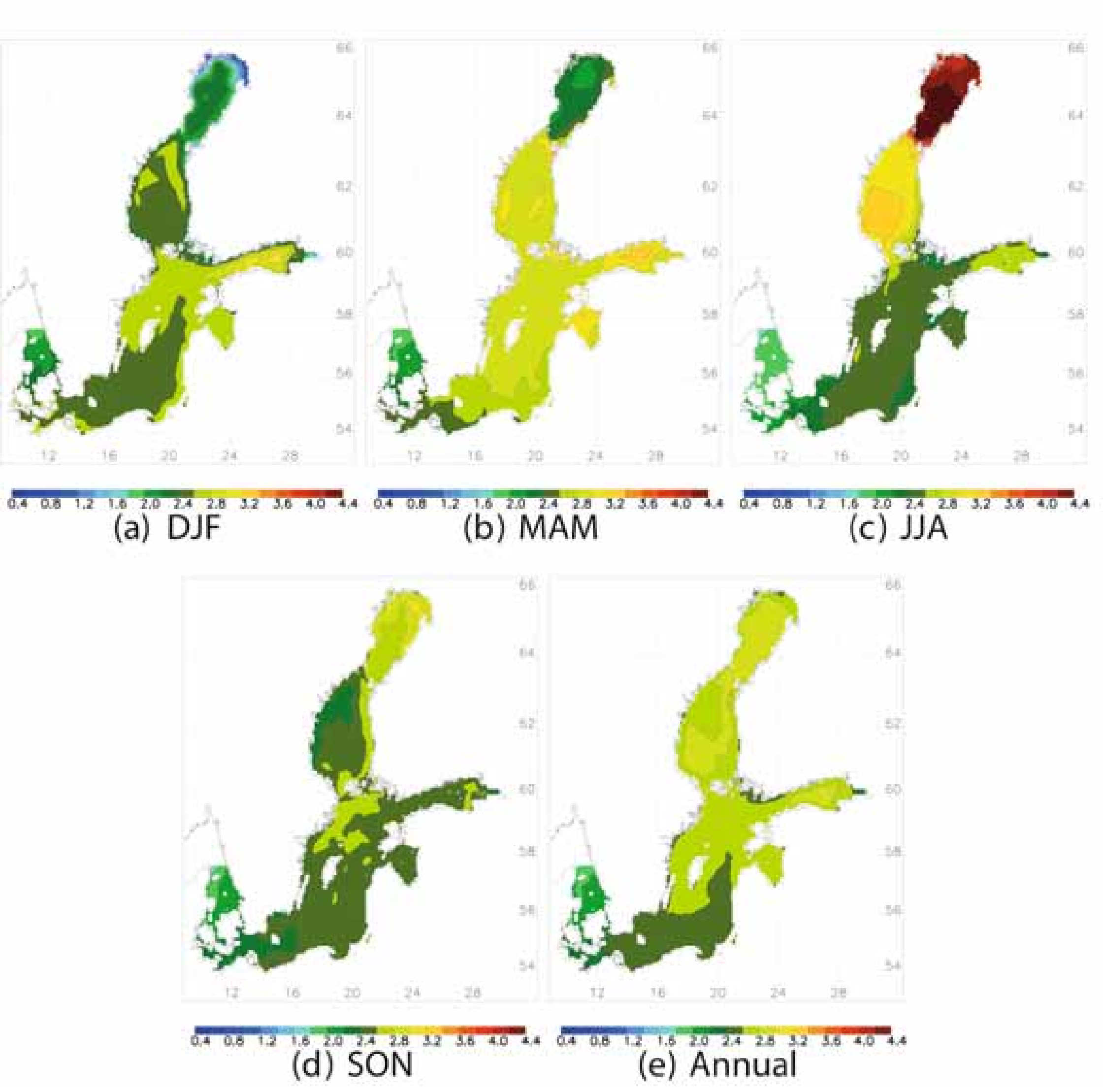
Over the past five years there has been a considerable increase in the number of relevant scenario simulations in relation to anthropogenic climate change for the Baltic Sea. This section covers mainly the results showing ensemble mean changes between 2069-2098 and 1978-2007 scenario simulations calculated with three coupled physical-biogeochemical models of the Baltic Sea forced with RCM data driven by two GCMs at the lateral boundaries and two greenhouse gas emissions scenarios (IPCC SRES A1B and A2).

In the southern Baltic, river discharge is expected to rise due to increased winter precipitation, while summer will be drier. This major shift may have serious economic consequences for local societies. Photo: Christof Hermann.

Water temperature

The annual and seasonal mean ensemble average changes in sea-surface temperature are shown in Figure 20. The largest changes are projected to occur in the Bothnian Bay and Bothnian Sea during summer and in the Gulf of Finland in the spring. Using the A1B and A2 emissions scenarios, the summer sea-surface temperature will increase about 2 °C in the southern parts of the Baltic Sea and about 4 °C in the northern parts. At least part of the larger change in the northern Baltic is caused by the ice-albedo feedback owing to the decrease of sea ice in winter. In all sub-basins of the Baltic Sea the surface water layer is projected to warm more than the deep water. This would be expected to cause greater vertical stratification and greater stability across the seasonal thermocline; however, the projected changes in salinity dominate over the temperature changes and scenario simulations imply that there will be a decrease in vertical stratification across the permanent halocline between the surface and deeper water layers. There is currently no scientific consensus on the overall impact on vertical stratification.

Owing to the use of regionally limited models with lateral boundaries in the Kattegat or Skagerrak, these results are not reliable for the Kattegat. A separate study investigating both the Baltic Sea and the North Sea simultaneously found that the warming is larger in the Baltic Sea than in the North Sea. These results are also in accordance with a larger study that found that the shelf sea



(a) DJF (b) MAM (c) JJA

(d) SON (e) Annual

Figure 20. Seasonal (DJF, MAM, JJA, SON) and annual mean ensemble average sea-surface temperature changes (in °C) between 2069-2098 and 1978-2007 using the A1B and A2 emissions scenarios (see Meier et al., 2012).

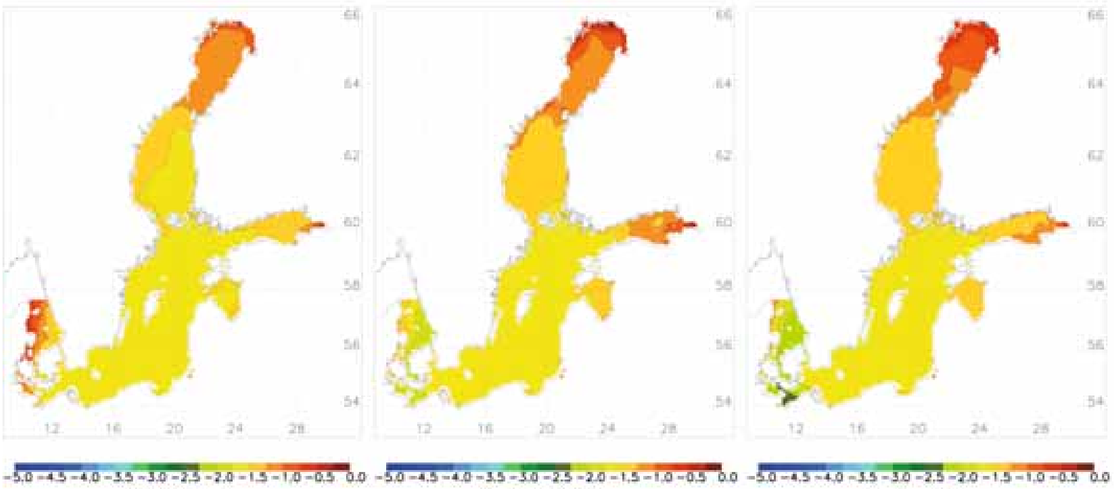
regions will warm substantially more than the open ocean.

Salinity

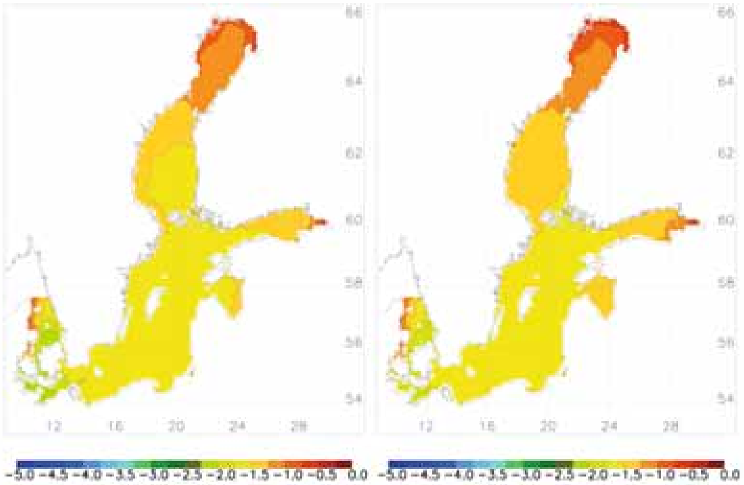
Results of multi-model simulations indicate that changes in sea-surface salinity will be largest in the region of the Danish straits, especially in the Belt Sea, and small in the northern and eastern Baltic, with the smallest change in the Bothnian Bay (Figure 21). Changes in sea-surface salinity are projected to be rather uniform among seasons.

In the Bornholm Basin and the Gotland Basin, the reductions in salinity with depth are nearly constant and were 1.5 to 2 g/kg in the ensemble mean; changes in the deep water were somewhat larger than in the surface layer in these sub-basins. In more weakly stratified basins, such as the Gulf of Finland and the Bothnian Bay, there were larger differences in salinity changes in the surface and bottom layers, causing a reduction in the vertical stability.

In the ensemble presented here, the changes in salinity are caused by a changing runoff that was projected to increase by between 15% and 22%, as estimated from the difference between precipitation and evaporation over land calculated from the RCM output directly. However, if a hydrological model is run with the same atmospheric forcing, the changes in runoff would be somewhat smaller, with increases between 4% and 13%.



(a) DJF (b) MAM (c) JJA



(d) SON (e) Annual

Figure 21. **Seasonal (DJF, MAM, JJA, SON) and annual mean ensemble average changes in sea-surface salinity (in g/kg) between 2069-2098 and 1978-2007 using the A1B and A2 emissions scenarios (see Meier et al., 2012).**

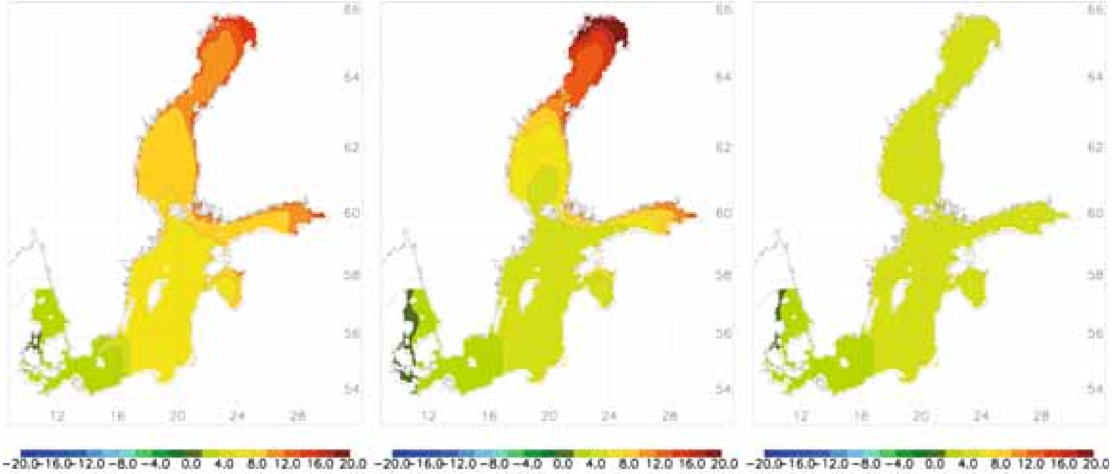
Sea ice

The future reduction of sea-ice cover in the Baltic Sea mainly depends on the projected changes in air temperature during winter, with other factors such as the wind being less important. Although the projections depend on the greenhouse gas emissions scenario, the GCM, and the Baltic Sea model used, all new scenario simulations indicate that there will be a drastic decrease in the sea-ice cover in the Baltic Sea in the future; this is in agreement with earlier studies.

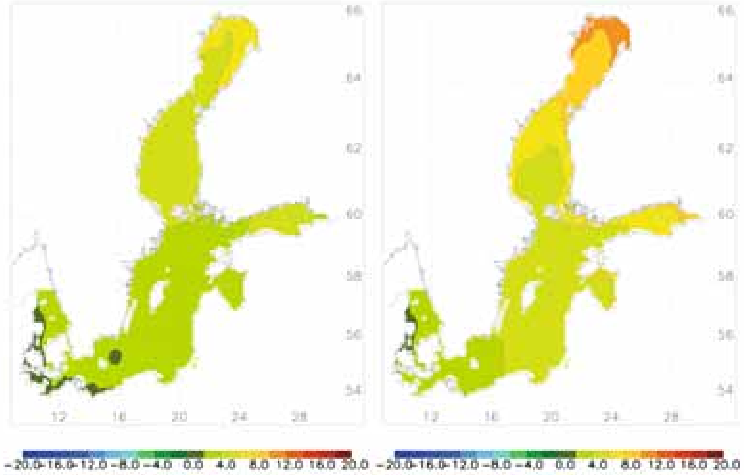
Storm surges

The results of multi-media ensemble simulations of projected changes in sea-level extremes caused by changes in the regional wind field indicated that at the end of the 21st century the largest changes in mean sea-surface height will occur during spring, amounting to up to 20 cm in coastal areas of the Bothnian Bay (Figure 22). The maximum change in the annual mean sea-surface height will be 10 cm. However, these results do not take into account large-scale sea-level rise or the land uplift in the Baltic Sea area.

Another study that also took into account available global sea-level rise scenarios and simulated regional wind speed changes found that sea-level rise has a greater potential to increase storm surge levels in the Baltic Sea than does increased wind speed. This study projected large increases of storm surge levels at the entrance to the Baltic Sea, but the relative impact of changing wind speed on



(a) DJF (b) MAM (c) JJA



(d) SON (e) Annual

Figure 22. **Seasonal (DJF, MAM, JJA, SON) and annual mean ensemble average changes in sea-surface height (in cm) between 2069-2098 and 1978-2007 using the A1B and A2 emissions scenarios (see Meier et al., 2012).**

sea-level extremes may be even greater for areas in the eastern Baltic, such as St. Petersburg.

Sea level

Sea levels are rising owing to global warming, primarily as a result of the loss of ice masses on land and the thermal (steric) expansion of seawater. Sea-level rise varies in complex spatial patterns depending on a number of factors. In addition, in the Baltic Sea relative sea level is influenced by the large ongoing Glacial Isostatic Adjustment resulting from the loss of the Fennoscandian ice sheet at the end of the last glacial period.

In past centuries, there was a balance between the radiation from the sun reaching the Earth and being absorbed by it and the amount that was re-radiated to space as heat. However, the increasing concentrations of greenhouse gases in the atmosphere are trapping more of the re-radiated heat from the Earth's surface causing more energy to be retained on Earth, thus creating an energy imbalance. Most of this energy imbalance will be absorbed by the oceans, which will cause a thermosteric expansion of the oceans. This expansion will be largest in the open ocean where the water is deepest. Even though the steric effect will be very small in the comparatively shallow Baltic Sea, the increase in ocean steric sea-surface heights will drive a redistribution of ocean mass from the interior of the ocean to shallower regions. Changes in ocean circulation and in the hydrological cycle will also induce thermosteric and halosteric changes.

Surface mass loss of land-based ice, particularly from the Antarctic Ice Sheet and the Greenland Ice Sheet, as well as from the many thousands of mountain glaciers and ice caps, will also contribute to global mean sea-level rise. It has been difficult to estimate the amount of this mass loss and particularly to project future land-based ice loss because models cannot reproduce the rapid dynamic loss of mass of the ice sheets that has occurred in recent years. On a relative basis, however, owing to the geoid changes induced by the melting of the large ice sheets (resulting from changes in gravity owing to the loss of ice mass and resulting upward movement of the land under the ice sheet and subsidence of ocean basins receiving the meltwater), the Baltic Sea will only experience a small fraction of the global average sea level contribution from the mass loss from the Greenland Ice Sheet, but a slightly greater than average response from the Antarctic Ice Sheet.

The magnitude of future sea level rise is highly contested in the scientific community, and several more years may be needed to reconcile the various estimates. More data extending over longer periods are needed, in particular for estimating the contributions from Greenland and Antarctica. The forthcoming IPCC AR5 report is expected to summarize the state of knowledge regarding the global issue, with the change in the Baltic Sea strongly conditioned by these global changes.

There is considerable uncertainty in projections of sea-level rise over the 21st century, and disagreement over the level of confidence assigned to different modeling approaches. A compilation of mid-range and high-range sea-level rise scenarios, prepared through an assessment of process model projections and uncertainties, projected respectively a 0.6 m and 1.1 m sea-level rise in the Baltic Sea over the 21st century. This local sea level rise is partly compensated by vertical land movement, as described in Section 3.3, above, for different regions of the Baltic Sea.

Thermosteric: The ocean expands as it warms and therefore a warming ocean will drive a 'thermosteric' rise in sea level even without additions to the ocean mass from the melting of land-based ice.

Halosteric: Seawater density is also a function of the salinity because seawater expands when it becomes fresher and contracts when it becomes saltier; this contribution is termed 'halosteric' sea-level rise.

5 Impacts of Current and Future Climate Change

5.1 Impacts on marine biogeochemistry

The biogeochemical processes in the marine environment of the Baltic Sea are mainly controlled by the biological production and decomposition of organic matter taking place in the context of the hydrography of the region. Carbon, nitrogen, phosphorus and oxygen are the major elements in these processes, and their distributions and concentrations strongly influence the ecosystem of the Baltic Sea. The availability of the major nutrients nitrogen and phosphorus influences the formation of organic matter and this, in turn, affects the oxygen conditions in deeper water layers where organic matter is mineralized, consuming oxygen and possibly eventually producing highly toxic hydrogen sulfide. Thus, eutrophication is an important factor in the Baltic Sea biogeochemical processes. Carbon is not only the backbone of organic matter, but its inorganic form, CO_2, also largely controls the acid/base balance of seawater, which is gradually shifting to more acidic conditions owing to the rising atmospheric concentrations of CO_2.

External forcing, including both climate-driven forcing and the input of biogeochemically reactive substances via rivers, water exchange with the North Sea and the atmosphere, has a strong impact on biogeochemical processes and internal fluxes. Physical forcing controls water transport, stratification, temperature and salinity in the Baltic Sea; these then influence the distribution of nutrients and carbon and thus have an impact on biogeochemical processes.

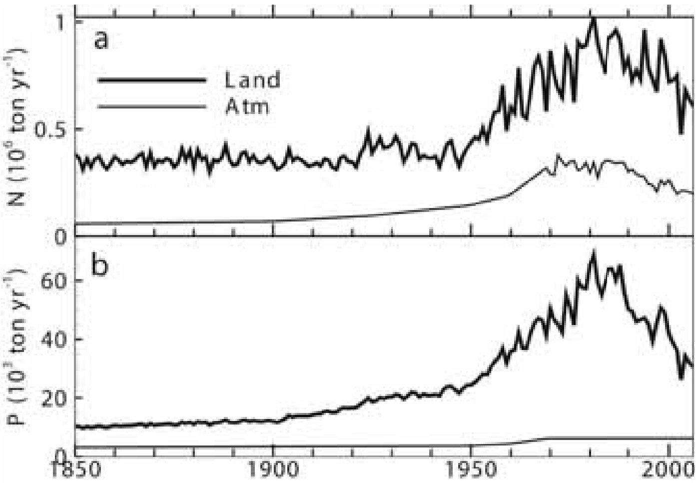


Figure 23. **Historical development of the waterborne and airborne a) total nitrogen and b) total phosphorus inputs into the Baltic Sea (Gustafsson et al., 2012).**

Agriculture in the Baltic Sea catchment area has caused increases in inputs of nitrogen and phosphorus over the past 150 years. Photo: Metsähallitus NHS / Jan Ekebom.

Anthropogenic activities such as agriculture and industrialization in the Baltic Sea catchment area have caused large increases in inputs of nitrogen and phosphorus over the past 150 years (Figure 23). These inputs peaked around 1980, after which emission reduction measures brought the inputs of these substances down to about their levels around 1960.

Blooms of nitrogen-fixing cyanobacteria also provide a significant input of nitrogen to the Baltic ecosystem through nitrogen fixation, thus increasing the production of organic matter and sedimentation. Cyanobacteria blooms are formed by the species *Nodularia* spp., *Aphanizomenon* spp., and *Anabaena* spp., which are favoured by high water temperatures and calm conditions. This input by nitrogen fixation is comparable to the annual riverine nitrogen inputs to the Baltic Proper. An increase in nitrogen fixation by cyanobacteria of 30% over the past two decades in the central Baltic Sea has been estimated.

Surface winter concentrations of dissolved inorganic nitrogen (DIN) and, with the exception of the Bothnian Bay, also dissolved inorganic phosphorus (DIP) have increased in all basins of the Baltic Sea since monitoring began in the 1970s (Figure 24). Since the mid- to late 1980s, winter DIN concentrations have been observed to decrease in all Baltic sub-basins except the Bothnian Bay. This decline in winter DIN while DIP remained high has resulted in a strong decrease in DIN/DIP ratios in the Baltic Proper, Gulf of Finland and Gulf of Riga since the mid- to late 1980s.

The increase in winter nutrient concentrations is reflected by increases in primary production. Measurements in the Kattegat and Belt Sea area showed that eutrophication resulted in a doubling of primary production between 1950 and 1980; estimates for the Baltic Proper also indicate a doubling of primary production in the 1970s and 1980s since the early 20th century. This has resulted in large increases in sedimentation, with model estimates of a doubling in sedimentation since the 1950s and a nearly fourfold increase since 1900.

Organic matter in the sea ultimately undergoes biologically induced oxidization, termed mineralization, which is an oxygen-consuming process that plays a key role in the cycling of carbon and nutrients. In the Baltic Sea, the oxygen conditions are a result of the physical transport of oxygen and the consumption of oxygen by biogeochemical processes. Owing to the permanent density stratification in the central basins, oxygen cannot be transported from the surface waters to the deeper waters below, which can only be ventilated by dense inflowing water from the entrance to the Baltic. Part of the organic matter produced in the surface layer of the Baltic Sea sinks down into the deeper waters and is oxidized there, thus decreasing the oxygen concentrations of the deep water.

Eutrophication is the main factor controlling the low oxygen concentrations in the deep water of the Baltic Sea during the past 100 years. The occurrence of oxygen deficiency and the production of hydrogen sulfide have become much more frequent in recent decades, particularly in the deep water of the Gotland Deep.

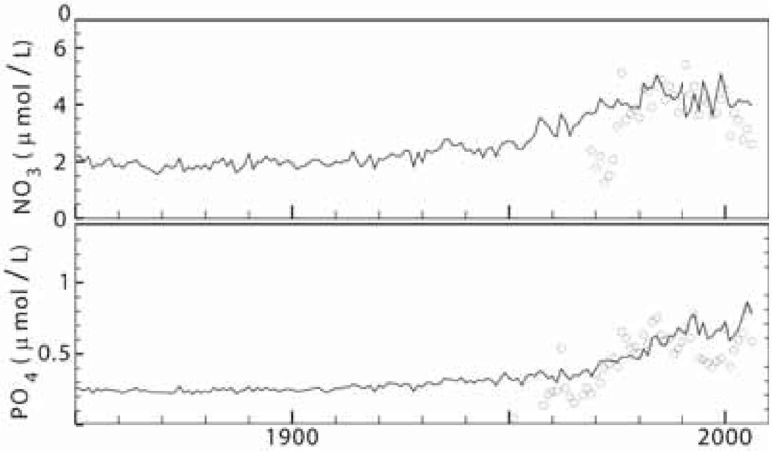


Figure 24. Simulated (line) and observed (dots) winter nutrient concentrations in the surface layer of the central Baltic Sea (Gustafsson et al., 2012).

The sediments are also the site of processes that affect the cycling of nitrogen and phosphorus. An important process in the nitrogen balance is denitrification, by which nitrate is reduced to elemental nitrogen and thus removed from the nutrient pool. Denitrification is most effective in the organic-rich upper sediment layers that are in contact with oxygen-containing water. Although there are no long-term data on the amount of denitrification in the Baltic Sea, it may be considered to have increased with the increasing primary production. Phosphate in the water column can be adsorbed onto particulate material and sediment onto the sea bottom. Under oxic conditions in iron-rich sediments, phosphate is adsorbed onto iron-oxyhydroxides at the surface; this form of phosphorus is abundant in surface sediments under oxic bottom water in the Baltic Sea. However, when the bottom waters become anoxic, the phosphate is released from the sediment (Figure 25) and can enhance eutrophication if vertical mixing in the water column can bring the released phosphate to the productive surface layers.

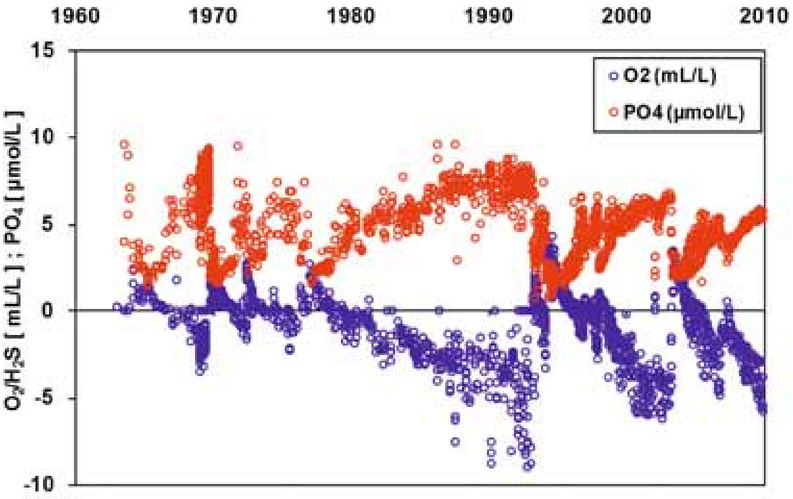


Figure 25. Variation in the concentration of dissolved O_2 in the deep water in the central Gotland Sea followed by variations in PO_4 concentrations from the mid-1960s to the present. Negative O_2 represents the concentration of H_2S (Swedish National Monitoring, SMHI).

Large amounts of inorganic and organic carbon also enter the Baltic Sea via rivers. Most of the organic carbon is in the form of dissolved organic carbon (DOC), and more than 50% of the annual input of DOC is mineralized in the Baltic Sea and thus converted to CO_2. The annual inputs of inorganic carbon from land-based sources are approximately 60% larger than those of organic carbon. The concentrations of total CO_2 in river water are mainly controlled by the alkalinity, which results primarily from limestone dissolution in the catchment area. Increases in the input of alkalinity to the Gulf of Finland via the Neva River and also to the eastern Gotland Sea have occurred during the past century, resulting in an increase in pH of 0.02 to 0.03 units since the 1930s. This can be seen in contrast to the rising concentrations of atmospheric CO_2 that cause enhanced dissolution of CO_2 and decrease the pH in seawater. The rate of increase of atmospheric CO_2 has grown since 2000 and is now averaging 2.0 ppm/yr (Figure 26).

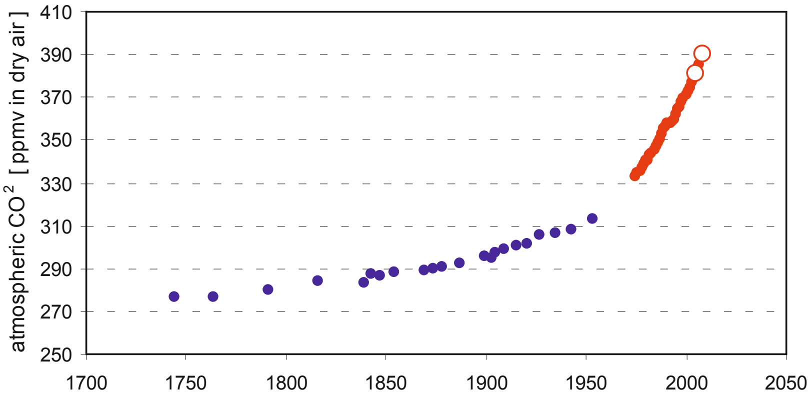


Figure 26. Annual mean for atmospheric CO_2 obtained from the analysis of air in ice cores (blue) (Neftel et al., 1994) and direct atmospheric measurements (red) at the northern hemisphere background station Barrow in Alaska (full red circles) (Keeling et al., 2008) and over the Baltic Sea (open red circles) (Schneider, 2011).

The marine CO_2 system regulates the pH of seawater. The large-scale distribution of total CO_2 in the Baltic Sea is widely controlled by the alkalinity, which originates mainly from the weathering of limestone in the catchment. This arrives mainly from the southern and eastern rivers that carry large amounts of alkalinity from limestone-rich catchment areas. An important variable for the CO_2 system is the CO_2 partial pressure, pCO_2, which is proportional to the CO_2 concentration. The pCO_2 is directly associated with the pH and shows a pronounced seasonality, with a high pH of about 8.5 during the spring/summer productive period and a low pH of around 7.9 during the deepening of the mixed layer in autumn/winter.

The uptake of anthropogenic atmospheric CO_2 also causes changes in the marine CO_2 system. The increase of atmospheric CO_2 from 280 ppm during the pre-industrial era to a level of almost 400 ppm in 2010 has led to a corresponding increase in the mean pCO_2 in surface water. In marine systems, this would be expected to cause a decrease in the pH by 0.15 units; however, the increase in alkalinity in the central parts of the Baltic Sea over the past 60 years has diminished this decrease by roughly 0.03 units. Increasing dissolution of atmospheric CO_2 normally also implies a decrease in the calcium carbonate saturation, which may affect the growth of organisms that form shells consisting of calcite or aragonite. However, owing to the eutrophication-related high biological production, large quantities of CO_2 are consumed, overriding the effect of the increasing atmospheric pCO_2 in the upper water layers during spring and summer in the past few decades. This has resulted in a strongly enhanced calcium carbonate oversaturation of surface water during the spring and summer. However, the increased production also results in increased mineralization and high CO_2 concentrations in deeper water layers that are mixed into the surface during autumn and winter adding to the elevated atmospheric CO_2, thus causing an enhanced undersaturation of calcite and aragonite later in the year.

The removal of carbon, nitrogen, and phosphorus from the ecosystem through burial is important in relation to eutrophication and the CO_2 balance. In the Baltic Sea, the large input of terrestrial material, the shallow water column, eutrophication causing the production of organic matter, and the variable topography of the sea bottom all influence sedimentation and the burial of carbon, nitrogen and phosphorus. Burial in the open sea is effective in the deep basins, which accumulate resuspended material from erosion and transportation areas. Anoxic conditions favour the burial of organic matter, but not of phosphorus owing to its release from iron compounds under anoxia. Estimates indicate that the long-term sedimentation of organic matter, affecting the burial of carbon, nitrogen and phosphorus, has increased in the Baltic Sea during the second half of the 20th century.

There is limited knowledge of the impact that future changes in climate and other anthropogenic drivers will have on the biogeochemical cycles of the Baltic Sea. Various factors may influence these cycles in different ways. Changes in precipitation and runoff patterns will influence the inputs of nutrients and organic matter to the Baltic Sea. Higher temperatures will decrease the solubility of oxygen in seawater as well as accelerate many biological and biogeochemical processes. Future warming is expected to increase hypoxia given that temperature controls the stratification of the water column, the respiration of organisms, and the solubility of oxygen. Increasing areas of hypoxia and anoxia are anticipated owing to the increased nutrient inputs due to increased runoff, the reduced oxygen flux from the atmosphere due to higher temperatures, and the intensified biogeochemical cycling including mineralization of organic matter. Hypoxic and anoxic events are also expected to occur over longer periods in the main southern and central basins of the Baltic Sea. These projected changes in biogeochemical fluxes indicate that, even if nutrient loads are reduced according to the Baltic Sea Action Plan, it will only stabilize the Baltic ecosystem close to its present state. However, it must be emphasized that, at the present state of knowledge, the effects of climate change on stratification and the ventilation of deeper waters remain unclear.

Warming will also preferentially favour cyanobacteria blooms, which are expected to begin earlier in the summer and may increase nitrogen fixation. Pessimistic 'business-as-usual' scenarios for nutrient loads could result in increased negative effects on the marine environment in a future climate, with higher phytoplankton concentrations than at present.

In addition to eutrophication, the decreasing pH caused by increasing atmospheric CO_2 concentrations is considered a potential major threat. A biogeochemical model has been prepared that includes the cycling of carbon, and thus the marine CO_2 system, in seawater coupled with a catchment model to account for climate-induced changes in the riverine inputs of total CO_2 and alkalinity and of dissolved organic carbon (Omstedt et al., 2012). Simulations with the coupled models were performed for a variety of different climate, nutrient load, and land cover scenarios. The simulated development of pH until 2100 under a best-case and a worst-case forcing scenario is shown in Figure 27. The best-case climate change scenario is based on reductions of CO_2 emissions resulting in atmospheric CO_2 concentrations of about 550 ppm in 2100 combined with reduced nutrient loads to the Baltic Sea according to the Baltic Sea Action Plan. For the worst case, SRES A2 was used leading to a final CO_2 concentration of about 850 ppm and

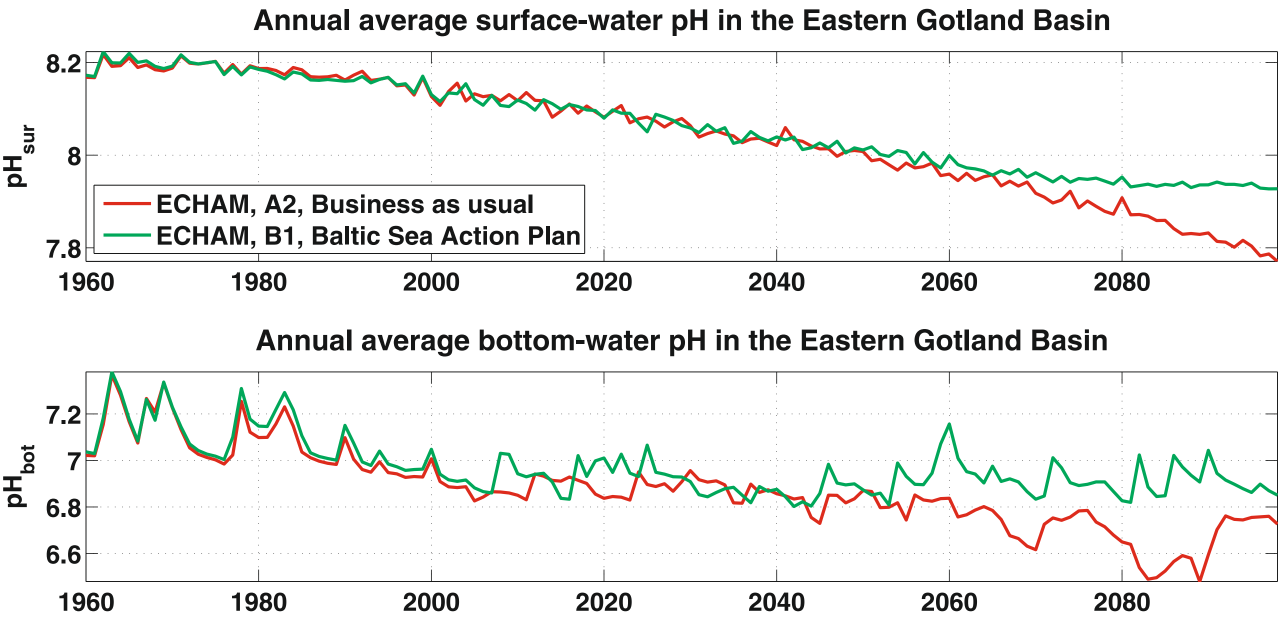


Figure 27. **Simulation of the surface and deep water pH in the eastern Gotland Sea. The temporal development was calculated for a worst-case scenario: atmospheric CO_2 increase up to 850 ppm and nutrient inputs according to business as usual (red lines) and a best-case scenario: moderate increase of atmospheric CO_2, up to 550 ppm and nutrient inputs according to the Baltic Sea Action Plan (green lines) (Omstedt et al., 2012).**

an increase in the nutrient loads according to business as usual. A decrease in pH of about 0.40 for the worst-case and 0.26 for the best-case scenario was found, with the changes in the surface water pH almost entirely due to rising atmospheric CO_2 concentrations. Although increasing nutrient loads caused enhanced biological production, changing the seasonal pH amplitude, they had no effect on the mean pH.

5.2 Impacts on the marine organisms and ecosystem of the Baltic Sea

Climate change may affect species ranges, biodiversity, and ecosystem functioning. Effects can include changes in the ecology of species, i.e., their physiological response, climate niche requirements, and dispersal capacities; the evolution of species, involving contemporary micro-evolution and macro-evolutionary trends; and the interactions between species, including changes in competition, facilitation and trophic relationships. Climate effects may directly affect individual organisms, their growth, survival and productivity, through changes in the properties of the water (for example, water temperature, salinity, chemical composition as well as such properties as stratification and water mixing) or they may cause indirect effects by changing species interactions or the seasonal succession, creating a mismatch of populations. These interactions affect the intensity of grazing, predation and competition and shape the structure and diversity of biological communities.

Temperature is the fundamental climate-driven factor that directly affects individual organisms. It drives biological processes and supports life-history traits, population growth, and ecosystem processes. An increasing temperature will favour warm-water species, including those from outside the Baltic Sea, but a high water temperature may also be harmful, especially to cold-water organisms. Salinity is also a fundamental factor because most of the species in the Baltic Sea are of either freshwater or marine origin; an increase in salinity would induce osmotic stress on freshwater species while a decrease would stress marine species. The oxygen concentration and pH of seawater are among other climate-driven factors that have direct effects on individual organisms.

Climate effects may directly affect individual organisms, their growth, survival and productivity. *Idotea balthica*. Photo: Metsähallitus NHS / Pauliina Ahti.

Phytoplankton and the microbial food web

Changes in freshwater discharge and the associated nutrient loads are expected to affect the total biomass and composition of the phytoplankton community in the Baltic Sea in both spring and summer. The spring bloom is dominated by only a few species of diatoms and cold-water dinoflagellates and the relative proportion between these two groups depends on water temperature and ice conditions, with warm winters favouring dinoflagellates. This could imply that climate change will promote a dominance of dinoflagellates in the Baltic spring bloom; however, the response of dinoflagellates to large-scale climate patterns is basin-specific, depending on local hydrography and community composition. Thus, an increase in dinoflagellates has only been found in the central and northern Baltic Proper, but not in the Baltic Sea as a whole. Species shifts in the spring affect the food web and thus the biogeochemistry and functioning of the pelagic ecosystem during the summer.

Long-term changes in the phytoplankton communities in the northern Baltic and Gulf of Finland have occurred, indicating a decline in the spring bloom, but an increase in the phytoplankton biomass during summer over the past 30 years. These changes appear to reflect both climate-induced hydrographic changes and the eutrophication process, with a decreased availability of nitrogen in the spring resulting in larger phosphate reserves in the summer (Table 1). The summer sea-surface temperature and the winter nitrate concentrations were the most important factors influencing the phytoplankton community in the Gulf of Finland.

Although an enhanced freshwater discharge with associated input of inorganic nutrients to the central Baltic Sea has been projected to increase primary production, this is not applicable to all basins. For example, studies indicate that increased freshwater runoff into the Gulf of Bothnia may cause a decreased primary production because riverine discharge in this area carries a large load of brown-coloured dissolved organic carbon (DOC) in addition to increased nutrient availability. This DOC reduces the amount of light that reaches the phytoplankton while also serving as a substrate for bacterial production, which may allow the bacteria to outcompete the phytoplankton for nutrients. An enhanced activity of the microbial loop (bacteria–nanoflagellates–protozoans–metazooplankton) will add length and complexity to the food web, which will decrease the food-web efficiency compared to a simpler system dominated by the phytoplankton–zooplankton grazing chain. Thus, the influence of climate change on the phytoplankton and microbial food web will depend on the basin-specific nutrient and carbon dynamics.

At present, the influence of future climate conditions on water stratification in the Baltic Sea is not clear. One possibility is that, under a future climate, the higher surface-water temperatures may enhance thermal stratification, which would favour summer communities such as the cyanobacterium *Nodularia spumigena*. Climate change may thus prolong the cyanobacterial bloom season in the Baltic Sea, which could shift the main productive period from spring to summer. Changes in the composition of the spring bloom community would also influence the quantity and quality of organic matter sinking to the seabed and thus also affect the benthic dynamics. The spring bloom, consisting mainly of diatoms and dinoflagellates, is the most important input of high-quality organic matter to the macrobenthic community below the halocline, while cyanobacteria are poor food for both pelagic and benthic consumers.

Table 1. Summary of short-term effects of freshwater discharge and temperature on the microbial food web and phytoplankton as reported in the current literature. Where effects are similar for the climate drivers, synergistic consequences for the food web are expected.

Food web component	Higher freshwater discharge	Higher temperature
Phytoplankton	Reduced productivity	Lower biomass and size / No consensus
Bacterioplankton	Maintained growth	Increased growth
Protozooplankton	Maintained growth	Increased growth
Sedimentation	Reduced amount and quality	Reduced amount and quality
Food web efficiency	Reduced efficiency	No consensus

Zooplankton

Climate change may exert direct effects on zooplankton in the Baltic Sea because salinity and temperature play important roles for key mesozooplankton species. This has been shown by a decline in *Pseudocalanus acuspes*, a marine species that is an important source of food for cod larvae and planktivorous fish, when the salinity declined in the Baltic during the 1980s. A positive correlation was found between the copepods *Acartia* spp. and *Temora longicornis* and spring temperature in the central Baltic Sea.

Hydrographic conditions, such as periods of low salinity usually cause a decline in marine zooplankton, which is the food preferred by clupeids including sprat and herring. Photo: Riku Lumiaro / SYKE.

The emergence of a new population of Baltic copepods, many species of which overwinter as resting eggs in the sediments, may be influenced by the timing of ice melt and the warming of the water in spring, which are strongly controlled by climate. Mesozooplankton in many coastal areas, including the Gulf of Riga, the Archipelago Sea, and the east coast of Sweden, have been shown to respond positively to mild winters. In late summer and autumn, climate-induced changes in populations of planktivores such as clupeids may also influence zooplankton populations by heavy predation. The quality of food for zooplankton, which is indirectly influenced by climate variation, also affects the growth rates and population dynamics of zooplankton.

It is difficult to predict zooplankton dynamics and thus their response to climate change, however, as zooplankton dynamics are controlled by both hydroclimatic forces and predation pressure, which in turn are affected by environmental variables and fisheries, and the relative importance of these factors varies spatially, seasonally and interannually.

Fish

In the central and northern Baltic Sea, hydrographic conditions influence the upper levels of the pelagic ecosystem including the zooplankton, planktivores such as clupeid fish, and piscivores particularly cod. Periods of low salinity usually cause a decline in marine zooplankton, which is the food preferred by clupeids including sprat and herring, thus lowering the food availability for these planktivores. On the other hand, the warmer water of mild winters increases the survival of sprat eggs thus increasing sprat recruitment. Many hydrographic factors affect the reproduction of Baltic cod, which depends on the volume of sufficiently saline and oxygenated water for egg development. After spawning, cod eggs sink to a depth at which they are neutrally buoyant, at a salinity of about 11; if water at this depth is too low in oxygen, the eggs die.

This climatic and hydrographic influence can be seen by the 'regime shift' that occurred in the central Baltic in the 1980s. From 1950 to the 1970s, there was a relatively high salinity level during which the marine species were abundant, there was a sufficient volume of water suitable for cod reproduction, and the populations of clupeids, which are consumed by cod, were at an intermediate level. However, from the early 1980s to the mid-2000s, there were no major inflows of saline water into the Baltic Sea, resulting in a decline in salinity, an expansion of the anoxic layer in the central and northern Baltic Sea, and a collapse of cod reproduction in the central Baltic Sea (1986-1993). After the collapse of the cod stocks, sprat stocks increased rapidly and a simultaneous decrease in zooplankton suggests a cascade down from planktivores to zooplankton. The predation-related decline in marine zooplankton accompanied by a decrease in their abundance associated with the decline in salinity then caused starvation and low growth of clupeids, especially herring, in the late 1980s (Figure 28). Thus, it is clear that cod stocks are influenced by climate and that cod stocks influence their prey, the clupeids,

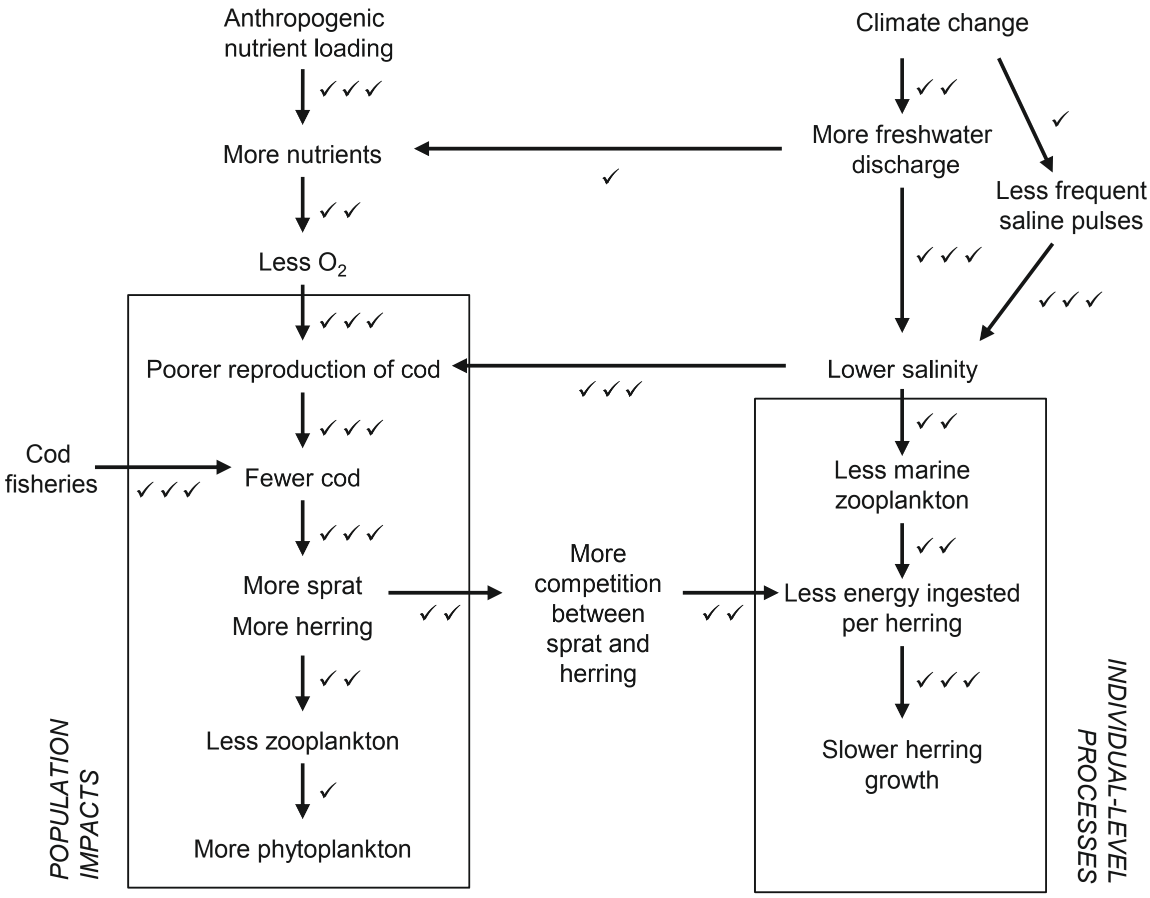


Figure 28. A schematic presentation of the interactions between different trophic levels and some environmental factors in the pelagic ecosystem of the central Baltic Sea. Estimated confidence levels depicted as: √: low confidence, √√: medium confidence, √√√: high confidence.

which in turn probably also influence zooplankton stocks. Although the environmental situation in the Baltic Sea has not changed, cod stocks began to recover after 2005 concurrent with a reduction in fishing mortality, indicating that fisheries are still an important regulator of cod population dynamics in the Baltic Sea. However, it is unlikely that a return of cod could improve the state of the Baltic Sea. Nutrient loading needs to be reduced first. Nonetheless, it is obvious that the decline of cod populations has been an indication of ecosystem-level problems, such as large-scale anoxia and overfishing. A healthy Baltic Sea would be less eutrophied and contain a balanced community of cod, clupeids, zooplankton and primary producers.

Benthos

The distribution of benthic communities in the Baltic Sea is regulated by the decreasing salinity towards the north, which reduces the diversity of macrozoobenthos and affects the structure and function of benthic communities. The distribution is also influenced by strong vertical gradients, with larger habitat diversity and more species in shallow-water communities than in the communities below the halocline, which are dominated by only a few species. Climate variability plays a major role for benthos in the Baltic Sea as it affects salinity, mixing, and stratification and thus the distribution of hypoxic waters.

The range of benthic marine species follows the bottom water salinity levels, with the northward expansion of this range in the mid-1950s after a large saltwater inflow followed by a reverse when a decrease in salinity led to a shift in the dominant species from marine to brackish-water taxa in the southern and western parts over the past few decades.

A potential continued decrease in salinity in the future would probably influence the distribution of benthic species, with a retreat of marine species towards the south. Nonetheless, bottom-water conditions will continue to have a greater influence on species distribution.

Due to both eutrophication and climatic conditions favouring stagnation, the area of hypoxia in the Baltic Proper has increased and is now the most widespread on record; this has caused the disappearance of benthic macrofauna from the open sea areas of the Baltic Sea. If climate change enhances eutrophication, the increased deposition of organic matter will increase hypoxia in areas with limited water exchange, further limiting macrobenthos. However, in some areas such as the Gulf of Bothnia, the increased discharge of freshwater may lead to a decrease in primary production and thus a decrease in the supply of food for the benthos. The various different possible types of ecological responses in the different sub-basins of the Baltic Sea, together with the degree to which the HELCOM countries implement phosphorus and nitrogen input reductions under the Baltic Sea Action Plan, mean that it is currently not possible to predict whether the climate-mediated hydrodynamic changes will improve or worsen the oxygen conditions in the Baltic Sea.

In shallow-water hard and soft bottoms in the Baltic Sea, the benthic communities differ from those in deeper waters because the light conditions allow the growth of algae and vascular plants. The composition and species richness of the shallow-water communities decline from the Kattegat through the Baltic Proper into the Bothnian Bay and the innermost part of the Gulf of Finland. The distributions of shallow-water benthic species are determined mainly by their ability to adapt to low salinities, but also to variations in water level, wave exposure, light and oxygen availability, grazing, predation, and competition for space. This sensitivity to salinity variations may make the shallow-water communities vulnerable to climate-related changes, particularly the projected increase in freshwater discharge. Species that are living near their hydrographical tolerance levels are sensitive to seasonal salinity changes and their reproductive phase may be especially vulnerable. In the littoral zone, a potential decrease in salinity may affect key species such as fucoids and eelgrasses. Some marine species such as the eelgrass *Zostera marina* may disappear from areas such as the Gulf of Finland that could have a lower future salinity. By affecting habitat-forming species, climate-induced changes in hydrography will also influence their associated flora and fauna.

A climate-induced decline in salinity would also lead to a decrease in the growth rate and shift of the northern limits of the blue mussel community further to the south. The decline of mussel beds may affect the associated flora and fauna as well as have an indirect effect on the coastal phytoplankton community, which serves as a major food source for mussels. Changes can also be expected in the food availability for mussel-eating seabirds, such as the eider, on the northernmost Baltic Sea coasts.

Acidification associated with high levels of CO_2 in the sea may also have severe implications for calcifying organisms such as bivalves. Key physiological processes including growth, metabolic rate, reproduction and activity are also likely to be affected, thus potentially affecting the abundance, diversity and functioning of benthic communities. Recent measurements of pH have indicated that the pH of the Baltic Sea has decreased since 1993, with the largest changes in the Bothnian Sea and the southern Baltic Proper. Consequences to the Baltic Sea ecosystem remain unclear.

Some aspects of climate change may have positive effects on certain components of the ecosystem, such as the littoral vegetation. Milder winters with less coastal sea ice will reduce the scraping of ice in the uppermost part of the algal belt that removes key species. It has been shown that a denser growth of *Fucus* occurs after mild winters, contributing to a higher production of associated invertebrate fauna.

5.3 Impacts on the coastal zone and shorelines of the Baltic Sea

Marine, terrestrial, and atmospheric processes interact in the coastal zone. This transitional zone between the terrestrial and marine environments is considered quite alterable and unstable in the

Baltic Sea Basin, owing particularly to the land uplift, and it is affected by sea-level rise and drainage basin processes. The coastal zone comprises both the marine areas under terrestrial influence and the terrestrial areas under marine influence, and the ecosystems of the coastal areas are unique in combining both areas. Furthermore, human influences from the often densely populated coastal areas exert a large variety of impacts on the coastal zone.

The total shoreline of the Baltic Sea is 76,000 km long. There is a large variety of shorelines, from bedrock-dominated coasts to soft depositional shores. The shore density, which is the length of shoreline per unit area, is highly variable in the Baltic Sea region and provides a good indicator of shoreline complexity (Figure 29). There is also a wide regional variation in the amount of near-shore area, both on the littoral and the terrestrial sides, with a prevalence of nearshore ecosystems in high-density areas compared to coastlines with less complexity (Figure 29). These different types of areas may respond differently to changes such as climate-induced sea-level rise. Areas with a wide coastal zone from the land to the outer islands may be particularly sensitive to environmental changes in the interface between the marine and terrestrial systems.

The glacial uplift occurs at different rates in the various regions of the Baltic Sea Basin. The greatest uplift, of nearly 1 cm/yr, occurs in the Bothnian Bay, while coasts in the southernmost parts of the Baltic Sea are submerging slightly (Figure 30). These differences will be very important in relation to the projected acceleration of global sea-level rise.

The response to climate-related changes also differs for the various shore types in the Baltic Sea. Shore types include chalk cliffs, rocky shores, barrier islands with coastal lagoons, sandy beaches, flat clay shores, and esker shores. Each of these shore types has its own erosional and depositional processes that are mediated by various

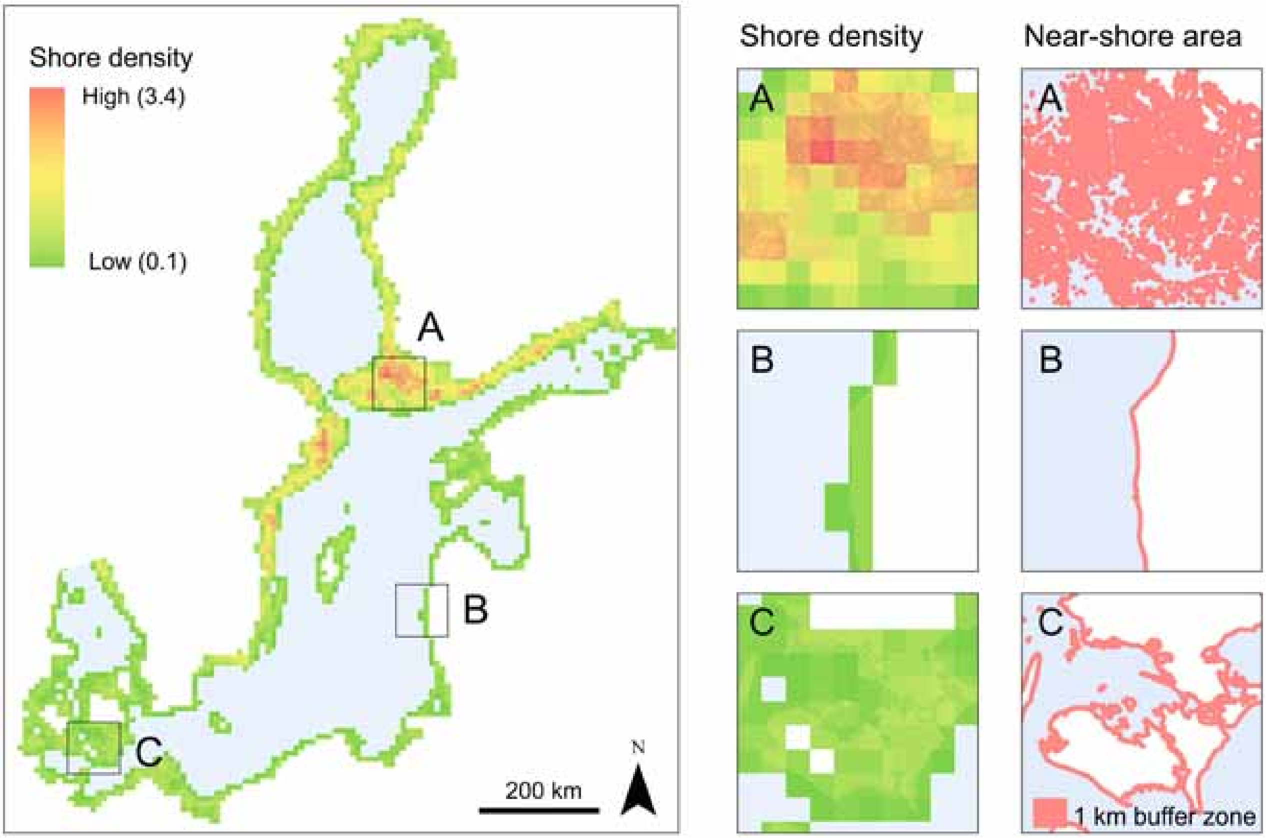


Figure 29. Left: Shore density in 100 km^2 square cells along the Baltic Sea coast. Right: Three 100 km by 100 km example areas showing the shore density and the nearshore zone as a buffer area extending 1 km from the shoreline. The near-shore zone covers 74% in area A, 2% in B and 19% in C. Computed from HELCOM (2012).

shore-forming forces such as wave energy. Sensitivity to the influence of climate change will also vary by shore type.

The impact of wave energy on a shore also depends on the shore openness, which indicates the exposure of a shore to the open sea and thus the potential for wave formation. Coasts with a low shore density usually have high shore openness, whereas on coasts with a high shore density most of the shoreline is sheltered by surrounding islands. Clearly shores that face the open sea will receive an increase in average and maximum wave energy if increasing storminess will occur in the Baltic Sea.

The formation of sea ice also influences the shores of the Baltic Sea. Ice usually forms first in shallow inland bays and the contact of the sea ice with the shore can cause local erosion. Simulations that project warmer winters indicate significant changes in ice conditions in the Baltic Sea, with the consequence that the interaction of the shores with sea ice may become less important while the impact of wave energy may become more important. These changes will have a significant impact on coastal morphodynamics and ecosystems.

The low coasts and beaches of the Baltic Sea will be strongly affected by sea-level rise and more frequent storms. Photo: Metsähallitus NHS / Jan Ekebom.

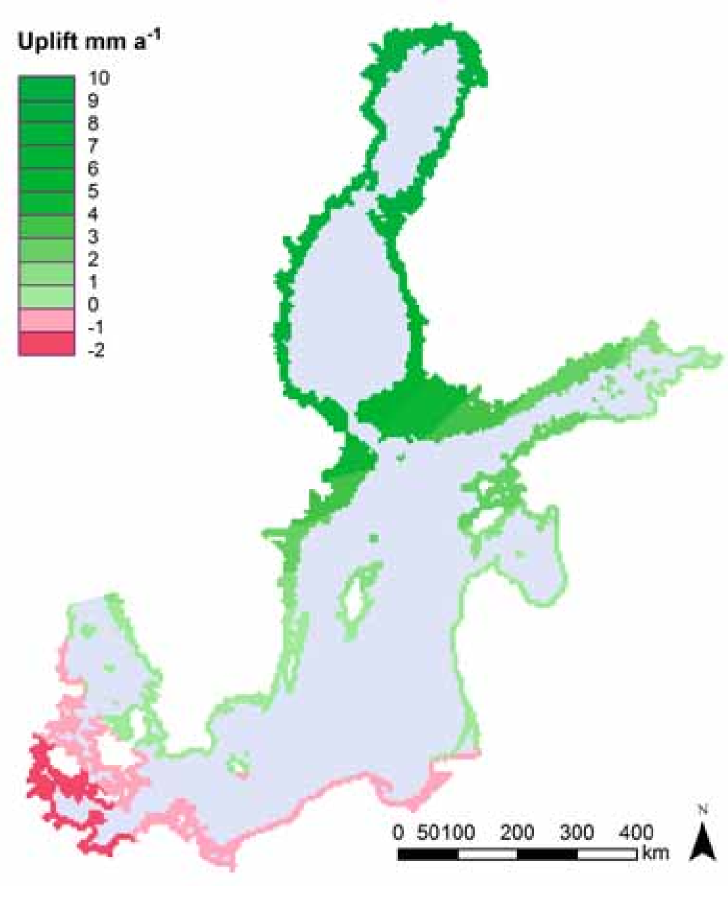


Figure 30. **Rate of post-glacial land uplift in 25 km^2 square cells along the coasts of the Baltic Sea (after Voipio and Leinonen, 1984).**

Maritime activities and shore protection also cause physical stress on the shoreline, particularly on shallow coasts and archipelagos. A summary of some potential impacts of climate change on coastal areas of the Baltic Sea is provided in Table 2.

The low coasts of the Baltic Sea will be strongly affected by sea-level rise. The Estonian beaches have been shrinking owing to an increase in storm frequency including major storms in 2005 and 2007; the January 2005 storm eroded 15 to 30 m of the gravel and pebble beaches on Saarema Island. The beaches in the Kaliningrad region have also been eroding by from 5 m to up to 40 m in bays. Over the past 20 years, some Lithuanian beaches have disappeared due to westerly storm surges. The average retreat of the Polish coast, mainly formed of sandy sediments, is between 0.5 and 1.5 m/yr. Storm surges in recent years have caused dune erosion and retreat. The beach on the northwest side of the Danish island Anholt has recently been eroding at the rate of 10 m/yr.

Table 2. **Summary of some potential impacts of climate change on the coastal areas of the Baltic Sea.**

Global scale change	Consequences		Response
Atmospheric warming	Warming of terrestrial ecosystems		Northward migration of terrestrial and aquatic species, longer productive season
	Warming of coastal seawater		
	Decrease in extent, thickness and duration of annual ice cover in coastal waters		Changes in marine ecosystems and physical features of the sea
Increase of precipitation	General increase in terrestrial runoff	Decreased salinity of coastal waters	Changes in species composition and ecosystem functions
	Increase in riverborne sediment, dissolved organic material and nutrient loads	Changes in water chemistry, decrease in coastal water transparency	Oligotrophication in the Gulf of Bothnia; eutrophication in the other sub-basins; shallower distribution of aquatic plants, decrease and fragmentation of benthic and littoral habitats
Acceleration in global sea-level rise	Decreased or reversed relative to land uplift	Shoreline retreat slows or reverses	Changes in littoral ecosystems, need for coastal defense
	Increased land submergence	Accelerated shoreline advance	

Rising sea levels are expected to aggravate coastal erosion in these low-lying areas.

Soft cliffs in Denmark, Germany, Poland and Latvia are also eroding due to heavy rain and storm surges. The combination of high water levels with strong wind can result in severe damage to soft coastal cliffs. The annual erosion of Polish coastal cliffs is up to 1.3 m/yr. In contrast, the rocky cliffs of Sweden and Finland are mainly formed from hard granites and are resistant to erosion.

Coastal erosion reduces the area for plant and animal communities. Consequently, coastal habitats are expected to be very sensitive to a rise in sea level. The erosion of dunes is causing the loss of valuable coastal habitats. The entire vegetation of cliff slopes is threatened due to repeated landslides. Many of these habitats are listed in Natura 2000.

Over the past 20 years, some Lithuanian beaches have disappeared due to westerly storm surges. Photo: Elena Bulycheva.

6 Summary of Some of the Main Impacts of Climate Change

Enhanced anthropogenic nutrient inputs via rivers and atmospheric deposition during the past century have resulted in major changes in the biogeochemistry of the Baltic Sea. Although the implementation of reduction measures since about 1980 have decreased inputs to a level that is comparable to that in around the 1960s, this is only reflected in a decrease in the nitrate concentrations in the winter surface water of the Baltic Proper. However, this is not the case for phosphate concentrations, which can partly be explained by the long residence time of phosphorus in the Baltic Sea. The increasing nutrient concentrations that mainly control the net organic matter production and export into deeper water layers has resulted in an increase in the frequency of hydrogen sulfide occurrence. This may have enhanced the recycling of phosphate and favoured blooms of nitrogen-fixing cyanobacteria. Available data indicate that the net marine biomass has increased since the 1920s and 1930s by a factor of about 2.5. Furthermore, the data show that the alkalinity in the Baltic Proper has increased, which has dampened the lowering of the pH caused by rising atmospheric CO_2 concentrations.

Model simulations of scenarios concerning the future biogeochemistry of the Baltic Sea have estimated that, taking into account climate change, the implementation of the Baltic Sea Action Plan will result in a slight decrease in the deep-water area covered with hypoxic and anoxic waters. In contrast, the 'business-as-usual' nutrient input scenario yielded an approximate doubling of the anoxic area whereas a moderate increase of about 30 % was obtained for the hypoxic area. Simulations of the future development of the pH in the Baltic Sea using a model system that included the cycling of organic carbon and CO_2 in the Baltic Sea as well as in the catchment area showed that the rising atmospheric CO_2 mainly controls future pH changes in the surface water, while eutrophication and enhanced biological production would not affect the mean pH. The worst-case CO_2 emission scenario yielded a significant decrease in pH by the end of this century.

Investigations of the consequences of climate change on the Baltic ecosystem indicate that, for phytoplankton, a temperature increase will result in an increasing proportion of dinoflagellates in spring and cyanobacteria in summer. The projected changes in salinity and temperature are also likely to decrease the abundance of marine copepods and increase that of the surface community of zooplankton. This will have negative consequences for the food conditions and growth of the main planktivores, namely, Baltic herring and sprat. The results of mesocosm studies indicate that climate change may differentially influence the seasonal

Oxygen deficiency is the single most important environmental factor reducing the biodiversity of benthic invertebrates. Photo: Metsähallitus NHS / Mats Westerbom.

succession of both phytoplankton and zooplankton and potentially increase the temporal mismatch between these groups in the spring.

Although there is no scientific consensus on the influence of climate change on salinity, currently most simulations indicate that salinity would decrease. A climate-induced decrease in salinity would also have a negative influence on cod, the main Baltic piscivore. Until recently, overfishing together with a largely climate-driven decrease in the volume of water appropriate for the development of cod eggs severely decreased the cod stocks in the Baltic Sea. Investigations have confirmed that this has caused cascading effects on planktivorous fish and apparently also on zooplankton, while effects on phytoplankton are unclear.

Oxygen deficiency is the single most important environmental factor causing habitat loss and reducing the biodiversity of benthic invertebrates. Up to 70,000 km^2 of the Baltic seabed is completely devoid of macrofauna owing to oxygen deficiency. The projected salinity decline will result in geographical shifts in the distribution of species in both deep-water and shallow-water communities. The loss of marine benthic fauna will have profound effects involving losses in functional diversity including bioturbation potential. The present understanding of the climatic influence on water stratification and future oxygen conditions is not adequate to make firm conclusions concerning potential changes in oxygen conditions in deep waters or on benthic-pelagic coupling. The increase of freshwater discharge and associated nutrient load induced by climate change could increase primary production and the sedimentation of organic matter. However, in some Baltic basins, especially the Gulf of Bothnia, climate-driven changes in food-web structure may result in a decrease in the amount and quality of sedimenting organic matter.

The increasing temperature in the Baltic Sea will decrease the extent and duration of the sea ice, resulting in a loss of habitat for ice-dwelling organisms and changing ice-modulated land-sea interactions. This may also result in changes in nutrient dynamics within and under the sea ice. The effects on overall productivity of the Baltic Sea are not clear; however, they are expected to be relatively small. Nonetheless, the loss of sea-ice habitat could possibly alter the magnitude of the spring bloom as well as the distribution and occurrence of cold-adapted Baltic plankton species.

In addition to the climate-related changes in conditions such as water temperature, salinity, stratification, and currents that will induce changes in marine biodiversity, human-induced pressures including overfishing and eutrophication may erode the resilience of the ecosystem, making it more vulnerable to changes in the climate. This is clear for Baltic cod, where both fisheries and environmental factors have influenced the interactions within the upper trophic levels of the pelagic ecosystem. The reduced genetic diversity of populations of organisms in the Baltic Sea possibly also makes the ecosystem particularly vulnerable to changes in the climate.

The influence of climate change on the eutrophication conditions and productivity of the Baltic Sea is not clear at this time and will probably vary in the different basins of the sea. Trophic dynamics can be expected to vary from basin to basin depending on the ultimate outcome from the various counteracting processes that occur. In some areas, climate change may cause an increase in primary production resulting in greater eutrophication, while in other areas there may be an opposite response.

Currently, it is difficult to combine results from biogeochemical models and food-web models in the Baltic Sea, because biogeochemical models do not account for dynamics of trophic levels above phytoplankton, while food-web models do not extend below zooplankton. To solve this problem it is necessary to develop models that account for all trophic levels from microbes to fish and preferably also include marine mammals, as well as the interactions between them. More research on cascading trophic interactions in the Baltic Sea is needed before reliable long-term projections on the effects of climate change on the pelagic food web can be made. In addition, the influence of atmospheric forcing on carbon cycling, including DOC, and the functioning of the microbial loop need to be included in models for assessing the effects of climate change on marine productivity. The role of the less investigated ecosystem compartments, such as sea ice, and processes, e.g. acidification, also needs to be incorporated in these models.

7 What should be done to counteract impacts of climate change on the Baltic Sea?

7.1 Will the Baltic Sea Action Plan ensure a good environmental status in a future climate?

According to the scenarios for the western Baltic Sea, reductions of nutrient loads according to the HELCOM Baltic Sea Action Plan (BSAP) will result in a decrease in chlorophyll-α concentrations and cyanobacteria and an increase in water transparency after a lag period.

Even with the full implementation of the BSAP, it is likely that oxygen levels in the deep main basin will decrease further although there would be a slight decline in the anoxic and hypoxic area. The oxygen saturation maximum is lower in warmer water and a decrease of oxygen levels has an impact on other processes as well. Without drastic nutrient load abatements, hypoxic and anoxic areas are projected to increase. The BSAP will not result in a return to the environmental conditions of the pre-1960s.

The BSAP maximum allowable inputs, as currently set, are the same regardless of the climate. This means that more stringent measures will likely be required to reach the maximum allowable inputs if, e.g., precipitation, runoff and loads will be higher due to climate change. On the other hand, a maximum allowable input sufficient to reach targets for good environmental status today may not be enough to reach targets in the future climate and nutrient loads will need be reduced further to reach eutrophication status targets that in the past were reached with smaller reductions. This should be taken into account implementing the nutrient reduction targets of of the BSAP.

Reductions of nutrient loads will increase water transparency. Photo: Metsähallitus NHS / Mats Westerbom.

7.2 Proposals for action

Climate change impacts should be included into the Baltic Sea Action Plan load reduction scheme review

In their 2013 meeting, the HELCOM ministers and high-level representatives should aim at acknowledging that changes that are due to the warming of the climate risk undermining efforts that are being taken to combat eutrophication and environmental contamination by hazardous substances. Warmer water will lead to higher prevalence of hypoxia and anoxia, shifting the oxygen targets further away from being reached. Climate change will challenge the reduction of eutrophication in the Baltic Sea, possibly requiring additional measures to reach agreed environmental targets and emphasizing the need to ensure that the BSAP nutrient load reductions will be fully implemented. HELCOM should include climate change considerations already into its review of the Baltic Sea Action Plan nutrient reduction scheme in 2013, as far as possible, although it is apparent that it will not be possible to produce quantitative information on these aspects. Ensemble modeling and hierarchical modeling are needed in the future work of HELCOM, especially on the nutrient load reduction scheme revisions.

Impacts of climate change in the catchment should be better accounted for when planning nutrient reduction measures, e.g., changes in land use and agricultural practices.

Inclusion of the atmospheric deposition of nutrients into the Baltic Sea Action Plan is expected to improve with the BSAP revision. In the future, the deposition of nitrogen in the Baltic Sea may change due to climate change but this is a less well-known issue and more information on it is needed.

Other human pressures should be decreased to mitigate climate impacts on biodiversity

Human pressures are prevalent in all areas of the Baltic Sea, as has been demonstrated, e.g., by the HELCOM Initial Holistic Assessment. Climate change acts in multiple different ways on the ecosystem structure and function resulting in changes.

With warming and the shortening of the ice period, ranges and distribution of cold-adapted species will diminish and move towards the north. Populations of ice-breeding seals, particularly ringed seal, will have slower recovery potential, which together with other prevalent pressures may endanger the viability of these populations.

In order to counterbalance the impacts from climate change, HELCOM Contracting Parties should take action to decrease inputs of nutrients, organic matter and pollutants, hunting pressure, habitat disturbance, noise, fishing, by-catch of marine mammals and seabirds, as well as physical disruption of the coastal zone. Reduction of eutrophication should be the focus as it will lead to a diminished pressure on biodiversity and increase the resilience of the ecosystem to the effects of climate change.

Fishing practices should be adjusted to take into account the additional pressure of climate change, e.g., maximum sustainable yields need to be adjusted to take into account the weakened condition of fish stocks.

Communities around the Baltic Sea should take into account the additional pressure of climate change when carrying out environmental impact assessments of coastal development and offshore installations. For this, communication with stakeholders and a good knowledge base are also necessary for cost-efficient and informed decision making.

Better knowledge of the occurrence and status of many of the species, the distribution of habitats and species, characteristics and sensitivities of habitats and understanding of the biology (growth and mortality) of many species and their reaction to threats, as well as better understanding of the food web and ecosystem functions of different species (especially phytoplankton and zooplankton species), is still needed.

Fishing practices should be adjusted to take into account the additional pressure of climate change. Photo: Martin Karlsson / SLU Aqua.

An ecologically coherent network of protected areas is essential to ensure a safe space for species and habitats

There should be a strong and ecologically coherent network of protected areas where species and habitats can develop undisturbed by effects from other anthropogenic impacts. In the future, it may be necessary to assess the boundaries of marine protected areas (MPAs) to take into account possible changes in the distribution of species and habitats caused by changes in temperature and salinity. The network of protected areas should be evaluated at regular intervals as it may need to be adjusted to better support species and habitats with special needs. Management of MPAs should take into account potential impacts of climate change, including the possible need to protect species that are not already included in the HELCOM Red List. Future analyses of the necessity to complement the network of protected areas, e.g., with MARXAN analyses, should take climate change into account.

Non-indigenous species may increase and cause an additional pressure

Warming and a longer growth period open up new ecological niches for non-indigenous invading species. Introductions of non-indigenous species can add pressure to Baltic species and habitats which are already living under stressful conditions.

Monitoring programmes should also accommodate for early warning, e.g., detecting non-indigenous species. Port monitoring of non-indigenous species should include improved monitoring of plankton species. There is a need to maintain a database on non-indigenous species, and this should include also plankton.

Shipping and aquaculture should take effective measures to minimize the risk of introduction of alien species.

Balancing acts are necessary to decrease the effects of toxic pollutants when climate change puts an additional physiological pressure on the organisms

Pollution by certain hazardous substances is an additional anthropogenic pressure. The changing properties of the marine environment, including declining salinity and pH, will cause an extra pressure on Baltic Sea organisms, the majority of which are already living at the margins of their physiological adaptation capacity. The cumulative impacts of climate and pollution stressors are projected to increase with climate change. In order to reduce pressures from toxic pollutants, balancing actions in the future in the form of stricter measures against widespread Persistent, Bioaccumulating and Toxic, PBT substances, pesticides and pharmaceuticals are recommended. Use of such compounds is likely to increase due to climate change and this poses a risk to the marine environment that should be addressed.

Acidification requires attention

The global ocean takes up about one fourth of the anthropogenic CO_2 emitted to the atmosphere, causing acidification of the marine environment. This has been noted in the international arena as the Ocean Acidification International Coordination Centre (OA-ICC) was established at the Environment Laboratories of the International Atomic Energy Agency (IAEA) in July 2012. Although current knowledge indicates that acidification has not progressed alarmingly in the Baltic Sea, acidification and its effects on biota of the Baltic Sea are still poorly understood and further observations, as well as research, are needed to better understand, e.g., the process of acidification and its possible linkages to other acidifying substances in the Baltic Sea. In particular, the effects of acidification on Baltic biota need more attention in the future.

Climate risks and vulnerability

Climate change increases the risk for potentially dangerous phenomena such as flooding, strong storms and storm surges, and associated sea-level rise and coastal erosion in the coastal zone. Better preparation is needed and HELCOM groups such as MARITIME, Nature protection and biodiversity (HABITAT) group and Land-based pollution group (LAND) should consider these risks and vulnerabilities and how to address them in their work.

Develop and maintain marine monitoring and data assimilation

Ongoing economic hardships put a pressure on and risk decreasing ongoing monitoring and observation activities of the marine environment. At the same time, the changing climate and ecosystem make long-term observations more valuable than ever before. Long time series of observations are essential for detecting changes in the environment and for validating mathematical models.

Mathematical models enable creating future scenarios along with hindcasts of past events to better understand the functioning of the marine ecosystem. In addition, data assimilation to operational models is still an area that needs to be further developed. To enable basin-wide analysis and verification of climate change effects on the marine ecosystem, availability and easy access to data from national monitoring programmes and other relevant research should be facilitated by HELCOM. Ensemble modeling and hierarchical model approaches (incorporating models that address different spatial and temporal scales of complexity) should be an aim.

There is a need to be able to monitor climate-induced changes in the ecosystem and therefore develop indicators for monitoring change and drivers of change. Better and sufficient monitoring to capture impacts of climate change should be ensured. Increased use of novel observation tools as well as mobile monitoring stations should be encouraged. The HELCOM monitoring and assessment programme should be able to answer the question: is there a change and what is causing the change? Developing a methodology to assess the confidence of attributing the contribution of different drivers to the change should also be a priority to support HELCOM monitoring and assessment activities.

Apply a multiple-stressor and holistic approach

HELCOM should increasingly aim at employing models that capture the multiple-stressor holistic approach in order to address various types of pressures that may act synergistically or antagonistically. These models should also be used to review and further develop targets for good environmental status in such a way that climate change and its impacts are taken into account. In some cases, it is possible that current targets cannot be reached due to climate change.

Research needs

Nutrient retention in the coastal zone is poorly understood. The bioavailability of nutrients is accounted for differently between models. Sensitivities of the different models vary in their response to changing nutrient loads. Global climate models cannot be used to force regional or local scenarios. Further study of the bioavailability of nutrients in a warmer climate is important.

The new IPCC assessment should be used for new scenario simulations. Salt water inflows should be addressed in more detail to understand why there is a decrease in inflows under the present climate and to better account for the smaller inflows in the models. Interactions and feedbacks from climate to land use to socio-economics should be further studied. More cost-effective implementation of the BSAP could be achieved by optimizing nutrient ratios at a smaller scale. More plausible nutrient load scenarios consistent with large-scale socio-economic developments are needed. Further knowledge of changes in the catchments is also needed in order to enable efficient action in the catchment areas.

Impacts of climate change, especially changes in temperature, salinity, and acidification, on underwater habitats and species, e.g., on their reproductive success, need to be investigated.

So far, many climate-related issues have been identified at a qualitative level and there is a need to strive for research that enables quantification as far as possible.

Research on the influence of climate change on hazardous substances and their effects should be paid more attention in the future.

Overall, HELCOM should encourage more applied research.

It would be helpful to assess (1) the confidence of the likelihood that ecosystem change will take place as a result of climate change; (2) the severity of the impact on the ecosystem; and (3) the severity of the impact on human populations in the Baltic Sea area.

Communicate uncertainties

There is a general need to better communicate uncertainties related to scientific findings, especially when communicating with the decision-makers and media. This should be done with the view that displaying error bars will also enable implementation of the precautionary approach.

The changing properties of the marine environment, including declining salinity and pH, will cause an extra pressure on Baltic Sea organisms, the majority of which are already living at the margins of their physiological adaptation capacity. Photo: Metsähallitus NHS / Essi Keskinen.

Improve the communication between science and policy

Communication is dependent on the cultural framework and this should be taken into account in the Baltic Sea context. Communication should not be primarily top-down, from experts to laymen, and natural scientists should increasingly learn from social scientists how to be in dialogue with stakeholders. Positive developments should also be highlighted.

Education of young people on the topics of climate change and the marine environment is important.

Science should be communicated at an early stage and accompanied with uncertainties, ranges of knowledge and knowledge gaps. For decision-makers, an early dialogue allows for timely consideration of the feasibility of scientific findings and inclusion of stakeholders in the considerations. Cross-sectorial communication with the aim to ensure better cross-sectorial integration is needed.

Better cross-sectorial integration is needed. Photo: Metsähallitus NHS / Jan Ekebom.

Scientific advisors to political processes evaluate and digest scientific information and for this it is crucial to have high-quality science with complete background information and transparent presentation of modeling processes. Protocols for scenario simulations and assessments developed by independent review groups are needed and this type of activity could be incorporated into the HELCOM activities in the future.

Visualization, including films, is a powerful tool and should be increasingly used to communicate knowledge about climate change, its impacts and adaptation needs.

HELCOM could consider creating a concept for the briefing of journalists that could be implemented by the Contracting Parties.

Knowledge on climate change and Baltic Sea impacts should be reviewed at regular intervals

A assessment of knowledge on climate change and its effects on the Baltic Sea should be conducted at regular intervals within HELCOM. Following the adaptive management approach, any changes in this knowledge should be communicated to the decision-makers to enable possible changes to the policies. HELCOM could consider including this activity into its six-year assessment cycle and work towards further strengthening the cooperation with Baltic Earth, the BALTEX successor, in such a way that knowledge assessment activities could be carried out in collaboration with Baltic Earth also in the future.

This regular activity should also aim at contributing to the harmonization of HELCOM, WFD and MSFD assessments, targets, approaches and regional differentiations; one holistic view is the goal.

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