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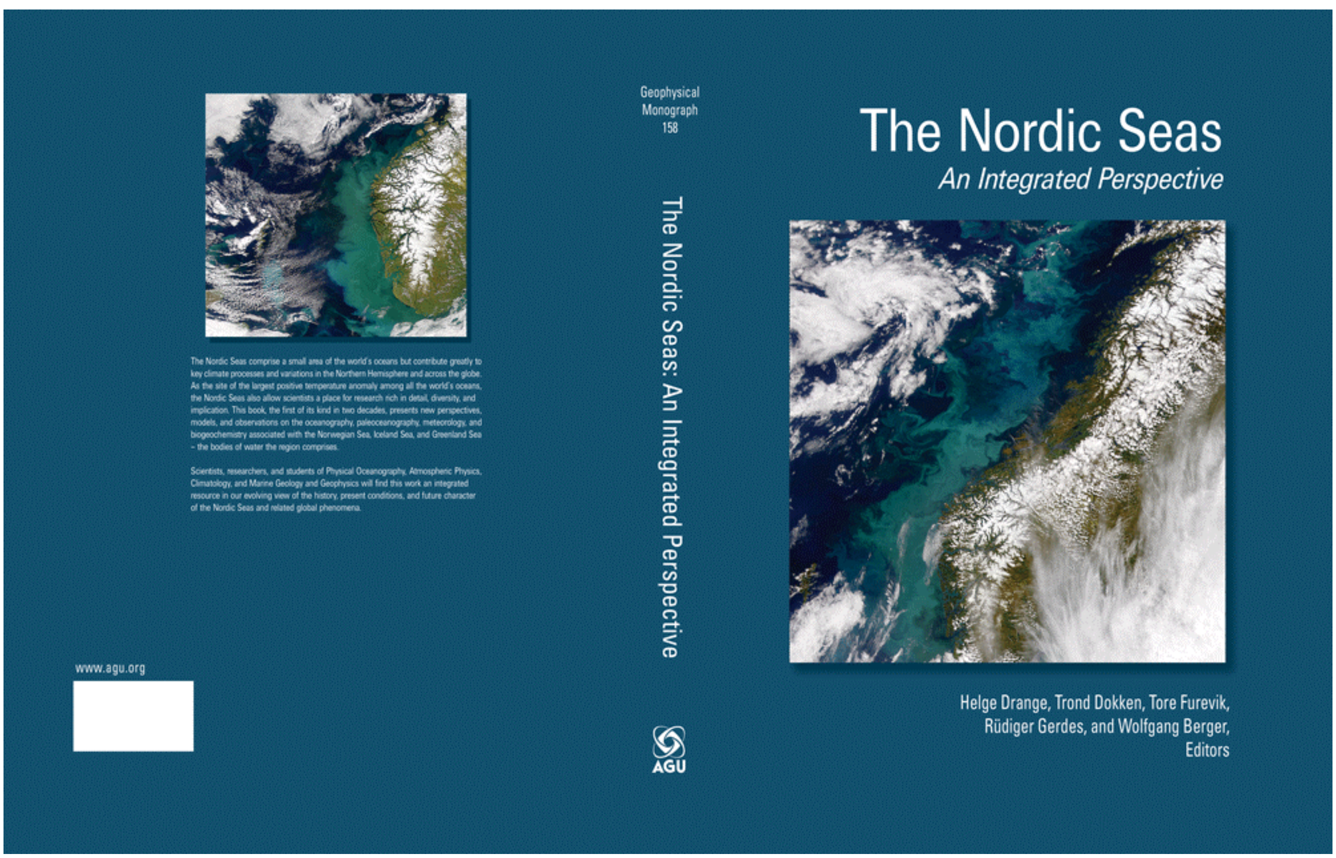

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THE NORDIC SEAS: AN OVERVIEW

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The aim of this overview paper is to provide a brief synthesis of the five review papers contained in the monograph. Prevailing south-westerly winds, oceanic flow patterns, and oceanic summer heat storage make the Nordic Seas region having temperatures 10 to 20 °C above the mean temperature at similar latitudes. The combination of the large heat import from south and the polar location implies that the region is prone to natural climate variations and particularly vulnerable for external forcings. Proxy data for the Holocene epoch indeed reveal large high-frequency climate fluctuations, as well as long-term variations spanning the 'medieval warm period' and the 'little ice age'. In phase with a strengthening of the westerly winds since the 1960s, several oceanic key variables show trends unprecedented in available instrumental records, some of which extends back 50-100 years. State of the art climate models indicate that several of the changes may be linked to increased greenhouse gas forcing, and are therefore likely to be sustained or even amplified in the future. Furthermore, the marine cycling of carbon, and by that the major greenhouse gas carbon dioxide, is closely linked to the climate state of the region. The Nordic Seas region is, as one of few ocean locations, a sink for atmospheric carbon dioxide throughout the year. With the rapid developments in data acquisition, computational resources, and societal concerns for climate change and environmental issues, the review papers give an updated account of the present knowledge of the complex climate states of the Nordic Seas, and how the Nordic Seas influence the climate outside the region.

1. BACKGROUND

The region north of the Greenland-Scotland Ridge (GSR) and south of the Fram Strait-Spitsbergen-northern Norway transect (e.g. Fig. 1 in *Furevik and Nilsen* [this issue]), here defined as the Nordic Seas, covers about $2.5 \cdot 10^6$ km^2, or about 0.75%, of the area of the world oceans. The region is, despite its small extent, very dynamic and diverse [*Blindheim and Østerhus*, this issue; *Furevik and Nilsen*, this issue*; Nesje et al.*, this issue; *Skjelvan et al.*, this issue; *Skjoldal,* 2004, and references therein]: The topography of the sea floor is complex with shallow shelves, deep basins, mid oceanic ridge systems, and steep slopes. The typical dynamical length scales are small, ranging from a few to some tens of kilometers. The atmosphere-ocean transfers of momentum, heat, fresh-water and gases are strong, notably during the cold winter months from November to April. Water masses originating from low and high latitudes meet and interact by means of frontal mixing, deep convective mixing, subduction, and entrainment. Sea ice is formed in the northern and western parts of the Nordic Seas in winter, whereas the region is essentially ice-free during summer. New primary production commonly equals or exceeds regenerated primary production, and fish stocks are large and the fisheries rich, particularly in the waters influenced by the warm and nutrient-rich Atlantic Water (AW). The flux of carbon per unit area from atmosphere to the ocean is among the highest in the world oceans.

All of the above conditions within the Nordic Sea are well appreciated and tied to its "hot spot" status as an extraordinary warm anomaly. For the present day climate, the annual and winter mean temperatures of the central and eastern Nordic Seas are respectively 10 and 20 ºC higher than the zonal means (Fig. 1). The anomalously high temperatures are caused by three mechanisms, all of which are important [*Seager et al.*, 2002; *Rhines and Häkkinen*, 2003]: (1) Prevailing westerly and southwesterly vapor-laden winds; (2) poleward transport of heat by the Gulf Stream and the North Atlantic Current system; and (3) heat released from the seasonally warmed North Atlantic mixed layer. Changes in any of the three mechanisms have the potential to significantly alter the climate in the region.

The anomalously mild climate of the Nordic Sea and the adjacent land regions has been crucial for survival at these high latitudes for untold generations [e.g., see The King's Mirror (Speculum Regale) from the early 13th century, presented by Hellvik, 1976]. But the region is also important in a wider context:

− For the present-day climate, about 6 Sv (1 Sv=10^6 m^3 s^{-1}) of cold and dense water spills over the GSR [Hansen and Østerhus, 2000; Blindheim and Østerhus, this issue]. This volume transport is about one third of the transport of water associated with the Atlantic Meridional Overturning Circulation (AMOC), and it drives about two thirds of the AMOC volume transport by entraining ambient water downslope of the ridge [Hansen et al., 2004].

− The intense surface forcing in the Nordic Seas has a profound impact on the hydrographic properties of the waters that enter the Atlantic Ocean either as overflow waters across the GSR or as surface waters through the Denmark Strait [Hansen and Østerhus, 2000; Blindheim and Østerhus, this issue]. It also strongly modifies the Atlantic Water that eventually ends up in the Arctic Ocean [Furevik, 2001; Karcher et al., 2003; Furevik and Nilsen, this issue].

− The fresh water fluxes through the Nordic Seas are substantial, representing, together with the flow through the Canadian Archipelago, the key routes for the oceanic limb of the hydrological cycle at high northern latitudes [Aagaard and Carmack, 1989; Houghton and Visbeck, 2002; Peterson et al., 2002].

− The Northern Hemisphere atmospheric circulation is sensitive to the distribution of sea surface temperature and sea ice in the Nordic Seas and in the neighboring Labrador, Barents and Kara Seas [Deser et al., 2004; Kvamstø et al., 2004; Magnusdottir et al., 2004].

− The Nordic Sea is one of the few regions of the world oceans that take up substantial amounts of atmospheric carbon dioxide (CO_2) throughout the year. The ocean-uptake of atmospheric CO_2 is large, ranging from 20-85 g C m^{-2} y^{-1}, among the highest such fluxes in the world oceans [Anderson et al., 2000; Takahashi et al., 2002; Skjelvan et al., this issue].

Central questions with regard to the large-scale climate implications of the above-mentioned perspectives and with regard to the ecosystems in the Nordic Sea region are:

− How stable is the oceanic circulation of the Nordic Seas?

− What are the time and space characteristics of the natural variability modes?

− In which way and to which extent will global warming influence the mean climate state and the climate variability modes?

To adequately address these questions it is necessary to employ a multi-disciplinary approach in documenting available knowledge of past and present climate change, and in identifying and quantifying the underlying dynamics and thermodynamics of the climate system. Based on such information, the fingerprints of global warming can be identified and quantified within forthcoming climate observations and model simulations. With this approach in mind, the five review chapters presented in this book have been organized to summarize available knowledge about the Nordic Sea climate system based on climate reconstructions from the Holocene epoch (last 11.500 years) [*Nesje et al.*], ocean observations covering the period of instrumental records (mainly last 50 years) [*Blindheim and Østerhus*], the dynamics of the ocean response to atmospheric forcing for the period 1948 to present (the period with atmospheric reanalysis products) [*Furevik and Nilsen*], observations and analyses of the cycling of inorganic carbon covering the last decades [*Skjelvan et al.*], and numerical ocean-sea ice modeling covering the atmospheric reanalysis period [*Drange et al.*].

2. PAST AND PRESENT CLIMATE OBSERVATIONS

In *Nesje et al.* [this issue], a synthesis of temperature and precipitation reconstructions from pollen-analysis, tree-line variations, chironomids (non-biting midges), tree-ring records, speleothem (chemical fingerprints of cave formations) data, glacier variations, and marine records (stable isotopes, species abundance, lithological changes) demonstrate that the climate of the Nordic Seas region has been, in general, milder than the 1961-1990 mean throughout most of the

Holocene epoch. A climate optimum is found for the period from about 9000 to 5000 calendar years before present (cal. yr BP). During this period, most of the present-day glaciers in Norway and on Svalbard were completely melted, and Scots pine was found well above the present tree line in the mountain regions in Scandinavia. The annual surface temperature during this period has been estimated to be 1.8-2.0 ºC higher than the 1961-1990 mean [*Nesje et al.*, 2001; this issue]. The main reason for this climate optimum was a very high summer insolation, which at 60ºN exceeded the present insolation by as much as 8-10%. Furthermore, the coldest period throughout the entire Holocene was likely the 'Little Ice Age', covering the time period ca. 1550-1925, with mean annual temperatures approximately 1 ºC below the 1901-1995 mean value [*Luterbacher et al.*, 2004].

Figure 2 displays reconstructed, observed, and simulated sea surface temperature (SST) variations for the period 2000 cal. yr BP to the year 2100. In Fig. 2a, the deduced variability of reconstructed SST from the eastern Norwegian Sea is provided for the last two millennia. The time series show a fairly constant SST for the period prior to year 700. Thereafter, three periods with a gradual century-scale warming of 0.5-1 ºC are seen between year 700-1000, 1200-1400, and 1500-2000. Both the first and the second warming are terminated by rather quick cooling events. The cooling around year 1425 is particularly rapid and strong: Here the SST decreases by about 1 ºC in a few decades. Thus, the reconstructed SST time series clearly demonstrate that the marine climate of the Nordic Seas has experienced both century-scale warming and rapid cooling periods over the last two millennia.

The availability of high-resolution (annual to decadal resolved) climate time series covering several millennia represents a break-through in documenting the major variability modes in the past climate. With spatially distributed time series of similar kind, patterns and amplitudes of past climate variability modes can, for the first time, be constructed. Documentations of decadal and longer time scale climate variability modes are of key importance for separating between natural and human-induced climate variations, and for evaluating and improving climate models beyond the relatively short instrumental period.

The Nordic Seas is a region with a long and extensive history of instrumental observations [e.g., *Blindhem and Østerhus*, this issue]. A source of invaluable importance in this respect is the surface to abyss hydrographic observations from Ocean Weather Station Mike (OWS M) going back to 1948 [*Østerhus and Gammelsrød*, 1999]. In Fig. 2b, the variations in summer SST from OWS M are presented (thick gray line). A gradual cooling is seen for the period prior to 1979, followed by first a gradual and then a rapid warming. The recent warming is strong; the mean of the years 2002-2004 is 1.62 ºC above the 1948-2004 summer SST average (Fig. 2b), and 0.94 ºC above the annual mean temperature average for the same period (both when applying a three-year mean filter).

It is well documented that most regions at high northern latitudes were anomalously warm during the period from the 1920s to 1950s [e.g., *Delworth and Knudson*, 2002; *Johannessen et al.*, 2004]. It is also likely that the extent of Arctic sea ice was less than normal during this period [*Zakharov*, 1997; *Johannessen et al.*, 2004]. Based on instrumental air temperature from e.g. Stykkishólmur, Iceland (Fig. 3 and *Blindheim and Østerhus* [this issue]), it is possible that the early twentieth-century warm period was the warmest since the early 19th century. In Fig. 2b, the three-year annual mean 0-200 m temperature from the Kola section in the Barents Sea is shown for the period 1901-2001 (thin line). The decadal-scale fluctuations in the Kola and OWS M time series follow closely. Furthermore, based on the OWS M data, it is likely that the recent warming exceeds the early twentieth-century warm period. While most of the early twentieth-century warm period can be attributed to natural climate fluctuations, it is likely that at least part of the recent warming is owing to human activities [e.g., *Delworth and Knudson*, 2002; *Johannessen et al.*, 2004].

By comparing the temperature fluctuations along the Kola section and at OWS M (Fig. 2b) with the reconstructed time series from the past 2000 years (Fig. 2a), one can argue that there are indications that the recent warming is exceptional also on a millennium time perspective. This observation is, however, speculative because of uncertainties inherent in the transfer functions of the different proxies [e.g. *Mikalsen et al.,* 2001], which affect the actual interpretation of the time series [e.g. *Mann et al.,* 1999; *von Storch et al.,* 2004; *Moberg et al.,* 2005]. Bridging of reconstructed and instrumental observations, a challenging field of research, is therefore of the greatest importance for the coming years.

3. FUTURE CLIMATE AND CLIMATE MODELLING

The evolution of the climate of the Nordic Sea depends, on a large degree, on changes in the ocean circulation, affecting the poleward-directed heat flow. In Fig. 2c, two 21st century climate realizations from the Bergen Climate Model [*Furevik et al.*, 2004; *Bentsen et al.*, 2004] are presented, one based on the rather strong IPCC SRES A2 scenario, and one with the more modest IPCC SRES B1 scenario (for definitions of the SRES scenarios, see e.g. *http://www.ipcc.ch*). The two model realizations give a warming of the summer SST of 2.13 ºC/100 yr for SRES A2 and 0.53 ºC/100 yr for SRES B1. The corresponding figures for the annual average SST are 2.26 ºC/100 yr and 0.62 ºC/100 yr, respectively. It is worth noting that the warming rate in SRES B1 is similar to the warming between year 1200-1400 (Fig. 2a). The rapid and strong termination of the 1200-1400 warming period does illustrate that similar cooling events may also happen in the future.

A compilation of historical temperature records and possible changes in the surface air temperatures in the Nordic Seas region, represented by Bergen, Stykkishólmur and Jan Mayen, are presented in Fig. 3. The above-mentioned early twentieth-century warm period is seen in the Stykkishólmur time series, but is not evident in the Jan Mayen time series, illustrating the non-uniform climate in the region. The simulated evolution of the 21st century temperatures indicate that global warming may dominate any of the observed temperature fluctuations within a few decades.

It is important to note here that robust assessments of the development of the regional Nordic Sea climate system must be based on ensembles of integrations with thoroughly tested and evaluated climate models, and not on individual model realizations like those displayed in Figs. 2c or 3. Averaging over many model systems or multi-model ensembles yields, in general, a realistic range of expectations, which is not necessarily the case for individual models or model integrations [e.g., *Cubash et al.*, 2001; *Kuzmina et al*, 2004]. Furthermore, pulses of fresh water from the Arctic Ocean [*Dickson et al.*, 1988] and the dynamics of the warm and saline North Atlantic sub-tropical gyre and the cold and fresh North Atlantic sub-polar gyre [*Hátún et al.*, 2005] are important for decadal-scale fluctuations of the hydrographic properties of the Nordic Seas. One must assume that such fluctuations are affected by changes in climate, including anthropogenic changes. Reliable assessment of the future Nordic Seas climate will therefore require climate models that are capable of realistically simulate the temporal and spatial characteristics of the major variability modes in the region.

4. OCEANIC CHANGES DURING RECENT DECADES

For proper descriptions of local climate features, especially changes in oceanic circulation, overflows and convection, high spatial resolution are needed in the oceanic components of climate models. As an example, the ocean component in the climate model used in Figs. 2c and 3 is about 80 km, whereas a spatial resolution of 20-40 km would, in general, greatly improve results [*Drange et al.*, this issue].

It is encouraging that the current generation of coupled sea ice-ocean models is able to describe many of the key climate parameters in the Nordic Seas region [see *Drange et al.*, this issue]. The current generation of coupled sea ice-ocean models can, for the first time, complement available ocean observations and can be used to guide forthcoming ocean observation strategies [e.g. *Hátún et al.,* this issue]. This potential for interactive research is welcome news because it will lead, over some time, to an improved representation of Nordic Sea processes in coupled climate models.

The inflow of Atlantic Water to the Nordic Seas is one of the key components for climate and ecology in the region, in addition to being an important factor for climate variations far outside the region. Prediction of the inflow of Atlantic Water over time scales of months to years is therefore of importance for many applications, ranging from basic needs of understanding the climate system to socio-economic decisions addressing e.g. fisheries resource management. On interannual time scales, *Orvik and Skagseth* [2003] demonstrated that the major northward volume transport of Atlantic Water off the Norwegian coast at 62ºN responds to the North Atlantic wind stress at about 55ºN with a time lag of about 15 months. Figure 4 shows a one and a half year extension of the analyses period presented in *Orvik and Skagseth* [2003]. It follows that the analyses is still valid, and that the major branch of Atlantic Inflow is predicted to decrease until summer 2005. This strongly suggests that the North Atlantic wind stress is of key importance for the variability of the Nordic Sea climate [see the synthesis by *Furevik and Nilsen*, this issue].

The near-surface properties of the Nordic Sea climate are intimately linked to the climate of the abyssal Nordic Sea. The hydrographic time series from OWS M are the longest continuous deep-water time series of the world oceans. In Fig. 5, the annual mean temperature at 2000 m is shown for the period 1948-2004. The trend recapitulates the rapid warming documented up to 1996 by *Østerhus and Gammelsrød* [1999] and continues until 1998, with a weak warming thereafter. The warming trends shown in Figs. 2b and 5 are caused by different mechanisms [*Blindheim and*

Østerhus, this issue; *Furevik and Nilsen*, this issue]: Changes in the surface waters are mainly governed by the hydrographic properties of the Atlantic Inflow and the local air-sea heat fluxes, whereas changes at depth are related to the formation rate of intermediate to deep waters, particularly in the Greenland Basin. An important task is to discover the links between these processes.

The warming shown in Fig. 5 is partly linked to the gradually intensified North Atlantic westerlies since the mid 1960s [*Hurrell*, 1995; *Furevik and Nilsen*, this issue]. The increasing trend in the NAO index between 1970 and the mid-1990s was accompanied by increasing exchange rates of volume, heat and salt between the Atlantic and the Nordic Seas, as well as between the Nordic Seas and the Arctic Ocean. It also set a stop to the sea ice processes important for the existence of deep convection in the Greenland Sea [*Gerdes et al.*, this issue] and thus contributed to the warming of the deep waters (Fig. 5) that lack recent ventilation with waters formed at near freezing point temperatures.

A gradual freshening in the Nordic Seas occurred since the passage of the fresh-water burst known as the 'Great Salinity Anomaly' in the late 1960s [*Dickson et al.*, 1988]. This fresh water originated from the Arctic Ocean, from where it propagated quickly southward towards and through the Denmark Strait in the late 1960s [*Dickson et al.*, 1998; *Haak et al.*, 2003], possibly followed by a return to the eastern part of the Nordic Seas in the mid 1970s (Fig. 6). Recent analyses have demonstrated that essentially all of the intermediate to deep waters of the Nordic Seas and the North Atlantic have experienced a freshening over the past four decades [*Dickson et al.*, 2002; *Curry et al.*, 2003]. As during the Great Salinity Anomaly, the likely source of this freshening is a reduction in both sea ice and liquid fresh water reservoirs in the Arctic Ocean.

Recent observations of the salinity of the Atlantic Inflow show higher values than ever observed (Fig. 6). The high salinity values are concurrent with the recent record-high SST at OWS M (Fig. 2b). It is still open to which extent the exceptional warming of the Atlantic Water in recent years (Fig. 2b) is linked to the interannual flow field variations of the Atlantic Inflow (Fig. 4) [e.g., *Orvik and Skagseth*, 2005].

5. INORGANIC CARBON CYCLE

An important component of the climate system involves the marine cycling of carbon, and then particularly the air-sea exchange of the greenhouse gas carbon dioxide (CO_2). Global compilations of the air-sea disequilibria of CO_2 show that the northern North Atlantic and the Nordic Seas are among the most intense sinks of atmospheric CO_2 [*Takahashi et al.*, 2002]. In *Skjelvan et al.* [this issue], the physically, chemically and biologically mediated carbon transports are quantified based on available observations and modeling.

A newly established time series of the seasonal cycling of total dissolved inorganic carbon (C_T) at OWS M is displayed in Fig. 7. From the figure, large fluctuations are seen in the surface water. This variability is, to a large extent, governed by biological activity. It follows that the plankton organisms start to grow in April in response to increasing insolation and stratification, resulting in rapid consumption of carbon. At 50 m depth, the effect of the bloom is seen as a slight decrease in C_T followed by a slight increase due to respiration and remineralization. At this depth, mixing between surface waters low in C_T and deeper waters rich in C_T becomes dominant in August-September. C_T is close to constant at depths greater than 500 m. Here the downward transport of biologically mediated carbon is close to be balanced with advection and mixing. The presented time series is far too short to detect interannual signals, but it will be a useful tool to link observed changes in hydrography (Fig. 2b and 6) and transport (Fig. 3) to the air-sea exchange of CO_2. The deep water C_T content at selected stations from the TTO/NAS (Transient Tracers in the Ocean – North Atlantic Study) expedition in 1981 [*Brewer et al.*, 1986] have been briefly compared to deep water C_T content at OWS M from 2003, and an increase of about 6 μmol kg^{-1} is seen which reflects that the anthropogenic carbon signal has reached the abyss Norwegian Sea during the 22 years period.

6. SUMMARY

The Nordic Sea plays an important role in the dynamics of climate of the North Atlantic realm. Compared to its latitudes it has the strongest positive sea surface and surface air temperature anomalies in the world, and is a region particularly important for water mass modification and formation, for air-sea interaction, and as the major transport route for fresh water and heat between the North Atlantic and the Arctic Oceans. Large changes in the climate state of the region have been revealed for the Holocene epoch and instrumentally documented for the last 50-190 years. A gradual change in the hydrography of the region has been observed since the 1960s, partly in response to large-scale changes in the atmospheric circulation. In recent years, record-high temperature and salinity values have been recorded.

It is not known how the climate of the Nordic Sea will evolve in the 21st century. We would like to know in which way and to which extent the observed changes, if continued along present trends, will influence the large-scale ocean circulation, and thereby the large-scale climate system. There are indications that the observed change in the climate of the region over the recent decades is at least partly a result of global warming. The perception of what is normal and what is extraordinary will thus be even more challenged in the years to come.

The majority of contributions to the book have benefited on the investments from national and international programs which have made it possible to collect relatively long observational time series from weather stations and research cruises, and to deploy instruments for measuring physical and biogeochemical properties of the main water masses within thee main body and through the boundaries of the Nordic Seas. It is essential for the understanding of natural climate variability modes and for proper assessment of possible changes in the climate system that key components of these campaigns continue.

The coming years will, without doubt, show many examples where climate reconstructions from the past, instrumental observations and numerical models are used together to detect and understand causes and effects of observed changes in the climate system, and to assess how the ocean will respond to anomalous air-sea fluxes of heat, fresh water, and momentum, or how the entire climate system may change in response to, for instance, increased greenhouse gas forcing. The review papers presented in this book provide a basis for applying the present knowledge of the climate of the Nordic Sea to the challenges ahead.

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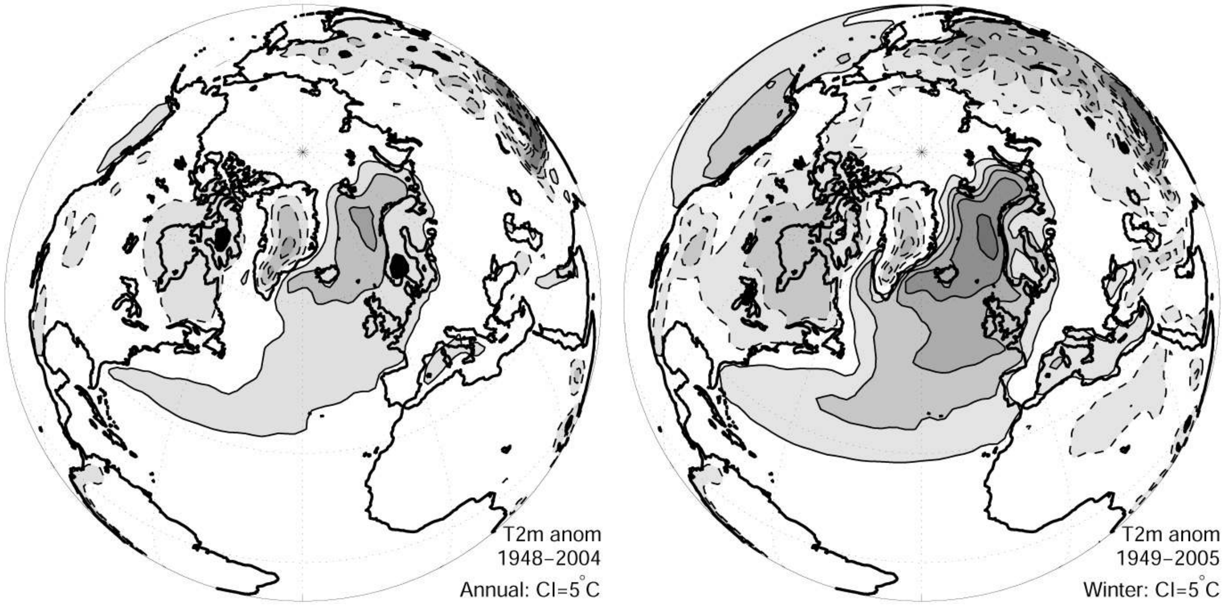

Figure 1. Deviations from zonal mean 2 m temperature for annual (left) and December-February (right) means. Contours are shown for every 5 (C. Solid (dashed) lines indicate positive (negative) anomalies. The figures are based on temperature data from the NCEP/NCAR reanalysis program [Kalnay et al., 1996].

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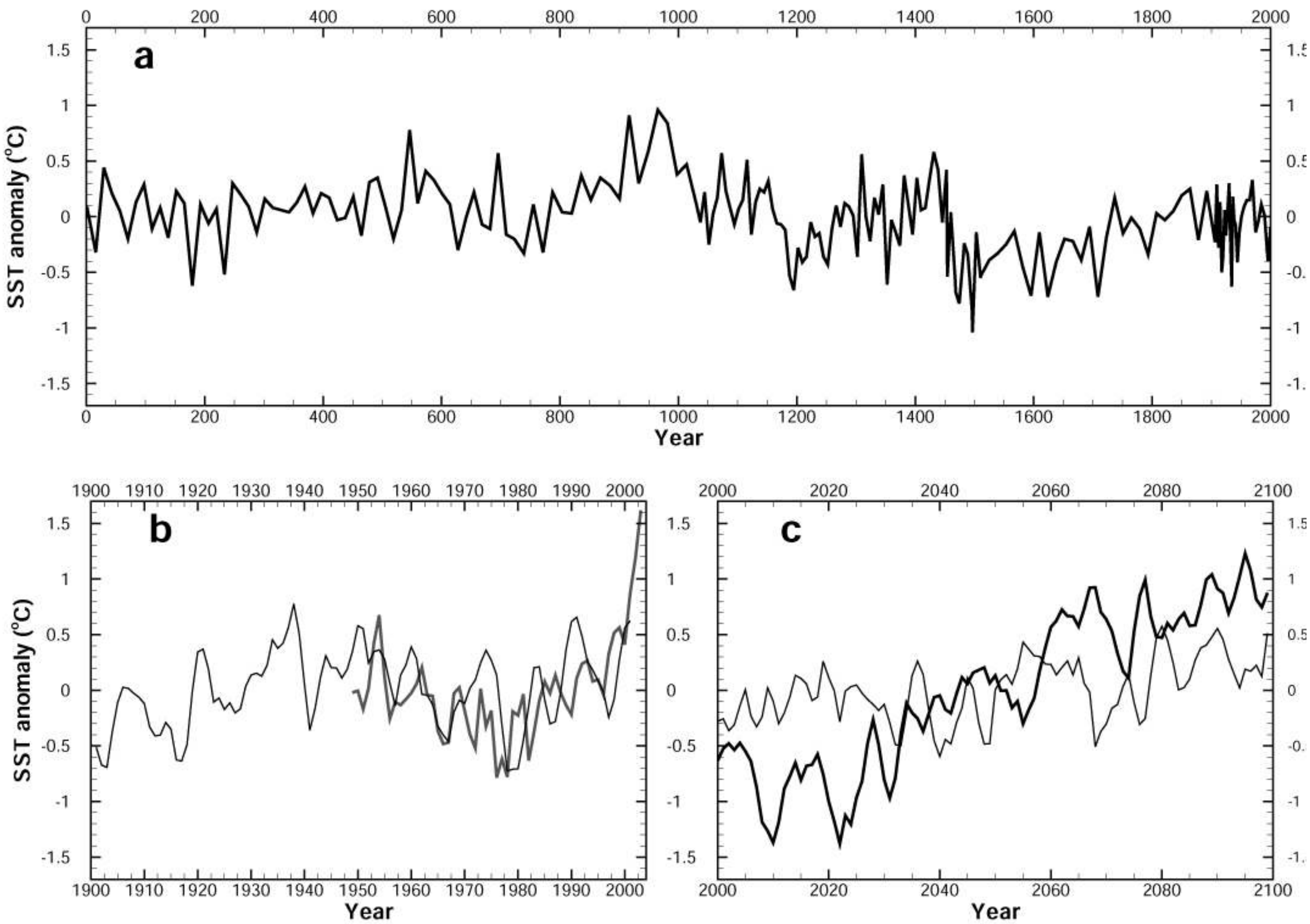

Figure 2. Temperature anomalies (ºC) in the eastern and northern Nordic Seas. a. Diatom-inferred August SST variations [Jansen and Koc, 2000; Birks and Koc, 2002; Koc and Jansen, 2002; Andersen et al., 2004] during the last two millennia (extracted from Fig. 5b in Nesje et al. [this issue]). b. Observed three-year annual mean 0-200 m temperature variations at the Kola transect in the Barents Sea (70°30'-72°30'N, 33°30'E, thin line: updated from Bochkov [1982]; Tereshchenko [1997]) and observed three-year mean July-September SST variations at OWS M (66ºN, 2ºE, thick gray line: Østerhus, unpublished data). c. Simulated change of three-year mean July-September SST anomalies from the eastern Norwegian Sea for the period 2000-2100 based on IPCC scenarios SRES A2 (thick line) and SRES B1 (thin line) with the Bergen Climate Model [Furevik et al., 2003; Bentsen et al., 2004]. The horizontal model resolution in the Nordic Seas is about 300-by-150 km in the atmosphere, and 80-by-80 km in the ocean. In all panels, the anomalies are relative to the mean value of the time series.

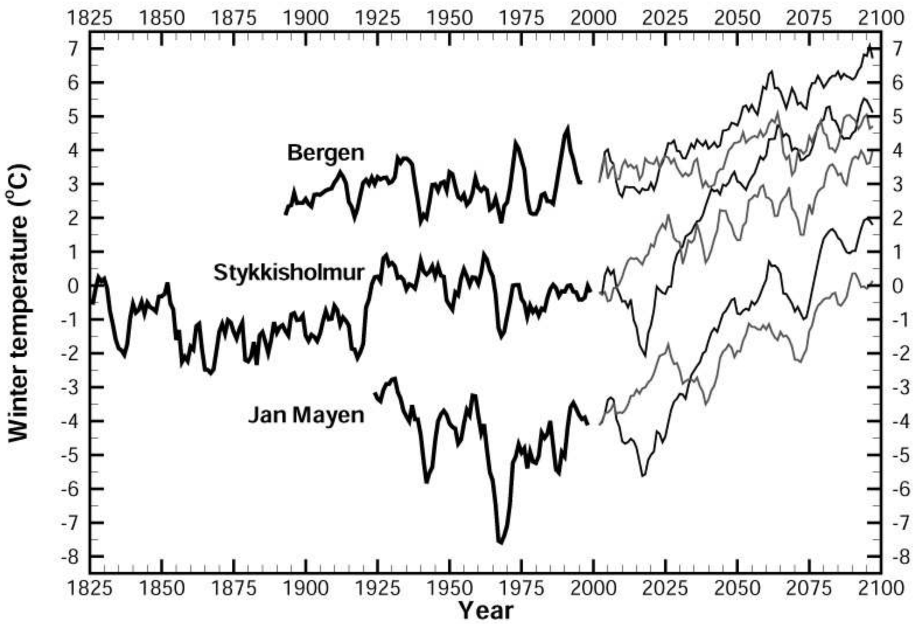

Figure 3. Observed (thick lines) and simulated (thin lines) five-year averaged December-April 2 m temperature (ºC) at Bergen, Norway (60ºN, 5ºE), Stykkishólmur, Iceland (65ºN, 23ºW), and Jan Mayen, central Nordic Seas (71ºN, 8ºW). The two simulations are based on the IPCC SRES A2 (thin black lines) and SRES B1 (thin gray lines) with the Bergen Climate Model.

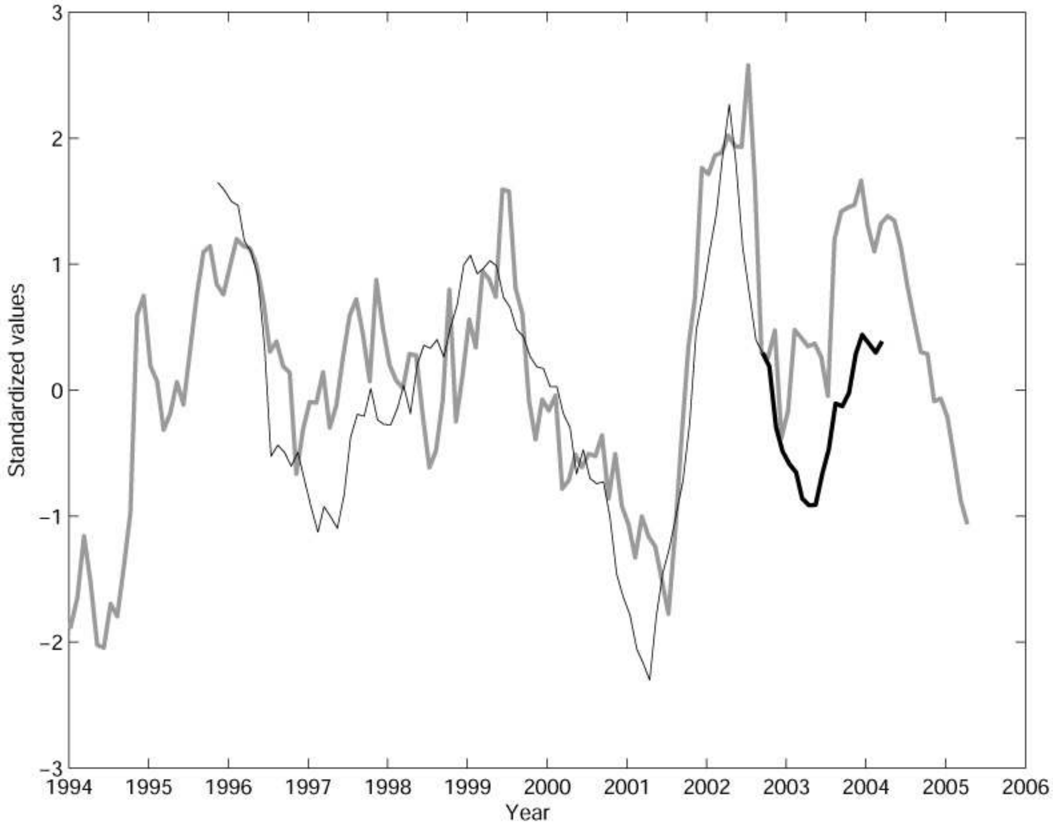

Figure 4. Time series representing the observed variability of the poleward flow of Atlantic Water at the Svinøy section off the coast of Norway at 62 ºN (black lines) and the North Atlantic wind stress curl at 55ºN (gray line). The thick black line is updated from Orvik and Skagseth [2003]. In the figure, the wind stress curl is leading the flow through the Svinøy section by 15 months.

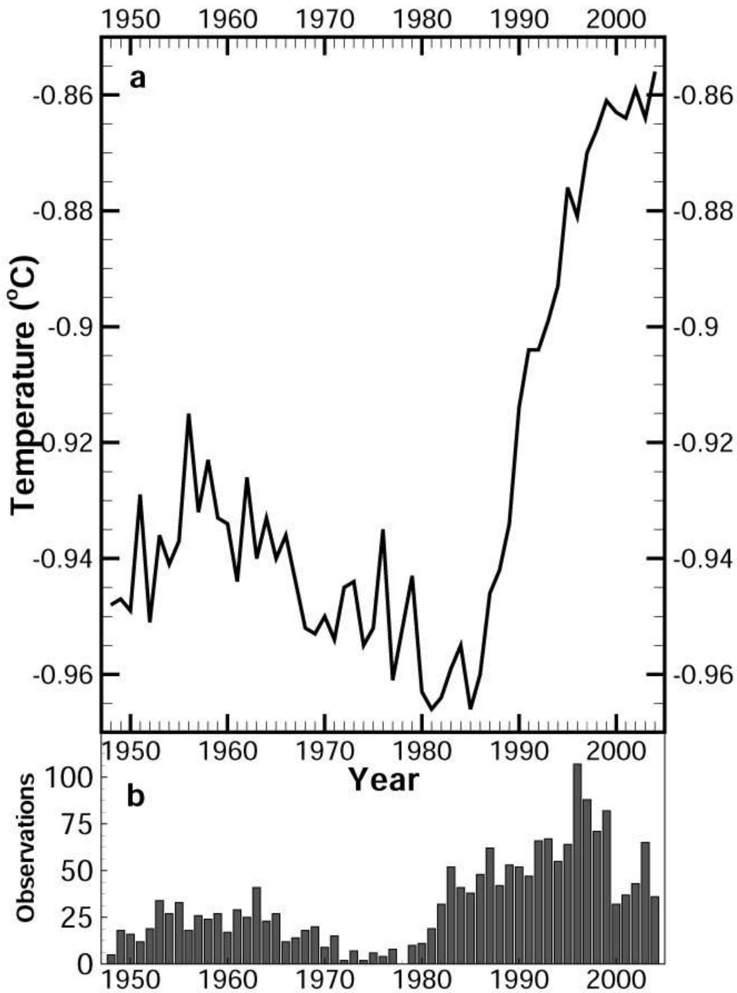

Figure 5. a. Time series of annual mean temperature (ºC) at 2.000 m depth from OWS Mike for the period 1948-2004 (updated from Østerhus and Gammelsrød [1999]). b. Number of observations per year.

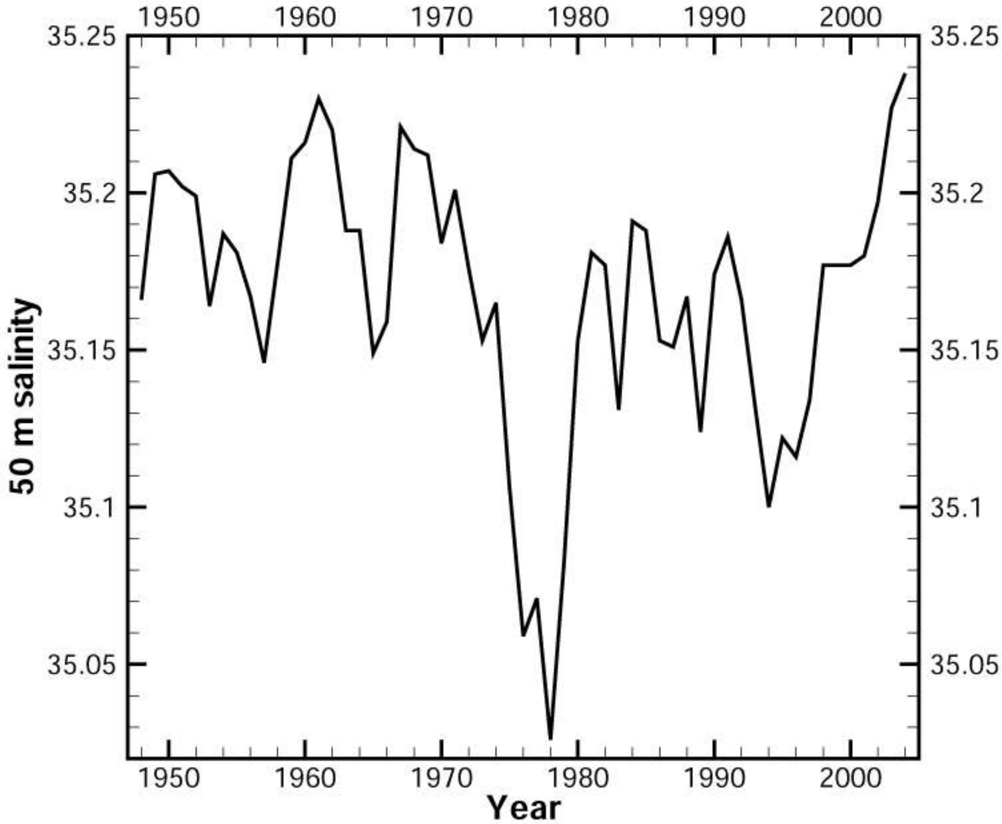

Figure 6. Time series of annual mean salinity at 50 m depth from OWS M for the period 1948-2004 [Østerhus, unpublished data]. The mean salinity in 2004 is 35.238.

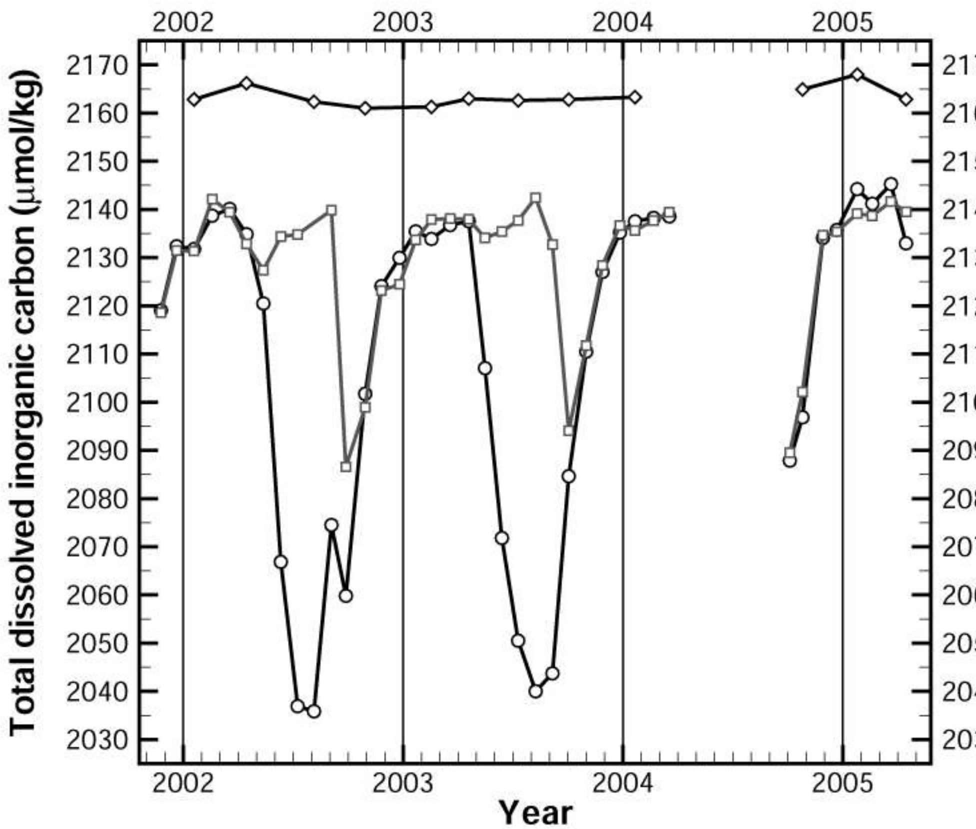

Figure 7. Illustration of the seasonal cycle of total dissolved inorganic carbon at 10 m (circles), 50 m (squares) and 2.000 m (diamonds) at OWS M, with the curves indicating variations in time. Skjelvan, unpublished data.