Interannual variability in water masses in the Greenland Sea and adjacent areas

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Oceanographic data covering the period 1950–1998 are used to determine interannual variations in the convection intensity and water mass structure in the Greenland Sea and adjacent areas. Extremely cold winters throughout 1965–1970 assisted intensification of the water vertical exchange in the Greenland and Norwegian seas. As a result, cold and fresh Greenland Sea Deep Water (GSDW) production was extremely high in the central Greenland Sea while in the southern Norwegian Sea warm and salty water spread downwards. The recent rapid warming in the Greenland Sea Gyre interior from 1980 originates, we argue, from an increase in the Atlantic Water (AW) temperature due to the advection of warm waters into the region with the Return Atlantic Current. The negative water temperature and salinity trends in the upper 300 m layer of the Atlantic Water in the Norwegian Sea prevailed during 1950–1990, whereas during 1980–1990 the water temperature trends are indicative of warming of that layer. Observation series obtained onboard the Ocean Weather Ship *Mike* confirmed the existence of layers with advection-driven high oxygen concentrations in intermediate and deep layers. The depth of oxygen maxima and the values of oceanographic parameters at this horizon can be regarded as indicators of the convection intensity in the Arctic domain. A simultaneous rise in NAO index and GSDW temperature points to a link between atmospheric and thermohaline circulation. Weakening in water exchange with the North Atlantic could be the reason for the Polar Water recirculation increase within the Nordic seas.

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A challenge to oceanographers in the last decade has been to better understand the mechanisms of development of deep water convection in the Greenland Sea. In this paper, we combine new oceanographic data collected during the last ten years of field studies in the Nordic seas with historical data covering the period from 1950 to 1990 to elucidate interannual variations in the convection intensity and water mass structure in the Greenland Sea and adjacent areas.

Several factors determine the intensity of intermediate and deep water formation in the central area of the Greenland Sea. Atmospheric circulation and air temperature affect the surface water cooling rate, current dynamics, ice formation and ice drift. The inflow of fresher water and ice into the areas of winter convection tends to stabilize the water column and prevents the convection from deepening. A key factor in developing deep water convection is a high level of salinity in the upper layer (Alekseev et al. 1994). The main mechanism regulating salinity in the Greenland Sea Gyre (GS Gyre) is the advection of Atlantic Water (AW) and Polar Water (PW).

Water of Atlantic origin contributes mostly to the upper layer formation in the central Greenland Sea. According to Carmack & Aagaard (1973), up to 90 % of the water mass volume in this layer consists of AW, whereas PW accounts for only 1 - 2 %. Blending of these waters results in a wide spectrum of thermohaline properties depending on the relative abundance of the initial water masses. The occurrence of saline water at the surface of the GS Gyre as compared to PW is thought to be a consequence of a two-pathway water transport. The first one is the inflow of AW, which is transported by both the West Spitsbergen Current and the Return Atlantic Current along the eastern and northern outskirts of the GS Gyre (Johannessen et al. 1996). The second pathway is a rise of saline and warm intermediate water to the surface as a result of winter convective mixing. Within the gyre, intermediate water layers underlie the PW and the freshened surface water mass.

Interannual variability in the Greenland Sea Gyre

The Norwegian and Greenland seas oceanographic database (NGDB) used in this study has been developed at AARI (Ivanov et al. 1996) and has been expanded with recent data with the support of the INTAS project (Johannessen et al. 2000). The NGDB contains data from about 130 000 oceanographic stations at which the measurements were taken from the end of the 19th century until 1998. These data were obtained from the World Oceanographic Data Centres and some national and international projects, including important data from 42 large-scale surveys carried out between 1976 and 1990 in the framework of the Russian national projects "Polex-North" and "Sections". The measurements taken in the course of the above surveys relate to fixed positions at 2° 30' intervals. As many as five research vessels have been operating simultaneously within the area between 60° - 80° N. In addition, mesoscale surveys were conducted in the Faroe–Shetland Channel, in the vicinity of the Ocean Weather Ship *Mike*, in the Lofoten Basin, Fram Strait and the GS Gyre. The most abundant data relating to the period 1950–1990 are stored in the NGDB. All data were verified and interpolated at the standard levels in strict accordance with the procedures used for creating the *World ocean atlas 1994* (Levitus et al. 1994).

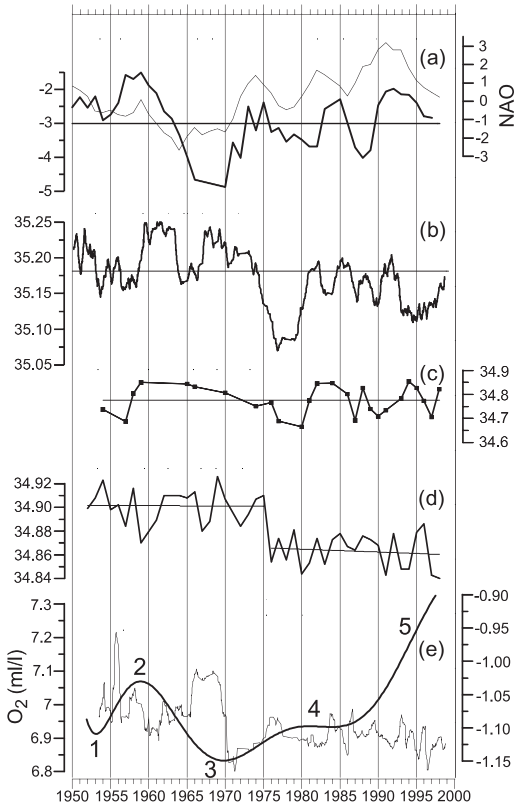


Fig. 1. Time series of (a) 3-year running means of surface air temperature at Jan Mayen (bold line) averaged for October–April (mean for 1950–1998 is also shown) and NAO winter index; (b) 100 m salinity running means at OWS *Mike*; (c) winter surface salinity averaged in the central Greenland Sea (73° 30' - 76° 30' N, 5° W - 3° E) region; (d) salinity at 200 m in the central Greenland Sea; (e) water temperature at 2000 m (bold line) in the central Greenland Sea and 1500 m dissolved oxygen concentration at OWS *Mike*. Polynomial and linear fits are shown.

The water temperature at 2000 m is usually regarded as an indicator of deep water renewal intensity driven by the winter cooling over the Greenland Sea (Aagaard 1968). Its correlations with transient tracer observations (Bonisch et al. 1997) confirm the close relation between a low deep water temperature and high deep water formation rates, and the correlation between a

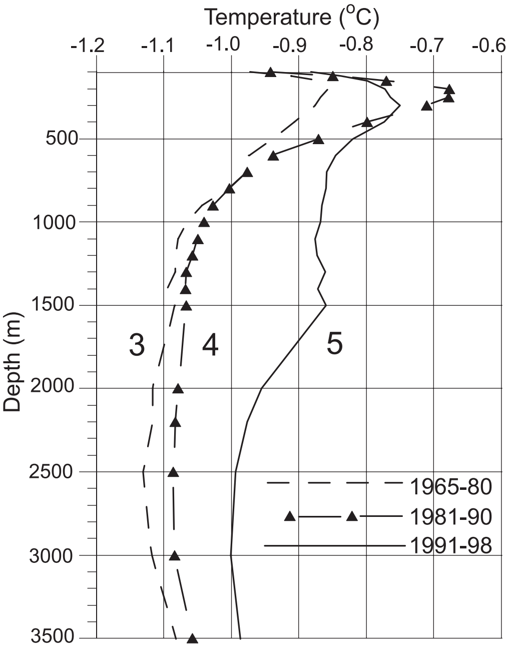


Fig. 2. Temperature vertical profiles averaged in the central Greenland Sea (73° 30' - 76° 30' N, 5° W - 3° E) for different time intervals (3: 1965–1980, 4: 1981–1990, 5: 1991–98). Upper 1000 m part averaged for the February–March period, below for January–December. Profiles are shown from 100 m depth level.

high deep water temperature and low deep water formation rates. On this basis two periods with increased Greenland Sea Deep Water (GSDW) production rates and two periods with decreases were revealed from water temperature records during 1952–1994. In this paper, a complete temperature time series at a depth of 2000 m was constructed and then subdivided into five periods (Fig. 1). In the 1950s, the temperature contrast between cold (1) and warm (2) periods was less than 0.1 °C. The temperature increase between phases 5 and 3 was about 0.25 °C. These stages are separated by period 4, when the water temperature was stable. Time records of the air temperature at Jan Mayen, the NAO winter index, salinity series at the OWS *Mike*, surface and 200 m salinity series in the GS Gyre support the hypothesis that high deep water formation rates during the late 1960s–early 1970s were controlled by a combined effect of certain climatic conditions. High salinity levels in the AW in the Norwegian Sea (Fig. 1b) as well as high winter salinity levels at the surface and high mean annual salinity at a 200 m depth in the GS Gyre (Fig. 1c, d) were accompanied by abnormally cold winters during the late 1960s (Fig. 1a). These features support the contention of Helland-Hansen & Nansen (1909) that "forming the bottom water must chiefly depend on its salinity". Favourable conditions ceased after a rapid salinity decrease in the Norwegian Sea in the late 1970s. This event was either caused by the Great Salinity Anomaly (GSA) advected from the North Atlantic in the late 1970s (Dickson et al. 1988) or/and by a change in the dynamics balance between the AW flow and East Icelandic Current (Hansen & Kristiansen 1994). Caused by the advection of GSA, low temperature and salinity levels in the upper layer in the Norwegian Sea proved to be persistent due to increased freshwater supply from the Arctic Ocean. This water supply is thought to be a consequence of the atmospheric circulation pattern characterized by a high NAO wintertime index (Blindheim et al. 2000). Although the winter surface salinity in the GS Gyre from 1982 onward is comparable with the salinity levels in 1965–1975, the tracer observations reported by Rhein (1991) are indicative of the cessation of convection. In contrast with the above winter surface salinity variations, the subsurface mean annual salinity levels have decreased since 1975 (Fig. 1d).

The mean temperature profiles (Fig. 2) relating to the last three periods (see Fig. 1e) demonstrate that the upper 200 - 400 m layer was considerably warmer during the fourth period in comparison with the subsequent period, while in deeper layers the profile was similar to the one observed during the previous cold period. The average temperature profile for the period 1991–98 reflects a rapid warming of the water column below 500 m, while the subsurface temperature maximum is less pronounced. The processes responsible for the temperature increase are depth-dependent. First of all, the identified cessation of deep water formation eventually resulted in the GSDW temperature increase. The latter was caused by the advection of warm and saline Arctic Ocean Deep Water (Aagaard et al. 1991). Meincke et al. (1997) suggested that high water temperature in the upper layer of the Greenland Sea resulted from either the increase of the AW temperature and inflow (both or separately), or from the reduction of the AW heat loss to the atmosphere. Narrowing of the Norwegian Atlantic Current is regarded as conducive to a reduced cooling. It was also noted that warming is stronger in the northern

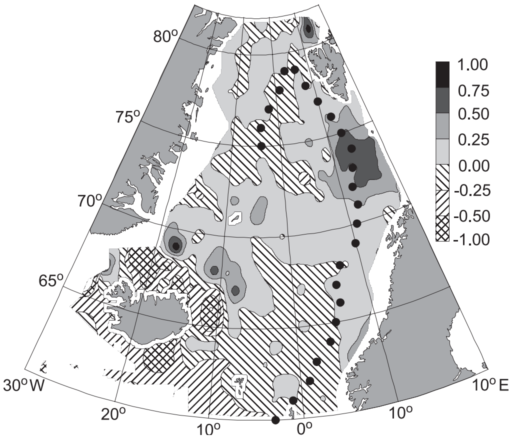


Fig. 3. Distributions of water temperature anomalies at 100 m computed as the difference between mean temperatures for 1980–1990 and 1950–1990 time intervals. Black dots indicate position of section along the salinity core of Atlantic Water at 100 m.

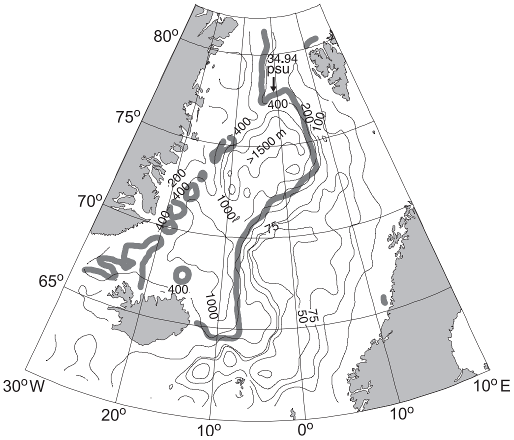


Fig. 4. Depth distribution (m) of the subsurface salinity maxima defined from vertical salinity profiles averaged inside 1° × 1° squares for the period 1900–1990. Position of the 34.94 psu isohaline is shown (thick grey line).

part of the Norwegian Sea than in the inflow area (Blindheim et al. 2000). Deepening of the intermediate temperature maximum in the Greenland Sea from 1993–96 with a rate of about 150 m/year (Budeus et al. 1998) supports the hypothesis of a large-scale permanent convection with a sink in the central part of the basin. Distribution of water temperature anomalies at a depth of 100 m over the period 1980–1990 (Fig. 3) reveals an area in the northern Norwegian Sea characterized by high positive values of anomalies. The vertical extension of the warm anomaly exceeds 400 m and provides a basis for the hypothesis that the rapid warming of the GS Gyre interior is related to the AW temperature increase during the 1980s. The appropriate link between the northern Norwegian Sea and the central Greenland Sea is likely to be the AW circulation in Fram Strait, backed up by the Return Atlantic Current.

Distribution and transformation of the Atlantic Water in the Norwegian and Greenland seas

The AW is considerably transformed before reaching the Greenland Sea. It is cooled in the Norwegian Sea due to a considerable heat loss to the atmosphere, and freshened by mixing with waters of both the Norwegian Coastal Current (NCC) and Arctic Water carried by the East Icelandic Current. The vertical distribution of the subsurface salinity maximum was determined from the average salinity profiles calculated for 1° squares (Fig. 4). Mean salinity in the AW core ranges from 35.3 psu in the Faroe–Shetland Channel to 35 psu in Fram Strait. The core depth increases from 50 m in the central part of the Norwegian Sea to 200 - 400 m near the Norwegian coast and in Fram Strait. It increases sharply up to over 1000 m in the central Greenland Sea. A “tongue” of higher salinity water observed to the north of the GS Gyre results from the return circulation of the AW in the Fram Strait in the 200 - 400 m range of depths.

To investigate the transformation of the temperature and salinity anomalies advected from the North Atlantic, time series correlation analysis was applied along the AW pathway in the Nordic seas. Time series of the annual mean temperature and salinity were established for all standard levels inside 22 boxes (1° longitude × 2° latitude), which have been chosen along the AW salinity core at a depth of 200 m within the 60° - 81° N latitudinal zone. First, the initial point for calculation was fixed in the Faroe–Shetland Channel. The results obtained indicate that the temperature anomalies vanish after crossing the 63° N latitude, while the salinity anomalies persist up to Fram Strait. The strongest anomaly changes take place in the zone of influence of the East Icelandic Current. When the initial point for calculating the correlation coefficients was shifted to the OWS *Mike*, significant correlation coefficients both for

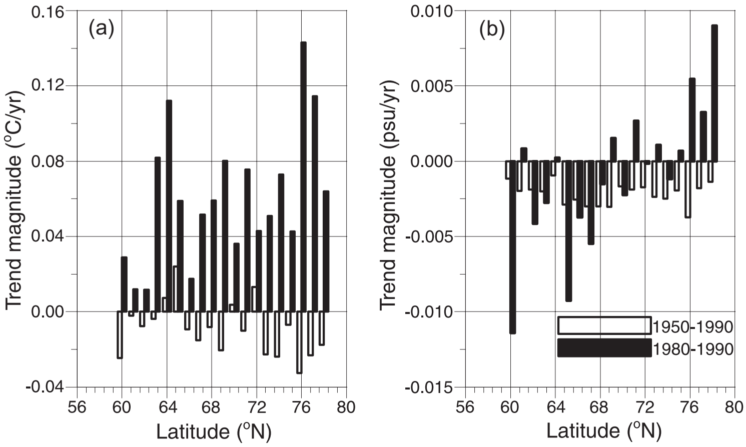


Fig. 5. (a) Water temperature and (b) salinity trends in the 10 - 300 m layer averaged inside 1° longitude × 10° latitude boxes crossing the Atlantic Water for 1950–1990 and 1980–1990 time intervals. Western and eastern box boundaries have been chosen as deviation from Atlantic Water salty core position at 100 m (shown in Fig. 3).

salinity and temperature were obtained over the study area extending as far as Fram Strait. The correlation analysis also shows that the advected anomalies sink progressively northwards. These results allow us to to conclude that temperature anomalies are generated mainly inside the Nordic seas, with an increased role played by interaction with the atmosphere to the north.

To determine the temperature and salinity trends along the AW pathway, time series of the mean temperature and salinity inside 1° latitude × 10° longitude boxes were calculated. The western and eastern box boundaries were defined as a deviation from the AW salinity core location at 100 m. Linear trends in the upper 10 - 300 m layer (Fig. 5) depend on the latitude, but they indicate that there is an overall temperature and salinity reduction during the period from 1950 to 1990. This is in contrast with the apparent warming in the upper 300 m column in the North Atlantic as reported by Levitus et al. (2000). A rapid warming of the upper layer began in the 1980s, with the maximum trend magnitudes along 64° N and 76–77° N latitudes. Salinity trends (Fig. 5b) point to a common salinity decrease, although at some latitudes (mostly in the area of the northern Norwegian Sea) the situation proved to be inverse. A closer insight into the AW salinity variations may be obtained from the OWS *Mike* observations (Fig. 6). A mixed layer formed during the winter–spring convection period stores the integral information about the summertime freshening and intensity of winter vertical mixing. The salinity anomalies in Fig. 6 were calculated for January–May. Prior to the early 1970s, AW with high salt content prevailed and two positive salinity anomalies could be revealed in the data relating to the 1958–1964 and 1966–1971 periods. A downward salt redistribution is easily distinguishable below 1000 m depth for the period 1970 –1990. Two strong negative anomalies occurred during 1973–79 and 1993–98. Negative density anomalies drift near the surface while positive ones drive the upper layer properties downward. It is likely that the 1966–1971 positive density anomaly brought about a modification of intermediate and deep layers characteristics. The main difference between two strong low salinity events in the vicinity of the OWS *Mike* is that GSA originating from the Arctic Ocean was first advected to the North Atlantic while the anomaly which happened in the middle 1990s was transported directly from Iceland Sea to the Norwegian Sea. The explanation can be done from the point of redirection of PW pathways between Denmark Strait and the East Icelandic Current.

The Return Atlantic Current advects the AW to the GS Gyre area. The mean positions of the 35.1 and 34.94 psu isohalines inside 1° longitude × 3° latitude boxes for different time intervals (Fig. 7) are plotted along the section (shown in Fig. 3). A 800 km shift in the 35.1 psu isohaline location established for two time periods (1973–79 and 1954–1972) reflects the AW salinity changes. The 34.94 psu isohaline at the margins of the GS Gyre was quite stable during the lifetime of the low salinity regime. However, there are obvious indications of its shift towards the GS Gyre centre during the high salinity period. This shift is especially pronounced at depths exceeding 150 m.

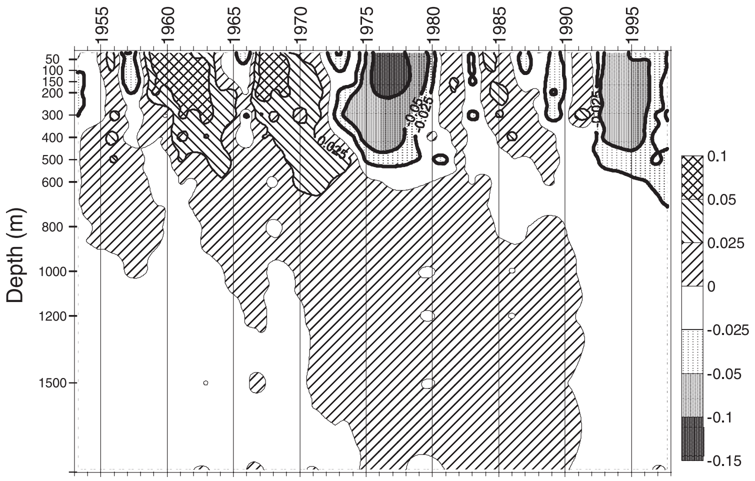


Fig. 6. Time-depth salinity anomaly (psu) evolution at OWS *Mike* averaged for January–May.

Relation between the convection regions in the Arctic area and the southern Norwegian Sea

Variations in oceanographic parameters in the vicinity of the OWS *Mike* were considered as possible indirect indicators of convective processes in the Arctic area. It was suggested that layers with dissolved oxygen maxima are likely to be advected from some convection activity areas in the Iceland and the Greenland seas and the southern Norwegian Sea (Johannessen et al. 2000). Consequently, intermediate (ca. 600 m) and deep (ca. 1500 m) oxygen maxima store the information about water formation at the surface and about the mixed layer depth. The depth of oxygenated layers is not stable and varies throughout 1953–1998 within the 300 and 600 m ranges for upper and deeper layers, respectively. The oxygen concentration change is also an indicator of convection intensity (Fig. 1e). The density surfaces distribution, along which the water mass originating from convection regions spreads, depends both on the long-term climatic variations and the surface conditions in a given year. Therefore, the oceanographic parameters' variations at the oxygen maximum depths are the integral characteristics. The most remarkable changes had occurred at the depth of deep oxygen maximum. From 1982 onwards, the water temperature increased by 0.15 °C, while its salinity decreased by about 0.03 psu. These trends were accompanied by a decline of water density.

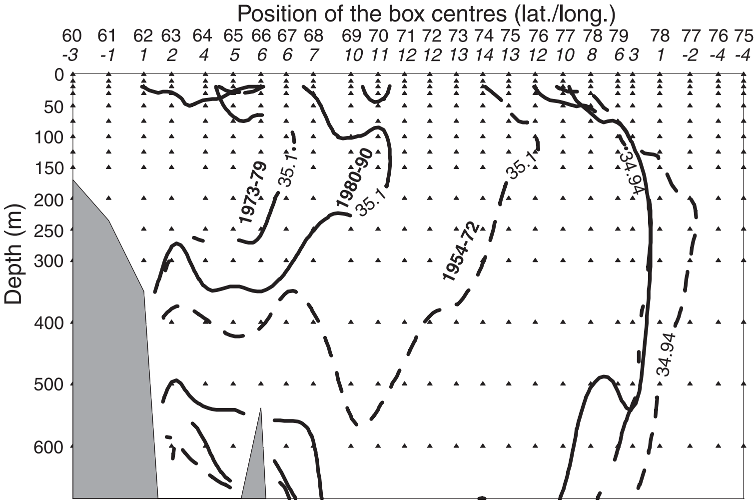
Discussion and conclusions

The history of changes in water mass characteristics in the Greenland Gyre represents two periods with increased deep water formation rate (early 1950s, late 1960s–early 1970s) and two periods with a reduced rate (late 1950s, early 1980s–today). The GSDW temperature increase at 2000 m was 0.25 °C during 1970–1998. Initial warming has been caused by the warm and salty Arctic Deep Water impact until the gradient in deep layer was observable (Budeus et al. 1998). Afterwards the evolution of the thermal structure of the GS Gyre changed from a significant subsurface layer (200 - 400 m) warming during the 1980s to a rapid temperature increase of the entire water column during the 1990s.

Intensive spreading of the saline AW within the Nordic seas during 1960s was accompanied by extremely cold winters throughout 1965–1970. A joint effect of these factors contributed to intensification of a vertical exchange in the Greenland and Norwegian seas. The cold and fresh GSDW production was extremely high in the central Greenland Sea while in the southern Norwegian Sea warm and saline water was redistributed downward leading to increased gradients between the basins.

In the absence of efficient ventilation, the recent changes in the GS Gyre thermal structure were caused by variations in the AW characteristics. From the correlation of the temperature and salinity time series along the AW pathway it became clear that the advected temperature anom-

Fig. 7. Position of 35.1 and 34.94 psu isohalines averaged inside 1° longitude × 3° latitude boxes in the core of Atlantic Water flow along the section between Faroe–Shetland Channel and the central Greenland Sea (shown in Fig. 3) for 1954–1972, 1973–79 and 1980–1990 time intervals.



alies were suppressed after crossing the Faroe–Shetland Channel, while the salinity anomalies persisted up to Fram Strait. The transformation in question is especially intense in the zone of influence of the East Icelandic Current. Trends in the upper 10 - 300 m layer along the sections crossing the AW saline core within the 60° - 78° N latitudinal zone depend on the latitude. They reflect, however, the overall temperature and salinity reduction during the 1950–1990 period. In contrast, the AW temperature trends for the 1980–1990 period are indicative of a continuous increase. The temperature anomalies for the same period demonstrate that an area with abnormal water warming was located in the northern Norwegian Sea. Further to the north, the observed intensification of warming can be explained either by reduction of the heat loss to the atmosphere or the increased volume of the AW inflow from the North Atlantic. There are no direct data confirming the intensification of the AW inflow into the Nordic seas and the relative contributions of thermohaline forcing and atmospheric circulation to the AW flux are not obvious yet. Although deep water formation reduction is a candidate mechanism bringing about a decline of thermohaline forcing (Hansen & Osterhus 1999), the total overflow flux to the North Atlantic varies only slightly on time scales ranging from a season to a decade. However, recent estimates show at least a 25 % decrease in deep flow volume in the Faroe Bank Channel in the period 1950–2000, which contributes about one third of the total overflow from the Nordic seas (Hansen et al. 2001).

Blindheim et al. (2000) suggested that the observed narrowing of the NAC is the major driver of the AW heat loss reduction. Observations from the OWS *Mike* show that the AW extension to the west is associated with enhancement of downwelling heat and salt fluxes. Therefore, the observed temperature increase to the north could also be attributed to a reduced exchange of water in upper layers with underlying water due to the upper layer freshening and stability increase. Dickson at al. (2000) assume that the additional freshwater input takes place along the NAC between the low and high NAO extremes and that about 60 % of the AW temperature variance in Fram Strait is explained by the NAO wintertime index. The depth of the winter mixed layer strongly depends on both the upper layer salinity and cooling. A recent freshening of the upper layer in the central Norwegian Sea under relatively (compared to the late 1960s) mild temperature conditions confirms the idea that the AW lost a lesser amount of salt redistributed downward that leads to freshening of intermediate and deep layers. Variations in position of the 35.1 psu isohaline (Fig. 7) are much larger than those reported for a 300 km shift in the west–east AW area (Blindheim et al. 2000). A convectively homogenized layer could extend to well below a 500 m depth in the northern Norwegian Sea (Aken et al. 1991), which is close to the lower boundary of the warm anomaly during 1980–1990. Therefore, due to a decline in the convection intensity a lesser amount of heat is removed from the subsurface AW flow, which, in turn, results in an additional strengthening of the previously formed warm anomaly.

Based on the observation series obtained onboard the OWS *Mike*, the existence of layers with advection-driven enhanced oxygen concentrations in intermediate and deep water layers was confirmed. These layers can be considered as the most probable zones of supply of water masses from the adjacent areas. The depth of deep water oxygen maxima and the values of oceanographic parameters at those levels can be regarded as indicators of the convective regime change in the Arctic area.

From the results presented we conclude that the ocean climate in the Nordic seas during last two decades has formed under the increased impact of PW, causing deep convection reduction and consequent weakening of thermohaline circulation. It leads to redirection of the low salinity water pathway and water freshening within the Nordic seas. Coordinated increase both in the GSDW temperature and the winter NAO index reflect the correlation between atmosphere and thermohaline circulation realized through stability of the upper layer that is governed by salinity variation. Observations show that GSA advection can be regarded as the initial point for alteration in vertical exchange. Generation of water temperature positive anomaly upstream of AW flow in the Nordic seas reflects an increased role of interaction with the atmosphere, possibly reinforced by global warming amplification to the north.

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