Simulated North Atlantic-Nordic Seas water mass exchanges in an isopycnic coordinate OGCM

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[1] The variability in the volume exchanges between the North Atlantic and the Nordic Seas during the last 50 years is investigated using a synoptic forced, global version of the Miami Isopycnic Coordinate Ocean Model (MICOM). The simulated volume fluxes agree with the existing observations. The net volume flux across the Faroe-Shetland Channel (FSC) is positively correlated with the net flux through the Denmark Strait (DS; $R = 0.74$ for 3 years low pass filtering), but negatively correlated with the net flux across the Iceland-Faroe Ridge (IFR; $R = -0.80$). For the Atlantic inflow across the FSC and IFR, the correlation is $R = -0.59$. For the transports through the FSC and DS, the simulation suggests that an atmospheric pattern resembling the North Atlantic Oscillation is the main driving force for the variations, involving Ekman fluxes and barotropic adjustment. The model also shows a 0.7 Sv reduction of the Atlantic inflow to the Nordic Seas since the late 50's. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4255 Oceanography: General: Numerical modeling; 9315 Information Related to Geographic Region: Arctic region; 1635 Global Change: Oceans (4203); 1620 Global Change: Climate dynamics (3309). **Citation:** Nilsen, J. E. Ø., Y. Gao, H. Drange, T. Furevik, and M. Bentsen, Simulated North Atlantic-Nordic Seas water mass exchanges in an isopycnic coordinate OGCM, *Geophys. Res. Lett.*, *30*(10), 1536, doi:10.1029/2002GL016597, 2003.

1. Introduction

[2] The Atlantic Meridional Overturning Circulation (AMOC) is a dynamically active component of the climate system, in particular on multi-annual to decadal time scales [*Eden and Jung*, 2001]. The amount of heat and salt carried by Atlantic Water (AW) northward across the Greenland-Scotland Ridge (GSR) is substantial, and both quantities are of importance for the water mass and sea ice distribution of the Nordic Seas and the Arctic Ocean. The main exchange of watermasses between the North Atlantic Ocean and the Nordic Seas occurs through the Denmark Strait (DS), the Iceland-Faroe Ridge (IFR), and the Faroe-Shetland Channel (FSC) with the Faroe-Bank Channel (FBC) at its entrance (Figure 1).

[3] The exchanges over the GSR have been reviewed by *Hansen and Østerhus* [2000] (hereafter HØ). A schematic overview of the surface current system in the region is provided in Figure 1. Gulf Stream waters from the southwest spread with the North Atlantic Current (NAC) via diverse pathways across the whole Northeast Atlantic [*Orvik and Niiler*, 2002]. Most of the AW in the Irminger Current (IC) joins the southbound East Greenland Current (EGC), while only a minor part enters the Nordic Seas through the Denmark Strait. East of Iceland, surface water in the northern Iceland Basin crosses the IFR. Upon meeting the Arctic Water north of the ridge, the two form the Iceland Faroe Front and the AW turns eastward along the ridge as the Faroe Current (FC). This flow continues along the 2000 m isobath into the Norwegian Sea as the western branch of the Norwegian Atlantic Current (NWAC). Through the FSC the major source of AW is the slope current along the Scottish Slope, and this flow continues northwards along the Norwegian Continental shelf-break as the eastern branch of the NWAC. Some of the FC turns southwards along the Faroese continental slope into the FSC, but most of it recirculates into the slope current on the eastern side of the channel.

[4] The overflow across the GSR from the Nordic Seas into the North Atlantic is an important source for the North Atlantic Deep Water [*Dickson and Brown*, 1994], and it forms the deepest part of the AMOC. In recent years, much attention has been put on the volume transport of the AW [*Orvik et al.*, 2001] and the overflow water [HØ; *Hansen et al.*, 2001; *Dickson et al.*, 1999; *Girton et al.*, 2001] across the GSR. In this paper, the mean values and the multi-annual to decadal scale variability in volume transports through all three gaps are investigated using a 52 year hind-cast simulation with a medium-resolution global version of the Miami Isopycnic Coordinate Ocean Model (MICOM). The

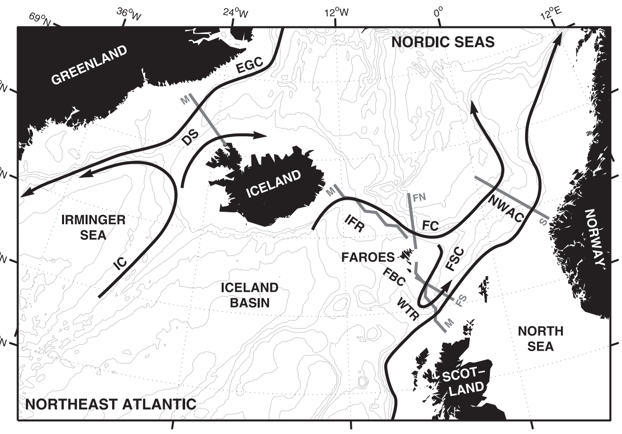

Figure 1. Greenland-Scotland Ridge and its surrounding waters. Isobaths are drawn for every 500 m. Schematic surface currents with key references are indicated. Abbreviations are explained in the text. Grey lines indicate model (M), Faroe north (FN) and south (FS), and Svinøy (S) sections.

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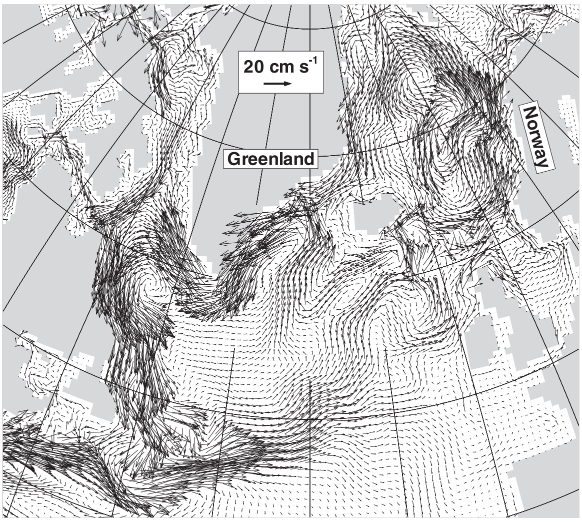

Figure 2. Simulated mean velocity in the mixed layer for the period 1948–1999.

model output is compared with available observations and observation-based estimates from the region, and a possible link between the simulated variability and the atmospheric forcing is presented.

2. Model Description

[5] The model system applied in this study is MICOM [*Bleck et al.*, 1992], fully coupled to a dynamic-thermodynamic sea-ice module. The model set-up and integration follow the description of the synoptic hind-cast simulations in *Furevik et al.* [2002], and only key features are provided here.

[6] The model has 25 vertical layers with fixed potential densities, and an uppermost mixed layer with temporal and spatial varying density. In the horizontal, the model is configured with a local orthogonal grid mesh with one pole over North America and one pole over western part of Asia [*Bentsen et al.*, 1999] yielding a grid-spacing of 30 to 40 km in the entire North Atlantic-Nordic Seas region. The bathymetry is computed as the arithmetic mean value based on the ETOPO-5 data base.

[7] The diffusive velocities (diffusivities divided by the size of the grid cell) for layer interface diffusion, momentum dissipation, and tracer dispersion are 0.015 m s^{-1}, 0.01 m s^{-1} and 0.005 m s^{-1}, respectively. The diapycnal mixing coefficient K_d (m^2 s^{-1}) is parameterised according to the expression $K_d = 3 \times 10^{-7}/N$, where N (s^{-1}) is the Brunt-Väisälä frequency. The model is integrated with daily NCEP/NCAR reanalysis forcing fields [*Kalnay et al.*, 1996] for the period 1948–1999. No relaxation is used for temperature, whereas a diagnosed weekly resolved annually repeated restoring flux is applied for the sea surface salinity.

3. Results

[8] The model manages to capture the major features of the observed flow fields in the North Atlantic-Nordic Sea region (Figure 2). The water from the Gulf Stream spreads out over the whole Northeast Atlantic. Only a small fraction of the waters in the Irminger Current enters through the Denmark Strait, while the bulk part turns southward and follows the EGC. The major part of the NAC enters the Nordic Seas on both sides of the Faroe Islands. The general surface ocean circulation within the Nordic Seas is dominated by the warm and saline NWAC to the south and east, and the cold and fresh EGC to the north and west.

[9] In the following, the term "inflow" denotes all the watermasses which flow into the Nordic Seas across the GSR, and "outflow" comprises both dense overflow and surface outflows. The net fluxes are defined as positive in the direction of the mean flows, i.e. northwards for FSC and IFR, and southwards for the DS.

[10] In order to put emphasis on the interannual to decadal variability, time series of the simulated transports over the GSR have been low-pass filtered using a Butterworth filter with cut-off period of 3 years (Figure 3). All sections reveal substantial variability, with typical amplitudes for the transport anomalies of the order 1–2 Sv. The net flow through the FSC, for instance, was very low during the first 20 years (1.8 Sv), then for the next 17 years the average was 3.3 Sv, before decreasing to near 2 Sv for the remaining part of the simulation. The total inflow across the GSR however, has its highest transport from the late 50's to early 70's.

[11] The mean simulated transports over the GSR are summarized and compared to estimates cited in the literature in Table 1. Taking into consideration the variability on multi-annual to decadal time scales in the simulated transports (Figure 3), the model-data comparison has been performed for the relevant timespans of data collection.

[12] The net volume flux through the FSC is positively correlated with the net volume flux through the DS, while negatively correlated with the net volume flux accross the IFR. The correlation coefficients calculated from the low-pass filtered time series are R = 0.74 and R = −0.80, respectively. The inflows over the IFR and through the FSC are also negatively correlated (R = −0.59).

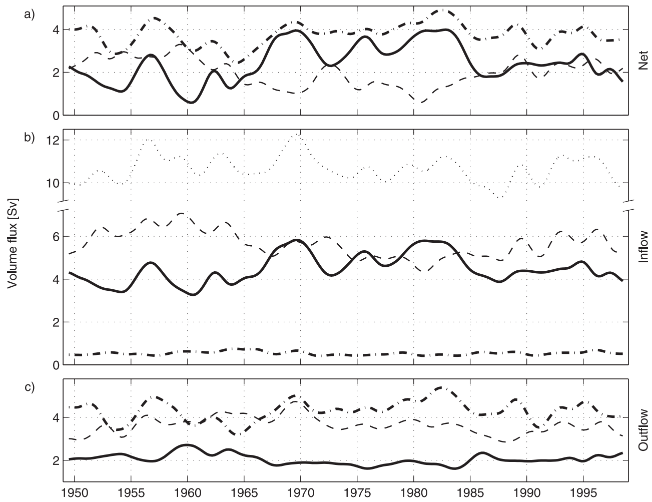

Figure 3. Temporal variation of the 3-years low-pass filtered simulated net (a), inflow (b), and outflow (c) volume transports through the FSC (solid lines), IFR (dashed lines), DS (dot-dashed lines), and total inflow (dotted line). Note that the net flux through the DS is defined positive southwards.

Table 1. Simulated and observation-based mean northward (N) and southward (S) volume transports in Sv (1 Sv = 10^6 m^3 s^{-1}) over the GSR

Section		Simulated 1948–99	Simulated Period	Observed Value	Observed Period	Sources
DS	N	0.5		1.0		1
	S	4.3		4.3		1, 2
IFR	N	5.6	5.8	3.3	1995–1998	1
	S	3.6		1.0		1
FSC	N	4.4	4.2	4.3 (3.2)	1994–2000	3
			4.3	4.2	1995–1998	4
	S	2.1	2.2	4.5 (2.6)	1994–1998	1, 5, 6, 7

The observation-based transport estimates without indicated measurement period are general. Values in parenthesis are the northward flow corrected for recirculation of the FC, and the southward flow of the deep waters alone. [1]*Hansen and Østerhus* [2000]; [2]*Fissel et al.* [1988]; [3]*Turrell et al.* [2003]; [4]*Orvik et al.* [2001]; [5]*Turrell et al.* [1999]; [6]*Østerhus et al.* [1999]; [7]*Ellett* [1998].

[13] The role of the atmospheric forcing has been investigated by regressing the (unfiltered) winter mean sea-level pressure (SLP) field from NCEP/NCAR reanalysis data onto simulated volume transport anomalies. The regression maps (Figure 4) reveal that variations in both inflow and net transports through the DS and FSC are linked to an NAO-like pattern in SLP [*Hurrell*, 1995], having centres of action located in the central Nordic Seas and in a zonal belt extending eastward from the Azores. Correlations in the two centres reach 0.6 and 0.5 respectively, and are well above the 99% significance level. Regression using monthly mean data gives qualitatively the same patterns (not shown). Furthermore, no relation is found between SLP and inflow over the IFR, while the outflow reaches a maximum in negative NAO winters (not shown). For the summer months, correlations with SLP are not significant, and regression maps are therefore not shown.

4. Discussion and Conclusions

[14] The mean simulated northward flow through the DS of 0.5 Sv is below the observation-based estimate (Table 1). However, the inflow estimates are dependent on water mass definitions, and values for the northward DS transport range from 0.6 to 2 Sv (HØ). For the net southward transport through the DS and the Canadian Archipelago, HØ obtained a value of 6.0 Sv, while *Fissel et al.* [1988] obtained a transport estimate of 1.7 Sv through the Canadian Archipelago alone. These numbers yield an estimate of DS outflow of 4.3 Sv, a value that matches the simulated transport precisely. The use of this estimate is further substantiated by the simulated outflow through the Canadian Archipelago of 1.8 Sv. It should be mentioned that the estimates of HØ and *Fissel et al.* [1988] are both uncertain, as discussed by HØ. For the sake of completeness, the simulated inflow through the Bering Strait is 1.0 Sv, the same value as *Roach et al.* [1995] calculated from direct measurements. Over the IFR the simulated flow both northward (5.6 Sv) and southward (3.6 Sv) exceed estimates from measurements. However, the simulated net transport (2.0 Sv) matches the observation-based transport of 2.3 Sv quite well. This inconsistency might imply the existence of some recirculation through the IFR section in the model. The simulated inflow through the FSC closely matches the recent observational estimates in the channel [*Turrell et al.*, 2003], as well as downstream in the eastern branch of the NWAC [in the Svinøy-section, Figure 1; *Orvik et al.*, 2001]. The interpretation of this depends on whether the observed recirculation in the channel is properly simulated (See Figures 1 and 2). If the recirculation in the model is realistic, the match indicates a realistic mean inflow of Atlantic Water, and the simulated inflow should be corrected for the southward surface flow. On the other hand, if the recirculation is too weak in the model, then the flow from the south or southwest is equally overestimated. The observation-based estimate of southward flow of 4.5 Sv is the sum of outflow below 450 m through the FBC [2.5 Sv; *Østerhus et al.*, 1999], deep flow over the Wyville-Thompson Ridge [WTR; 0.1 Sv; *Ellett*, 1998], and southward flow in the upper layers of the FSC [1.9 Sv; *Turrell et al.*, 1999]. The simulated outflow of 2.2 Sv is far too weak to match these observations, but given the above-mentioned possibility of a weak or non-existent southward surface flow through the model section, proper comparison might be with deep outflow alone (2.6 Sv). Finally, the simulated net transport of 4.3 Sv across the Iceland-Scotland ridge is close to the estimate of 4.0 Sv by HØ.

[15] Based on hydrographic observations from the Svinøy section for the period 1955 to 1996, *Mork and Blindheim* [2000] calculated the geostrophic volume transports in the two branches of the NWAC, and found that they appeared to be in opposite phase and NAO-controlled during summer (since 1978). This out-of-phase relationship is also found in the model, where the transports through the IFR and the FSC are negatively correlated ($R = -0.59$).

[16] Further explanation for this anticorrelation as well as a relation between the atmospheric pressure systems and the fluxes are provided by *Blindheim et al.* [2000] who found that the westward extent of NWAC-waters is negatively correlated with the NAO-index on long (>3 years) time

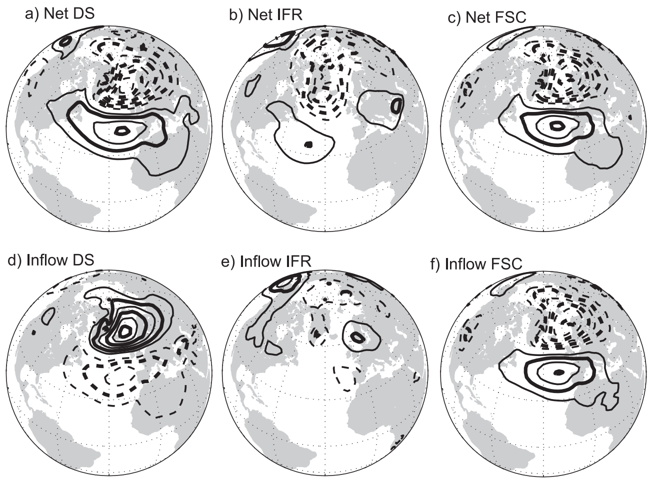

Figure 4. Regression maps showing the NCAR/NCEP winter (December–March) mean SLP regressed on standardized simulated net transports (upper panels) and inflow (lower panels). Isolines are drawn at 0.5 mb intervals, negative values with dashed lines. The net flow is directed along the mean flow (south for the DS, north for the IFR and FSC). Correlations in the centers of action reach 0.6 (northern) and 0.5 (southern) and are highly significant.

scales. They attribute this to changes in the pathways of the flow over the ridge rather than the local wind forcing, since increased westerlies in a high NAO-index situation tend to shift the NAC eastward. This is supported by *Belkin and Levitus* [1996], who report large meridional displacements of the NAC near the Charlie Gibbs Fracture Zone. Furthermore, based on nearly four years direct measurement (April 1995 to February 1999) along the Svinøy section, *Orvik et al.* [2001] revealed a strong connection between the NAO-index and the transport in the eastern branch of the NWAC even on interannual time scales (i.e. high FSC-inflow coincides with high NAO-index).

[17] Not only the westerlies in the North Atlantic change with NAO-like forcing. The northerlies modulating the southward flow of the Arctic Waters in the western parts of the Nordic Seas are also controlled by these large scale changes in the pressure system [*Hilmer and Jung*, 2000]. In this way, stronger northerlies together with increased southward extension of Arctic Waters may inhibit inflow in both the Denmark Strait and over the Iceland Faroe Ridge [*Blindheim et al.*, 2000].

[18] Supporting the above theories, the regression patterns for the DS and the FSC (Figures 4a, 4c, 4d, and 4f) clearly indicate pressure gradients giving both northerly winds along the east coast of Greenland and westerlies in the North Atlantic, associated with larger transports through these straits. The IFR inflow however, does not show any NAO-resembling regression pattern (Figures 4b and 4e). The explanation for this lies in the intermediate position of this opening, making it susceptible to the changes in position of the northern center of action (NCA) of the NAO [*Hilmer and Jung*, 2000]. In years when the NCA is shifted eastward the northerlies affect the IFR as described above, but when the NCA is in its westward position (southwest of Iceland) positive NAO gives southwesterlies in this opening. Furthermore, this shift in direction of the NAO forcing offers an explanation for anticorrelation between the IFR and the FSC inflow on a longer timescale, since the FSC inflow does not experience any reversal in its relation to NAO-forcing.

[19] Neither winter mean nor monthly mean data show any time lag between the wind forcing and transports. This suggests that the dominant mechanism is barotropic, where Ekman fluxes are changing the surface elevation gradient, with a rapid barotropic adjustment taking place.

[20] Finally, the model shows a reduction in total inflow of 0.7 Sv since 1957 (also when considering the net inflow through the other openings to the Arctic Mediterranean). It is thus interesting to note that *Hansen et al.* [2001] found indirect evidence of a reduction in overflow through the FBC of 0.5 Sv over the last 50 years, implying that the Atlantic inflow has been reduced to a similar degree. This issue and the more fundamental roles of the AMOC and wind driven transport certainly need to be addressed in as well high resolution ocean- as global climate-models to improve the details of the volume exchanges across the GSR, and thereby reduce the uncertainties in climate predictions.

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References

Belkin, I., and S. Levitus, Temporal variability of the Subarctic Front near the Charlie-Gibbs Fracture Zone, *J. Geophys. Res.*, *101*, 28,317–28,324, 1996.

Bentsen, M., et al., Coordinate transformation on a sphere using conformal mapping, *Mon. Weather Rev.*, *127*, 2733–2740, 1999.

Bleck, R., C. Rooth, D. Hu, and L. T. Smith, Salinity-driven thermohaline transients in a wind- and thermohaline-forced isopycnic coordinate model of the North Atlantic, *J. Phys. Oceanogr.*, *22*, 1486–1515, 1992.

Blindheim, J., V. Borovkov, B. Hansen, S. A. Malmberg, W. R. Turrell, and S. Østerhus, Upper Layer Cooling and Freshening in the Norwegian Seas in Relation to Atmospheric Forcing, *Deep-Sea Res.*, *47*, 655–680, 2000.

Dickson, B., J. Meincke, I. Vassie, J. Jungclaus, and S. Østerhus, Possible predictability in overflow from the Denmark Strait, *Nature*, *397*, 243–246, 1999.

Dickson, R., and J. Brown, The production of North Atlantic Deep Water: Sources, rates, and pathways, *J. Geophys. Res.*, *99*, 12,319–12,341, 1994.

Eden, C., and T. Jung, North Atlantic interdecadal variability: Oceanic response to the North Atlantic oscillation (1865–1997), *J. Climate*, *14*, 676–691, 2001.

Ellett, D., Norwegian Sea Deep Water overflow across the Wyville Thompson Ridge during 1987–1988, *ICES Coop. Res.*, 195–205, 1998.

Fissel, D., J. Birch, H. Melling, and R. Lake, Non-tidal flows in the Northwest Passage, *Tech. Rep. 98*, Canadian Institute of Ocean Science, Sidney, British Columbia, Canada, 1988.

Furevik, T., M. Bentsen, H. Drange, J. A. Johannessen, and A. Korablev, Temporal and spatial variability of the sea surface salinity in the Nordic Seas, *J. Geophys. Res.*, *107*, 8009, doi:10.1029/2001JC001118, 2002.

Girton, J. B., T. B. Sanford, and R. H. Käse, Synoptic sections of the Denmark Strait Overflow, *Geophys. Res. Lett.*, *28*, 1619–1622, 2001.

Hansen, B., and S. Østerhus, North Atlantic-Nordic Seas Exchanges, *Prog. Oceanog.*, *45*, 109–208, 2000.

Hansen, B., W. R. Turrell, and S. Østerhus, Decreasing overflow from the Nordic Seas into the Atlantic Ocean through the Faroe Bank channel since 1950, *Nature*, *411*, 927–930, 2001.

Hilmer, M., and T. Jung, Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export, *Geophys. Res. Lett.*, *27*, 989–992, 2000.

Hurrell, J., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.

Kalnay, E., et al., The NCEP/NCAR 40-year Reanalysis Project, *Bull. Am. Met. Soc.*, *77*, 437–471, 1996.

Mork, K. A., and J. Blindheim, Variation in the Atlantic Inflow to the Nordic Seas, 1955–1996, *Deep-Sea Res. I*, *47*, 1035–1057, 2000.

Orvik, K. A., and P. Niiler, Major pathways of Atlantic water in the northern North Atlantic and Nordic Seas towards arctic, *Geophys. Res. Lett.*, *29*, 2002.

Orvik, K. A., Ø. Skagseth, and M. Mork, Atlantic Inflow to the Nordic Seas. Current structure and volume fluxes from moored current meters, VM-ADCP and SeaSoar-CTD observations, 1995–1999, *Deep-Sea Res. I*, *48*, 937–957, 2001.

Østerhus, S., B. Hansen, R. Kristiansen, and P. Lundberg, The overflow through the Faroe Bank Channel, *Int. WOCE*, 35–37, 1999.

Roach, A., K. Aagaard, C. Pease, S. Salo, T. Weingartner, V. Pavlov, and M. Kulakov, Direct measurements of transport and water properties through the Bering Strait, *J. Geophys. Res.*, *100*, 18,443–18,457, 1995.

Turrell, W., et al., Direct observations of inflow to the Nordic Seas through the Faroe Shetland Channel 1994–1997, *ICES CM 1999/L*, 1–15, 1999.

Turrell, W., B. Hansen, S. Hughes, and S. Østerhus, Hydrographic variability during the decade of the 1990's in the northeast Atlantic and southern Norwegian Sea, in *Hydrobiological Variability in the ICES Area, 1990–99*, ICES Mar. Sci. Symp., ICES, in press, 2003.

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