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Atmospheric forcing of DSOW salinity

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Abstract

The temporal evolution of the characteristics of Denmark Strait Overflow Water (DSOW) is reconstructed using hydrographic data and compared with possible atmospheric forcing mechanisms. It is concluded that the main factor influencing the DSOW characteristics at a time scale of one to several years is the difference in mean sea level pressure across, respective wind along Denmark Strait. The main process which leads to salinity changes in the DSOW is therefore changing percentages of the different water masses involved in the DSOW formation and not the changes of the characteristics of these water masses.

1 Introduction

The densest and therefore deepest northern component of the global thermohaline circulation is the Denmark Strait Overflow Water (DSOW). Different water masses, formed outside or within the Greenland-Island-Norwegian (GIN) seas, are carried southward towards Denmark Strait within the East Greenland Current (EGC). These water masses contribute to the formation of DSOW, which is found south of Denmark Strait flowing along the continental slope southwards into the deep North Atlantic. Figure 1 shows a sketch of the circulation and water masses involved in the formation of DSOW and Rudels et al. (2002) give an overview of the different water masses and processes involved north of Denmark Strait. The overflow itself has been extensively studied; Saunders (2001) gives a short overview for the WOCE (World Ocean Circulation Experiment) and pre-WOCE era, many studies were conducted during the VEINS (Variability of exchanges in the Nordic Seas) and ASOF (Arctic-Subarctic Ocean Fluxes) programs.

The North Atlantic Oscillation (NAO) is the most prominent and recurrent pattern of atmospheric variability in the North Atlantic (Hurrel et al., 2003) and it is thought that the deep and intermediate water formation in is strongly influenced by it (Dickson et al., 1996). Over the last four decades the whole deep North Atlantic Ocean showed a rapid freshening (Dickson et al., 2002) which can be linked to the increase from a low NAO-index in the 1960s to high NAO-index in the 1990s. The purpose of this paper is to show, that on time scales of order one to two years the water mass characteristics of the DSOW are closely related to the atmospheric forcing. But it is not the large scale NAO but more local forcing in and just north of Denmark Strait. This means that on this time scales changes in the DSOW characteristics are not governed by changes in the source water masses composition but only by the mixing ratio of the different source water masses forming the DSOW.

2 Data

The data used is historical data from different sources and recent data from several cruises. Sources of the historical data used are the World Ocean Database (Conkright et al., 1998, data publicly available from ICES including the VEINS data collection; available from http://www.ices.dk), and data from WOCE (WOCE Data Products Committee, 2002). Most of the recent data come from yearly cruises done from the Institut für Meereskunde Hamburg, which follow the station pattern from VEINS. Temporal resolution is inadequate in the 1970s and 1980s. There are more data between 1957 and 1967, but these data is bottle data with restricted vertical resolution and the interpolation error to a certain density is larger then with CTD data. Our main focus will therefore lie on the time from 1990 onwards. We did not use the temperature/salinity data from the current meters of the Angmasalik mooring array, as the measurement error of the Aanderaa current meters in conductivity are to large. Atmospheric data used are monthly means from the NCEP reanalysis (taken from ftp://ftp.cdc.noaa.gov in July 2003) and daily data from ECMWF ERA-40 (obtained from the ECMWF data server in May 2004), which were averaged to monthly means.

3 Variability of DSOW characteristics

To construct our main time series we first took all available data from an elliptical region along the spreading path of the DSOW along the Greenland continental shelf (Fig. 2) and determined the temperature and salinity on isopycnals in the DSOW range for each individual station. We used different σ_2 (density of the water if brought adiabatically to 2000 dbar) isopycnals with σ_2>37.04 kg m^{-3}. We will mainly present data from the single isopycnal σ_2=37.12 kg m^{-3}. The results did not depend much on the choice of isopycnal, but at higher densities data become sparse and at lower densities the DSOW signal is mixed with the signal of the entrained water. Waters with σ_2>37.04 kg m^{-3} can also be found in other water masses then DSOW, to exclude these data we restricted the region in the vertical to the pressure range 300–3500 dbar and data within 400 dbar of the bottom.

In the northernmost part of our region, the actual DSOW is formed by mixing in Denmark Strait (Rudels et al., 2002), this leads to large variations in the salinity on isopycnals north of 64.5° N (Fig. 3) and therefore we exclude the northernmost part in following calculations. Within the remaining geographical extent, the southward flowing DSOW mixes with surrounding waters and becomes saltier (Fig. 3). A linear fit through all the data (for pressures larger then 1500 dbar and irrespective of time) shows that the mean increase in salinity is about 0.003 PSU per degree latitude. This mean southward gradient was used to correct for mixing effects and to reference all salinities to a latitude of 60° N. The DSOW also needs time to flow southwards, the water found at 64.5° N at one time will be found somewhat later further south. We referenced all time to a latitude of 60° N by using a spreading rate of 280 days per 5° of latitude. This corresponds to spreading velocity of 2.3 cm/s north-south, and taking also into account the longitudinal displacement of about 3.4 cm/s along the DSOW path. This time correction also leads to a better temporal resolution, as a summer cruise to the whole region leads to temporal coverage of several months. Increasing the spreading speed to 120 days per 5° of latitude gives poorer temporal resolution, but does not change considerably the smoothed temporal evolution of the salinity. The mean current speed of the DSOW at 63° N is about 20 to 30 cm/s (Dickson et al., 1998) and as signal propagation in general is smaller then mean current speed, the used propagation speed is of the right order of magnitude.

The resulting temporal evolution (Fig. 4) shows that in the beginning of the 1990s salinity was about 34.885, then dropped to very low values of 34.85 in 1995. Then there is a sharp rise to a maximum of 34.895 in 1996. The salinity then decreases gradually to a minimum salinity of 34.86 in 1999 and then increased until 2003 reaching salinities around 34.89 and then dropped again to values around 34.865 in 2004.

To estimate the errors introduced by the mixing and spreading corrections we also determined the temporal evolution without these corrections using a smaller region near the southern tip of Greenland. This region as a good data coverage due to WOCE (section A1e), VEINS and ASOF (section 6) and other historic data (Fig. 5). The data is biased toward summer data, but as the very short term fluctuations at the source are low pass filtered due to mixing along the approximate 1000 km long path from the Denmark Strait to the chosen region, the single measurements in time are representative for a longer time period. The temporal evolution of the salinity found in this smaller region (Fig. 6) is similar to the one found in the larger region, only based on fewer data and with a coarser temporal resolution.

The data from selected summer cruises in this smaller region was used to construct mean potential temperature-salinity diagrams. The potential temperature (Θ) was referenced to 2000 dbar. All temperature and salinity values of one cruise within a σ_2 interval (± 0.02) kg m^{-3} around certain σ_2 values were averaged, the resulting Θ-S diagram is shown in Fig. 7. The temporal signal is very similar within the density range of the DSOW, therefore the temporal evolution at σ_2=37.12 kg m^{-3} as shown elsewhere in this article is representative for the whole DSOW density range. High salinities within the DSOW are found in 1991, 1992, 1997 and 2002 and low salinities in 1994, 1995 and 1999.

4 Atmospheric forcing

Changes in the characteristics of the DSOW can result from changes in each component and process leading to the formation of DSOW as depicted by Rudels et al. (2002). Ultimatly many of these changes are forced by the atmosphere. To identify how the atmosphere induces changes in the composition of the DSOW we made time lag correlations of our time series of DSOW salinity with several atmospheric parameters from the NCEP and ERA40 datasets. As we are interested in atmospheric changes that induce oceanic changes, we restricted the analysis to time lags where the atmospheric signals precedes the oceanic one. As our oceanic time series is smoothed, and also the oceanic mixing in and shortly after Denmark Strait acts as low pass filter, we smoothed the atmospheric data with a 3 month running mean.

Correlating a short and gappy time series with many different parameters at many places with different time lags gives several correlations with a high correlation coefficient. But high correlation coefficents do not imply neccesarily a direct coupling. For once it can be pure chance. Or there is indirect coupling, if A is the cause for B and C, the correlation coefficent between B and C can be large, without B causing C or vice versa. Therefore a large correlation coefficent is only one requirement. A second is a possible physical coupling process. Still another that the time lag is large enough, so that the signal has time enough to travel in the ocean from the geographic location of the found larger correlation coefficent to our defined DSOW region south of Denmark Strait.

We did correlations directly with different variables (mean sea level pressure, wind, temperature, etc) of the NCEP and ERA40 reanalysis, but also with EOF and rotated EOF analysis of these variables. Meaningful correlations found (Fig. 8) were with the wind west and north of Island, respective the difference of the mean sea level pressure (mSLP) across Denmark Strait. The time lag of about 9 months results in a propagating signal speed of order several cm/s, similar to the propagation speed used previosly to correct the hydrographic measurements for the DSOW time series. Scaling the atmospheric time series with a constant offset and factor to the DSOW salinity range and applying a time offset the good correlation with the time series of the DSOW salinity can be seen directly (Fig. 9). Using this kind of linear regression with the pressure difference across Denmark Strait explains about 40% of the total variance of the DSOW salinity time series from 1990 onward.

A weaker southward wind along Denmark Strait leads to an increase in the DSOW salinity. A simple explanation of this behaviour could be that with weaker southwards winds less northern, low saline water flows towards Denmark Strait and more higher saline water of southern origin is present at Denmark Strait. This shift in the proportions of water masses involved in the formation of DSOW leads to a more saline DSOW. There are also other ways to explain this behaviour. Weaker southward wind lead to a flattening of the border between low saline Polar Water (PW) and higher saline Return Atlantic Water (rAW), both coming from the north. This leads to a higher percentage of rAW compared to PW in the DSOW formation, increasing the resulting salinity. But with the data available to us it was not possible to pinpoint the process leading to the observed behaviour.

In the end this still unknown dynamical process leads to changing amounts of the different water masses involved in the DSOW formation, and, following the DSOW recipe of (Rudels et al., 2002), it is the last stirring in and just north of Denmark Strait which sets the DSOW characteristics on time scales from months to several years. And ultimatly the main factor is the wind along Denmark Strait.

5 Longer term changes

We saw that on shorter time scales the wind along Denmark Strait sets the value of the DSOW salinity. Extending the analysis to times before 1990, we see (Fig. 10) that the mean wind did not changed much, but salinity was much higher in the 1960s. The general decrease in salinity over the last 40 years as been noted before (Dickson et al., 2002). And it is also clear that this decrease cannot be explained with changes in the mSLP difference across, respective wind along Denmark Strait. The 1965–1970 signals could perhaps also be explained with the wind along Denmark Strait, but with the mean salinity being 0.065 higher in this period then in the 1990–2004 period. So the processes determing the shorter time changes are probably the same in this previous period as in the 1990–2004 period, but some other, longer term process changed the mean salinity between 1965 and 1990.

One possible candidate are advective processes, as proposed by Dickson et al. (1999). A signal in the Atlantic Water flowing northward along the Norwegian coast leads to a signal in the rAW and this signal is propagated along Greenland within the EGC and finally into the DSOW. But Dickson et al. (1999) also explain the shorter term changes with this advective process, while we saw that the shorter term changes are set in Denmark Strait. Taking into account all the mixing and entrainment processes between Fram Strait and Denmark Strait (Rudels et al., 2002), which work like a low pass filter, it is not very probable that shorter term fluctuations survive this journey. Due to the low pass filtering effect of oceanic mixing a large salinity jump in Fram Strait will only lead to a more gradual change in Denmark Strait. But a longer term gradual increase in salinity could pass this system almost unhindered. So the advective way along the EGC is a possible candidate to explain the longer term changes in the DSOW salinity, although also other processes (e.g. advection from the south, changes in ice export) are possible.

6 Conclusions

For time scales up to a few years the salinity of the DSOW is determined by the wind along Denmark Strait. This leads to a certain predictability of the DSOW characteristics from atmospheric data of about several months.

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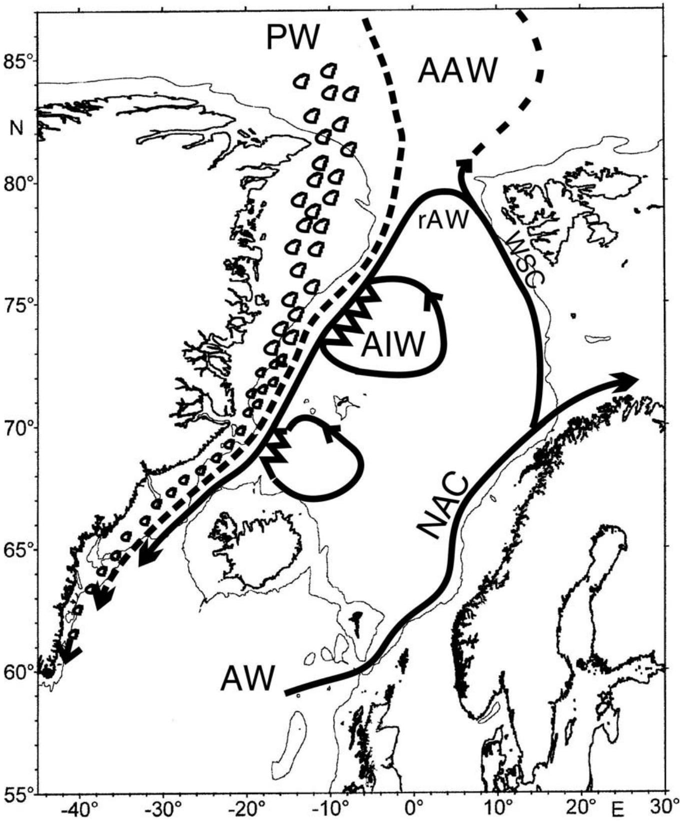

Fig. 1. Sketch of the water masses of the East Greenland Current, which contribute to the formation of DSOW (AW = Atlantic Water, NAC = North Atlantic Current, WSC = West Spitzbergen Current, rAW = return Atlantic Water, AAW = Arctic Atlantic Water, PW= Polar Water, AIW = Arctic Intermediate Water).

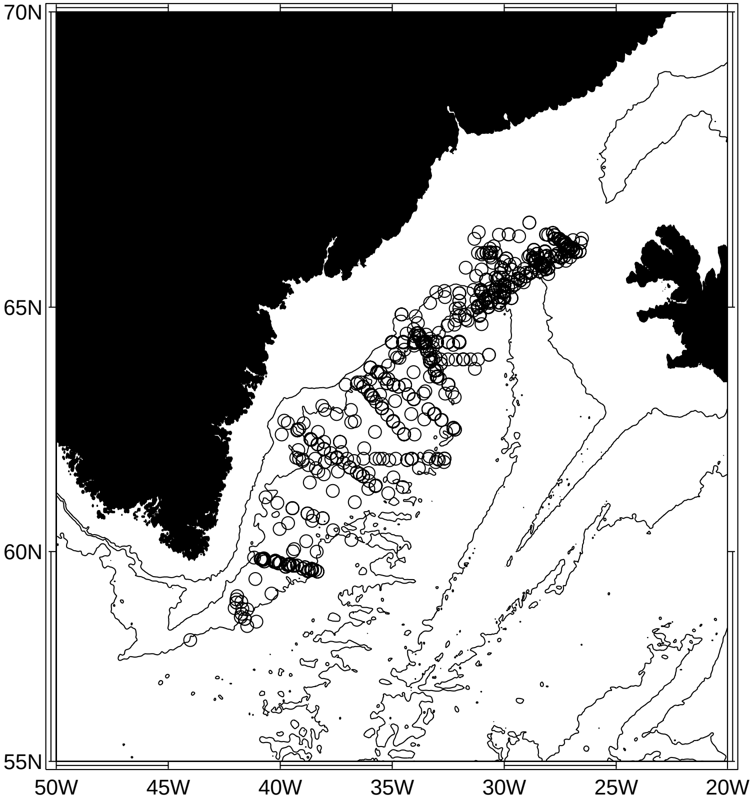

Fig. 2. Position of the hydrographic stations in the main region used in constructing the time series of DSOW characteristics. Stations north of 64.5 N were not used due to too large noise.

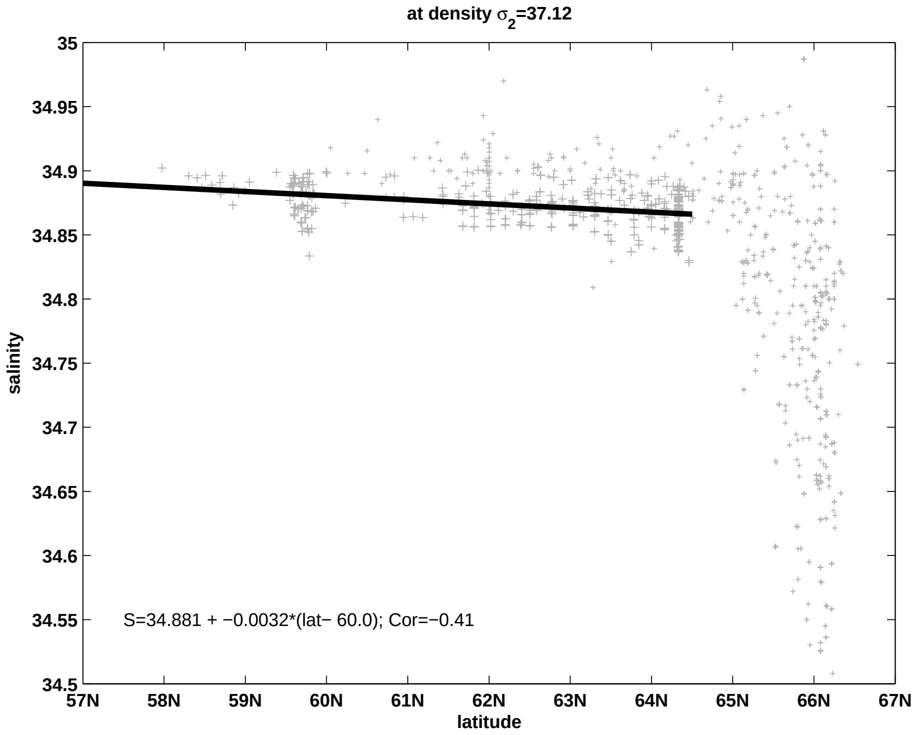

Fig. 3. Salinity at σ_2=37.12 kg m^{-3} as a function of latitude. Data north of 64.5° N (small crosses) were not used due to the large range of salinities. The line is a fit through all data south of 64.5° N giving a mean salinity increase towards the south of 0.0032 per degree of latitude.

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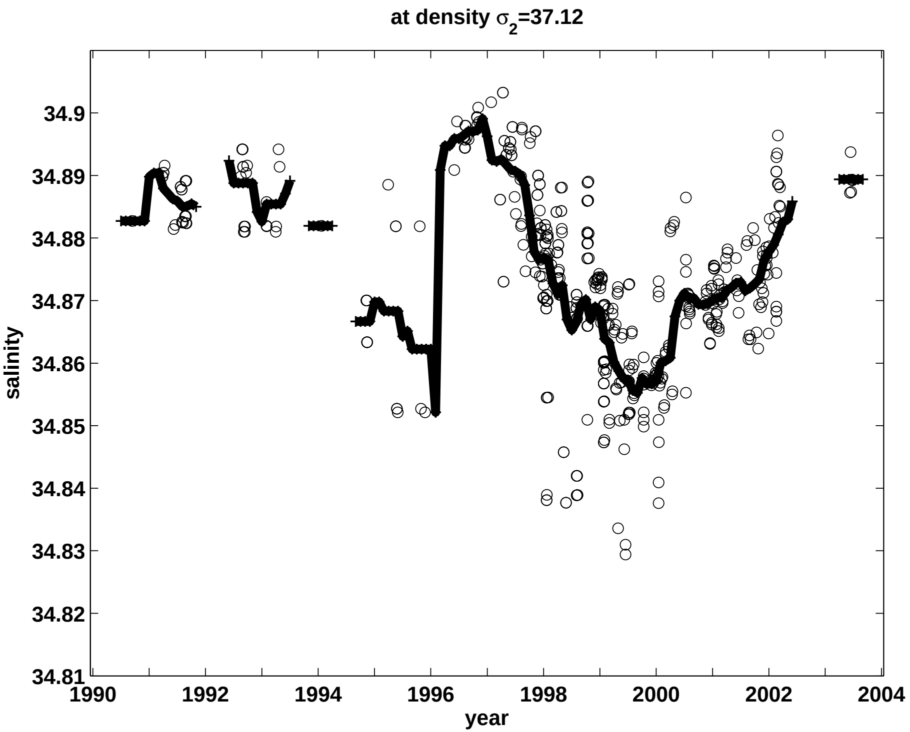

Fig. 4. Time evolution of the DSOW salinity at σ_2=37.12 kg m^{-3} and reference latitude of 60° N. Circles are data from individual hydrographic stations and the black line is the running mean through all data.

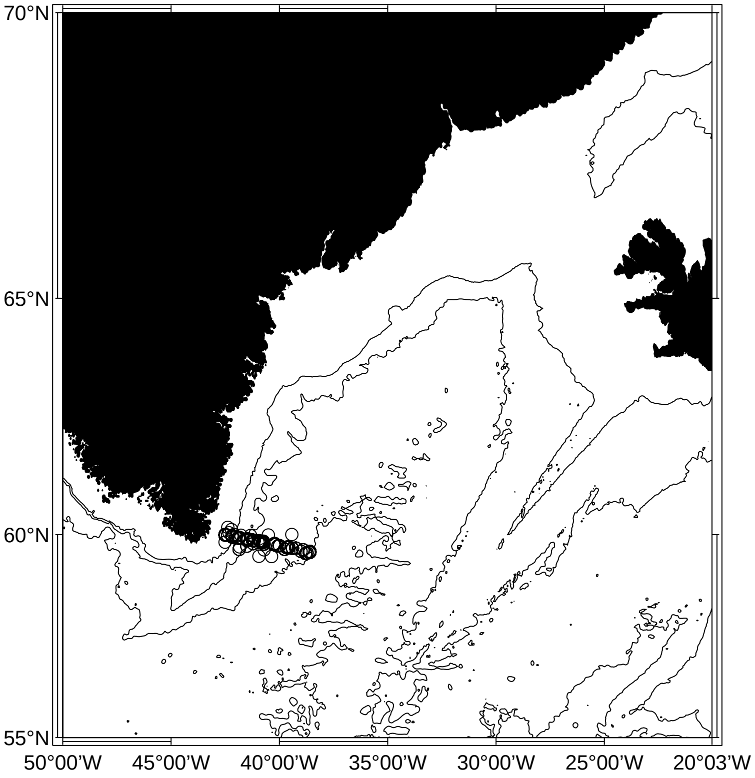

Fig. 5. Position of the hydrographic stations in the first region used in constructing the time series of DSOW characteristics.

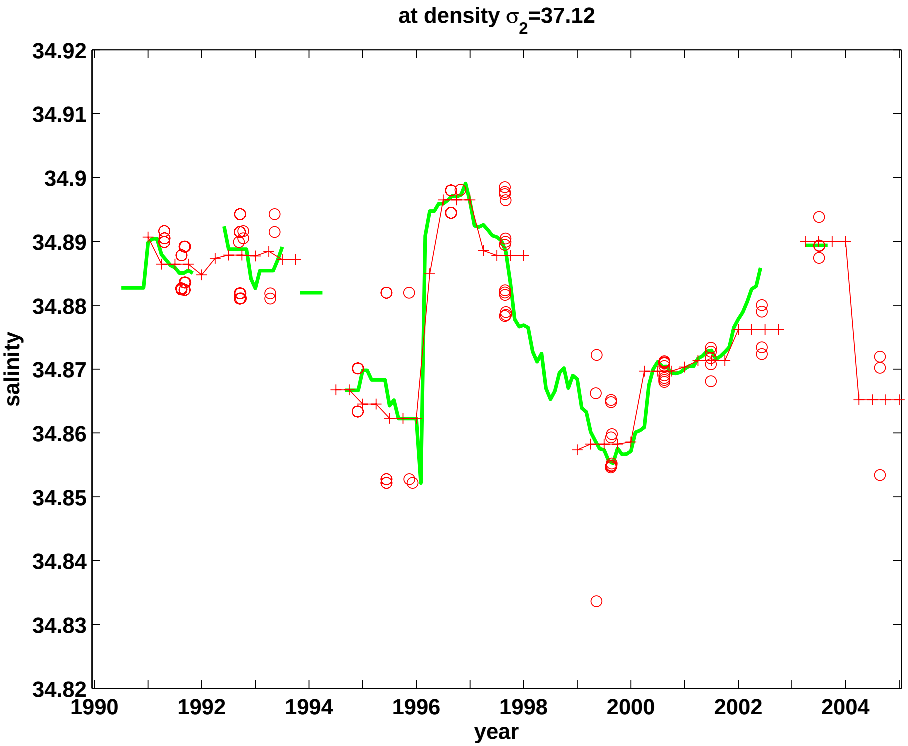

Fig. 6. Time evolution of the DSOW salinity near the southern tip of Greenland at σ_2=37.12 kg m^{-3}. The red circles are data from individual hydrographic stations, the red line is the running mean through these data and the green line is the mean salinity of the main region.

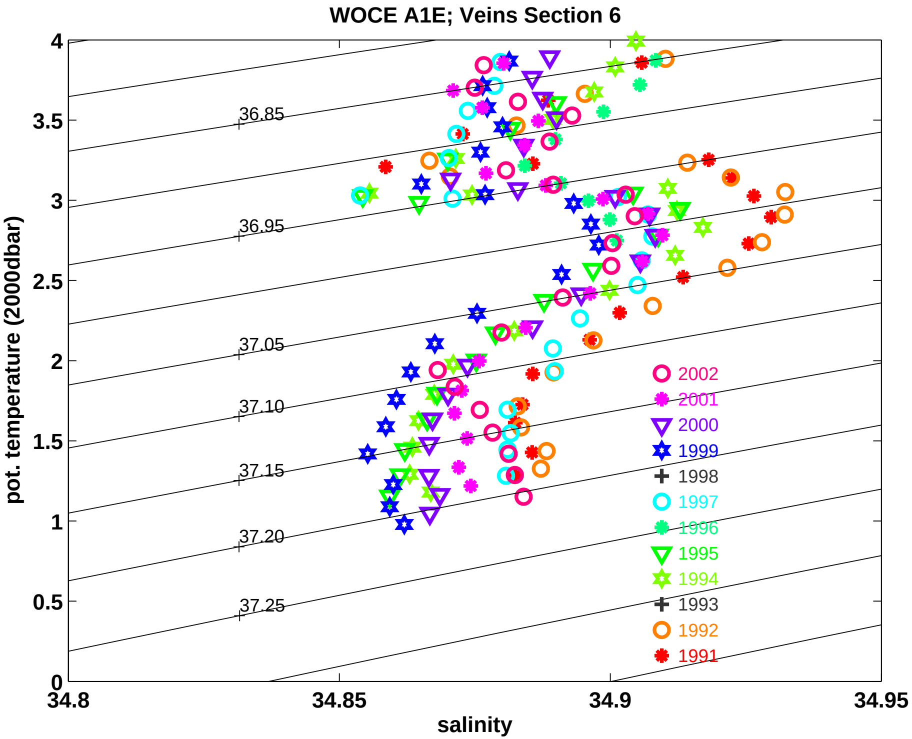

Fig. 7. Diagram of mean potential temperature and salinity at VEINS sections 6 for individual sections in different years. The means were calculated in 0.02 kg m^{-3} σ_2-density intervals. The used sections come from the cruises Meteor 18 in 1991, Valdivia 129 in 1992, Meteor 30 in 1994, Valdivia 152 in 1995, Valdivia 161 in 1996, Meteor 39 in 1997 (Schott et al., 1998), Meteor 45/4 in 1999 (Schott et al., 2000), Poseidon 263 in 2000, Meteor 50/3 in 2001 (Schott et al., 2002) and Poseidon 290 in 2002 (Holfort, 2002).

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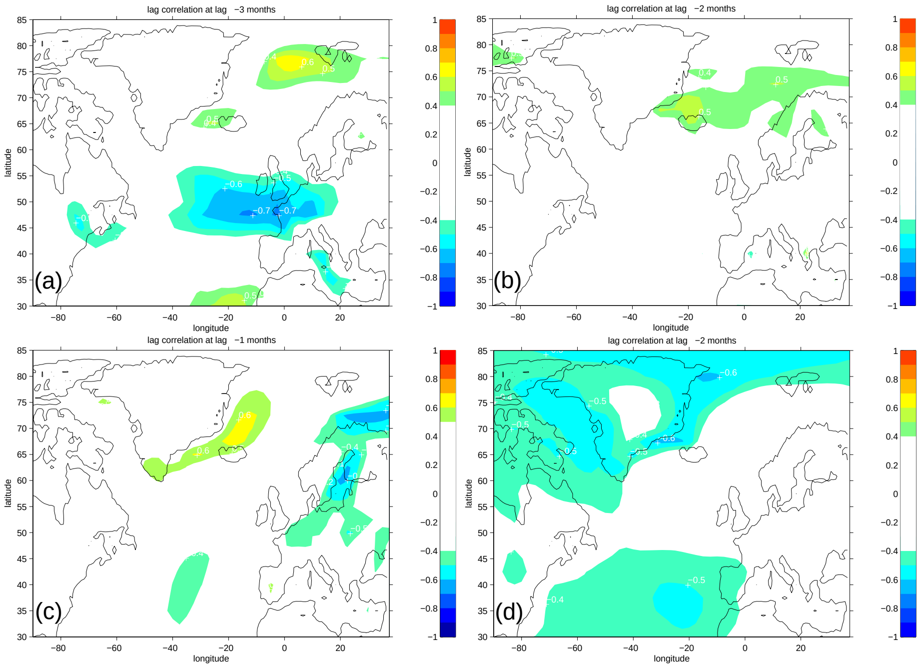

Fig. 8. Correlation of monthly atmospheric data (smoothed using a 3 months running mean) with the DSOW salinity: **(a)** with the meridional NCEP wind at a time lag of −3 months, **(b)** with the meridional ERA40 wind at a time lag of −2 months, **(c)** with the zonal NCEP wind at a time lag of −1 month and **(d)** with the difference of the NCEP mean sea level pressure (mSLP) and the mSLP above Island at a time lag of −2 months (time shifts are relative to 64.5° N).

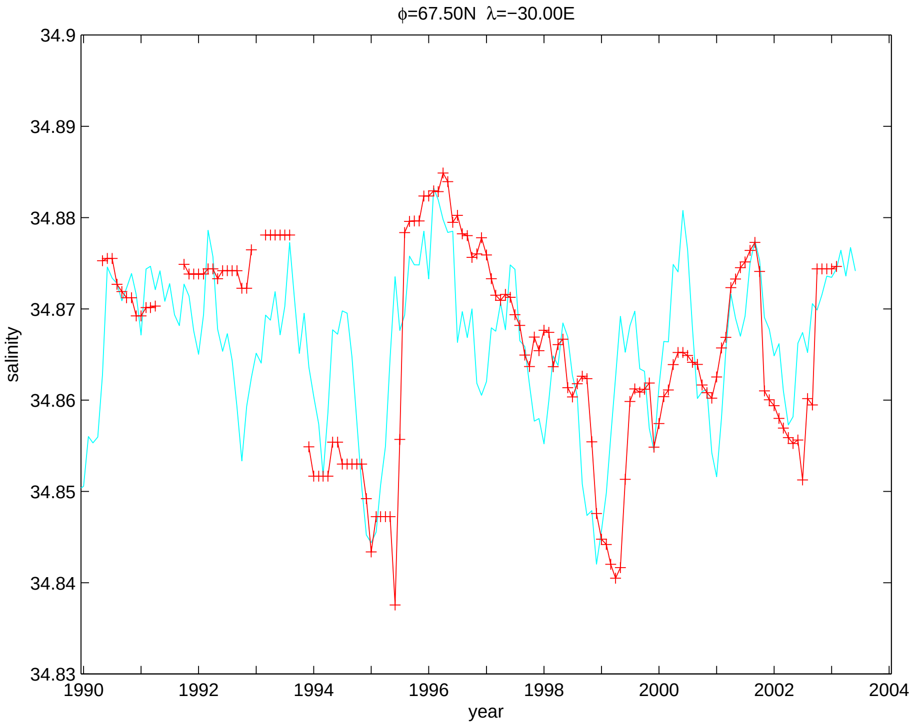

Fig. 9. The time series of DSOW salinity (red) and the scaled difference of the mean sea level pressure (NCEP) between 67.5° N 30° W and Island (cyan).

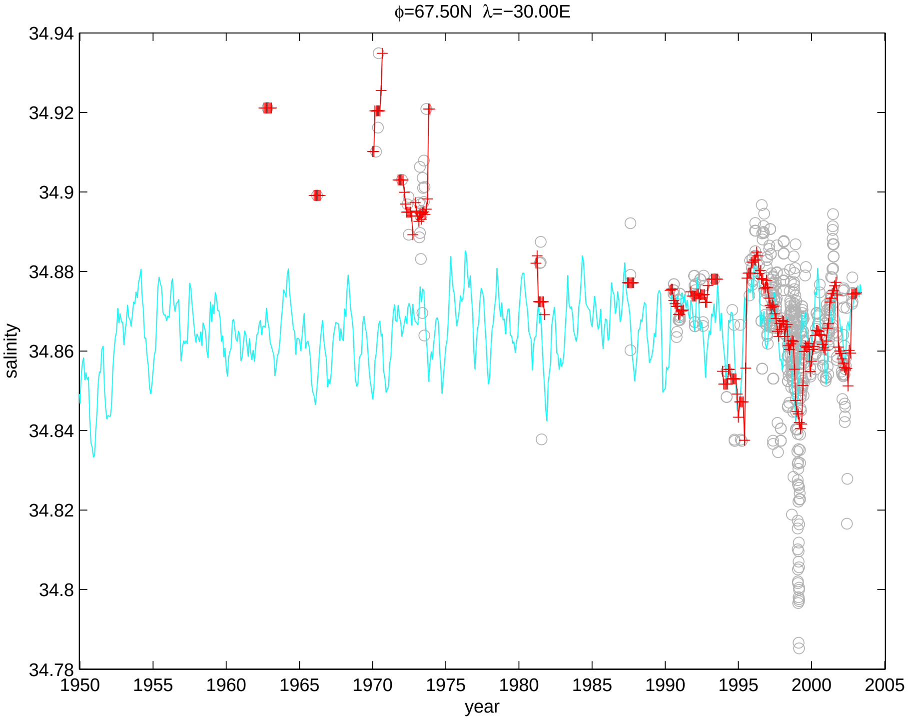

Fig. 10. Salinity of individual stations at σ_2=37.12 kg m^{-3} (grey circles) and a running mean through this data giving the time series of the DSOW salinity (red) and the scaled difference of the mean sea level pressure between 67.5° N 30° W and Island (cyan) including also data before 1990.