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Interannual variability of the Subpolar Mode Water properties over the Reykjanes Ridge during 1990-2006

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Abstract:

Combining hydrographic data from the OVIDE (Observatoire de la Variabilité Interannuelle à Decennale/Observatory of the Interannual to Decadal Variability) section (Greenland-Portugal) with Argo and historical CTD data over the period 1990–2006, we estimate the variability of the core properties of a variety of Subpolar Mode Water (SPMW) observed on the eastern flank of the Reykjanes Ridge. This SPMW acquires its core properties in the winter mixed layer along the eastern side of the Reykjanes Ridge. We find that the February sea surface temperature along the ridge is a proxy for its core temperature. The sources of this mode water are water masses advected by the mean cyclonic circulation in the Iceland Basin. A density compensated tendency for cooling and freshening of the SPMW core properties is observed in the early 1990s. It stops in 1996 and is followed by an increase in temperature and salinity (+1.41°C and +0.11 psu) and a decrease in density (−0.12 kg m−3) until at least 2003. During the entire period, the data do not show any significant modification in the depth of the mode water core while they suggest that the thickness of the layer shrank. The variability of the local air-sea freshwater and heat fluxes cannot explain the observed salinity and temperature variations. They are most likely related to the modifications of the properties of the SPMW sources due to the recently evidenced changes, driven by the North Atlantic Oscillation, in the relative contributions of subtropical waters and subpolar waters in the Iceland Basin.

Key words : North Atlantic Ocean; subpolar mode water; North Atlantic Oscillation.

1. Introduction

Formed in deep winter mixed layers, mode waters are identified by nearly uniform properties in the vertical near the top of the permanent pycnocline. They cover large horizontal areas in all oceans (see *Hanawa and Talley* [2001] for a review). Their locations and properties are set by complex interactions between air-sea fluxes of buoyancy and momentum, circulation and mixing. The forcings being subject to interannual to interdecadal variability, mode water characteristics vary at the same time scales. In the eastern North Atlantic, *Gonzàlez-Pola et al.* [2005] show that Eastern North Atlantic Central Water (ENACW) in the Bay of Biscay warmed and slightly freshened over the period 1992-2003 ($+0.032 \pm 0.008$ °C yr^{-1} and -0.002 ± 0.001 psu yr^{-1}, respectively). The core density of this mode water decreased from about 27.2 to 27.1 kg m^{-3} and the interannual salinity variations seem to be related to the local P-E (precipitation minus evaporation) regime. Further north, in the subpolar gyre of the North Atlantic, the process of transformation of the warm, saline subtropical waters into intermediate and deep waters [*McCartney and Talley*, 1982; *Read*, 2001; *Perez-Brunius et al.*, 2004] results in several varieties of Subpolar Mode Water (herefater SPMW) distributed around the gyre. SPMW along 20°W and north of 40°N are warmer (~ 0.7°C), saltier (~ 0.1) and lighter in 2003 than in 1993 [*Johnson and Gruber*, 2007]. According to those authors, those changes are related to the NAO (North Atlantic Oscillation), the dominant mode of atmospheric variability in the North Atlantic sector. The densest variety of SPMW, the Labrador Sea Water (LSW), which is the main contributor to the lower limb of the Meridional Overturning Circulation, is also subject to large decadal property variations [*Dickson et al.*, 1996; *Yashayaev*, 2007]. In the Labrador

Sea, the ocean heat loss decreased since the mid 1990s which limited the convection to the upper 1200 m and led to the generation of a new salinity minimum layer and to a warming and salinisation of the older deep LSW due to lateral mixing [*Bersch et al.*, 2007]. The decadal variations of the convective activity in the Labrador Sea are correlated with the NAO and because of the horizontal pattern of the atmospheric forcing, those variations are anti-correlated with the convective activity in the Greenland Sea and in the Sargasso Sea [*Dickson et al.*, 1996]. In this latter area, *Kwon and Riser* [2004] and *Peng et al.* [2006] show that both temperature and subduction rate of the Subtropical Mode Water are correlated with the NAO on decadal time scales, with NAO leading by 2-3 years. Among the processes that account for the changes in the LSW properties, changes in the properties of the water masses that enter the Labrador Sea are thought to be important. Before any attempt to quantify the impact of the upstream water masses changes on the LSW, we must document the properties and variability of those water masses, which is the aim of this paper. We focus on a mode water found in the North Atlantic Ocean over the Reykjanes Ridge (Fig. 1) because it lies in a central position along the path of the subpolar gyre where exchanges between the eastern and western parts of the gyre occur. It also contributes to the warm and salty waters that enter the Labrador Sea by the West Greenland Current and that influence both convection and restratification in the Labrador Sea [*Cuny et al.*, 2002; *Myers et al.*, 2007; *Yashayaev*, 2007]. In complementing other studies on subpolar mode water variability that were undertaken either in the eastern Atlantic [*Holliday*, 2003; *Johnson and Gruber*, 2007] or in the Labrador Sea [*Dickson et al.*, 1996; *Yashayaev*, 2007] but neither in the central part of the subpolar gyre, this work helps providing a basin scale view of the mode water variability in the

North Atlantic. Finally, documenting the variability of this mode water is also important for models because it lies in a region where models have deficiencies in representing water masses properties and circulation [*Treguier et al.*, 2005].

The NAO index is defined here as the principal component time series of the leading EOF of winter (December through March) Sea Level Pressure anomalies over the Atlantic sector (20-80°N, 90°W-40°E) [*Hurrell*, 1995]. The horizontal pattern of this index consists of a north-south dipole with two centers of opposite sign located near Iceland and Azores, respectively. The NAO index was in a high positive state at the beginning of the nineties. It shifted to a negative value in the winter 1995/1996. Although it remained in a moderate positive state over the period 1996-2006, the NAO index presented an overall downward trend and occasionally reached negative values (Fig. 2a).

The NAO index variations are correlated to large-scale fluctuations in the air-sea fluxes of heat, freshwater and momentum over the North Atlantic Ocean and to changes in the ocean circulation (see *Visbeck et al.* [2003] for a review). Since the mid-nineties, the winter mean momentum flux and winter mean heat loss averaged over the Iceland Basin (52-63°N and 33-10°W) and the subpolar gyre (50-65°N and 45-15°W, not shown) decreased (Fig 2b,c). These recent decadal changes in the air-sea fluxes induced a decrease in the gyre intensity [*Flatau et al.*, 2003; *Häkkinen and Rhines*, 2004; *Hátún et al.*, 2005] accompanied with a northwestward shift of the subarctic front in the central Iceland basin (roughly identified in the 1990s by the position of the winter 7°C SST isotherm; see *Flatau et al.* [2003] and Fig. 10 in Sec. 3.2) and with a modification of the relative contributions in the Iceland Basin of cold and low-saline waters of subpolar origin and warm and salty waters of subtropical origin [*Bersch*, 2002; *Hátún et al.*, 2005]. According to *Johnson and*

Gruber [2007], these latter changes mainly explain the mode water variability along 20°W. On these decadal time scales, the ocean response to the NAO is complex with significant changes near strong mean current systems [*Visbeck et al.*, 2003]. On interannual time scales, however, the ocean variability is dominated by NAO-induced changes in the air-sea fluxes [*Visbeck et al.*, 2003].

The OVIDE project (Observatoire de la Variabilité Interannuelle à Decennale/Observatory of the Interannual to Decadal Variability) repeats a trans-oceanic hydrographic section across the North Atlantic every other year since 2002 in order to monitor and understand the low-frequency fluctuations of the oceanic Atlantic Meridional Overturning Cell, heat and tracer transports and water mass characteristics in the North Atlantic Ocean [*Lherminier et al.*, 2007]. The OVIDE section consists of full-water column hydrographic stations between Portugal and the southern tip of Greenland (Cape Farewell) (Fig. 1). The western part of the section is coincident with the A01E section repeated several times since 1991 between Cape Farewell and Ireland (Fig. 1 and Table 1). The common part of the two sections samples the Irminger Basin and part of the Iceland Basin. It crosses the Reykjanes Ridge around 59°N where a thick pycnostad, highlighting the presence of a SPMW variety, is clearly present near 300-500 m depth (Fig. 3). The aim of this paper is to investigate the interannual variability of this mode water over the period 1990-2006. This is made possible because an adequate time series has been created in combining CTD (conductivity-temperature-depth) measurements from hydrographic cruises (OVIDE, A01E and few others, see Sec. 2) and Argo profiling floats. Owing to the Argo array, we can also document properties of the SPMW in the northern

North Atlantic (50-66°N, 45-0°W) over the Argo period 2001-2006 to put the mode water observed on the Reykjanes Ridge in a wider spatial context.

The data set is presented in Section 2. The mode water over the Reykjanes Ridge is described in section 3. We also describe the interannual variability of its properties and we discuss the source and formation area of this mode water. Section 4 discusses the results and we conclude in Section 5.

2. Dataset and Mode Water Identification

The high-quality hydrographic stations carried on during the OVIDE 2002, 2004 and 2006 sections (Table 1) used a Neil Brown Mark III CTD02 probe. The rosette was equipped with 28 8-liter bottles for tracers measurements and calibration purpose. The CTD02 measurement accuracies are thought to be better than 1db for pressure, 0.002°C for temperature, 0.003 for salinity and 1μmol kg^{-1} for dissolved oxygen [*Branellec et al.*, 2004]. High-quality CTD data from the A01E WOCE section (which is also referred to as AR07E section) collected in 1991, 1992, 1995, 1996 and 1997 [*Bersch*, 1995; *Bersch et al.*, 1999; *Bersch*, 2002; *Bersch et al.*, 2007] complement the OVIDE data, as well as data from two additional cruises realized in 1990 as part of the NANSEN project [*van Aken and Becker*, 1996] and in 1991 during the CONVEX-91 survey [*Read*, 2001] (Fig. 1 and Table 1).

Argo data downloaded from the Coriolis data center (http://www.ifremer.fr/coriolis/) complement the dataset. The Coriolis data center provides quality-controlled in-situ data in real-time and delayed mode and is a gateway to the global Argo data. Three levels of quality control are performed to the Argo data. First, a series of standard automatic quality control (QC) is applied (see the Argo quality control manual [*Argo*, 2005] for more details). As the automatic real-time quality control procedure cannot identify small salinity drifts or offsets that Argo floats experience due in particular to biofouling [*Wong et al.*, 2003; *Boehme and Send*, 2005], a second quality control is performed at Coriolis, following *Gaillard et al.* [2007], to remove dubious profiles. Finally, the delayed-mode procedure [*Wong et al.*, 2003; *Boehme and Send*, 2005] is applied to correct (when necessary) offsets and drifts and to generate a qualified Argo dataset [*Argo*, 2005]. Among the 4578 Argo profiles downloaded for this analysis, half contain delayed-mode salinity data and 25% (about 600 profiles) have been corrected. Since the beginning of the Argo program, float and sensor technology has been improved and it is expected that this percentage will decrease with the replacement of the old fleet by new generation of floats. At the time of our analysis, Argo profiles from SOLO floats with FSI CTD may have incorrect pressure values [*Schiermeier*, 2007]. They have been excluded from our dataset. Real time and delayed-mode Argo data containing both temperature (T) and salinity (S) are considered in this study. T and S have a nominal accuracy of 0.01°C and 0.01 psu. In case of duplicates, delayed-mode profiles replace real time data.

We will show in this study that the data from the Argo/Coriolis database provide results that are fully consistent with that deduced from the ship-based high-quality CTD measurements (see Sec. 3.1 and Fig. 7). This gives good confidence for using this dataset in the future for the monitoring of the mode water properties.

During summer, mode waters are isolated from the atmosphere and their properties do not evolve much, which allows the robust characterization of their properties. They are characterized by a thick pycnostad between the seasonal and the permanent pycnocline and can be identified by a minimum in the potential vorticity q [*Hanawa and Talley*, 2001]. For each profile collected from June through September (Fig. 1), the mode waters are identified as the layer where q < 6×10^{-11} m^{-1} s^{-1} [*Johnson and Gruber*, 2007]. Analyzing the WOCE dataset collected in 1997, *Talley* [1999] uses a different criterion ($q < 4\times10^{-11}$ m^{-1} s^{-1}) but that of *Johnson and Gruber* [2007] appears more adequate for the identification of recent mode water vintages that are more stratified than those formed at the beginning of the 90s (Fig. 5). The LSW is excluded in considering only the layers where the potential density is less than 27.7 kg m^{-3}. A visual inspection is then performed to eliminate the selected profiles that do not contain SPMW. Finally, we retain the thickest layers in imposing that the thickness of the mode water layer must be greater than 100 db. For each profile and in the layer satisfying the above conditions, the core properties of the mode water are defined at the level where the potential vorticity is minimum. Examples are displayed on Fig. 5. Potential temperature (θ), potential density (σ_0) and q are deduced from the T and S profiles. θ and σ_0 are referenced to 0 db. A 4th-order Butterworth filter with a cut-off wave length of 50 dbar is applied to the potential vorticity estimated from the 1-db vertical resolution ship-based CTD measurements. Due to the coarser vertical sampling, the Argo data are not filtered.

3. The Subpolar Mode Water over the Reykjanes Ridge

3.1. Properties and Interannual Variability

The profiles collected from 2001 to 2006 during the Argo period allow us to determine the localization and the properties of the SPMW in the northern North-Atlantic (Fig. 6). SPMW are distributed around the subpolar gyre. They are found south of Rockall Plateau and in Rockall Trough, in the northern part of the Iceland Basin, on the eastern flank of the Reykjanes Ridge and in the northern part of the Irminger Basin. This picture is fully consistent with an analysis based on data collected in 1997 by *Talley* [1999]. In the eastern Iceland Basin, the density (salinity and potential temperature) of SPMW increases (decrease) northward from 27-27.1 kg m^{-3} (35.5-35.6 and 11-12°C) at the southern limit of the Rockall Trough to 27.4-27.5 kg m^{-3} (35.1-35.2 and 7-8°C) in the northern Iceland Basin. The SPMW are absent in the central part of this basin. There, well-stratified water masses are embedded within one of the three main branches of the North Atlantic Current (NAC) [*Talley*, 1999; *Read*, 2001]. Along the Reykjanes Ridge, the mode water variety has the following properties: $\sigma_0 \sim$ 27.4-27.5 kg m^{-3}, $\theta \sim$ 7-8°C and S$\sim$ 35.1-35.2. The densest variety (excluding LSW) is observed in the northern part of the Irminger basin with a density greater than 27.5 kg m^{-3} and salinity and potential temperature usually lower than 35.1 and 7 °C, respectively.

Let us now consider the SPMW observed over the Reykjanes Ridge (it is called Atlantic Water by *Read* [2001]). A comparison of the properties of this SPMW with previous estimates shows large variability. The pool of uniform salinity water associated with this SPMW was more saline by about 0.1 in 2004 than in 1992 (Fig. 4). Also, with a density greater than 27.5 kg m^{-3}, this SPMW was denser in 1992 (Fig. 3b) and in 1997 [*Talley*, 1999] than over the period 2001-2006 when the density was less than 27.5 kg m^{-3} (Figs. 3a, 5 and 6).

Our data set allows us to investigate the interannual variability of the properties of the SPMW observed over the Reykjanes Ridge in a box located on the eastern flank of this ridge (57.5-59.5°N, 31.5-28.5°W) (Fig. 1). For this purpose, we define the yearly property value as the median of all estimates of the mode water properties in the box for a given year (from summer profiles). We use the median instead of the mean because we do not want to bias the result toward extreme values. The time-averaged of the yearly properties between 1990 and 2006 are $\sigma_0 = 27.51$ kg m^{-3}, θ= 7.07°C and S=35.13. The core of this mode water is located at 450 db. The time evolution of the core properties of this SPMW is depicted in Fig. 7. Removing the corresponding yearly values from each estimates, the standard deviation over 1990-2006 is estimated to 0.02 kg m^{-3} for σ_0, 0.2°C for θ, 0.02 for S and 73 db for the pressure at the mode water core. As not enough data are available to provide an accurate confidence interval for each yearly estimate, we consider that changes in the yearly values of the mode water properties are significant when they are greater than 2 times the estimated standard deviation.

From 1990 to 1995, mode water properties are relatively stable ($\sigma_0 = 27.56$ kg m^{-3}), although a slight density compensated trend toward fresher and colder mode water is observed (by about 0.04 and 0.24°C) (Fig. 7). The trend reversed in 1996. From 1996 to 2003, the salinity and the temperature of the mode water core increased. Those changes are not density compensated and during the same time the density decreased. In 2003, the SPMW was 1.41°C warmer, 0.11 saltier and 0.12 kg m^{-3} lighter than in 1995. The warming and salinisation ceased after 2003. The data even suggest that the trend has reversed since that year, but this has to be taken with caution as the 2003 yearly values are deduced from two profiles only. However, this is in full agreement with measurements collected along the AR7E section in 2003 and 2005 that shows the SPMW at 500 m depth over the Reykjanes Ridge was cooler and fresher in 2005 than in 2003 [*ICES*, 2006].

A gap in our data set does not allow us to describe the time evolution of the properties of this mode water between 1997 and 2002. It can be indirectly documented in considering the time series of the February Reynolds SST [*Reynolds et al.*, 2002] averaged in the

Reykjanes Box that follows fairly well the SPMW core temperature (Fig. 7, see also Sec. 3.2 for more details) and measurements collected in 1999 along the A01E section. Those data are not available for our analysis but are discussed by *Bersch* [2002] and *Bersch et al.* [2007]. The February Reynolds SST exhibits a warm anomaly in 1998-1999 and a visual inspection of the salty anomaly in the upper layers of the A01E section near 30°W (see Fig. 10 in *Bersch et al.* [2007]) reveals the presence of a positive anomaly in 1999. The long term trend in the core properties of the SPMW observed over the Reykjanes Ridge are thus modulated by interannual variability, with warm and salty anomalies in 1998-1999.

According to our dataset, no significant change in the depth of the mode water core occurred over the period 1990-2006, except in 2004 when the core was anomalously shallow (Fig. 7). In the Bay of Biscay, the ENACW core remains also at the same depth over 1992-2003 [*Gonzàlez-Pola et al.*, 2005] because, simultaneously, the isopycnal levels deepened and the core density of this mode water decreased from about 27.2 to 27.1 kg m^{-3}. We expect that the same process explains the stability of the SPMW core depth over 1990-2006. Finally, the data suggest that the thickness of the mode water layer was greater than 300 db before 1996, while it has been usually lower than this value since then (Fig. 8). The extreme value observed in 2002 (thickness $\sim$ 800 db) is due to an eddy sampled during the 2002 OVIDE section. The mode water in this eddy presents extreme properties with a density and a potential temperature at the core of the mode water less than 27.4 kg m^{-3} and greater than 8°C (Fig. 7). The two profiles displayed on Fig. 5 illustrate fairly well the contrast in SPMW properties between the recent years and the beginning of the 1990s.

3.2. Source and Formation Area

The Hydrobase 2 Atlas shows that the climatological 27.45, 27.5 and 27.55 kg m^{-3} isopycnals outcrop in winter southwest of Iceland parallel to the Reykjanes Ridge between the 1000 and 2000 m isobaths (Fig. 9), which identifies the potential formation region of the SPMW observed over the Reykjanes Ridge. Considering two boxes located along the outcropping region of the 27.45-27.55 kg m^{-3} isopycnals (Fig. 9), we show that the February SST averaged in these boxes and their time evolution are in fair agreement with those in the Reykjanes box (Fig. 7). This was expected since the SST isotherms are also parallel to the ridge (Fig. 10), and confirms uniform surface properties along the ridge. In addition, the February SST interannual variability along the Reykjanes Ridge follows the interannual variations of the SPMW core temperature in the Reykjanes box (Fig. 7). Since the February SST over the eastern flank of the Reykjanes Ridge, which represents the late winter mixed layer temperature, is also a proxy for the SPMW core temperature, we conclude that the SPMW is formed in the winter mixed layer over the eastern Reykjanes Ridge. Surface isotherms and isopycnals being parallel to the ridge, we expect uniform mode water properties between southwest of Iceland and the Reykjanes box, which is evidenced from the in situ data (Fig. 6).

In the Iceland Basin, the upper ocean waters overlying LSW are a mixture of cold, fresh subarctic water masses and warm, saline subtropical water masses. From a water mass point of view, there is some evidence that the warm and salty subtropical waters spread northward in the northeastern North Atlantic [*Bower et al.*, 2002], circulate around the northern Iceland Basin and flow southwestward along the eastern flank of the Reykjanes Ridge [*Read*, 2001; *Pollard et al.*, 2004]. This is confirmed by *Bower et al.* [2002] who, using acoustically tracked floats, estimated the mean circulation in the subpolar North Atlantic on the 27.5 kg m^{-3} isopycnal (level of the mode water core) over 1993-2001 (Fig. 11). After crossing the Mid-Atlantic Ridge between 50°N and 53°N, the NAC turns northward in the Iceland Basin and then splits into two main branches. One branch turns sharply anticlockwise to feed directly the Irminger Current on the western side of the Reykjanes Ridge while the other branch, after penetrating farther north into the Iceland Basin, returns southwestward along the eastern flank of the ridge and eventually crosses the Reykjanes Ridge to feed the Irminger Current. Although, the surface circulation pattern deduced from surface drifters drogued at 15 m depth exhibits an undefined mean flow along the eastern flank of the Reykjanes Ridge [*Reverdin et al.*, 2003; *Flatau et al.*, 2003], some of the 15-m drogued floats that were deployed south of Iceland moved southwestward along the eastern flank of the ridge [*Reverdin et al.*, 2003]. This near-surface circulation along the ridge would be better defined in winter (when the 27.5 kg m^{-3} isopycnal reaches the surface) than in summer which corroborates a southwestward circulation along the eastern flank of the Reykjanes Ridge on the 27.5 kg m^{-3} isopycnal. There is thus evidence from water masses and circulation that the SPMW observed over the Reykjanes Ridge is at least partly supplied by waters advected by the mean circulation from the northern and eastern Iceland Basin.

This latter conclusion does not mean that this SPMW is directly connected to the lighter SPMW variety lying in the eastern side of the Iceland Basin as hypothesized by [*McCartney and Talley*, 1982]. *Brambilla* [2007] shows that the connection between the (lighter) SPMW in the eastern Iceland basin and the (denser) SPMW over the Reykjanes Ridge is unlikely, although it might occur intermittently. *Read* [2001] also concludes that the SPMW properties are *"set primarily by modification of whatever segment of the temperature/salinity curve has reached the surface rather than by cooling and freshening of central water along an advective path as described by McCartney and Talley [1982]"*. Beside deep winter mixing and advection, the other factors that potentially help setting the SPMW properties are mixing with underlying and lateral water masses and eddy activity [*Read*, 2001].

4. Discussion

The warming and salinisation trend of the SPMW over the Reykjanes Ridge started in 1996 after the abrupt drop of the NAO index and persisted until at least 2003. During that period, the NAO index presented a decreasing trend and the air-sea forcing changed accordingly. We thus investigate the relationship between the properties changes of this SPMW and the NAO-driven circulation and atmospheric forcing field variability.

Changes in local air-sea forcings are quantified in the formation area of this mode water by averaging atmospheric fluxes in a box covering the northern part of the Iceland basin (52-63°N, 33-10°W, Fig. 2). We first consider the freshwater flux because its relation with the mixed layer salinity is straightforward due to the absence of feedback between surface salinity and evaporation or precipitation. The annual P-E anomaly exhibits a positive trend over the period 1990-2006 (Fig. 2), which excludes P-E as the driver of the salinisation of the SPMW over the period 1995-2003. This result is in full agreement with *Hátún et al.* [2005] and *Holliday* [2003], but it differs from *Josey and Marsh* [2005]' and *Gonzàlez-Pola et al.* [2005]' findings. *Josey and Marsh* [2005] show that on an interdecadal time scale, the freshening (~ 0.2) of the surface layers of the eastern half of the North Atlantic subpolar gyre from the mid 1970s until the 1990s can be largely explained by an increase in P-E in the gyre region. In the Bay of Biscay, the P-E regime on an interannual time scale seems to be the main driver for the ENACW salinity variations (in the range of 0.05 to 0.1) over 1992-2003 [*Gonzàlez-Pola et al.*, 2005]. Understanding those differences on the role of P-E (both geographically and at different temporal scales) deserves to be investigated in detail but is beyond the scope of this study.

Let us now provide some insight on the possible effect of the local air-sea fluxes variability on the winter SST and on mode water temperature. The NAO index was positive beginning of the 1990's and the winter heat loss and the winter zonal momentum were maximum during that period. The NAO index decrease since the mid-1990s is accompanied in the subpolar gyre with a decrease in both the zonal momentum and the total heat loss and an increase in the SST as revealed by the westward shift of the position of the February 7°C isotherm since 1996 (Fig. 10). In order to quantify the ocean response to the air-sea heat flux variability, we compute, for each profile in the Reyjkanes Box, the heat content anomaly relative to a reference temperature in the mode water layer as :

$$H = \int \rho Cp(T - T_R)dz \qquad (1)$$

with ρ and Cp the density and the specific heat capacity of seawater, z the depth in metres, T the potential temperature and T_R the reference temperature which is chosen as the mean temperature of the mode water core over 1990-2006 (here 7.07°C). The mode water layer is deduced from the mode water thickness and the depth of the mode water core and varies from one profile to the other. A yearly value is defined as the median of all estimates of the heat content anomaly in the box for a given year. We then compare the annual variations of this heat content anomaly to changes in the annual air-sea heat flux multiplied by time following *Holliday* [2003]. With variations of order 0.5 J m^{-2} over the period 1995-2006 compared to more than 2 J m^{-2} for the heat content anomaly, we estimate that the local heat flux variability is a minor contribution to the SPMW core temperature variations (Fig. 12).

Long-term changes in water mass properties have been reported in the whole eastern subpolar gyre over the last decade. *Hátún et al.* [2005] show clearly a continuous salinisation of the Atlantic Inflow to the Nordic Seas over 1995-2004 by about 0.1 psu. Analyzing SPMW property variations along 20°W, *Johnson and Gruber* [2007] observe extreme and opposite conditions in 1993 (colder and less saline) and in 2003 (warmer and saltier), while intermediate conditions are observed in 1988 and 1998. Analyzing data from the Extended Ellet Line in the northern Rockall Trough over the period 1975-2000, *Holliday* [2003] shows that temperature and salinity exhibit coherent decadal fluctuations with highs in the mid 1980s and late 1990s and lows in the late 1970s and early 1990s. Recent measurements along the Extended Ellet Line in the Rockall Trough show that since the late 1990s the temperature and salinity continue to increase (see these unpublished data on http://www.noc.soton.ac.uk/obe/PROJECTS/EEL, hereafter EEL web site): over the period 1995-2005, the changes are of order 0.8°C and 0.08 psu. The air-sea heat and freshwater fluxes cannot explain the amplitude of the temperature and salinity variations [*Holliday*, 2003; *Hátún et al.*, 2005] or the deep penetration of the changes [*Johnson and Gruber*, 2007]. In all cases, the authors conclude that the water mass variability is primarily attributable to NAO-related changes in the shape and strength of the subpolar gyre and in the regional circulation that modify the relative contribution of relatively fresh and cold water masses of subpolar origin (SubArctic Intermediate Waters) and warmer and saltier water mass of southern origin (Western North Atlantic Central Water that are transported by the North Atlantic Current and Eastern North Atlantic Central Water that comes from the intergyre area in the eastern North-Atlantic). *Häkkinen and Rhines* [2004] suggest that the gyre weakening after 1995 is primarily attributable to changes in the net heat flux. Using models, *Böning et al.* [2006] suggest that the wind stress is also a contributor to the gyre variability especially in the early 1990s when both the net heat flux and the wind stress acted in concert to produce an intense transport.

The variability of the SPMW observed over the Reykjanes Ridge is fully consistent with the variability of the Atlantic Inflow to the Nordic Seas [*Holliday*, 2003; *Hátún et al.*, 2005] and the variability of the mode water south of Iceland along 20°W [*Johnson and Gruber*, 2007]. All water masses exhibit coherent temperature and salinity variations and tend to be lighter, saltier and warmer since 1996. The variations are of order 0.1 in salinity and 1°C in 10 years. According to the mean circulation pattern on the 27.5 kg m^{-3} isopycnal (Fig. 11), to the fact that the SPMW over the Reykjanes Ridge is supplied by waters from the northern and eastern Iceland Basin and that the local P-E and heat flux variations in the formation area of this SPMW cannot explain the temperature and salinity changes over 1990-2006, we conclude that the variations of the core properties of this SPMW are likely mainly due to the variations in the properties of its source water masses.

The long-term trend in the core properties of the SPMW observed over the Reykjanes Ridge is modulated by interannual fluctuations. Warm and salty anomalies are observed in 1998-1999 and possibly in 2003 (Sec. 3.1). A peak in salinity is also observed in the upper layers of the Rockall Trough in 1998 and in 2003 (*Hátún et al.* [2005], see also the EEL web site). Those anomalies are lagged by one year with the anomalies reported by

Bersch et al. [2007] in the central part of the Iceland Basin in 1996-1997 and in 2002. According to these authors, the fast response of the Subarctic Front in the Iceland Basin to the drop of the NAO index during the winters 1995/1996 and 2001/2002 (Fig. 2a) induces a northwestward shift of the front with a time lag of 1 to 2 years. In 1999, when the NAO index returned to a positive value, the low saline subarctic water masses began to occupy again the Iceland Basin (see Fig. 10 in *Bersch et al.* [2007]). The interannual anomalies observed on the eastern flank of the Reykjanes Ridge, lagged to the NAO index by 2-3 years, are likely linked to those reported by *Bersch et al.* [2007].

The SPMW core warmed by about 1.4°C in 9 years which is one order of magnitude greater than the temperature increase of 0.274°C in the top 700 m depth of the North-Atlantic over 1955-2003 reported by *Levitus et al.* [2005]. Part of the observed changes might be related to this global warming but yet, the length of our time series and the volume of water considered here do not allow us to separate long term changes due to anthropogenic influence from intrinsic oceanic variability. For this purpose, we believe it is worth continuing the monitoring of the SPMW core properties in the North Atlantic in using ship-based hydrographic data and Argo data.

5. Conlusion

Combining CTD data from different hydrographic sections and Argo data collected in the northern North-Atlantic over 1990-2006, we provide a picture of the geographical distribution of the subpolar mode waters in the North Atlantic. The core property of the subpolar mode waters is individually identified in profiles collected from June through September. In particular, a variety of mode water is identified along the eastern flank of the Reykjanes Ridge. Its mean properties over 1990-2006 are $\sigma_0 = 27.51$ kg m^{-3}, $\theta=$

7.07°C and S=35.13. According to water mass properties and to the mean circulation pattern on the 27.5 kg m^{-3} isopycnal, we conclude that the sources of this SPMW are advected by the mean circulation from the northern and eastern Iceland Basin and that this SPMW acquires its final properties in the winter mixed layer southwest of Iceland on the eastern side of the Reykjanes Ridge roughly between the 1000 and 2000 m isobaths. We also show that the February SST along the Reykjanes Ridge is a proxy for the SPMW core temperature.

Our data set allows us to investigate the interannual variability of this SPMW in a box centered near 58.5°W and 30°W. The density compensated tendency for cooling and freshening observed in the early 1990s is interrupted in 1996 when the trend reversed until at least 2003. During that period, this SPMW warmed by 1.41°C and became more saline by 0.11. As a consequence, the density of the SPMW core decreased by 0.12 kg m^{-3}. Since 2003, the properties of this mode water are relatively stable with possibly a slight trend toward colder and fresher properties. In combining February SST data and results from data collected in 1999 along the A01E section, we suggest that the core properties of this mode water reached a local maximum (warm and salty anomaly) in 1998-1999. During the whole period (1990-2006), the data do not show any significant modifications in the depth of the mode water core but they suggest that the thickness of the layer shrank.

The warming and salinisation that are observed after 1995 occurred simultaneously with large changes in the NAO index that was largely positive until 1995 and, after a large negative value in 1996, never returned to large positive values. During the same time, the winter air-sea heat fluxes and momentum fluxes in the northern Iceland Basin decreased leading to decreased winter heat loss, warmer SST and potentially warmer

SPMW. However, we show that the local variations in the air-sea fluxes are a minor contribution to the warming trend. In addition, the annual freshwater flux exhibits a positive trend over 1990-2006 and cannot explain the observed salinity changes. The decrease in NAO index is associated with an invasion of warm and salty waters in the upper layers of the eastern subpolar gyre and in the Iceland Basin. Since the simultaneous changes in temperature and salinity cannot be explained by variations in local air-sea fluxes, we conclude that they are most likely due to the displacements of water masses associated with changes in gyre circulation and shape.

The long term trend of the core properties of the SPMW observed over the Reykjanes Ridge is modulated by interannual variations: warm and salty anomalies are observed in 1998-1999 and possibly in 2003. Those anomalies could be related, with a time lag of 2-3 years, to the abrupt drop of the NAO index that occurred in 1995/1996 and 2000/2001 and that induced a northwestward retreat of the Subarctic Front in the Iceland basin 1-2 years after the shift.

Anthropogenic variability (global warming) surperimposes to the intrinsic ocean variability but longer time series are needed to disentangle human-driven long-term trend from the natural oscillation of the system. This is an important issue as water mass properties variations in the subpolar gyre can have a large impact on the distribution and habitat of some fish species for instance [*Pedchenko*, 2005]. In the context of climate change, we are thus looking for some indicator of the oceanic and atmospheric state and mode water properties in the North-Atlantic ocean are a good candidate [*Banks and Wood*, 2002]. Indeed, they contribute to the preconditionning of the water masses before deep convection in the Nordic, Irminger and Labrador Seas, they contribute to the heat and

CO_2 storage in the ocean and they can be considered as an integrator of the oceanic and atmospheric variability. The monitoring of this mode water properties will be continued in the future owing to perennial observations (OVIDE project, Argo floats) and the role of each mechanisms presented in this paper will be investigated in details in using both data and models.

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Yashayaev, I. (2007), Hydrographic changes in the Labrador Sea, 1960-2005, *Prog. Ocean.*, *73*, 242–276, doi:10.16/j.pocean.2007.04.015.

Name	Date	Ship R/V	PI	Reference
NANSEN-90	07/1990	*Tyro*	Van Aken	*van Aken and Becker* [1996]
A01E-91	09/1991	*Meteor*	Meincke	*Bersch* [1995]
CONVEX-91	08-09/1991	*Darwin*	Gould	*Read* [2001]
A01E-92	09/1992	*Valdivia*	Sy	*Bersch et al.* [1999]
A01E-95	05-06/1995	*Valdivia*	Bersch	*Bersch et al.* [1999]
A01E-96	08-09/1996	*Valdivia*	Bersch	*Bersch et al.* [1999]
A01E-97	08-09/1997	*Meteor*	Sy	*Bersch* [2002]
OVIDE-02	06-07/2002	*Thalassa*	Mercier	*Lherminier et al.* [2007]
OVIDE-04	06-07/2004	*Thalassa*	Huck	
OVIDE-06	05-06/2006	*M. S. Merian*	Lherminier	

Table 1. High-quality hydrographic sections used in the analysis.

Figure 1. Bathymetry of the North-Atlantic. The isobaths 0, 200, 1000 and 2000 m are displayed. Points show the positions of the data (Section 2 and Tab. 1): (red) ship-based CTD measurements, (blue) Argo data. Only summer data (June-September) are displayed. Interannual variability of the SPMW properties are estimated in the box delimited by 57.5-59.5°N and 31.5-28.5°W.

Figure 2. (a) NAO Index [*Hurrell*, 1995]. (b, c, d) Anomaly over the period 1950-2006 of air sea fluxes averaged in the eastern subpolar gyre (52-63°N, 33-10°W), derived from the NCEP/NCAR reanalysis 1. (b) Winter (DJFM) total heat flux. A negative heat flux corresponds to a heat loss for the ocean. (c) Winter momentum flux. (d) Annual P-E (Precipitation minus Evaporation). Gray thin lines are winter mean or annual mean values and black thick lines are filtered values using a lanczos filter with a cut-off frequency of 5 years. Averaged values over the entire series are given in each panel.

Figure 3. Potential density along the OVIDE and the A01E sections from Greenland to 25°W in the center part of the Iceland Basin. (a) 2004 OVIDE section. (b) 1992 A01E section. RR indicates the Reykjanes Ridge.

Figure 4. Same as Fig. 3 but for the salinity.

Figure 5. Example of profiles containing Reykjanes Ridge Mode Water. The data were collected in 2002 at 58.41°N– 30.10°W (plain lines) and in 1995 at 58.32°N– 29.94°W (dashed lines). (a) Potential density (black lines) and potential vorticity (gray lines). (b) Potential temperature (black lines) and salinity (gray lines). The mode water core is identified by dots (2002) and squares (1995) and the corresponding properties are indicated in each panels.

Figure 6. Properties of the Subpolar Mode Water in the North Atlantic deduced from hydrographic stations and Argo profiles collected over the period 2001-2006 from beginning of June trough end of September. (a) Potential density. The Reykjanes Box (57.5-59.5°N, 31.5-28.5°W) is indicated. (b) Potential temperature. (c) Salinity.

Figure 7. Time evolution in the Reykjanes Box (57.5-59.5°N, 31.5-28.5°W) of the core properties of the SPMW from 1990 to 2006 estimated from ship-based hydrographic profiles (crosses) and from profiling floats (circles). Black squares are the median properties for each year. The vertical black line represents two times the standard deviation estimated as indicated in the text. Amplitude of the gray bars are proportionnal to the NAO index. (a) Potential density. (b) Potential temperature. The February Reynolds SST averaged in the Reykjanes Box (plain line) and in two boxes located along the Reykjanes Ridge (dashed line: 59.5-61.5°N, 30-26.5°W ; dotted line: 61.5-63.5°N, 25.5-22.5°W) are compared to the temperature of the mode water core. (c) Salinity. (d) Pressure.

Figure 8. Same as Fig. 7 but for the thickness of the mode water layer.

Figure 9. Climatological outcropping position in February of the 27.45 (light gray), 27.5 (dark gray) and 27.55 kg m^{-3} (black) isopycnals deduced from Hydrobase 2 (http://www.whoi.edu/science/PO/hydrobase/HB2_home.htm). The Reykjanes Box and two additional boxes (59.5-61.5°N, 30-26.5°W and 61.5-63.5°N, 25.5-22.5°W), in which we average the February Reynolds SST, are displayed.

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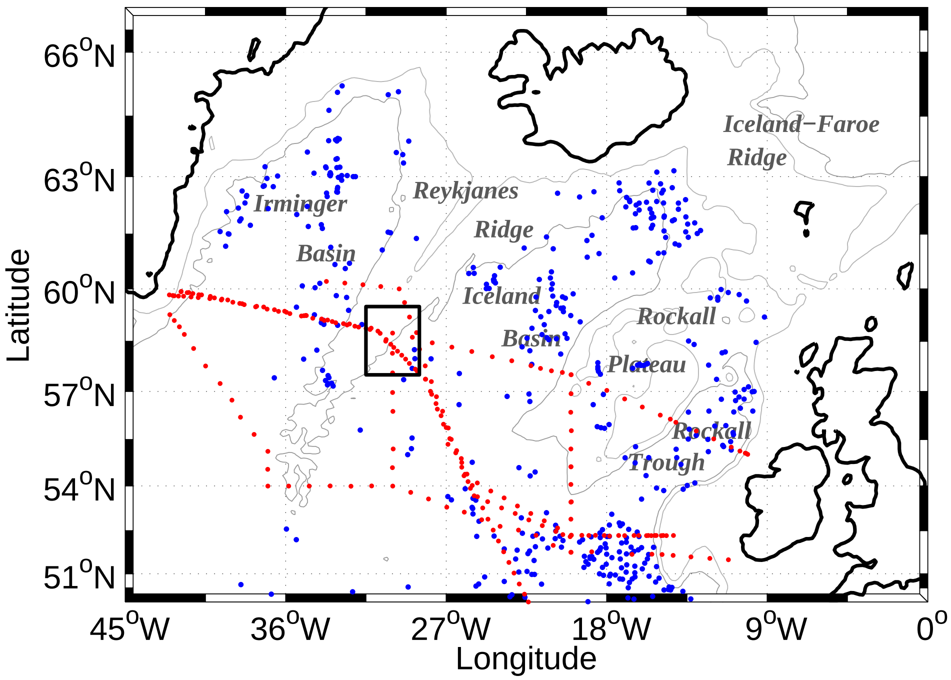
Figure 11. Mean streamfunction for the subpolar North Atlantic from subsurface floats on the 27.5 kg m^{-3} isopycnal. Arrowheads show the direction of flow along contours. The color bar give volume transport for a one-meter-thick layer. The 24,000 and 26,000 m^2 s^{-1} contours have been added (dashed). NAC, NWC and IC stand for North Atlantic current, Northwest Corner and Iminger Current, respectively. See *Bower et al.* [2002] for more details. Copyright Nature.

Figure 12. Oceanic heat content anomaly in the Reykjanes Box (squares) compared to changes in heat content due to atmospheric flux variations only (thick line). In both cases, the 1990-2006 mean is removed.



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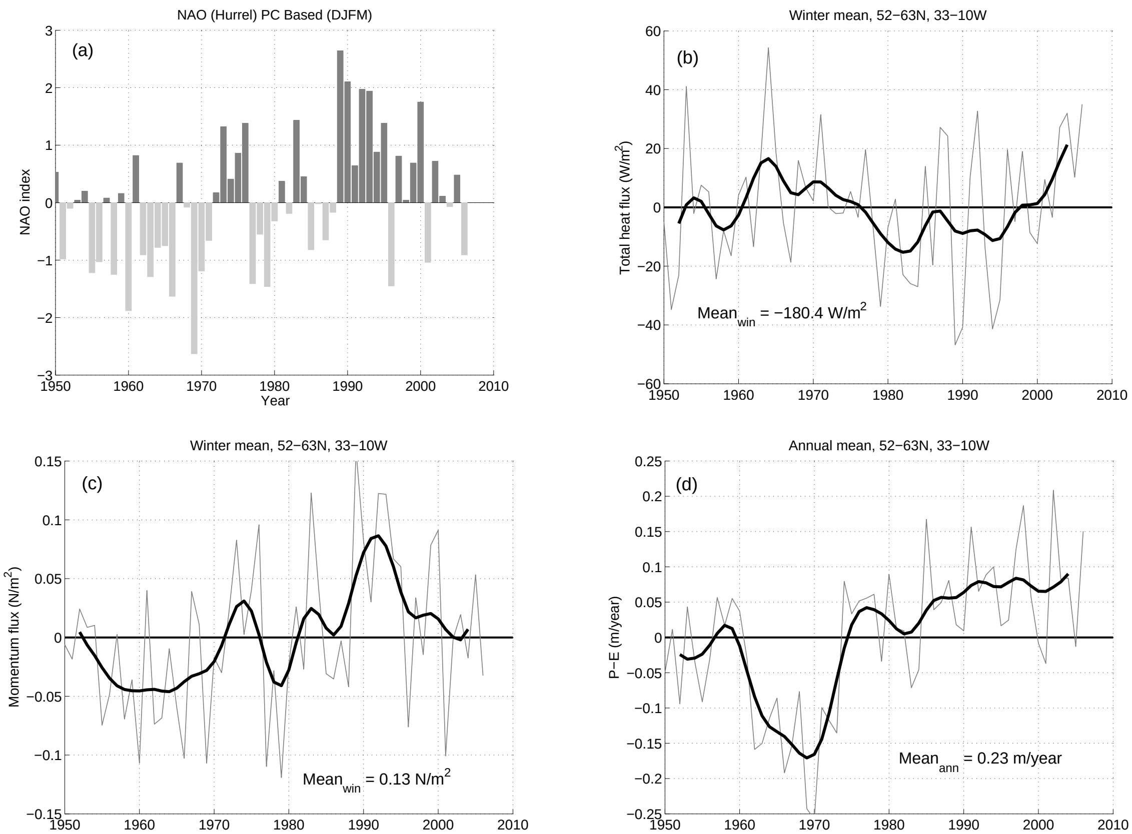

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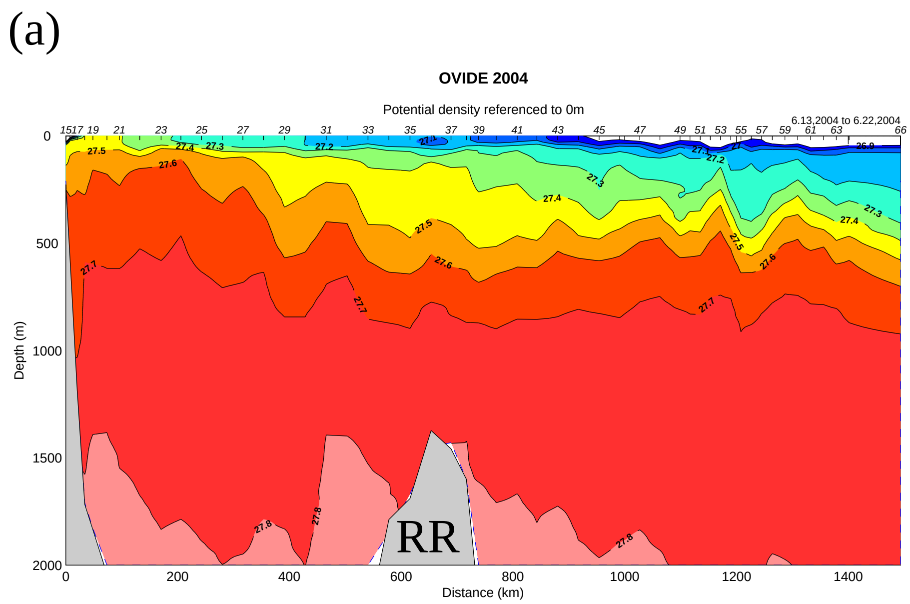

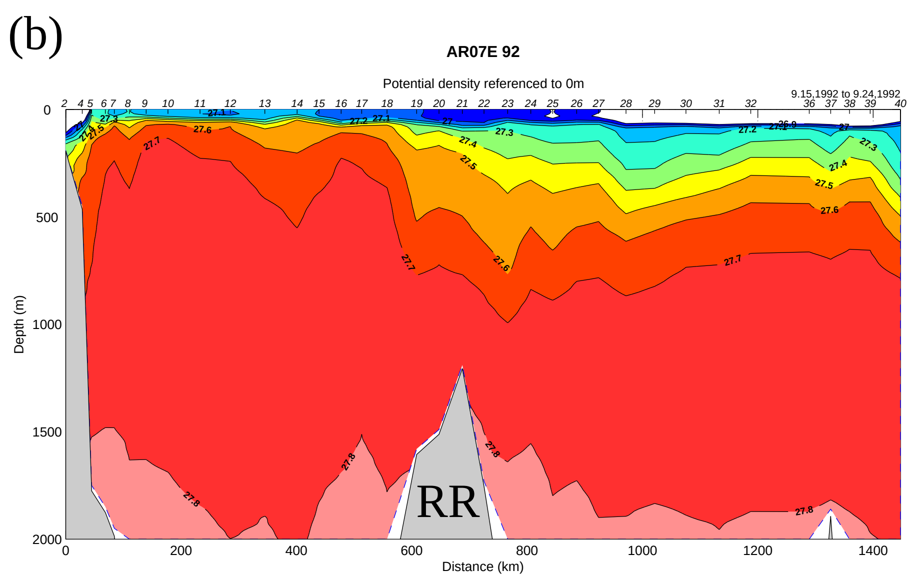

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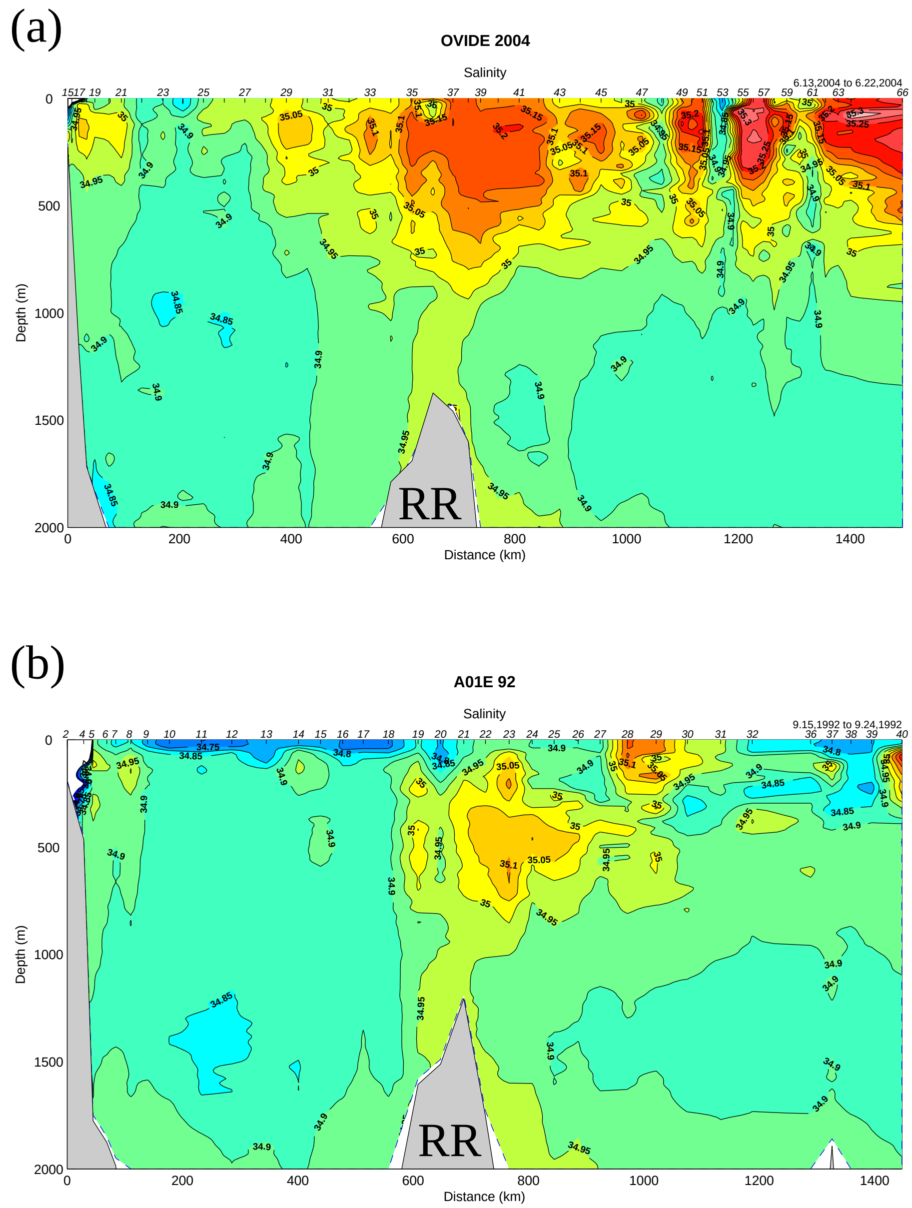
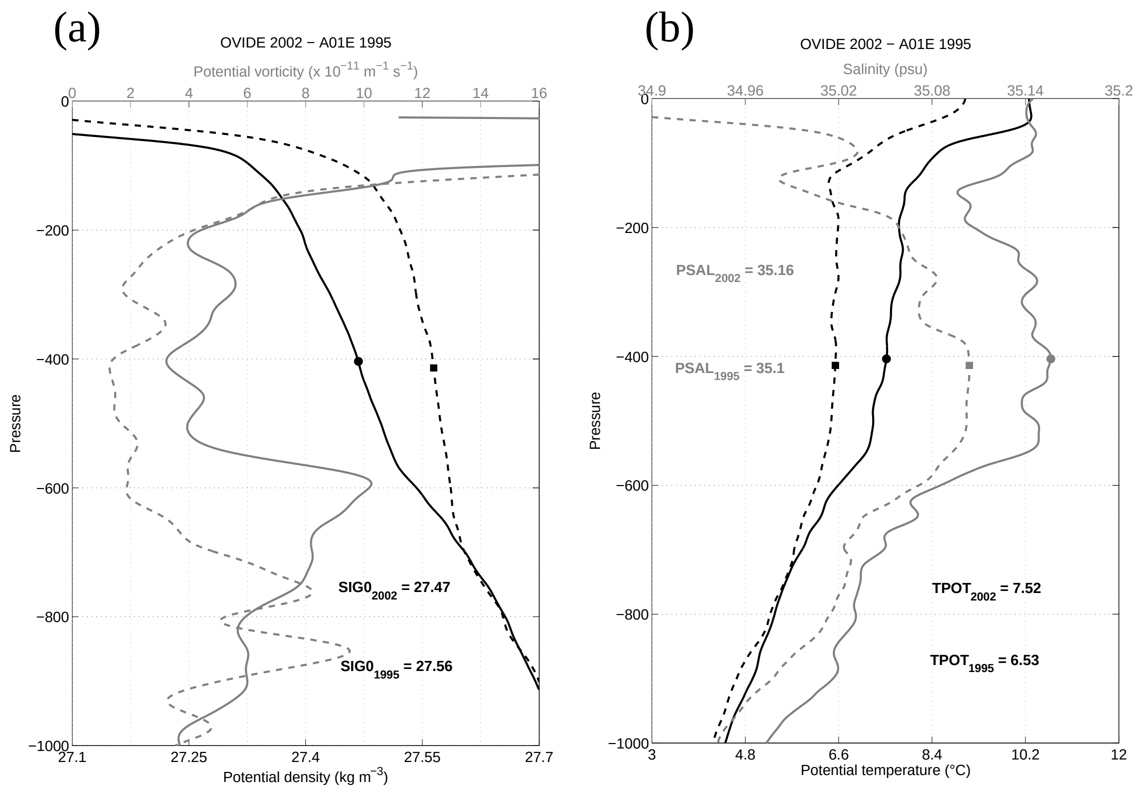


Figure 4. Same as Fig. 3 but for the salinity.



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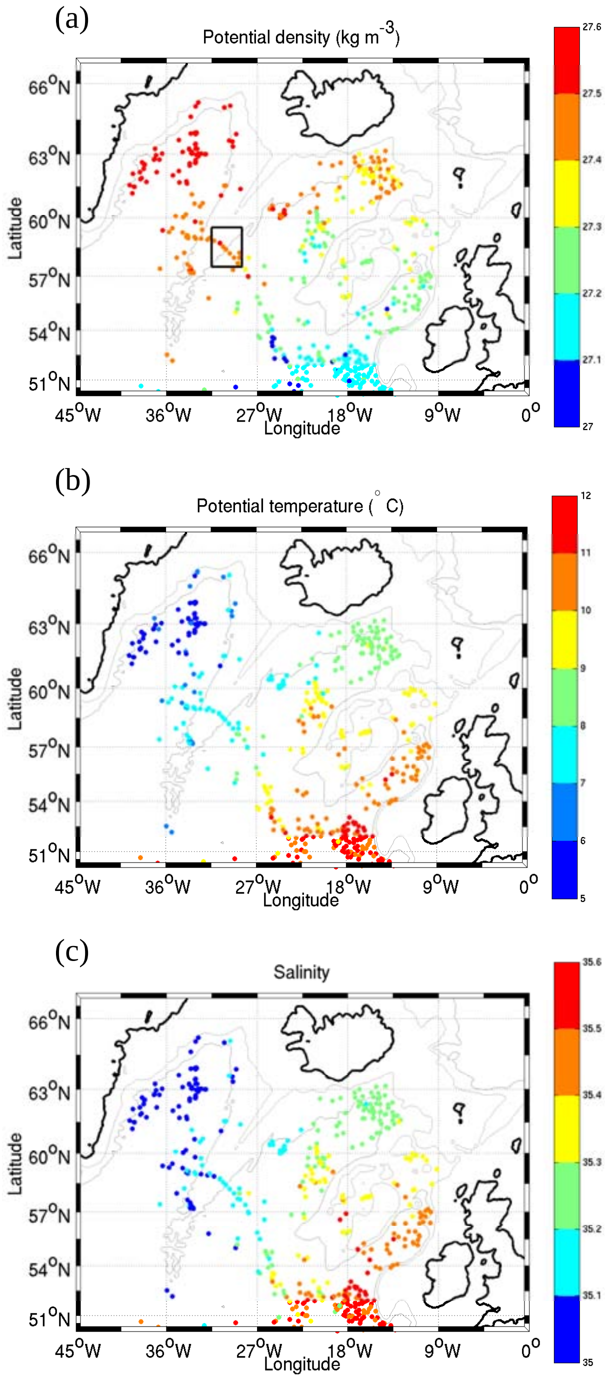

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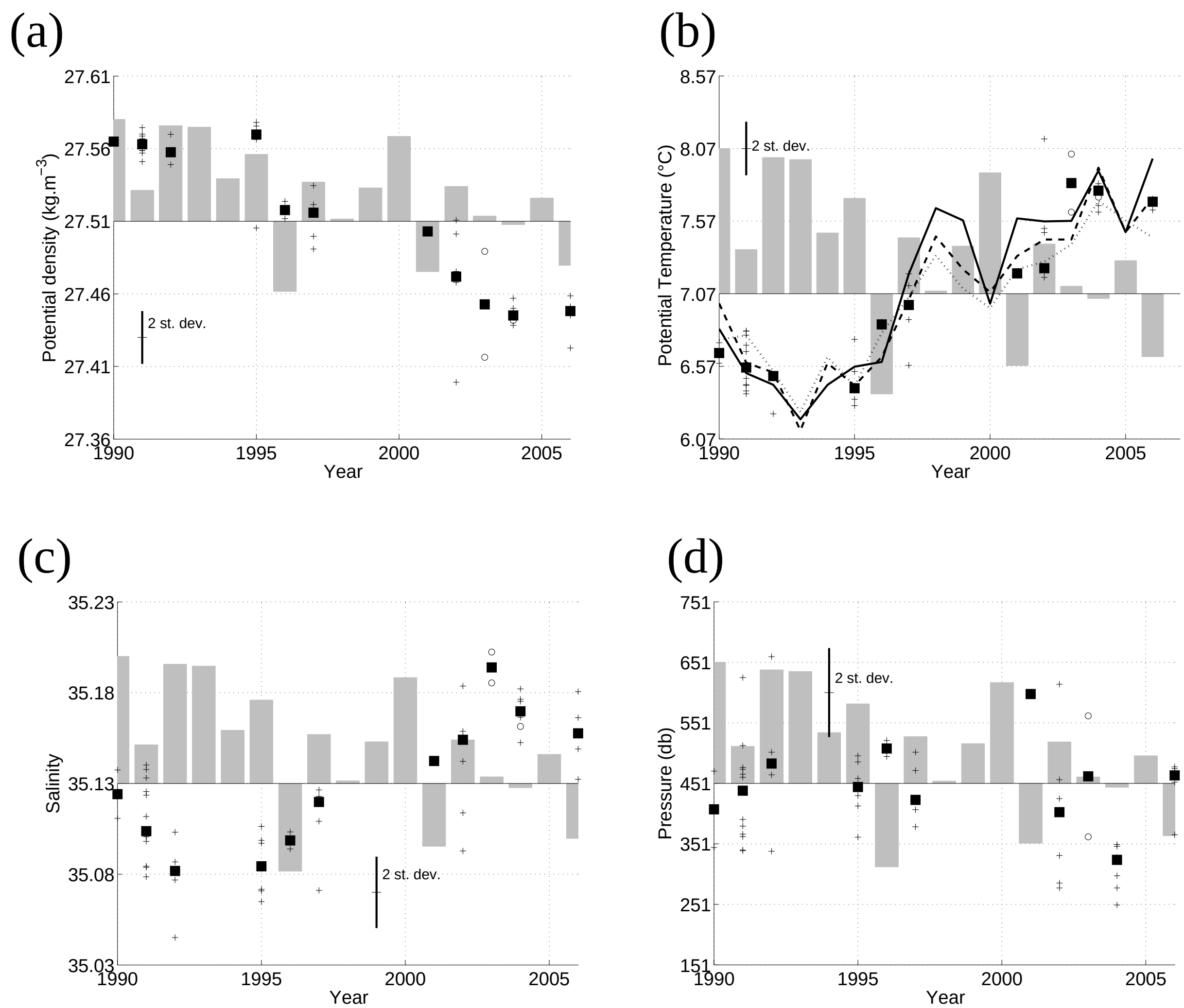

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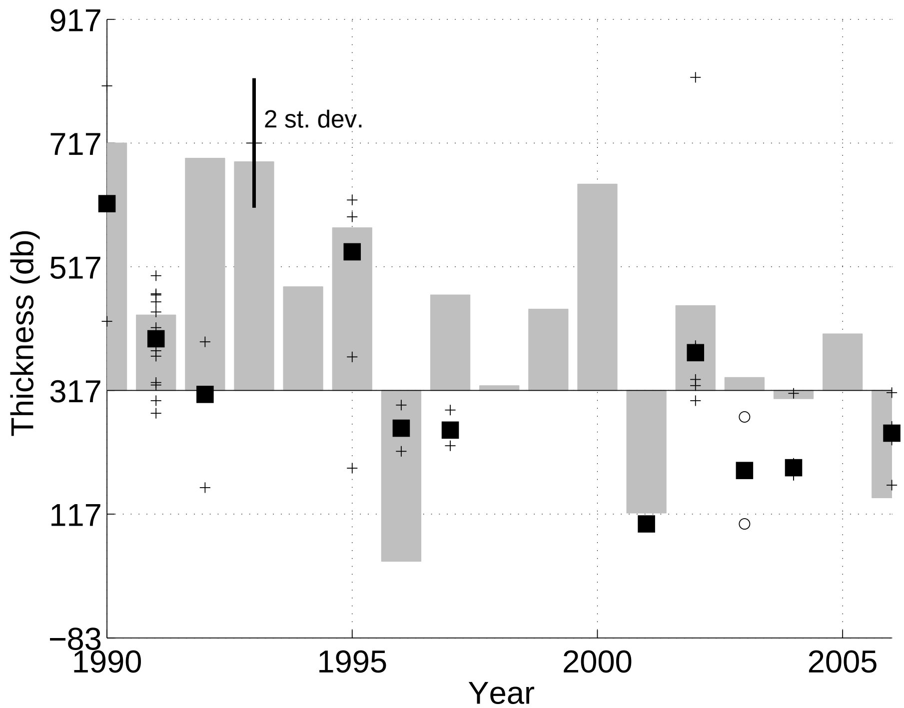

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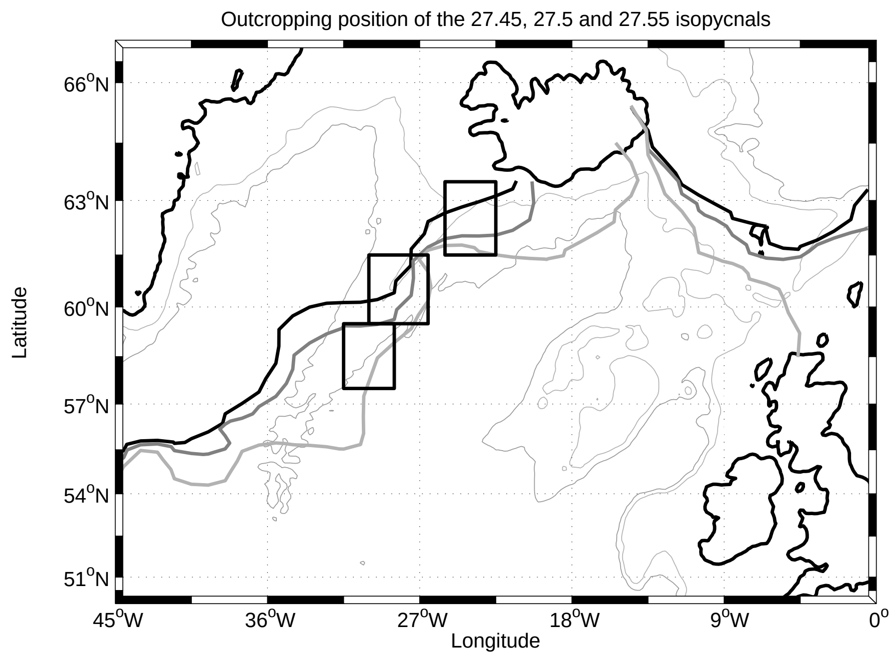

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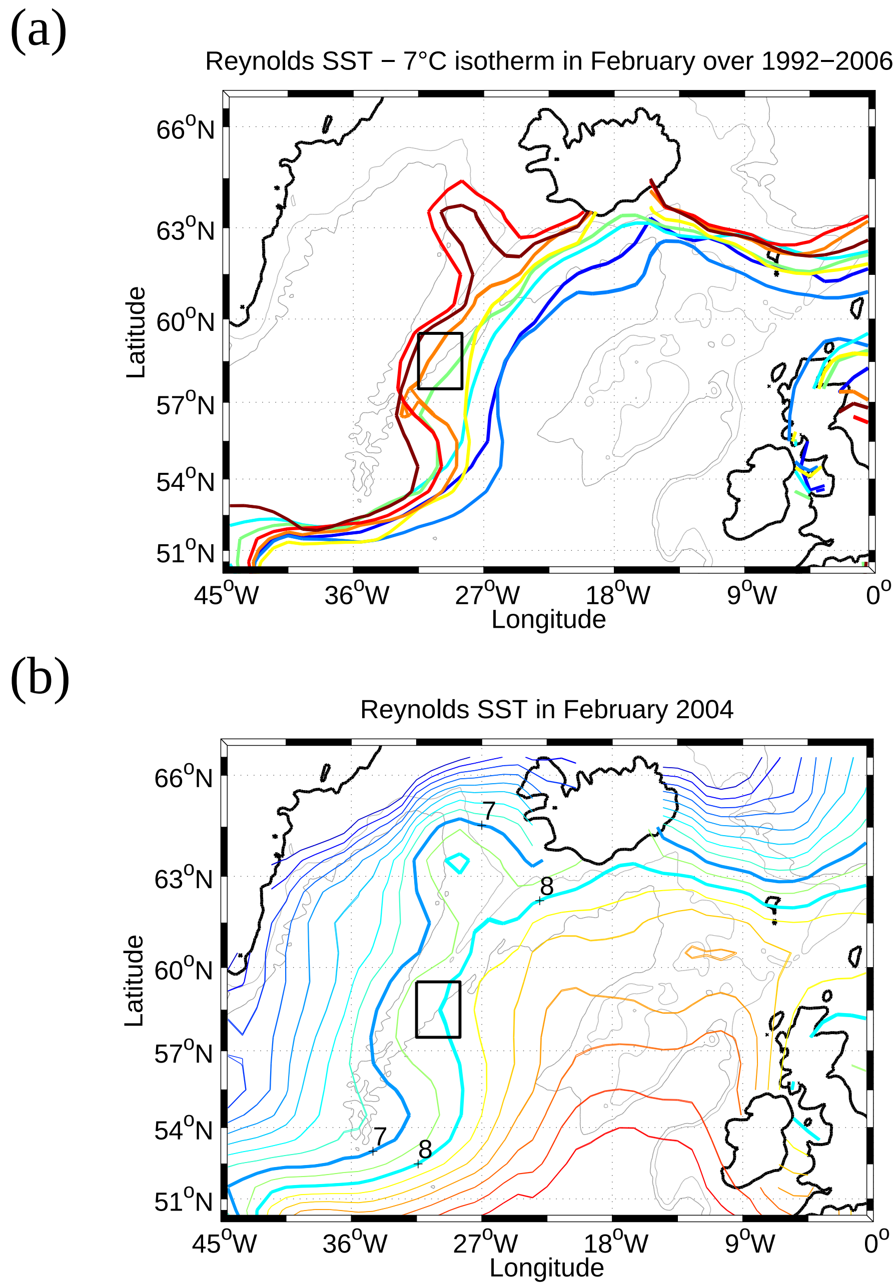

Figure 10. February SST from Reynolds' SST monthly fields [*Reynolds et al.*, 2002] : (a) Position of the 7°C isotherm in 1992 (dark blue), 1995 (blue), 1996 (cyan), 1997 (green), 2000 (yellow), 2002 (orange), 2004 (red) and 2006 (brown). (b) February SST in 2004. The thick blue and cyan lines are the 7 and 8°C isotherms, respectively. The contour interval is 0.5°C.

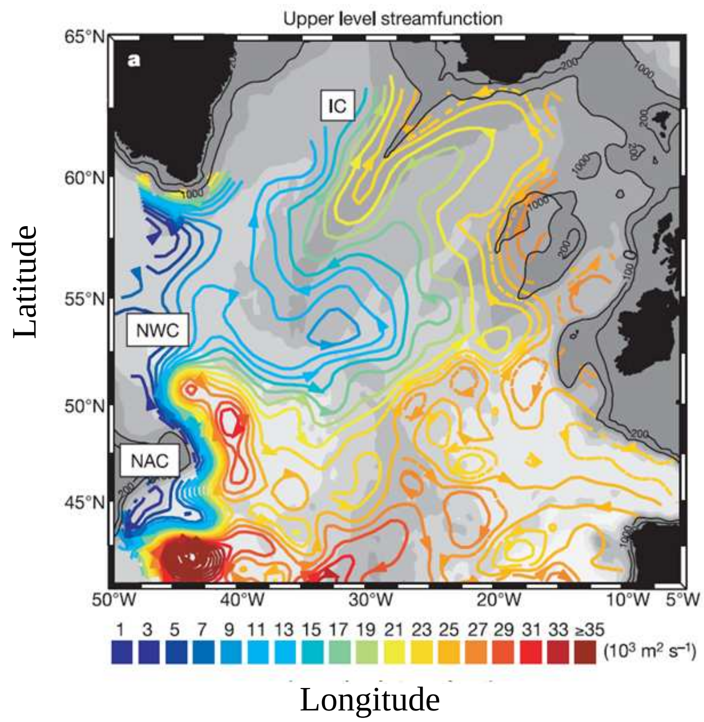

Figure 11. Mean streamfunction for the subpolar North Atlantic from subsurface floats on the 27.5 kg m^{-3} isopycnal. Arrowheads show the direction of flow along contours. The color bar give volume transport for a one-meter-thick layer. The 24,000 and 26,000 m^2 s^{-1} contours have been added (dashed). NAC, NWC and IC stand for North Atlantic current, Northwest Corner and Iminger Current, respectively. See *Bower et al.* [2002] for more details. Copyright Nature.

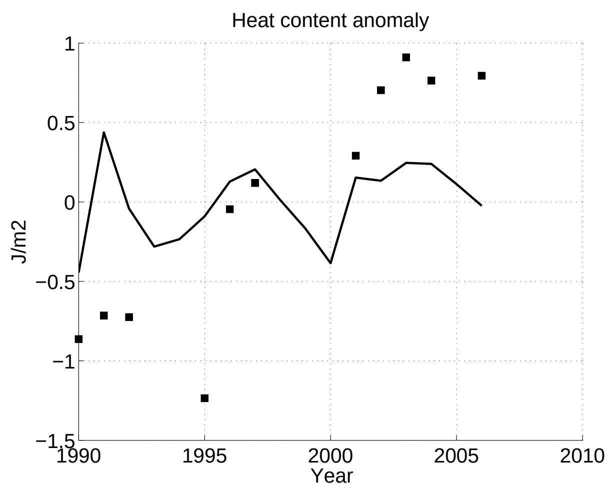

Figure 12. Oceanic heat content anomaly in the Reykjanes Box (squares) compared to changes in heat content due to atmospheric flux variations only (thick line). In both cases, the 1990-2006 mean is removed.