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Variability of heat and salinity content in the North Atlantic in the last decade

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Abstract

The analysis of the heat and salinity contents have been made for the Northern Atlantic for the decade between January 1999 and December 2008. This analysis is based on the Argo profiling data for the upper 2000 m. Basin-averaged values of anomaly of heat (AHC) and anomaly of salinity content (ASC) are robust and stable. The AHC and ASC demonstrate positive trends in the last decade in the upper 2000 m of the North Atlantic. The linear trend of AHC and ASC are $(126.43\pm18.52)\times10^{20}$ J, and $(47.07\pm6.90)\times10^{13}$ kg, respectively. Both trends are significant at 95% level of significance. The main contribution to the positive trend of AHC/ASC comes from the northern parts of the basin.

1 Introduction

The ocean salinity and especially heat content are major components of the climate system. The World Ocean has a heat capacity much higher than the atmosphere (more than three orders of magnitude) and therefore it plays an important role in the global heat content changes of the earth climate system (Levitus et al., 2005; Lyman et al., 2006).

The salinity content in the ocean mainly depends on fresh water fluxes from evaporation/precipitation and from the melting/freezing ice. The local salinity content is linked to the dynamical processes, as well. Global warming results in melting of continental and sea ice. Curry and Mauritzen (2005) have demonstrated that the Northern North Atlantic (i.e. the Nordic Seas and Subpolar Basins) were diluted by an extra 19 000±5000 cubic kilometers of freshwater influx between the mid 1960's and the mid 1990's. Furthermore a significant change in salinity content may result in a substantial change of the meridional circulation (thermohaline circulation), which can drastically change the meridional heat flux.

Is the ocean warming or cooling and what are the mechanisms responsible for this change, remain the prime important problems. The following questions need to be resolved for the improved understanding of the climatic variations:

1. Is the variability in heat content natural or human induced because of additional CO_2 production?

2. Is there a warming/cooling trend or is it part of large time-scale variability?

3. How good is the estimation of warming/cooling in terms of the data used? Is the data representative for such analysis?

A number of numerical experiments with the oceanic, atmospheric and coupled models have been made to answer the first question (Randall et al., 2007). Regarding the second question we can find periods of warming and cooling of the global or regional parts of the ocean if the study is for a sufficiently long period of time. Levitus et al. (2000) made an estimation of the warming of the World Ocean, between the surface and 3000 m for the period between the mid 1950's and mid 1990's, of 2×10^{23} J. In all oceans a substantial change in heat content occurred in the 300 to 1000 m layers; moreover, in the North Atlantic such strong changes also happen at depths greater than 1000 m. Analysis of the surface temperature for 140 years between 1861 and 2000 by Folland et al. (2001) have shown a global surface temperature increase of $0.61\pm0.16^{\circ}$C. Willis et al. (2004) estimated a global, interannual variability in the upper ocean heat content, temperature, and thermosteric expansion by combining the altimetric data with in situ temperature profiles. In the period between 1993–2003 the global heat content in the upper 750 m increased by about 0.92×10^{23} J.

Leadbetter et al. (2007) has shown that in the mid North Atlantic (36° N) cooling of the upper waters and warming of the intermediate waters between 1959 and 1981, were reversed between 1981 and 1985. The changes in the upper 800 m waters were principally due to a vertical displacement of the neutral density surface. In the intermediate waters (below 800 m) water mass changes become more important.

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The important problem of climate dynamics is to understand how the signals are transmitted from the surface to the deep ocean and then distributed throughout the basin (Potter and Lozier, 2004). A number of studies have shown the importance of the northern part of the North Atlantic, because of strong convection (Curry et al., 1998; Dickson et al., 1996, 2002). Potter and Lozier (2004) have shown that the Mediterranean outflow waters are an important contributor to the climatological changes of temperature and salinity at intermediate depths of the mid latitude North Atlantic. They noted that the warming and/or salinification of Mediterranean surface waters are density compensated.

All the estimations of warming and cooling are based either on the observational data, or on the outputs of models. The main problems in answering the third question is the spatial and temporal data density, synchronicity of the data, possible biases between the data from different instruments (Gouretski and Koltermann, 2007), and all the problems of data sampling, including interpolation and objective analysis. The distribution of the observations in the basin has to be dense enough for an adequate representation. The more dynamically active subdomain (e.g. the Gulf Stream area) with high eddy kinetic energy should have much higher density cover than other regions. Because of the seasonal cycle and eddy activity nonsynchronous observations can result in a large error in the estimation of heat content and its variability.

Using the Argo data allows a successful resolution of the problem of synchronisation. A more complicated problem is linked with the density of Argo observations, since it depends not only on the initial position but on the dynamics of the ocean. The most difficult regions are the strongly dynamical subdomains, since the buoys can be moved over a long distance in a short period of time. Despite these problems we are able to use the Argo data to estimate heat/salinity content of the upper 2 km ocean.

Resnyansky et al. (2009) made a statistical analysis of space variability of temperature and salinity data of the Argo profiles in the World Ocean and their subregions between January 2005 and December 2007. They confirm the continuing general warming, however with a pronounced geographical and vertical nonuniformity. The ratio of signal to noise μ is between 1.5 to 5.7. This ratio is reasonably high and much higher than that based on previous XBT data: μ is between 0.5 and 1.5 (White and Bernstein, 1979), μ is about 1 in the upper 400 m of World Ocean (White, 1995), and μ is between 0.5 to 2.9 for different subregions of tropical Pacific (Meyers et al., 1989), but the values of about 1 prevail (Resnyansky et al., 2009).

The main aim of this study is to calculate heat/salinity content in the Northern Atlantic and its variability during the "Argo" project (i.e. since 1999), by comparing these values with climatology and estimating their significance. The data and method is described in Sect. 2, stability of results in Sect. 3, anomaly of heat content in Sect. 4, anomaly of salinity content in Sect. 5, and summary and discussion in Sect. 6.

2 Data and method

The Argo temperature and salinity profiles were used as our data for the calculations of anomaly of heat content (AHC) and anomaly of salinity content (ASC). For the analysis we select the period between January 1999 and December 2008 for the area between 10° N and 70° N. The number of the accepted data strongly depends on the depth. The number of temperature profiles per month at the surface increased from 200–300 in 1999 toward 400 in 2001 and 800 in 2008. There were less than 100 salinity profiles per month available at the surface before 2001, while in 2008 it reached 700–800 per month. The number of profiles reduces with depth by 10–15% at 500 m, and by 25–30% at 1500 m, and decreases further down.

From the official Argo web-site 74 958 vertical profiles of temperature and 59 485 profiles of salinity were obtained. An Argo profile is excluded from the analysis if it belongs to one of three categories:

- It has not passed the quality control provided by Argo data centre

- It belongs to the officially published lists of the floats with uncorrectable pressure bias, particularly data obtained from a SOLO float with FSI CTD (Argo Program

WHOI) or APEX floats with APF8 controller board.

– It has not passed our own quality control

The initial Argo data passed the intensive quality control procedures described in Coatanoan et al. (2005) and Wong et al. (2006). These procedures include automated tests, visual control and objective analyses, applied both daily and weekly. Automated real-time tests verify the following parameters: date, position, speed, global ranges, spikes, density inversions and sensors drifts. The visual quality control performed by operators at the Coriolis Centre includes a comparison of a current profile against neighboring profiles, platform speed, density profile, T/S diagrams, its climatology and associated standard deviation. To detect gross errors and the setting of the quality flags for each profile the results of an objective analysis are taken into account. The Centre uses an objective analysis scheme based on the optimal estimation methods described in Bretherton et al. (1976). Profiles only with the appropriate quality control flag provided by the originators were downloaded and stored in our data set.

Regarding the second category, in February 2007 the Argo community was informed that profiles from Argo buoys deployed by WHOI program (i.e. SOLO floats with FSI CTD) may have pressure offset errors. Updated list of "uncorrecatble" platforms was announced in October 2007 at http://www-argo.ucsd.edu/Acpres_offset2.html.

Another list of suspicious profiles related to the drift in the pressure sensors in several APEX profiles was published in December 2008 at the CSIRO web site: http://www.marine.csiro.au/~cow074/quota/argo_offsets.htm. All "uncorrectable" observations from these types of instruments were removed from the initial data set (9240 SOLO and 747 APEX profiles). That information reduces the data set to 63 497 temperature and 48 630 salinity profiles.

The following procedures were used in our own quality control (third category). The differences between the observed (Argo) values and monthly climatology (Stephens et al., 2002) were calculated by subtracting from the observed value the climatological value which was obtained by interpolation a) temporally to the moment of observation between neighboring months, and b) geographically to the point of observation (surfacing of the float). These differences are called anomalies throughout the paper. Similarly the anomaly of heat/salinity content is the calculated heat/salinity content from which the climatological heat/salinity content is subtracted.

The criterion for eliminating profiles from the data set was 4 standard deviations (SD) from the monthly climatological values. This criterion can be compared with other values used in similar research. In some studies (Levitus et al., 1994; Lozier et al., 1995) a criterion of between 2.3 and 3 SD's has been applied. However, it has been shown (Levitus et al., 2000; Willis et al., 2004) that a larger criterion between 3 and 6 SD gives robust results.

After removing the data of all three categories the total number of temperature and salinity profiles decreases to 59 157 (temperature) and 47 585 (salinity).

The temperature and salinity anomalies fields were calculated with an objective analysis scheme, based on Gandin (1965) and Bretherton et al. (1976). This scheme uses the Gauss-Markov theorem, which gives a linear estimate that is unbiased and is optimal in the least squares sense. Another strong assumption required that the covariance of the data to be Gaussian. The scheme used in this study is similar to Lavender et al. (2005). The correlation length scales are prescribed constant values and in this study we applied L=350 km in both northward and eastward directions. This is more than twice the value used by Lavender et al. (2005), but it is necessary because of the low spatial resolution of the Argo data. To test the influence of this constraint on our results we have compared a range between 2 and 3 SD with a range of 5 to 6 SD. It has been found that with a range 2 and 3 SD the signals are smoother and the oscillations are of lower amplitude, than with the larger range of 5 and 6 SD. However, the overall shape of the signal shows good correspondence between the two cases. The main results, for example the sign of the anomaly and the trend in warming or cooling, remain similar if the criterion of the quality control is between 2 and 6 SD, and therefore the results are robust to changes in this constraint.

To calculate the anomaly of heat/salinity content, we use a monthly climatology

WOA2001 (Stephens et al., 2002). This climatology is based on historical hydrographical data from the end of the 1890's up to 2001. The majority of this data comes from the last half of the 20th century, and therefore is most representative of this latter period. The standard deviation has been calculated by using a total of 120 samples, i.e. 12 months multiplied by 10 years. AHC and ASC were calculated for $10^{\circ}\times10^{\circ}$ in latitude and longitude boxes and for all layers between the surface and 2000 m with the vertical increment of 25 m. Additional details about our quality control and objective analysis can be found in Ivchenko et al. (2006, 2007, 2008).

3 Stability of results

The Argo buoys are Lagrangian variables with variable positions and density of population. The stability of the results for heat and salinity content depend on the number and the density of the profiles. By stability we mean that the results should not be sensitive to a small variation in the number or the density of the profiles. This problem is especially complicated since the position of the profile strongly depends on the stochastic dynamics of the ocean currents with a high range of horizontal scales between micro-, meso- to large scales. Being positioned in a particular place a buoy can be driven by flow to a place far away from its initial position; moreover two buoys initially close to each other can be separated by a large distance after some time.

One possible way for the estimation of the stability of the obtained results is to separate the whole set of profiles into several subsets and calculate the values of AHC and ASC for each such subset. One can suppose, that the general results are stable if the corresponding values are close to each other. In this study we estimate AHC and ASC values for the whole set (experiment W), half set (H) and quarter set of the data (Q). In the experiments H and Q half and 3/4 quarter of the data were removed almost randomly from the whole set. In Fig. 1 one can see the profiles of the logarithm of the absolute value of AHC averaged over the whole domain for these 3 experiments. There is a definite similarity in their profiles. The absolute values for AHC for the whole

2000 m column are: -16.70×10^{20} J, -15.02×10^{20} J and -4.67×10^{20} J for the experiments W, H, Q, respectively. In all three logarithmic profiles there are maximums in the upper 1000 m, corresponding to the highest negative values of the AHC, especially at the depth of about 600 m, and a minimums of the logarithms of the AHC occur at the depth of 1400 m. Profiles are close to each other, especially the W and H experiments in the upper 1200 m. The profiles of the logarithm of the ASC also seem to be similar, especially in the upper 500 m (see Fig. 2). The values of the ASC at the depth in between the surface and 2000 m are: 24.10×10^{13} kg, 25.62×10^{13} kg, and 23.05×10^{13} kg, respectively.

Figures 3, 4 show profiles of the correlations between AHC/ASC for the experiments W and either H (i.e. W-H), or Q (i.e. W-Q). Both AHC and ASC correlations are reasonably high, especially in the upper ocean (more than 0.9 and 0.8, respectively in the W-H experiment). In the mid depth (i.e. between 500 and 1600 m) correlations are weaker. In the lower layer (1600–2000 m) correlations are increased because of more homogeneous distributions of temperature and salinity. All these correlations of AHC and ASC (i.e. on Figs. 3, 4) are statistically significant at the 95% level of significance.

4 Anomaly of heat content

The AHC demonstrates a positive trend during the last 10 years (see Fig. 5). The linear trend is $(126.43\pm18.52)\times10^{20}$ J. Most of the time the AHC was negative, i.e. the ocean was colder than the Levitus climatology. It was shown, that the strongest contribution to the total AHC in the upper 1500 m comes from the layers between 350 m and 900 m (Ivchenko et al., 2006).

The negative AHC for the top 2000 m occurs in the southern and mid North Atlantic (between 10° N and 50° N) and positive AHC occurs in the northern North Atlantic (between 50° N and 70° N), where the positive definite (warming) trend can be seen (see Fig. 6, Table 1). However in the other four zonal belts the trend is much smaller (Table 1). One can see a strong interannual variability with periods of between 1 to 3 years (Figs. 5, 6). The amplitude of the variability can be high, i.e. substantially deviate from the mean value. Despite this variability 10-year change in the heat content is significant at the 95% level for each zonal belt.

In the top 100 m for the whole North Atlantic there is a strong seasonal variability, in spite that this is an anomaly, not the absolute value of heat content (Fig. 7). This can be explained by a very strong seasonal cycle of temperature. If the climatological seasonal cycle differs systematically from the Argo field, as happens in our case, the anomaly can deviate from zero. For example, let us suppose that climatology has a seasonal cycle of temperature (heat content) in the upper ocean equal $A_1 \cdot \sin \varpi t$, where A_1 is the amplitude, ϖ is an annual frequency, and t is time. Let also suppose that the seasonal cycle from observational platform has the same frequency ϖ, but different amplitude A_2, i.e. $A_2 \cdot \sin \varpi t$. The total observational signal is $B+A_2 \cdot \sin \varpi t$. The anomaly is $B+A_2 \cdot \sin \varpi t$- $A_1 \cdot \sin \varpi t = B + (A_2 - A_1) \cdot \sin \varpi t$. If $A_2 - A_1$ is large enough compared to B the major seasonal cycle is visible. In our case $A_2 - A_1$ is about 15% of the climatology signal, which is high, because the seasonal cycle in the North Atlantic is a large signal. Similar profound seasonal variability of temperature anomalies in upper layers were found by Resnyansky et al. (2009). The seasonal cycle of the AHC is warmer in winter and colder in summer. The trend of the AHC is positive in the upper 100 m.

In the layer between 100 and 500 m there are some seasonal fluctuations, but not so regular as in the upper 100 m (Fig. 7). In the first four years the AHC was mainly negative and in the following six years the AHC was mainly positive. In the layer between 500 and 1000 m the AHC is negative. In the layer between 1000 and 2000 m the AHC is mainly negative from beginning to the end of 2005.

For the whole North Atlantic in the layers between 0–100m, 100–500 m, 500–1000 m and 1000–2000 m there are positive trends in heat content (Fig. 7, Table 2). The main contribution to the warming is the upper 1000 m. All the values of trend are significant at the 95% level.

The dynamics in the western and eastern North Atlantic separated by Mid Atlantic

Ridge is quite different, especially because of the influence of the Gulf Stream in the western part. For this reason an additional analysis was made for the western and eastern 10° boxes, separated by the Mid Atlantic Ridge. In Figs. 8, 9 one can see the vertical profiles for the west and east subregions for 10° belts between 10° N–20° N to 60° N–70° N. In the western parts of the southern and mid North Atlantic (up to 50° N) there is a profound negative AHC in the upper 1000m. In the southern belts (between 10° N–30° N) the negative values correspond to more shallow depths (less than 200 m). In the mid North Atlantic (between 30° N and 50° N) the strong negative minima occur at depth between 500–800 m. The northern belts of North Atlantic (50° N–70° N), in contrast with the southern and mid North Atlantic, have large positive values of AHC in the upper 500 m. Over much of the profile depth the standard deviation shows the reliability of the results (see Fig. 8). However, in some places, like between 30° N–40° N the SD is high and values of AHC are insignificant. In the deeper layers (more than 1000 m) the amplitude of the AHC is much smaller than in the layer above.

In the eastern subregions there are also mainly negative values of the AHC in the southern and mid North Atlantic (between 10° N and 40° N) (see Fig. 9). However the belt between 40° N and 50° N, as well as the northern North Atlantic (50° N–70° N) demonstrate positive AHC. The negative values of the AHC in the mid North Atlantic are not so large as in the western subregions.

5 Anomaly of salinity content

The ASC demonstrates a positive trend during the last 10 years for the whole 2000 m column (see Fig. 10).

In the first 3 years there are fewer good salinity values and therefore some caution has born in mind. However the linear trend is statistically significant at the 95% level, and is $(47.07 \pm 6.90) \times 10^{13}$ kg.

In the interior of the ocean away from the surface, bottom and western boundary layers, motion is mostly along isopycnals. As a result one can expect partial "com-

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pensation" in the temperature-salinity space. I.e. an increase in temperature is related to an increase salinity to maintain a constant density. Similarly the increase of heat content should relate to an increase in salinity content. There are strong correlations between AHC and ASC between 200 m and 2000 m in all western 10° belts. In the eastern belts such correlation is also strong for the southern belts, between 10° N and 30° N and in the uppermost north eastern belt between 60° N and 70° N. In between 30° N and 60° N the correlations are quite high, but statistically insignificant at the 95% level.

The anomaly of salinity content of the top 2000 m is mainly positive in most of the 10° belts (see Fig. 11). The positive trend is obvious in the northern belt between 50° N and 70° N (Table 1). The ASC in the most northern and southern belts should be used with caution, due to the lack of observational data at the beginning of the period.

The ASC in the top 100 m and in between 100 m and 500 m for the whole North Atlantic is positive with some seasonal variability (see Fig. 12). There is an obvious positive trend through the period of 10 years (i.e. salination) (Table 2).

In the layer between 500 and 1000 m the ASC demonstrates strong fluctuation between years. The nature of such variability is not obvious, and probably it reflects a combination of different processes happening in subregions which have to be studied on a regional basis. The trend is positive and statistically significant at 95% level, but it is almost an order of magnitude smaller than in the layer 100–500 m.

In the layer between 1000 and 2000 m the ASC is mainly negative with strong interannual fluctuations. The trend is negative (several times smaller than that in the top 1000 m), but also statistically significant.

In Figs. 13–14 there are vertical profiles of the ASC for the 10° belts. In many parts it is difficult to conclude about the sign of the ASC, because the error bar (i.e. one standard deviation) overlaps them. However the positive value is significant in the uppermost 150m in the western subregions, in the south and mid North Atlantic. In the very dynamical western belt between 30° N and 40° N the values for ASC are not reliable below a depth of 150 m.

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In the eastern parts of the 10° belts the variability is not as strong as in the western parts.

6 Summary and discussion

The AHC and ASC demonstrate positive trends in the last 10 years in the upper 2000 m of the North Atlantic. The decisive contribution to the trend comes from the northern part of the basin between 50° N and 70° N. In the southern and central parts of the North Atlantic one can see interannual variability. The strongest variability occurs in the central North Atlantic. In the southern and mid North Atlantic the trend in AHC is much smaller than that in the northern subdomain. Moreover, in the southern parts between 10° N and 30° N the linear trends of ASC show freshening. However, the magnitude of this decrease is much smaller than that of increase of salinity content in the north.

The average values of the AHC and ASC for the whole period of time for the upper 2000 m are negative for AHC and positive for ASC. The negative values of the AHC is unexpected, because in a number of studies a warming of the ocean was observed. The most reliable explanation for this is the use of different instruments (CTD, XBT, and MBT) result in a possible bias of the climatology (Gouretski and Koltermann, 2007). Gouretski and Koltermann (2007) have shown that the XBT data has a positive bias in the temperature field when compared to CTD data. Since XBT data contributed substantially to the data set in the North Atlantic from 1970 this bias may have a significant influence on the climatological temperature and therefore result in a negative AHC. We must remember, that the AHC represents a difference between observed Argo and climatological heat content. Note, that the negative sign of the AHC occurs not everywhere, but only in the southern and central regions whilst it is positive in the northern regions. The calculated trends are almost free from any bias in the climatology. Wijffels et al. (2008) show that heat content has much weaker decadal variability in the 1970s and higher rate of change for 1961 to 2003, if one uses the data corrected for the XBT bias.

Seasonal variability of the AHC in the upper 100 m is much more clear than the variability of the ASC. There is a positive trend of the AHC in the basin averaged upper ocean (0–100 m, 100–500 m, 500–1000 m and 1000–2000 m). The ASC demonstrates a positive trend in the upper 100 m, 100–500 m and 500–1000 m layers, but negative trend between 1000–2000 m.

The important question for any interpretation of observations in a basin-wide domain is: is the number of observations and their density population good enough for the estimations, based on such data? This question is especially relevant for the data with moving positions, like Argo buoys.

We have to understand what kind of estimation we are looking for. On a local scale in some particular places there are only few (if ever) observations at certain times and according to our methods the result would be close to the climatology. However, for the basin-averaged values the Argo data provides a stable base for the estimation of the AHC, and to some extent ASC. Removing half of the data leads to values not too far from the total set. In most parts of the upper 2000 m the time averaged AHC are statistically significant, as well as the time dependent series of the depth averaged AHC. There are clear signs of the negative AHC in the upper 1000 m in most parts of the southern and mid North Atlantic. There is also evidence for a positive sign of the AHC in the northern part of the North Atlantic.

Our calculations for the AHC and ASC are based on 10° boxes. Using finer spatial resolution (for example 1°) temperature and salinity fields demonstrate much more patchiness (see Ivchenko et al., 2007, 2008).

We should add the caveat about the salinity data, particularly in the southernmost and northernmost areas, because the number of salinity data in the first three years (i.e. 1999–2001) is rather small. The time-averaged AHC and ASC as a function of depth do not provide statistically significant values for estimation in many parts of the North Atlantic. The 10 years of observation does not produce a clear view about variability of these (i.e. vertical distribution of time averaged) fields, because of decadal ocean variability.

The coming new data for temperature and especially salinity will provide better estimations and increase the significance of the estimations.

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OSD

6, 1971–2003, 2009

Variability of heat and salinity content in the North Atlantic

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Table 1. Change in heat and salinity contents for the period of 1999–2009.

	Change in heat content in 10^{20} J	Change in salinity content in 10^{13} kg
10° N–20° N	3.00±2.68	−1.54±0.70
20° N–30° N	11.31±3.08	−3.59±1.70
30° N–40° N	11.93±7.30	9.84±2.92
40° N–50° N	16.69±10.79	7.83±2.86
50° N–60° N	42.57±8.06	13.49±2.24
60° N–70° N	40.62±6.52	19.87±2.27

Table 2. Change in heat and salinity contents for the period of 1999–2009.

	Change in heat content in 10^{20} J	Change in salinity content in 10^{13} kg
0–100 m	16.79±7.77	22.94±2.39
100–500 m	49.03±9.32	27.39±3.27
500–1000 m	41.70±4.60	3.43±2.15
1000–2000 m	18.58±6.08	−6.89±3.14

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6, 1971–2003, 2009

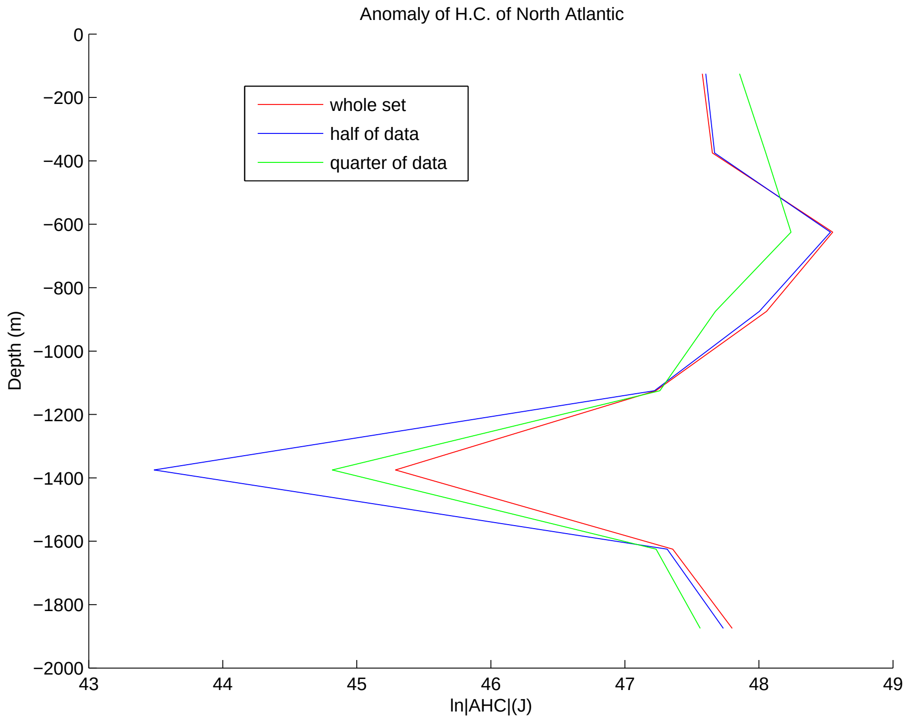

Fig. 1. Anomaly of heat content of the North Atlantic for the upper 2000 m. The red, blue and green curves represent the value of the whole set, 50% and 25%, respectively. The vertical discretisation is 250 m. The horizontal axes is the natural logarithm of the absolute value of the AHC in Joules.

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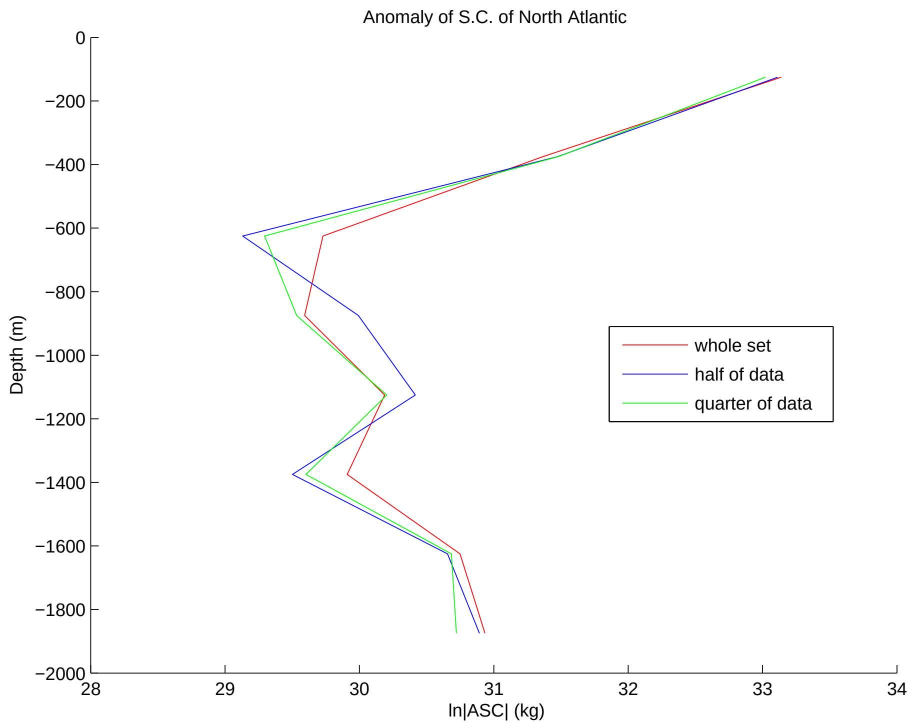

Fig. 2. Anomaly of salinity content of the North Atlantic for the upper 2000 m. The red, blue and green curves represent the value of the whole set, 50% and 25%, respectively. The vertical discretisation is 250 m. The horizontal axes is the natural logarithm of the absolute value of the ASC in kg.

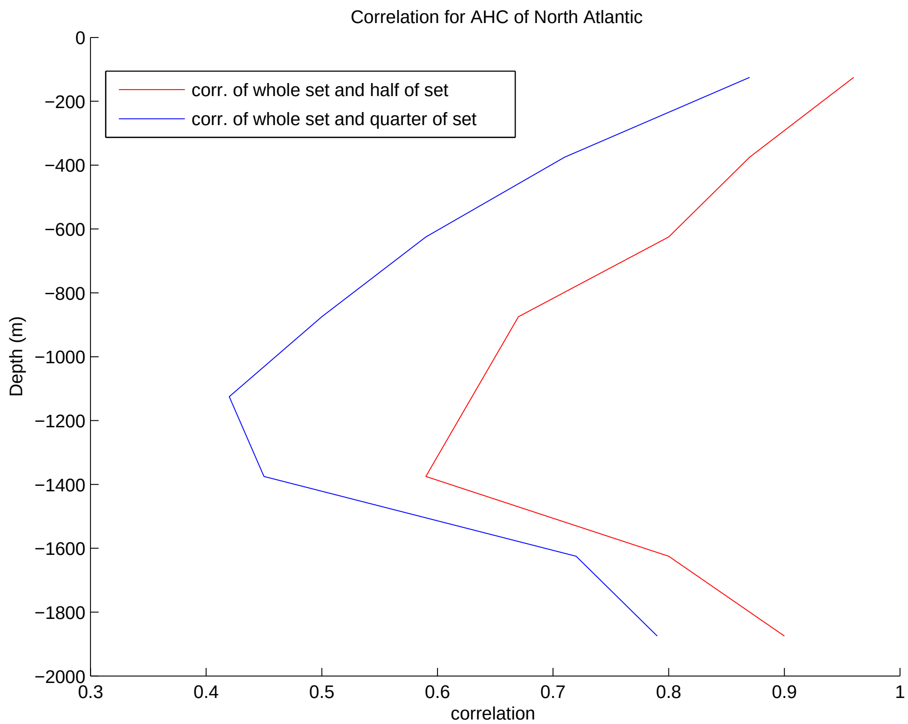

Fig. 3. Correlations between AHC for the whole set and 50% of data (red curve) and between whole set and 25% of data (blue curve). AHC is the averaged value of the North Atlantic, the vertical discretisation is 250 m.

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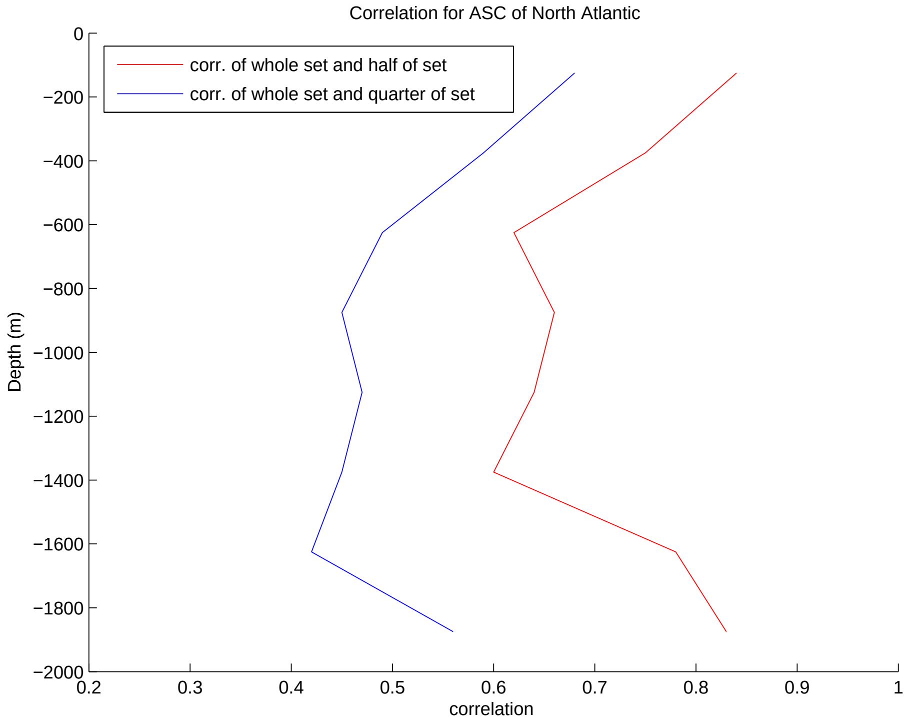

Fig. 4. Correlations between ASC for the whole set and 50% of data (red curve) and between whole set and 25% of data (blue curve). AHC is the averaged value of the North Atlantic, the vertical discretisation is 250 m.

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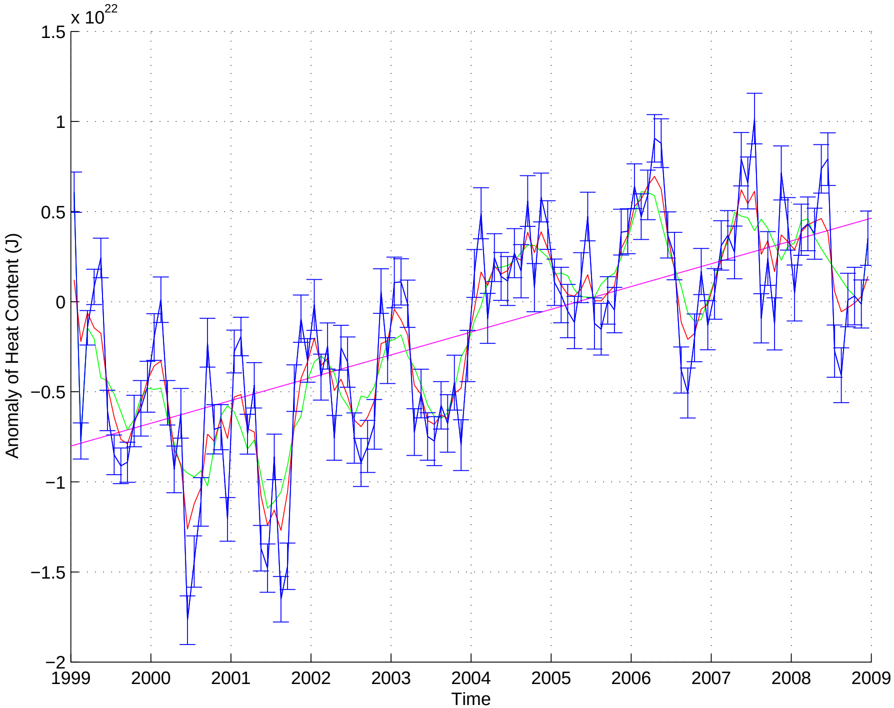

Fig. 5. AHC for the layer between 0 and 2000 m. The vertical bars represent one standard deviation. Blue is AHC, green is a moving averaged AHC and red is the AHC filtered with a 7 point low pass filter. The magenta represents a linear regression.

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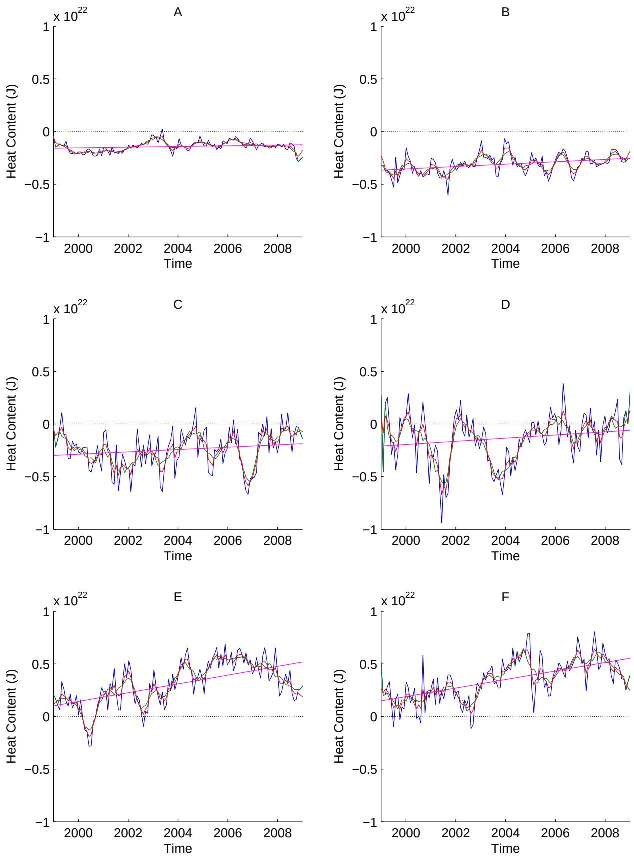

Fig. 6. Zonally integrated anomaly of heat content of the upper 2000 m for the 10° belts: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N.

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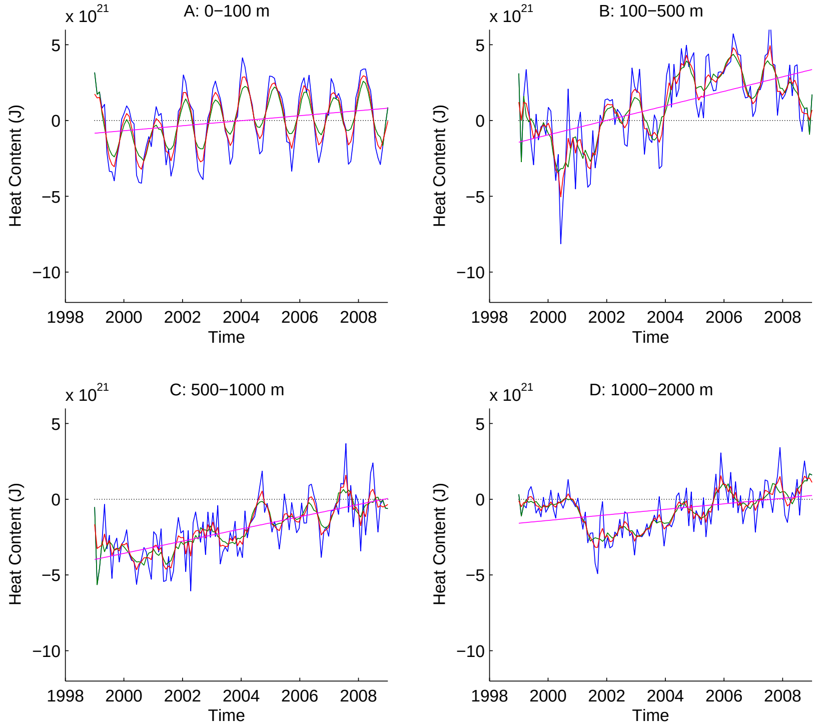

Fig. 7. AHC time series for the North Atlantic in selected layers: **(A)** 0–100 m; **(B)** 100–500 m; **(C)** 500–1000 m; **(D)** 1000–2000 m.

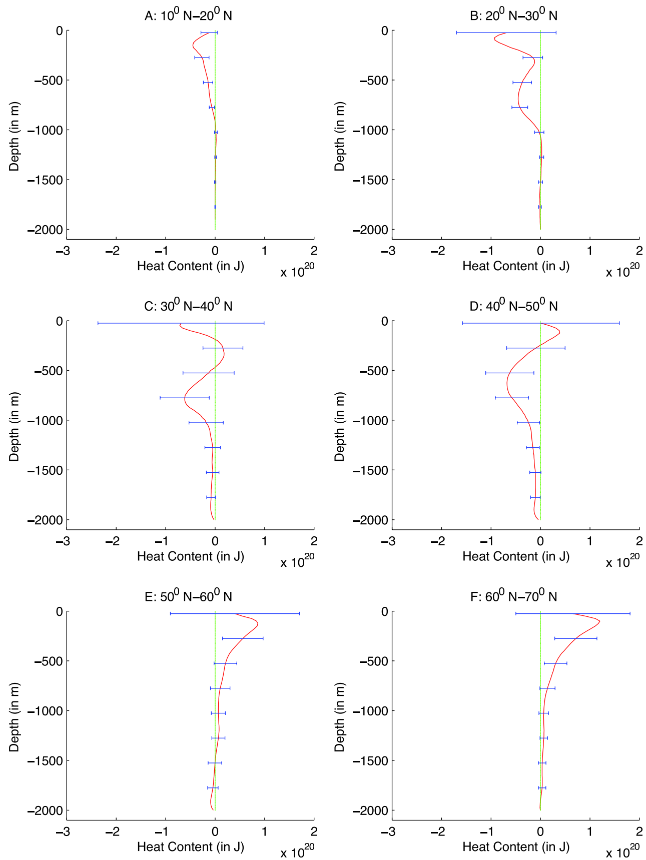

Fig. 8. Vertical distribution of the time averaged AHC of the upper 2000 m for the 10° belts of the western part of ocean: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N; the horizontal bars represent one standard deviation.

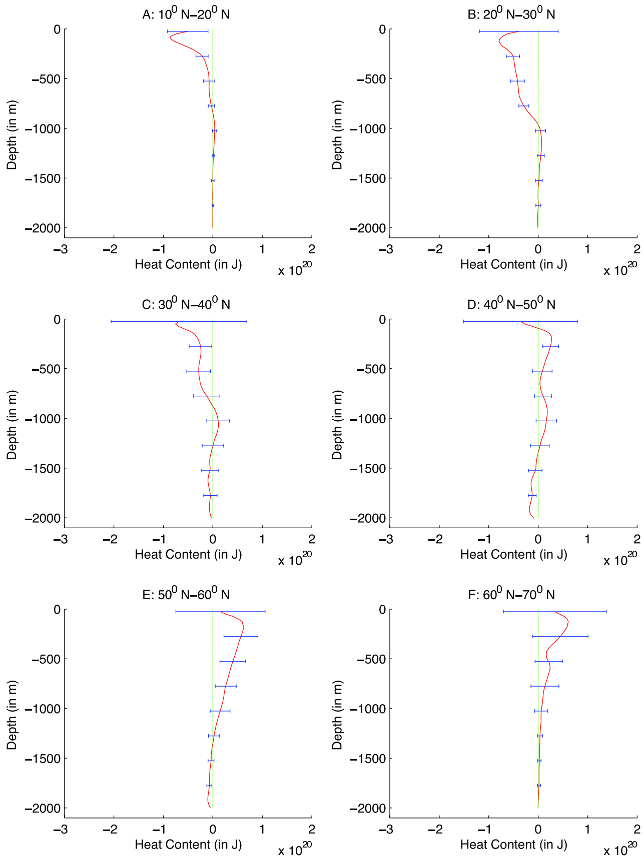

Fig. 9. Vertical distribution of the time averaged AHC of the upper 2000 m for the 10° belts of the eastern part of ocean: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N; the horizontal bars represent one standard deviation.

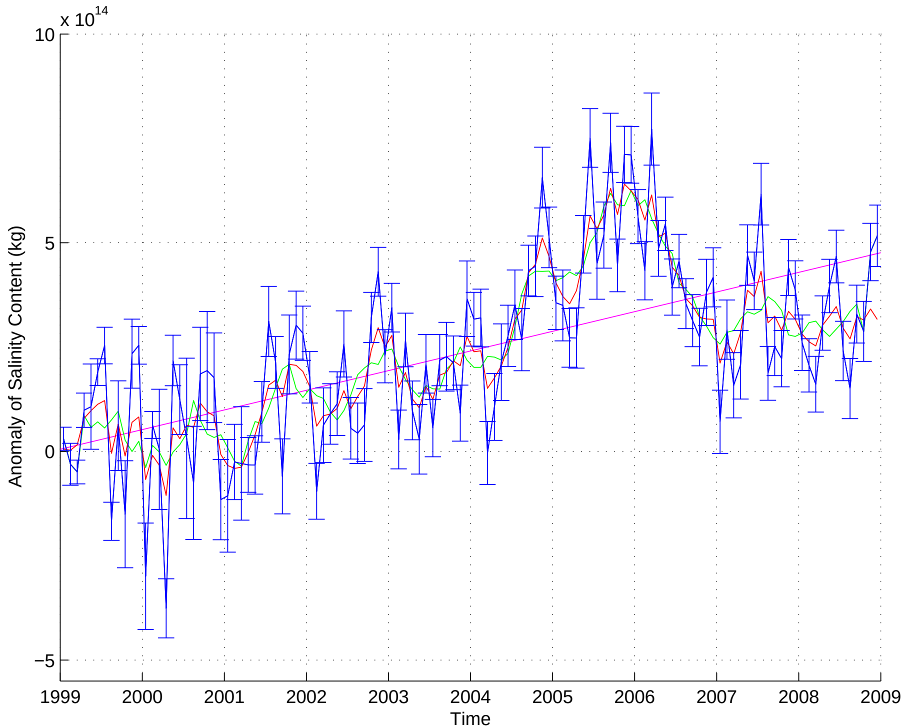

Fig. 10. ASC for the layer between 0 and 2000 m. The vertical bars represent one standard deviation. Blue is ASC, green is a moving averaged ASC and red is the ASC filtered with a 7 point low pass filter. The magenta represents a linear regression.

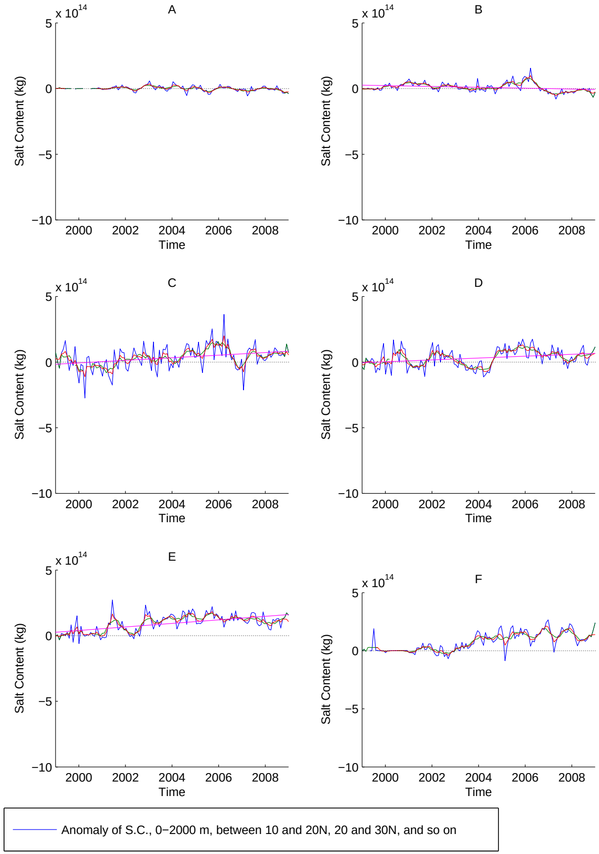

Fig. 11. Zonally integrated anomaly of salinity content of the upper 2000 m for the 10° belts: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N.

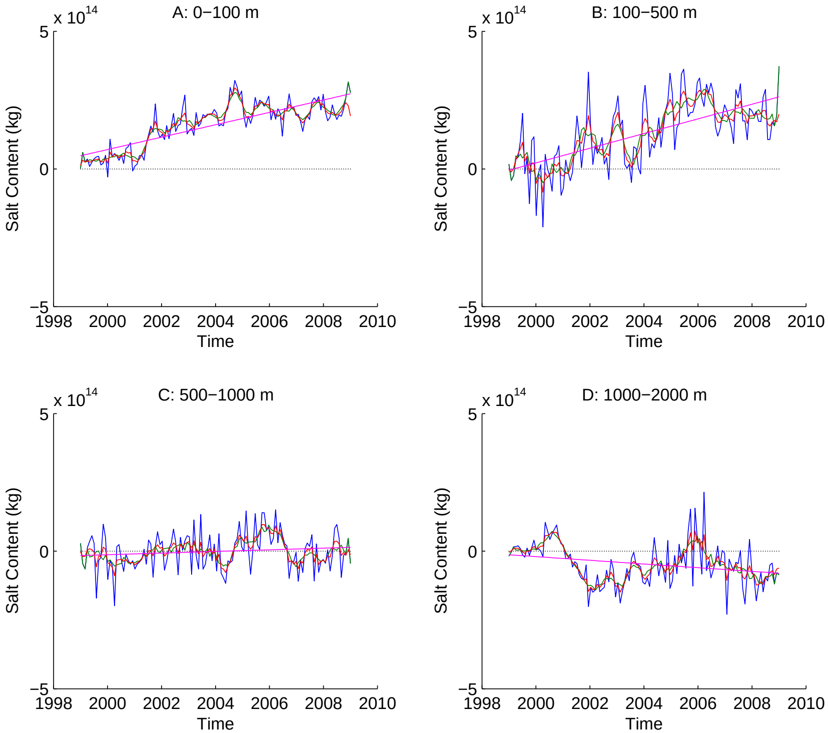

Fig. 12. ASC time series for the North Atlantic in selected layers: **(A)** 0–100 m; **(B)** 100–500 m; **(C)** 500–1000 m; **(D)** 1000–2000 m.

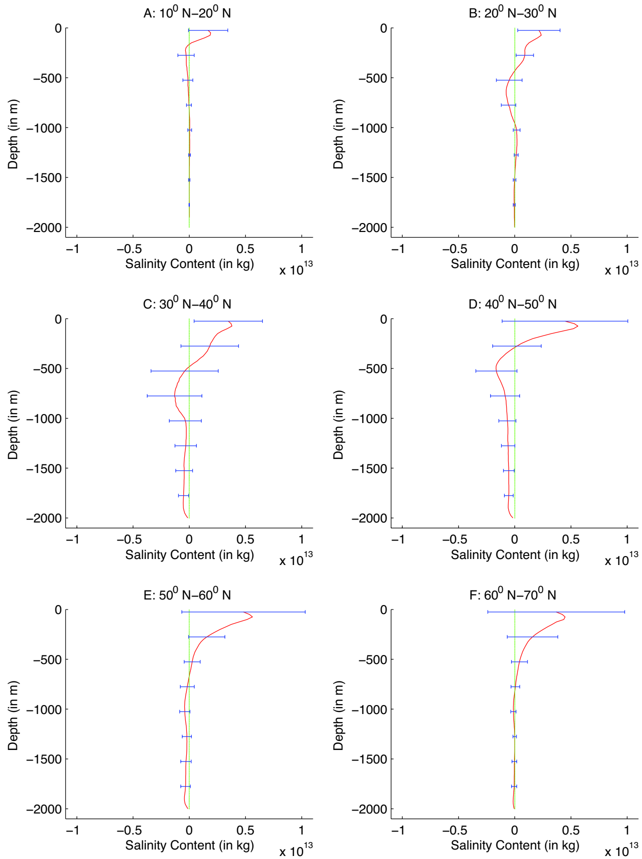

Fig. 13. Vertical distribution of the time averaged ASC of the upper 2000 m for the 10° belts of the western part of ocean: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N; the horizontal bars represent one standard deviation.

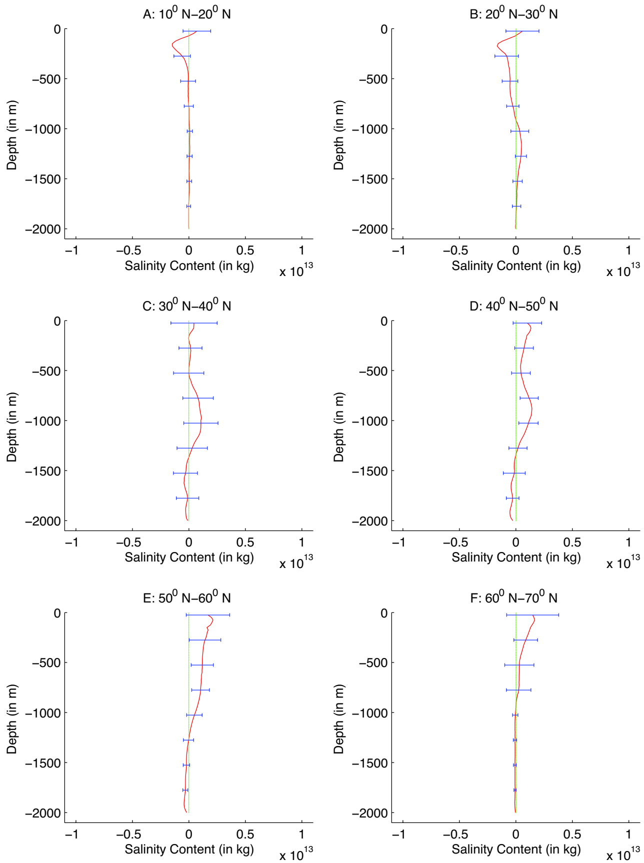

Fig. 14. Vertical distribution of the time averaged ASC of the upper 2000 m for the 10° belts of the eastern part of ocean: **(A)** between 10° N and 20° N; **(B)** between 20° N and 30° N; **(C)** between 30° N and 40° N; **(D)** between 40° N and 50° N; **(E)** between 50° N and 60° N; **(F)** between 60° N and 70° N; the horizontal bars represent one standard deviation.