Ocean Sci. Discuss., 10, 2363–2398, 2013
www.ocean-sci-discuss.net/10/2363/2013/
doi:10.5194/osd-10-2363-2013

Ocean Science
Discussions
Open Access

Comparison of N. Atlantic heat storage estimates during the Argo period (1999–2010)

N. C. Wells[1], **M. Couldrey**[1], **and V. O. Ivchenko**[2]

[1]University of Southampton, National Oceanography Centre, Southampton, UK
[2]Alfred-Wegener Institute, Bremerhaven, Germany

Received: 16 September 2013 – Accepted: 1 November 2013 – Published: 6 December 2013

Correspondence to: N. C. Wells (ncw@noc.soton.ac.uk) and M. Couldrey (couldrey.matthew@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Ocean heat storage is an essential component of the climate system and there is considerable interest in its accurate evaluation. There are a number of heat storage products produced by many different groups. These products are derived from Argo as well as other platforms, for example XBT and CTD, in the last decade. Here we compare two heat storage estimates for the North Atlantic 0–2000 m from 10° to 70° N. One derived solely from Argo data whilst the other is derived from Argo and other platforms. It is found that there is a positive trend in heat storage over the period 1999–2010. This trend is influenced by a strong air–sea interaction event in 2009–2010, and this reduces the upward trend 1999–2008 identified previously. Both data sets are consistent with each other for the layer 0–1000 m on a timescale of beyond 1 yr. There are significant differences at sub-annual time scales and in the layer 1000–2000 m.

1 Introduction

The heat content of the global ocean has received close attention over the last two decades for its detection of the anthropogenic radiative warming that the global ocean has been receiving since the 19th Century (Levitus et al., 2005, 2009). The heat and salt content in the North Atlantic Ocean has been investigated using pre-Argo data sets (Dickson et al., 1996, 2002; Lozier et al., 2008). These data sets have shown decadal variability in the North Atlantic Ocean in both temperature and salinity from 1950.

After 1998 the Argo profiling floats have provided consistent and accurate set of observations over the global upper ocean. The Argo programme has relied on floats extending to a maximum depth of 2000 m. The autonomous floats have been placed in the ocean by an international community of scientists. They are free floating and the profiles they have taken are of variable depth and frequency set by individual scientists. The international Argo group has endeavoured to set a 10 day repeat time and a spacing of 150 km × 150 km as a standard as well as advising on placing floats in

OSD
10, 2363–2398, 2013

poorly sampled regions. The data set is therefore heterogeneous in time and space which makes measurement of heat content over a large spatial domain difficult. In particular the floats will only be retained in strong western boundary currents such as the Gulf Stream for a short period of time of a few weeks and therefore these regions are sparsely sampled. Secondly floats have a mean life time of 3.7 yr and are replaced continuously to maintain an array of over 3000 floats. The floats are generally restricted to a depth of 1000 m or deeper and therefore exclude the ocean margin. Finally the floats have a nominal resolution of 150 km × 150 km and therefore they cannot resolve mesoscale eddies without additional information from other measurements for example the satellite altimeter and XBT profiles.

This paper compares two heat content data sets in the upper N. Atlantic Ocean (0–2000 m) from 1999 to 2010. The first data set is known as TAMARA. In particular the 12 yr trends in heat content in the upper North Atlantic since 1999 are compared with previous estimates from Ivchenko et al. (2010, 2006). These estimates of heat content are also compared with a data set from the UKMetOffice, over this 12 yr period and over a similar depth, and is known as EN3.

The question which will be addressed are how good are these estimates of heat storage and in particular what are the spatial and temporal scales that can be adequately resolved?

Finally on what time and spatial scales is there agreement between the two data sets (TAMARA and EN3)?

Ivchenko et al. (2010) used objectively-analysed Argo profiling float data to quantify trends in the heat content of the North Atlantic from January 1999 to December 2008. Spatially, the area of study was constrained to the upper 2000 m between 10 and 70° N and 90 to 0° E. The TAMARA data set has been extended to December 2010 using the same methodology as that described by Ivchenko et al. (2010). The Argo dataset is unique with regard to its coverage, and as such it is difficult to validate. However, the UKMetOffice EN3 data set, is a quality-controlled dataset of objectively analysed ocean temperature and salinity profiles (Ingleby and Huddleston, 2007, and

OSD
10, 2363–2398, 2013

http://www.metoffice.gov.uk/hadobs/en3/). This dataset employs a wide range of data, most importantly for the purposes of this paper, Argo, but also the World Ocean Atlas 2005 (WOA05), Global Temperature–Salinity Profile Programme (GTSPP) and Arctic Synoptic Basin-wide Observation (ASBO) at NOCS. Therefore, this dataset employs measurements from other platforms than Argo. This work uses this EN3 dataset to calculate trends of heat content anomaly (HCA), to provide a comparison for the values found by Ivchenko et al. (2010). The methods used here were intended to closely emulate those of Ivchenko et al. (2010) to provide the most robust comparison as well as extend the comparison from 2008 to December 2010. This study therefore provides information on the reliability of these estimates of heat content which are needed to constrain the heat budget of the N. Atlantic Ocean.

The data sets are described in Sect. 2 and the results of the comparison in Sect. 3, followed by a discussion and conclusions in Sect. 4.

2 Methods and data sets

The TAMARA Heat Content Anomalies were calculated for the 10° × 10° boxes for four depth layers (0–100 m, 100–500 m, 500–1000 m and 1000–2000 m) as in Ivchenko et al. (2010) for each month. The EN3 data set is composed of actual monthly heat contents and not anomalies, and therefore to obtain the corresponding anomalies for EN3 we subtracted the same monthly climatology as used in TAMARA (WOA01, Stephens et al., 2002) from the actual monthly values. The same depth levels were chosen for EN3 as TAMARA.

The construction of the TAMARA Heat Content Anomaly data set is based solely on Argo from 0 to 2000 m depth. For the analysis we select the period between January 1999 and December 2010 for the area between 10° N and 70° N at a horizontal resolution of 10° latitude by 10° longitude. This resolution was used because of the spatial coverage of the Argo floats in the early part of Argo period from 1999–2001 when there were fewer than 400 accepted profiles per month over the region 10–70° N.

OSD
10, 2363–2398, 2013

This has subsequently increased from 2008 to more than 800 accepted profiles per month.

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. The number of profiles reduces with depth by 10–15 % at 500 m, and by 25–30 % at 1500 m.

To accept the Argo profiles we used our own quality control scheme on the delayed mode profiles from the Coriolis data centre in France. This is discussed in detail by Ivchenko et al. (2006, 2010). To calculate the heat content anomaly, we use a monthly climatology WOA2001 (Stephens et al., 2002). This climatology is based on historical

hydrographic data from the end of the 1890's up to 2001. The majority of these data comes from the last half of the 20th century, and therefore is most representative of this latter period. This climatology is one of a number of ocean climatologies produced in the last decade and it has biases associated with it. In particular there is a bias caused by XBT errors and this is discussed by Willis et al. (2009). Our reason for using this climatology is that it does not incorporate Argo data, and therefore it is an independent climatology. The estimates of HCA were obtained by the following method. The WOA2001 at a resolution of 1° latitude by 1° longitude was time interpolated to the time of the float observation between neighbouring months. It was then horizontally interpolated to the position of the float and the anomaly was obtained. The anomalies were objectively interpolated to the centre of each 10° latitude by 10° longitude box. The anomalies were then averaged over the 10° latitude by 10° longitude box for each month. The criterion for eliminating the float profiles from the data set was 4 standard deviations from the monthly climatology.

OSD
10, 2363–2398, 2013

3 Results

3.1 HCA in EN3 and TAMARA

The comparison of the Heat Content Anomalies between EN3 and TAMARA showed that the EN3 anomalies here are higher than those of TAMARA in the upper layer 0–1000 m (Fig. 1). This offset is associated with the two different climatologies used. TAMARA used WOA 2001 whilst EN3 used WOA 2005. The EN3 data set consists of absolute values of monthly heat content whilst TAMARA has anomalies from the monthly climatology. For comparison purposes it was decided to calculate the EN3 anomalies with respect to WOA 2001 rather than WOA 2005. For these reasons we will focus here on the variations of these anomalies rather than on their absolute values.

The analysis of the results is done in the following way. The whole domain is considered first from 10–70° N for four depth layers: surface layer from 0–100 m, upper thermocline from 100–500 m, lower thermocline from 500–1000 m and deep layer from 1000–2000 m. These are combined into 0–1000 m and 0–2000 m heat content for the 12 yr period.

The TAMARA data set of Ivchenko et al. (2010) is extended by two extra years up to December 2010. The inclusion of another two years affects the trends of both datasets significantly, generally acting to reduce magnitudes of the trends. The trends for the two periods are shown in Tables 1 to 5 and Figs. 3 and 4.

From 2008 until the end of 2010, North Atlantic HCA decreased sufficiently to observably reduce the overall trend since 1999, shown in Figs. 1 and 2. This shows the importance of the interannual variability of North Atlantic HCA, and the sensitivity of the trend to the length of the time series.

Upon the inclusion of the years 2009 and 2010, basin-wide trends in the upper three layers of EN3 (0–100 m, 100–500 m and 500–1000 m) are no longer significant. The uncertainties become larger, relative to the trends themselves. In the TAMARA data, this is only seen for the 0–100 m layer, and the other trends remain significant at the

OSD
10, 2363–2398, 2013

95 % level. A large positive trend in the 1000–2000 m layer is apparent for EN3 which is not seen in TAMARA and this will be discussed below.

For the TAMARA data sets (Table 1) there are significant (at 95 % level) positive trends in all layers, except the surface layer. For EN3 only the 1000–2000 m and the combined data set 0–2000 m show a positive significant trend. The variability in EN3 is much greater than in TAMARA therefore the trends in EN3 are not significant at this level. The trends in both data sets for all depth layers are always positive. This agrees with previous TAMARA analyses for the period 1999–2008 (Ivchenko et al., 2010).

However, the layer 1000–2000 m in EN3 shows a very large upward trend when compared with TAMARA. There are number of possibilities:

1. different analysis methods
2. different instruments used
3. the number and the spatial and temporality of the observations changed over the 12 yr period.

Of these Argo floats about 85 % obtained profiles down to 500 m depth and at least 70 % obtained profiles down to 1500 m depth. Therefore the early part of the Argo period may not have been sufficient in time and space to obtain good heat storage estimates in the layer 1000–2000 m at the 10° × 10° resolution. This will be analysed in Sect. 3.4.

For the 1999–2010 time series, zonal trends, for each 10° latitude belt, were also calculated for both datasets up to December 2010, and shown in Table 2 and Fig. 5. The positive trends occur in the region 40–70° N in both data sets with the strongest HCA trend in the 50–60° N band. The TAMARA data shows consistently smaller trends than EN3 and smaller standard deviations than EN3.

Further south 20–40° N there are significant negative trends in EN3, whilst TAMARA shows a significant positive trend 20–30° N. At the southernmost latitude belt (10–20° N band) neither trends are significant.

OSD
10, 2363–2398, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

To further investigate the very strong trend in EN3 HCA between 1000–2000 m, the question arises whether this trend was evenly distributed across the North Atlantic, or confined to particular zonal bands. Table 3 and Fig. 6 illustrate the zonal trends in HCA for the layer between 1000–2000 m. The trends in EN3 for the northernmost three zonal bands 40–70° N are very much larger than the same latitudes derived from the TAMARA dataset and they are all positive trends.

The region 10–30° N show smaller positive trends in both data sets than at higher latitudes (> 40° N) though they are both significant. The region 30–40° N has both negative trends but only TAMARA is significant.

3.2 Comparison of trends 1999–2008 with trends 1999–2010

The large air–sea interaction event in 2009 perturbed the N. Atlantic circulation in the sub-tropical latitudes (Taws et al., 2011). From the commencement of the RAPID project in 2004 it was the largest measured change in the MOC with a reduction of the circulation by 30 % at 26° N during 2009 and a consequent reduction in northward heat transport by a similar amount (McCarthy et al., 2012; Bryden et al., 2013). The influence of this 2009 event on the trends is analysed in Sect. 3.5.

The trend in heat content for the whole domain (10–70° N 0–2000 m) showed a reduction in the positive trend from $10.44 \pm 3.16 \times 10^{21}$ for 1999–2008 to $5.56 \pm 2.52 \times 10^{21}$ J for 1999–2010 in TAMARA and $20.22 \pm 6.93 \times 10^{21}$ to $11.60 \pm 5.25 \times 10^{21}$ J in EN3 for similar periods. This is equivalent to a reduction in heat content of 53 % and 57 % respectively. Despite this large cooling event in 2009 the upward trend in heat content over the period 1999–2010 is above the 95 % significance level in both data sets.

Examination of the contributions of particular layers and latitude bands to the trends reveals differences between the two data sets. The TAMARA data set shows all layers, except the 0–100 m layer, still have significant positive trends for both time periods despite the cooling event in 2009. EN3 has significant upward trends for all the layers in the period 1999–2008 but only for the layer 1000–2000 m for the extended period 1999–2010. As we have discussed previously this layer has very different trends in the

OSD
10, 2363–2398, 2013

two data sets and therefore may be unreliable. The 0–1000 m layer has better correspondence between the two data sets and is shown in Tables 2 and 1. In TAMARA the latitude bands 20–30° N and 40–70° N have significant positive trends for both time periods, but in only EN3 are the latitude bands 20–40° N and 50–70° N regions significant.

To investigate the extended period further we consider a 3 yr period (2008–2010) which contains the cooler year 2009 and this is discussed in Sect. 3.5.

3.3 Time series analysis statistics: North Atlantic 10–70°, 1999–2010

Descriptive statistics were also calculated for the pairs of HCA time series. Firstly, correlations were calculated between the TAMARA and EN3 HCAs, shown in Table 6 and Fig. 7. Correlations were of consistently moderate values, with coefficient values between 0.43 and 0.55. The comparative variability of the two time series was quantified through the standard deviations of the de-trended data, shown in Table 7 and Fig. 8–10. The standard deviations of the EN3 data were generally larger than those of the TAMARA time series, which was also reflected in the uncertainties of HCA trends.

3.4 1999–2010 North Atlantic HCA analysis

To address the question about the lower number of Argo floats in the first six years and its influence on the overall heat content time series the data was split into two equal periods 1999–2004 and 2005–2010 respectively and from which the trends and correlations were calculated. In the first period TAMARA and EN3 had trends of $+1.26 \pm 5.1 \times 10^{21}$ and $+4.94 \pm 12.1 \times 10^{21}$ J respectively, whilst in the second period they had trends of $-0.88 \pm 4.1 \times 10^{21}$ and $-1.42 \pm 9.8 \times 10^{21}$ J respectively.

Given the uncertainty in the two time series it seems that there is no discernible difference in the two data sets. To further investigate this problem the trend in each period was removed and correlations were obtained. The correlation (r) between TAMARA and EN3 in the first period was 0.37 and in the second period was 0.32.

OSD
10, 2363–2398, 2013

From this analysis there is no evidence for a significant difference between TAMARA and EN3 in the first period compared with the two data sets in the second period. However this does not rule out the possibility of a bias in both data sets.

Further analysis of the both time series (Table 8) show that when the two time series were averaged over different time periods 3 months to 12 months the correlation (r) increased from 0.44 to 0.89. The EN3 again shows higher variance than TAMARA for all averaging periods. This was also investigated using filtering of the time series. When it was passed through a high pass filter with a cut-off period of 20 months the correlation was very low ($r = 0.19$) whilst with a low pass filter with a cut-off period of 20 months the correlation was high ($r = 0.77$).

3.5 2008–2010 North Atlantic HCA

The following analyses are just as described above, except they are only performed on the last three years of the HCA time series, when a large cooling event occurred. Note that zonal HCAs have been calculated using the full 2000 m depth range for this time period, rather than the surface 1000 m as was done earlier.

EN3 and TAMARA were also compared over a 3 yr period between 2008–2010 when there was a large change in the heat content 0–2000 m (Figs. 11–13, Tables 9 and 10). All the trends in TAMARA are significant at the 95 % significance levels, whilst only the zonal bands 30–40° N and 50–70° N are significant in EN3. Though the trends in both data sets are relatively similar the variability in the EN3 data set is much larger than in TAMARA.

The significant negative trend in both data sets is evident in the 30–40° N band and the values are not different within 95 % levels. The other two bands 50–70° N both have positive trends in EN3 and TAMARA, but the magnitude of the trend is larger in the former data set.

OSD
10, 2363–2398, 2013

4 Discussion and conclusion

To further investigate the very strong trend in EN3 HCA between 1000–2000 m, the question arises whether this trend was evenly distributed across the North Atlantic, or confined to particular zonal bands. It is shown that the trends in the northernmost three zonal bands (40–70° N) are very much larger in EN3 than those in the TAMARA dataset. Furthermore, all the zonal trends for the 1000–2000 m layer calculated from EN3 have a much larger magnitude than the equivalent TAMARA-derived trends. The discrepancy between the EN3 and TAMARA in the deepest layer 1000–2000 m is very large and warrants further investigation. The results suggest that the major discrepancy arises in the higher latitudes from 40–70° N.

A consistent difference between TAMARA and EN3 is the much larger variability in the latter data set. It is suspected that this variability is associated with the use of additional data to Argo, but also the different processing of the data and possibly different quality control procedures. The TAMARA data set may be less variable because of the more stringent quality control procedures used and there is some evidence for this from some recent reanalysis of the Argo data (King et al., 2013).

It is been found that despite the above differences between the two data sets the correspondence in both the basin trends and latitudinal bands is good between 0–1000 m. It can be concluded that the different analysis methods, quality control procedures and climatology used for the estimates of heat content anomaly, do not make a major difference to these basin wide estimates between 0–1000 m and on time scales greater than 1 yr.

References

Bretherton, F. P., Davis, R. E., and Fandry, C. B.: A technique for objective analysis and design of oceanographic experiments applied to MODE-73, Deep-Sea Res., 23, 559–582, 1976.
Bryden, H. L., King, B. A., and McDonagh, E. L.: Impact of a 30,% reduction in Atlantic Meridional Overturning during 2009–2010, Nature, submitted, 2013.

Coatanoan, C.: Coriolis Data Centre, In-situ data quality control procedures, Ifremer report, 17 pp., available at: http://www.coriolis.eu.org/content/download/4918/36060/file/cordo-rap-04-047-quality-control.pdf, 2005.
Dickson, R., Lazier, J., Meinke, J., Rhines, P., and Swift, J.: Longterm coordinated changes in the convective activity of the North Atlantic, Prog. Oceanogr., 38, 241–295, 1996.
Dickson, R., Yashayaev, I., Meincke, J., Turrell, W., and Dye, S.: Rapid freshening of the deep North Atlantic Ocean over the past four decades, Nature, 416, 832–837, 2002.
Gandin, L. S.: Objective analysis of meteorological fields, Israel Program for Scientific Translations, 242 pp., 1965.
Ingleby, B. and Huddleston, M.: Quality control of ocean temperature and salinity profiles – historical and real-time data, J. Marine Syst., 65, 158–175 doi:10.1016/j.jmarsys.2005.11.019, 2007.
Ivchenko, V. O., Wells, N. C., and Aleynik, D. L.: Anomaly of heat content in the northern Atlantic in the last 7 years: is the ocean warming or cooling?, Geophys. Res. Lett., 33, L22606, doi:10.1029/2006GL027691, 2006.
Ivchenko, V. O., Wells, N. C., Aleynik, D. L., and Shaw, A. G. P.: Variability of heat and salinity content in the North Atlantic in the last decade, Ocean Sci., 6, 719–735, doi:10.5194/os-6-719-2010, 2010.
King, B. A. and McDonagh, E. L.: A time series of objective mapping of Argo data in the North Atlantic, 2000–2012, J. Atmos. Ocean. Tech., in preparation, 2013.
Lavender, K. L., Owens, W. B., and Davis, R. E.: The mid-depth circulation of the subpolar North Atlantic Ocean as measured by subsurface floats, Deep-Sea Res., 52, 767–785, 2005.
Levitus, S., Boyer, T. P., and Antonov, J. I.: World Ocean Atlas 1994, 5, Interannual Variability of Upper Ocean, Thermal Structure, NOAA Atlas NESDIS 5, US Government Printing Office, Washington, D.C., 1994.
Levitus, S., Antonov, J. I., Boyer, T. P., and Stephens, C.: Warming of the world ocean, Science, 287, 2225–2229, 2000.
Levitus, S., Antonov, J. I., and Boyer, T.: Warming of the world ocean, 1955–2003, Geophys. Res. Lett., 32, L02604, doi:10.1029/2004GL021592, 2005.
Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E., and Mishonov, A. V.: Global ocean heat content 1955–2008 in light ofrecently revealed instrumentation problems, Geophys. Res. Lett., 36, L07608, doi:10.1029/2008GL037155, 2009.

OSD
10, 2363–2398, 2013

Lozier, M. S., Owens, W. B., and Curry, R. G.: The climatology of the North Atlantic, Prog. Oceanogr., 36, 1–44, 1995.
Lozier, M. S., Leadbetter, S., Williams, R. G., Roussenov, V., Reed, M. S. C., and Moore, N. J.: The spatial pattern and mechanisms of heat-content change in the North Atlantic, Science, 319, 800–803, 2008.
McCarthy, G. D., Frajka-Williams, E., Johns, W. E., Baringer, M. O., Meinen, C. S., Bryden, H. L., Rayner, D., Duchez, A., Roberts, C. D., and Cunningham, S. A.: Observed interannual variability of the Atlantic Meridional Overturning Circulation at 26.5° N, Geophys. Res. Lett., 39, L19609, doi:10.1029/2012GL052933, 2012.
Stephens, C., Antonov, J. I., Boyer, T. P., Conkright, M. E., Locarnini, R., and O'Brien, T. D.: World Ocean Atlas 2001, 1: Temperature (CD-ROM), edited by: Levitus, S., NOAA Atlas NESDIS 49, US Govt. Printing Office, Washington, D.C., 2002.
Taws, S. L., Marsh, R., Wells, N. C., and Hirschi, J. J.: Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO, Geophys. Res. Lett., 38, L20601, doi:10.1029/2011GL0489, 2011.
Willis, J. K., Roemmich, D., and Cornuelle, B.: Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, J. Geophys. Res., 109, C12036, 2004.
Willis, J. K., Lyman, J. M., Johnson, G. C., and Gilson, J.: In situ data biases and recent ocean heat content variability, J. Atmos. Ocean. Tech., 26, 846–852, 2009.
Wong, A., Keeley, R., Carval, T., and the Argo Data Management Team: Argo quality control manual, Version 2.2. P.33, Coriolis Data Centre, available at: http://www.coriolis.eu.org/cdc/argo/argo-quality-control-manual.pdf, 2006.

OSD
10, 2363–2398, 2013

Comparison of N. Atlantic heat storage

N. C. Wells et al.

Table 1. 1999–2010 Trends in Heat Content Anomalies 10–70° N.

Depth range (m)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±(95 %)	Trend	±(95 %)
0–100	0.78	1.19	0.75	0.99
100–500	1.69	1.16	0.89	2.25
500–1000	1.77	0.95	1.95	2.27
1000–2000	1.33	0.73	8.01	1.37
0–1000	4.23	2.46	3.59	4.73
0–2000	5.56	2.52	11.60	5.25

OSD
10, 2363–2398, 2013

Table 2. Zonal North Atlantic HCA trends 1999–2010, 0–1000 m.

Lat range (° N)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±(95 %)	Trend	±(95 %)
10–20	−0.04	0.90	1.33	1.46
20–30	1.09	0.74	−1.74	1.36
30–40	−0.19	1.07	−1.93	1.87
40–50	0.95	0.85	1.51	2.20
50–60	1.27	0.50	2.71	0.99
60–70	1.15	0.34	1.71	0.78

OSD
10, 2363–2398, 2013

Table 3. Zonal North Atlantic HCA trends 1999–2010, 1000–2000 m.

Lat range (°N)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±(95 %)	Trend	±(95 %)
10–20	0.34	0.11	0.78	0.29
20–30	0.25	0.18	0.72	0.42
30–40	−0.84	0.47	−0.21	0.78
40–50	0.46	0.30	3.03	0.41
50–60	0.65	0.12	2.02	0.28
60–70	0.47	0.06	1.67	0.21

OSD
10, 2363–2398, 2013

Table 4. 1999–2008 Trends in Heat Content Anomalies 10–70° N.

Depth range (m)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±(95 %)	Trend	±(95 %)
0–100	1.45	1.59	2.16	1.23
100–500	4.12	1.48	3.59	3.05
500–1000	3.85	1.18	4.21	3.09
1000–2000	1.02	0.93	10.27	1.74
0–1000	9.42	3.09	9.96	6.39
0–2000	10.44	3.16	20.22	6.93

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

OSD

10, 2363–2398, 2013

Comparison of N. Atlantic heat storage

N. C. Wells et al.

Table 5. Zonal North Atlantic HCA Trends 1999–2008, 0–1000 m.

Lat range (° N)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±(95 %)	Trend	±(95 %)
10–20	0.95	1.08	3.24	1.83
20–30	1.63	0.98	−0.81	1.86
30–40	1.59	1.31	0.22	2.40
40–50	1.36	1.16	−0.25	2.89
50–60	2.29	0.64	4.76	1.23
60–70	1.59	0.44	2.80	0.93

OSD
10, 2363–2398, 2013

Table 6. 1999–2010 Correlation between EN3 and TAMARA Heat Content Anomalies 10–70° N.

Depth Range (m)	Corr Coef	*P* value
0–100	0.43	1.07×10^{-7}
100–500	0.52	2.46×10^{-11}
500–1000	0.52	1.58×10^{-11}
1000–2000	0.47	3.43×10^{-9}
0–1000	0.44	3.41×10^{-8}
0–2000	0.51	9.94×10^{-11}

OSD
10, 2363–2398, 2013

Table 7. 1999–2010 Standard deviation in de-trended heat content anomalies 10–70° N.

Depth Range (m)	TAMARA ($J\,yr^{-1}$)	EN3, WOA01 ($J\,yr^{-1}$)
0–100	2.50×10^{21}	2.08×10^{21}
100–500	2.44×10^{21}	4.71×10^{21}
500–1000	2.00×10^{21}	4.77×10^{21}
1000–2000	1.52×10^{21}	2.86×10^{21}
0–1000	5.15×10^{21}	9.91×10^{21}
0–2000	5.27×10^{21}	1.10×10^{22}

OSD
10, 2363–2398, 2013

Table 8. Correlation (r) and standard deviation of detrended TAMARA and EN3.

	1 month	3 month	6 month	12 month
r	0.44	0.68	0.74	0.89
TAMARA Std $\times 10^{21}$ J	5.2706	4.4430	3.9359	3.2341
EN3 Std $\times 10^{21}$ J	10.998	7.1253	6.3708	5.7046

OSD
10, 2363–2398, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 9. 2008–2010 Trends in Heat Content Anomalies 10–70° N.

Depth range (m)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±	Trend	±
0–100	−3.58	9.25	1.94	8.74
100–500	−10.7	5.12	−10.10	12.1
500–1000	−9.16	6.64	−5.59	15.4
1000–2000	1.44	6.51	6.68	8.95
0–1000	−23.4	13.7	−13.8	26.6
0–2000	−22.0	14.7	−7.10	30.0

OSD
10, 2363–2398, 2013

Table 10. Zonal North Atlantic HCA trends 2008–2010, 0–2000 m, 95 % significance.

Lat range (° N)	TAMARA ($\times 10^{20}$ J yr^{-1})		EN3, WOA01 ($\times 10^{20}$ J yr^{-1})	
	Trend	±	Trend	±
10–20	9.16	8.07	9.45	10.63
20–30	−6.16	5.07	2.71	8.29
30–40	−28.82	8.98	−39.28	14.36
40–50	−6.07	5.89	−1.48	17.17
50–60	5.98	2.27	10.12	7.12
60–70	3.92	2.13	11.38	7.77

OSD
10, 2363–2398, 2013

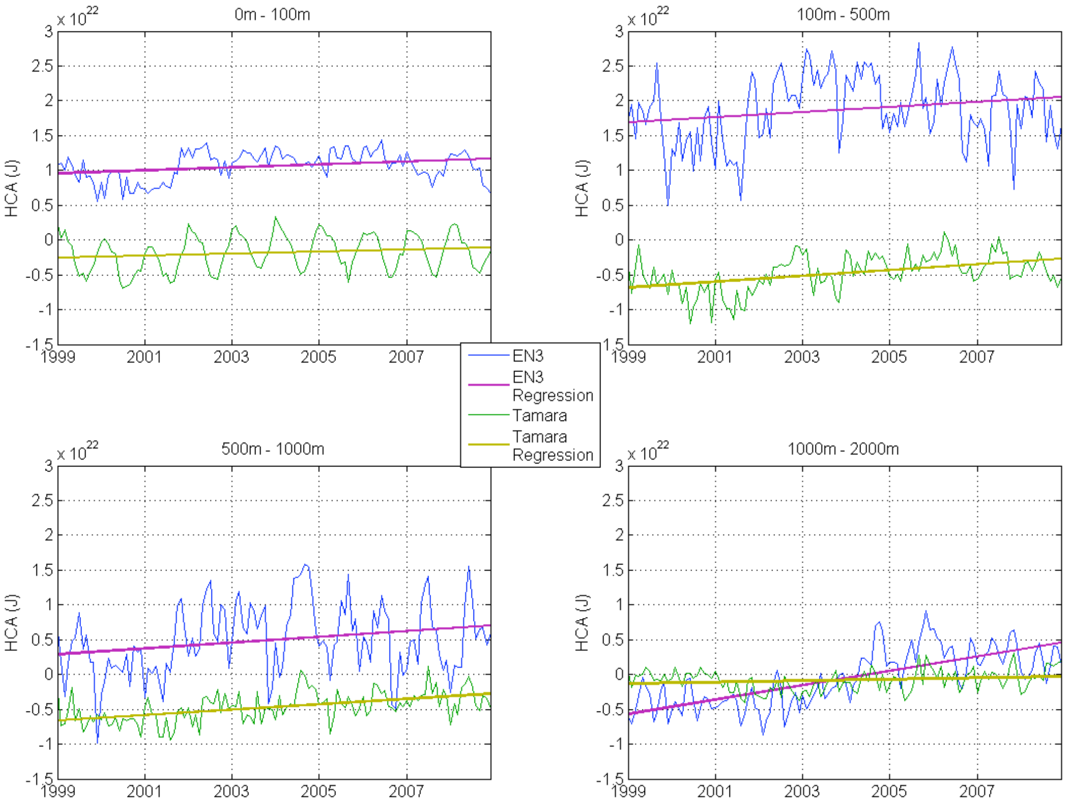


Fig. 1. Time series of two datasets of Heat Content Anomalies (HCA, J) of the North Atlantic, 10–70° N, January 1999–December 2010 in four depth layers: 0–100 m, 100–500 m, 500–1000 m and 1000–2000 m.

OSD
10, 2363–2398, 2013

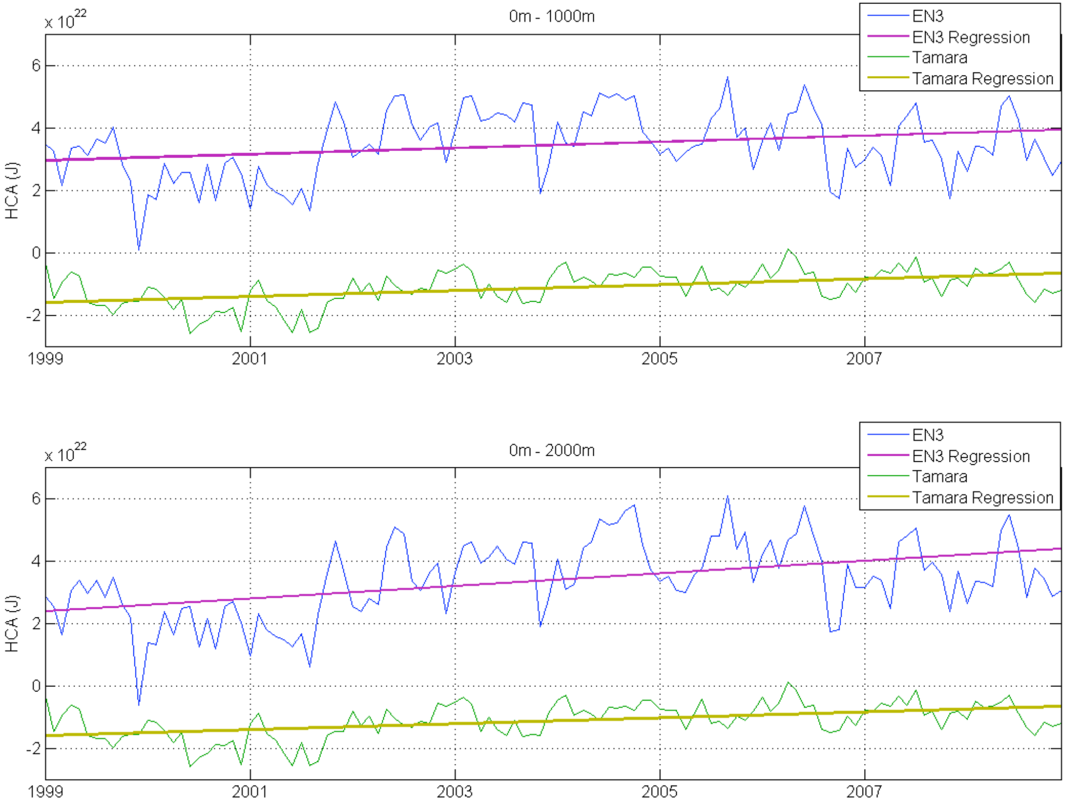
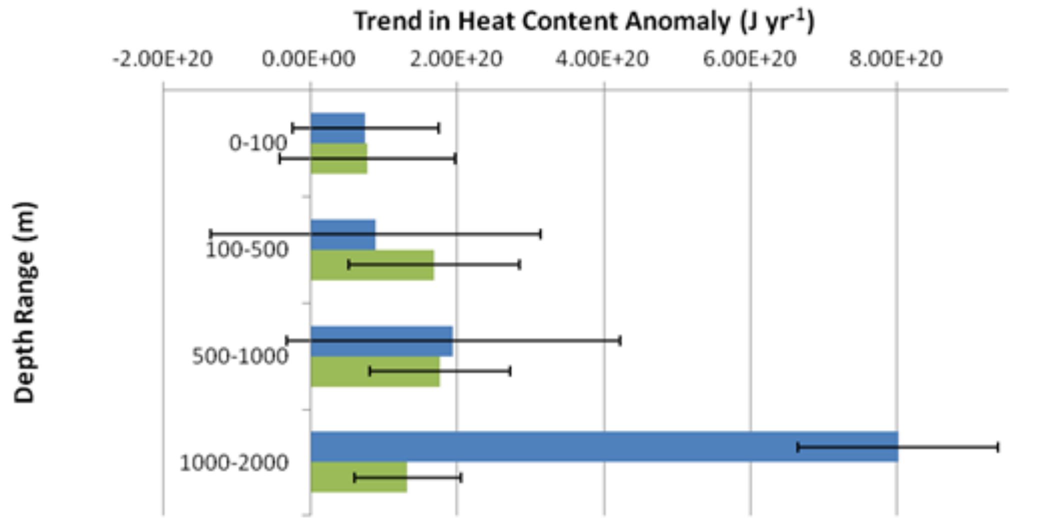


Fig. 2. HCA of the North Atlantic for uppermost 1000 and 2000 m, January 1999–December 2010.

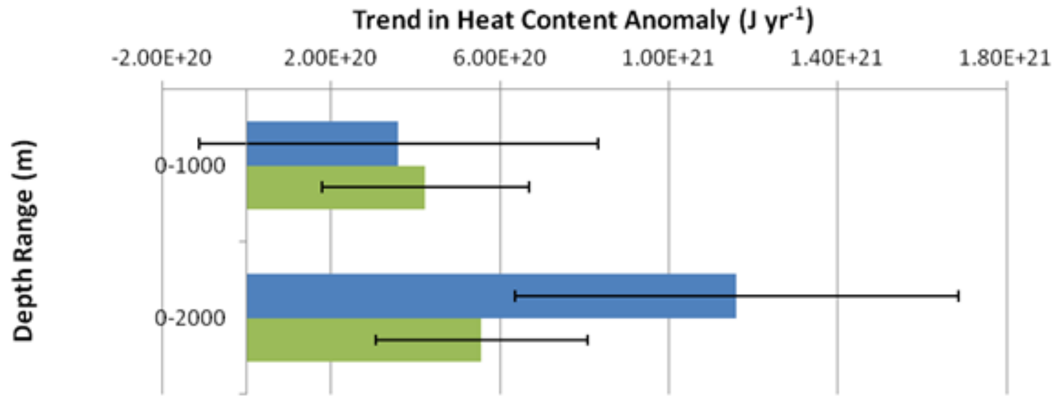
OSD
10, 2363–2398, 2013



	1000-2000	500-1000	100-500	0-100
EN3, WOA01	8.01E+20	1.95E+20	8.94E+19	7.53E+19
Tamara	1.33E+20	1.77E+20	1.69E+20	7.80E+19

Fig. 3. 1999–2010 Trends in Heat Content Anomalies 10–70° N in four depth levels.

OSD
10, 2363–2398, 2013

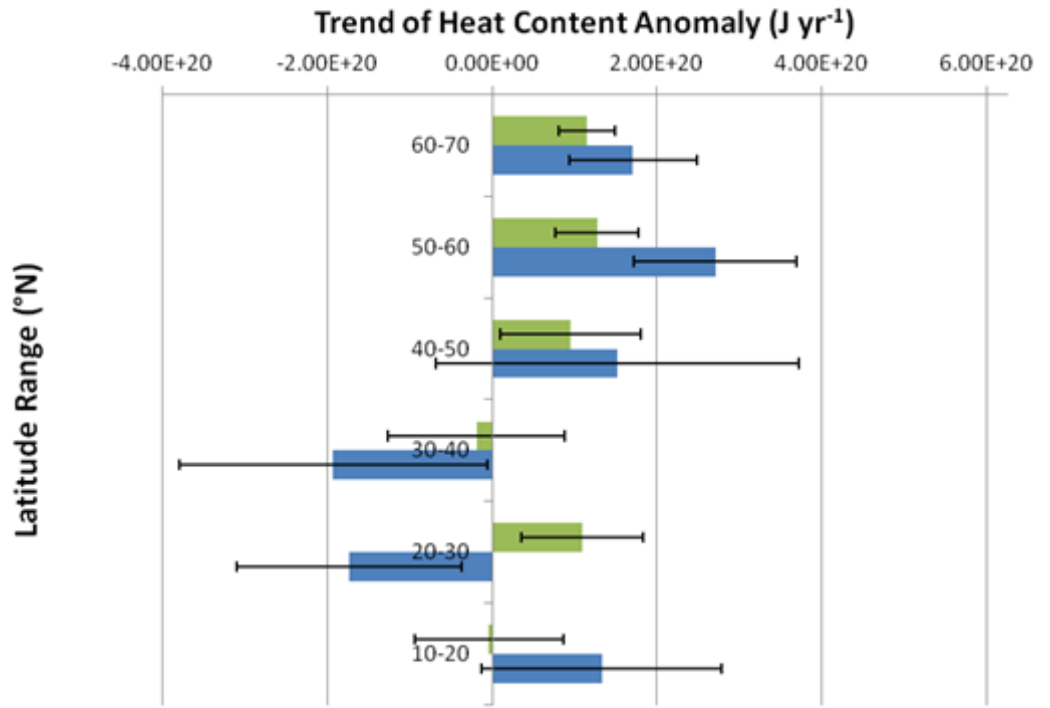


	0-2000	0-1000
EN3, WOA01	1.16E+21	3.59E+20
Tamara	5.56E+20	4.23E+20

Fig. 4. 1999–2010 Trends in Heat Content Anomalies 10–70° N in two depth levels.

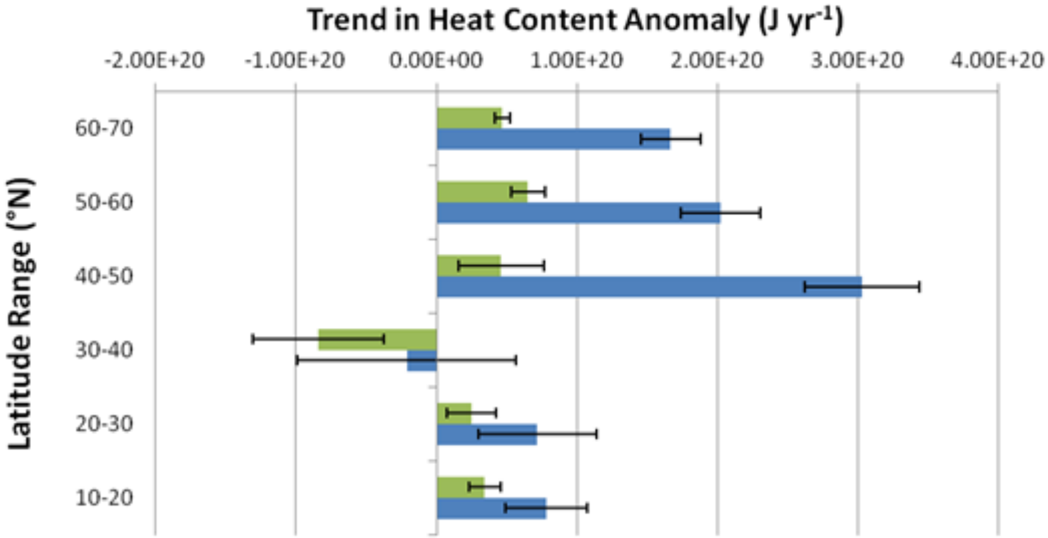
OSD
10, 2363–2398, 2013

OSD
10, 2363–2398, 2013



	10-20	20-30	30-40	40-50	50-60	60-70
Tamara	-4.12E+18	1.09E+20	-1.90E+19	9.54E+19	1.27E+20	1.15E+20
EN3, WOA01	1.33E+20	-1.74E+20	-1.93E+20	1.51E+20	2.71E+20	1.71E+20

Fig. 5. Zonal North Atlantic HCA trends 1999–2010, 0–1000 m.



	10-20	20-30	30-40	40-50	50-60	60-70
Tamara	3.43E+19	2.49E+19	-8.44E+19	4.59E+19	6.51E+19	4.69E+19
EN3, WOA01	7.81E+19	7.18E+19	-2.10E+19	3.03E+20	2.02E+20	1.67E+20

Fig. 6. Zonal North Atlantic HCA trends 1999–2010, 1000–2000 m.

OSD
10, 2363–2398, 2013

Comparison of N. Atlantic heat storage

N. C. Wells et al.

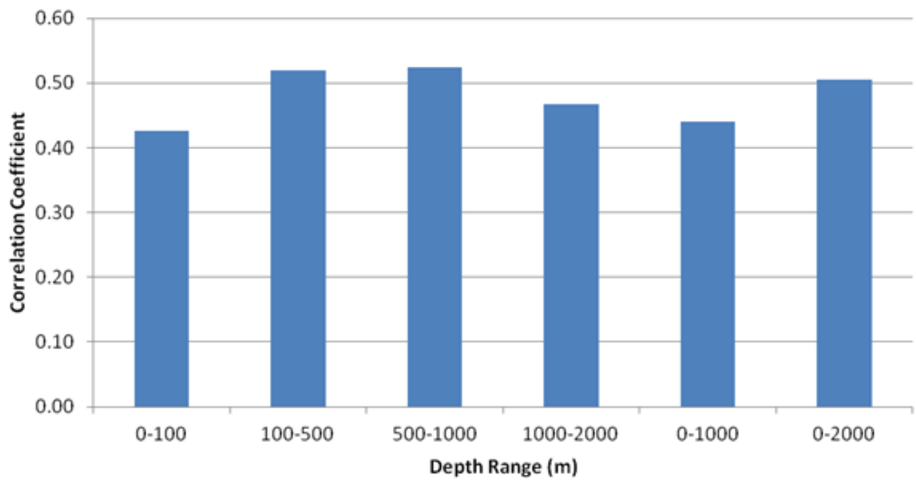
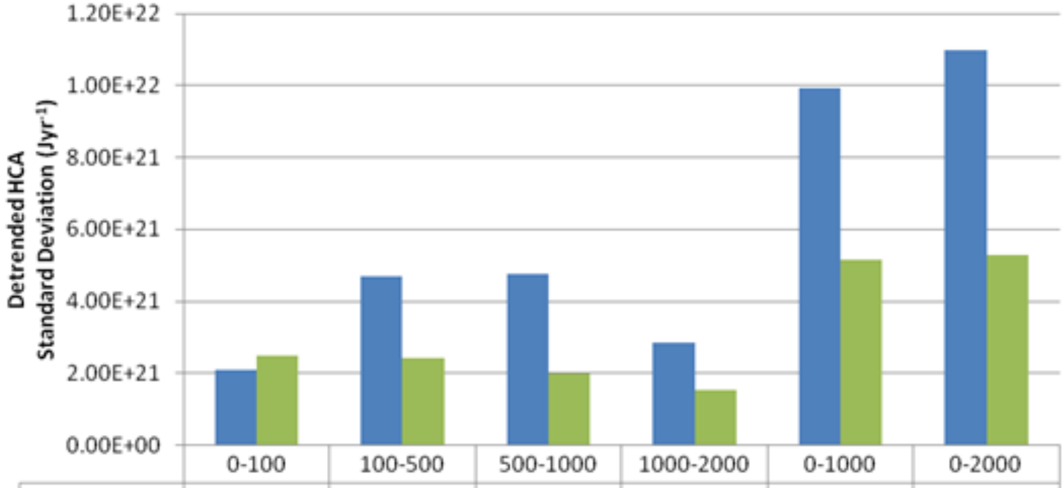


Fig. 7. Correlations between EN3 and TAMARA Heat Content Anomalies 10–70° N.

OSD
10, 2363–2398, 2013



	0-100	100-500	500-1000	1000-2000	0-1000	0-2000
EN3, WOA01	2.08E+21	4.71E+21	4.77E+21	2.86E+21	9.91E+21	1.10E+22
Tamara	2.50E+21	2.44E+21	2.00E+21	1.52E+21	5.15E+21	5.27E+21

Depth Range (m)

Fig. 8. 1999–2010 Standard deviations of de-trended HCA time series.

OSD
10, 2363–2398, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

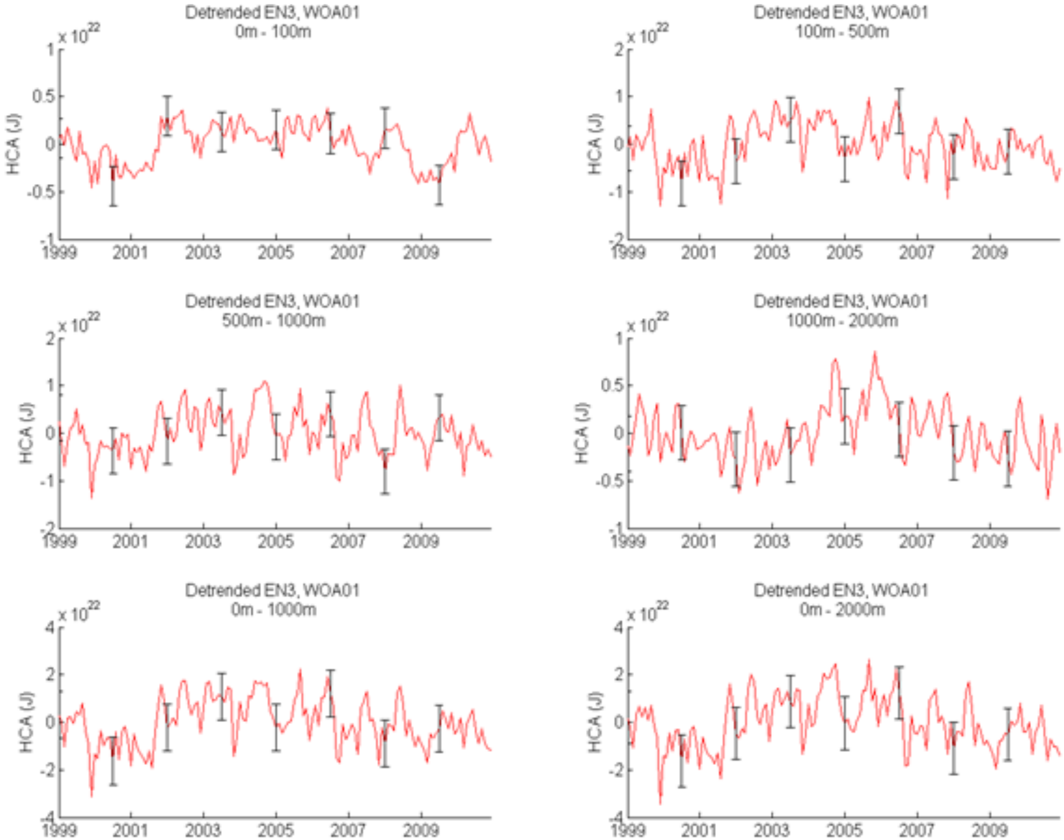


Fig. 9. Time series of EN3 layer HCA with linear trend removed and error bars showing ±1 standard deviation.

OSD
10, 2363–2398, 2013

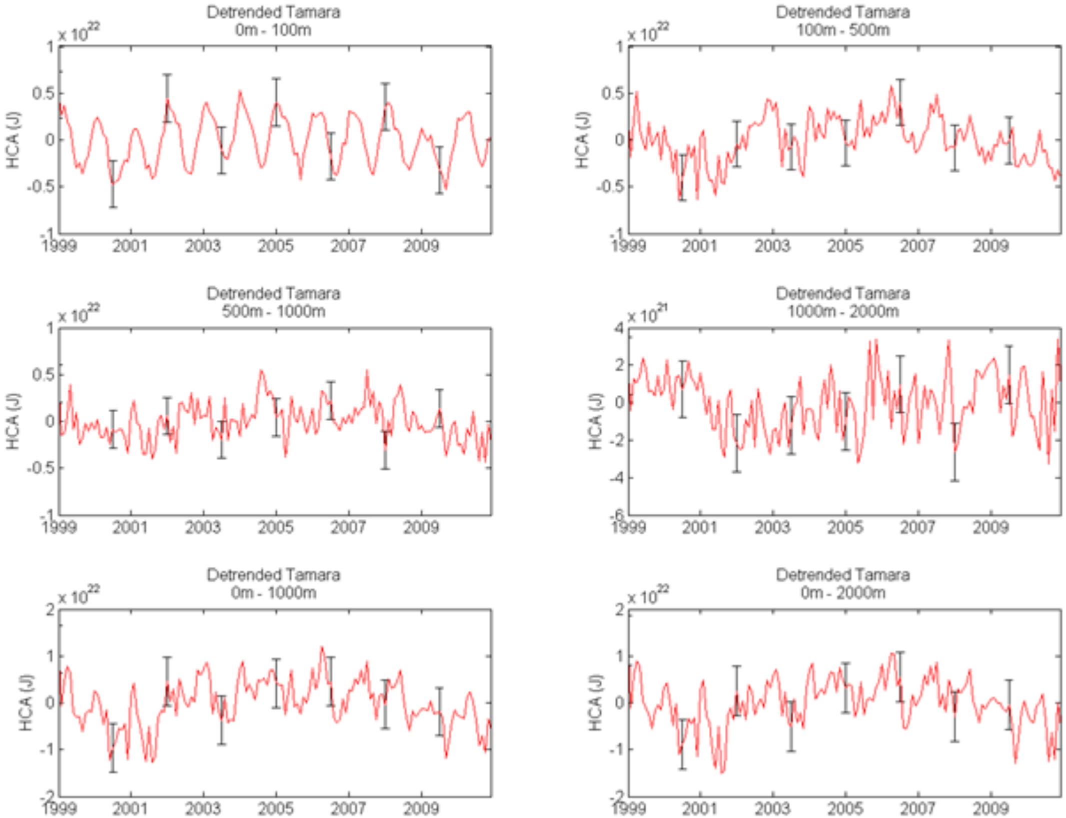
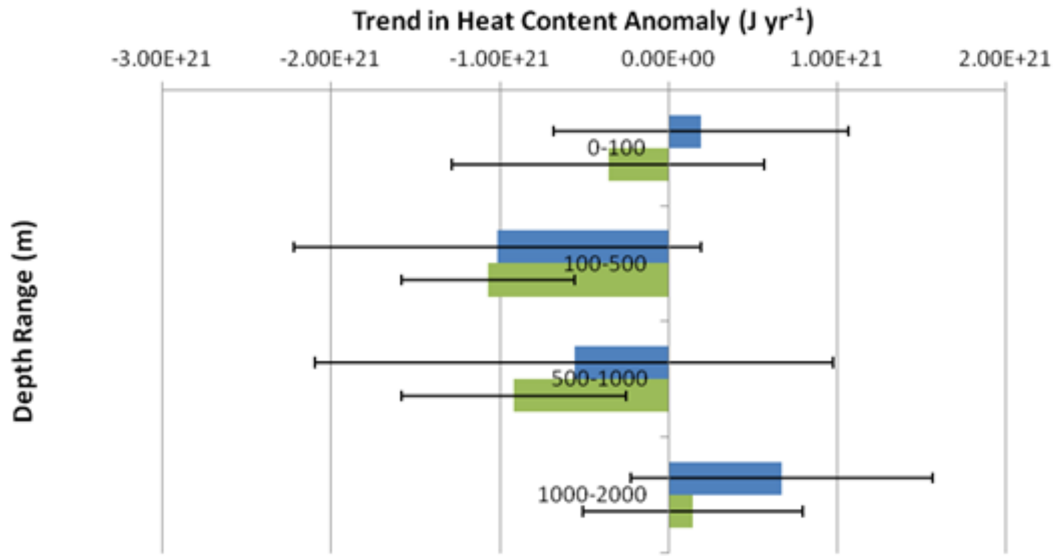


Fig. 10. Time series of TAMARA layer HCA with linear trend removed and error bars showing ±1 standard deviation.

OSD
10, 2363–2398, 2013

Comparison of N. Atlantic heat storage

N. C. Wells et al.



	1000-2000	500-1000	100-500	0-100
EN3, WOA01	6.68E+20	-5.59E+20	-1.01E+21	1.94E+20
Tamara	1.44E+20	-9.16E+20	-1.07E+21	-3.58E+20

Fig. 11. 2008–2010 Trends in Heat Content Anomalies 10–70° N in four depth levels.

OSD

10, 2363–2398, 2013

Comparison of N. Atlantic heat storage

N. C. Wells et al.

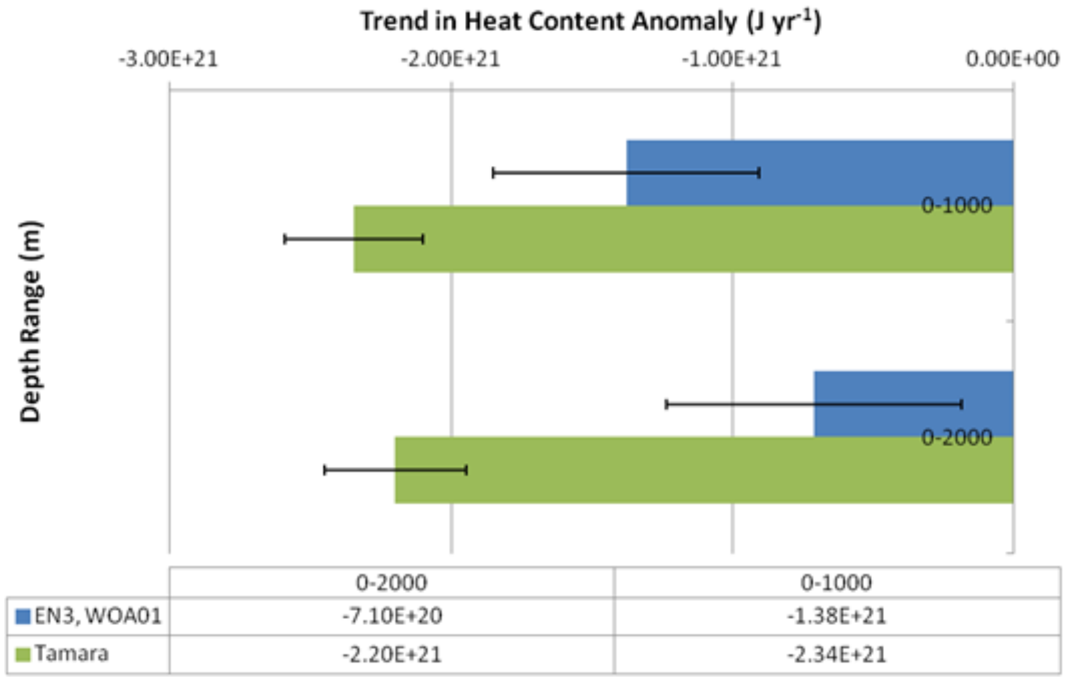
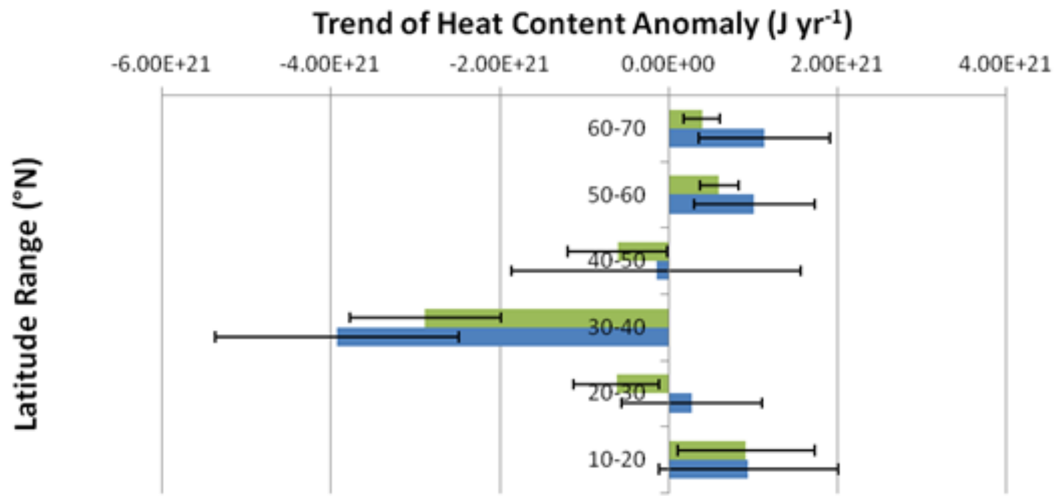


Fig. 12. 2008–2010 Trends in Heat Content Anomalies 10–70° N in two depth levels.

OSD
10, 2363–2398, 2013



	10-20	20-30	30-40	40-50	50-60	60-70
Tamara	9.16E+20	-6.16E+20	-2.88E+21	-6.07E+20	5.98E+20	3.92E+20
EN3, WOA01	9.45E+20	2.71E+20	-3.93E+21	-1.48E+20	1.01E+21	1.14E+21

Fig. 13. Zonal North Atlantic HCA trends 2008–2010, 0–2000 m.

OSD
10, 2363–2398, 2013

N. C. Wells et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion