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Revisiting the *Meteor* 1925–1927 hydrographic dataset reveals centennial full-depth changes in the Atlantic Ocean

Viktor Gouretski,[1] Johann H. Jungclaus,[2] and Helmuth Haak[2]

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[1] The hydrographic data set of the German Atlantic Expedition (GAE) 1925–1927 is compared with the contemporary profiling float and ship-based hydrography to reveal full-depth changes in the Atlantic Ocean between 19°N and 64°S. The volume-mean warming over the last 80 years amounts to 0.119 ± 0.067 °C, accompanied by an increase in salinity of 0.014 ± 0.010. A clear vertical structure of these changes is observed: on average, the ocean has warmed by 0.272 ± 0.093 °C and became saltier by 0.030 ± 0.014 down to about 2000 m, but cooled and freshened slightly in the deeper layers. These changes can be traced throughout the whole hydrographic survey, indicating the basin-wide character of the observed changes on a centennial timescale. The observed warming is consistent with climate model simulations over the 20th century, suggesting an attribution to anthropogenic forcing. Comparison with the pre-GAE cruises reveals no discernible warming between the 1870s and 1906/1911. **Citation:** Gouretski, V., J. H. Jungclaus, and H. Haak (2013), Revisiting the *Meteor* 1925–1927 hydrographic dataset reveals centennial full-depth changes in the Atlantic Ocean, *Geophys. Res. Lett.*, *40*, 2236–2241, doi:10.1002/grl.50503.

1. Introduction

[2] Detection and quantification of changes in the global ocean heat content and fresh water balance are of crucial importance for the assessment of the Earth's climate variability. However, there are few data sets of adequate quality and scope before the mid 20th century. Whereas the global ocean temperature time series for the upper 400 m were extended back to the beginning of the 20th century [*Gouretski et al.*, 2012], the estimation of temperature (heat content) and salinity changes in the deeper layers is hampered by a lack of measurement. The majority of the studies of temperature changes in the near-bottom layers are based on hydrographic data obtained since the 1980s. *Kouketsu et al.* [2011] estimated global temperature change rates below 3000 m and *Johnson and Doney* [2006] revealed a small warming in the bottom waters of the South Atlantic from the 1990s to the 2000s. The global heat content time series for the upper 2000 m by *Levitus et al.* [2012] begins in 1955. However, some historical data permit the study of long-term, climatic changes in the deep ocean. *Roemmich et al.* [2012] compared temperature data from the voyage of *HMS Challenger* (1872–1876) [*Thomson and Murray*, 1885] with the contemporary profiling float data and found a global averaged warming of 0.33 ± 0.14 °C for the layer 0–700 m. The German Atlantic Expedition (GAE) (1925–1927) [*Wüst et al.*, 1932] was the first basin-wide survey after the *Challenger* expedition. In the present study we compare the GAE and several other old hydrographic datasets against the contemporary data to quantify full-depth changes, which took place in the Atlantic Ocean south of 19°N since the beginning of the 20th century. Finally, we put the observed regional changes in context with the global climate evolution by comparing the GAE hydrographic data with climate model simulations.

2. Data

[3] The majority of the hydrographic data used in this study were taken from the World Ocean Database 2009 (WOD09) [*Boyer et al.*, 2009] (with the latest additions as of July 2012). Temperature profiles from the German ship *Stephan* (1911) were provided by G. Reverdin (personal communication, November 2012) and the *Challenger* temperature data were taken from [*Roemmich et al.*, 2012].

2.1. Historical Hydrographic Data (1873–1927)

[4] The GAE covered the Atlantic Ocean between 19°N and 55°S with 13 coast-to-coast full-depth hydrographic sections and a total of 310 stations resolving the thermohaline structure of an entire oceanic basin in unprecedented detail. A comparable coverage of the area was achieved by the global World Ocean Circulation Experiment (WOCE) [*Koltermann et al.*, 2011] in the 1990s. The GAE was the first major expedition where pairs of pressure protected and unprotected reversing thermometers were used on each station to measure the sampling depth with a mean error between 0.8% at 500 m and 0.4% at 3000 m—a significant improvement compared to the wire-put-out method, which is characterized by the depth errors often exceeding 5% [*Brennecke*, 1921]. In addition to the profile data available from the WOD09, the near-bottom data from the propeller-operated Sigsbee bottles attached to the wire above the sediment core sampler were digitized and added to the station profiles. At some locations, several shallow casts were conducted to investigate the time variability and these were averaged into a single profile. The technologies used by the GAE represented significant advances since the *Challenger* expedition and set the standard of hydrographic observations until the start of the electronic era in the1970s. In addition to the GAE data, we used temperature profiles from German cruises occupied between 1906–1911 aboard *Gazelle*, *Planet*, *Deutschland*, *Möwe*, and *Stephan*.

Additional supporting information may be found in the online version of this article.

[1] KlimaCampus, Hamburg University, Hamburg, Germany.
[2] Max-Planck-Institute for Meteorology, Hamburg, Germany.

Corresponding author: V. Gouretski, KlimaCampus, Hamburg University, Grindelberg 5, 20144 Hamburg, Germany. (viktor.gouretski@zmaw.de)

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2.2. Contemporary Hydrographic Data (1985–2012)

[5] The hydrographic observations accumulated during the recent decades provide a suitable reference for the estimation of changes which occurred in the ocean since the GAE. A total of 19,584 bottle and CTD profiles and 40,583 Argo float profiles from the WOD09 were used to characterize contemporary mean hydrographic conditions (1985–2012) (Figure S1 in the auxiliary material). All observed depth data were interpolated on 1 m levels using a parabolic interpolation method [*Reiniger and Ross*, 1968].

2.3. Data Accuracies and Possible Biases

[6] Assessment of the data accuracy and possible biases is crucial for the estimation of climate changes in the ocean [*Gouretski and Koltermann*, 2007]. Fortunately, the GAE expedition report [*Wüst et al.*, 1932] contains a detailed analysis of the measurement accuracy. On all GAE stations, the temperature was measured by means of reversing thermometers. For the upper and lower parts of the water column, thermometers graduated with the increments of 0.1 °C and 0.05 °C, respectively, were used. Normally, pairs of thermometers were used allowing for an additional quality control, and all thermometers were calibrated in the Imperial Physical-Technical Institute in Berlin. Comparison of the calibrations made before and after the expedition confirmed a high stability of the thermometers, with 75(53)% of the differences between the pre- and post-calibration values being within ±0.003 °C for 0.05(0.1) °C graduation.

[7] During the time of GAE, the Normal Hydrogen Scale (NHS) was in use, whereas the recent temperatures are based both on the International Practical Temperature Scale of 1968 (IPTS-68) and of 1990 (ITS-90). However, for the typical oceanic temperature range (-2 to 33 °C), the numerical differences in temperature due to different scales do not exceed 0.008 °C, being less than 0.003 °C for temperatures below 10 °C [*Preston-Thomas*, 1990, Figure 1]. Taking into account the above considerations, we tentatively estimate the magnitude of possible unresolved mean temperature bias in the GAE data to be about 0.005 °C.

[8] Titration of sea water samples with silver nitrate was used during the GAE to obtain salinity. Several improvements compared to earlier German cruises were implemented, which helped to increase the titration accuracy: (1) all samples were analyzed onboard; (2) each day a new standard water ampoule was used; (3) the same trained persons were engaged in the titration; (4) double titrations were made on several sections to ensure quality control; and (5) sealed bottles were sent to the Institute of Marine Research, Berlin, to conduct control titration there. Based on the results of the double titrations, the mean precision of the GAE salinity measurements is estimated to be ±0.01‰, and the after-cruise control titrations revealed no bias in the onboard salinity values. Although the Standard Sea Water was used as a reference standard both on the GAE and on the contemporary (1985–2012) cruises, the modern salinities are based on the conductivity measurements, which replaced the titration. Respectively, the modern salinities are based on the Practical Salinity scale. *Millero et al.* [1977] estimated the maximum difference between the chlorinity and conductivity salinities due to the use of different standard seawater batches to be about 0.01‰, whereas the mean difference was 0.0016‰.

[9] We assume the above estimate of ±0.01‰ as an upper limit of a possible bias in the GAE salinity data. Salinity data from the pre-GAE cruises are characterized by a considerably larger scattering within the deep water compared to the GAE data. We attribute this to a lower accuracy of chlorinity titrations and therefore do not analyze changes in salinity for the pre-GAE cruises.

[10] The modern CTD data used in this study are accurate to approximately 0.002 °C in temperature and 0.005 (practical salinity scale) in salinity, and $<0.5\%$ of full-scale pressure in depth [*Emery and Thompson*, 1997]. The Argo float data are accurate to 0.01 °C in temperature and to better than 0.02 in salinity. Analysis of the deepest portions of Argo profiles [*Roemmich and Gilson*, 2009] does not reveal any significant salinity bias. Considering a large amount of reference data and their higher accuracy and making an assumption of an even distribution of negative and positive offsets for individual profiles, we consider the reference data set to be on average bias free.

3. Calculation of Temperature and Salinity Difference and Their Uncertainties

[11] Mean parameter values for the contemporary period (2003–2012 above 1950 m and 1985–2012 below 1950 m) were evaluated using an inverse-distance weights $w = (R^2 - r^2)/(R^2 + r^2)$ when averaging temperature and salinity from ship-based hydrographic stations and float profiles within the bubble R (r is the distance to the analyzed GAE station). All profiles have been rigorously screened for quality. The mean number of floats within the $R = 166$ km amounts to 250–300 above 1000 m and drops to about 150 near 1950 m. Deeper, the conventional hydrographic data within the $R = 332$ km were used, with the WOCE data [*Koltermann et al.*, 2011] being outstanding in number and quality. The mean time difference between the GAE observations and the Argo/hydrographic profiles is 80 years within the upper 1950 m and 67 years for the deeper layers. For each GAE station, changes in a hydrographic property were evaluated as a function of depth by subtracting GAE values from the contemporary mean values. Above 100 m only data taken within the same month were used to account for seasonality, below the estimation of the contemporary mean parameter values was done using all available profiles.

[12] For the estimation of the number of independent data points at each level, the sample spatial autocorrelation functions were computed. Autocorrelations averaged over all sections are characterized by a low tail extending to about 10–15 stations before decreasing to the values close to zero (Figure S2), which corresponds to the mean correlation length of about 10 stations.

4. Temperature and Salinity Changes Since the German Atlantic Expedition 1925–1927

[13] Although a small part of the GAE data set was used in previous analyses for the estimation of decadal changes in the South Atlantic Ocean [*Arbic and Owens*, 2001; *Reverdin*, 1996], the potential of the whole GAE data set has not yet been fully used. An aggregated section showing the differences between the modern and the GAE data for the three parameters (in situ temperature, salinity, and in situ density) gives evidence of clear full-depth changes

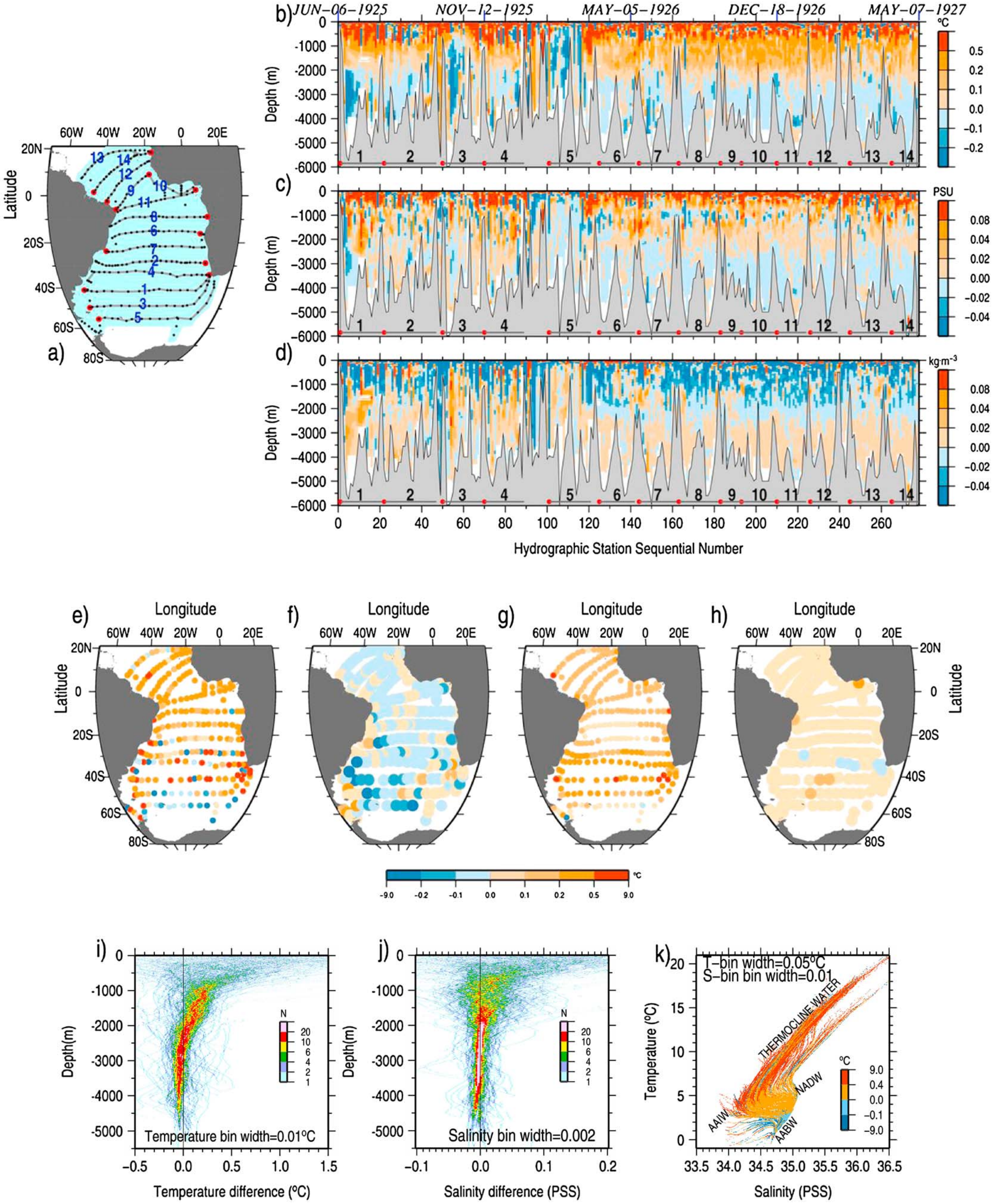

Figure 1. (a) Map of the GAE survey area (light blue) with 14 hydrographic sections (grey lines) and a total of 277 stations (black dots). Red dots mark the section starting points. (b–d) Temperature, salinity, and in situ density differences on the aggregated GAE section (mean contemporary values minus GAE). Grey lines at the bottom of each panel correspond to the sections shown in Figure 1a. Layer-averaged temperature differences. Color spots indicate the differences within the (e) 0–2000 m layer and for the (f) layer 2000 m—bottom. The color spots are centered on GAE station locations, the size of spots corresponds to the vicinity within which the contemporary data were selected. Layer-averaged temperature differences between decadal mean temperatures (1995–2005 minus 1920–1929) obtained from MPI-ESM-MR historical simulations. Ensemble means over three experiments for the (g) 0–2000m layer, and for the (h) layer 2000m—bottom. Data were interpolated from the 0.4° model grid onto the GAE station locations. Histograms of the contemporary hydrography minus GAE parameter differences. Differences versus depth: (i) in situ temperature, (j) salinity. Colours correspond to the frequency of the respective difference value according to the colour scales. Histograms are based on the interpolated profiles with the depth bin width of 10 m. (k) Temperature differences at depths attributed to the respective T-S diagram. Annotations locate main water masses as follows: AAIW, Antarctic Intermediate Water; NADW, North Atlantic Deep Water; AABW, Antarctic Bottom Water.

(Figures 1a–1d). Further, we find that the warming extends over the thermocline waters, the Antarctic Intermediate water, and the North Atlantic Deep Water, and the cooling is linked to the Antarctic Bottom Water (Figure 1k). Most of the different profiles show parallel changes in temperature and salinity, with warming/cooling being accompanied by a respective salinity increase/decrease—a feature known from previous studies [*Curry et al.*, 2003].

[14] Our comparison shows that temperature and salinity increased, and the water density decreased, within the upper 2000 to 2500 m since the mid 1920s. The mesoscale noise obviously hides the climatic signal at several locations. For instance, several Agulhas eddies can be identified along the section #2 above about 700 m as negative temperature and salinity anomalies. Maps of layer-averaged temperatures (Figures 1e, 1f) also suggest the basin-wide character of the changes. During the period for which Argo data were used for the analysis (2003–2012), the 0–2000 m layer-averaged temperatures were higher at 245 out of the total of 277 locations. For 247 stations deeper than 3000 m, the temperatures averaged below 2000 m were lower at 210 locations.

[15] The change in the observed parameters with depth is further illustrated by the parameter/depth histograms (Figures 1i, 1j), which have narrow modes below 500–1000 m. The magnitude of the warming diminishes from $0.859 \pm 0.184\,^{\circ}\mathrm{C}$ near the surface to $0.180 \pm 0.039\,^{\circ}\mathrm{C}$ at 1000 m and $0.042 \pm 0.020\,^{\circ}\mathrm{C}$ at 2000 m, whereas the average salinity increase at the surface, 0.122 ± 0.040, diminishes to 0.010 ± 0.008 at 1000 m (Table S1).

[16] The pattern of warmer contemporary temperatures is not found along the central part of the section #5 (Figure 1b), which lies to the south of the main core of the Antarctic Circumpolar current (ACC). Here the cooling prevails throughout the water column. This signature also emerges in density, suggesting that since the 1920s, the waters south of the ACC became denser, whereas those to the north experienced a decrease in density. Correspondingly, the density difference between section #5 and section #2 has increased by 0.5 kg m^{-3}, which translates into a 4% increase of the mean meridional density gradient, and thus suggests an acceleration of the baroclinic velocity of the ACC.

[17] Since the GAE survey covered the study area with a rather regular net of stations, robust estimates of the regional changes in heat and salt content are possible (Table S1). The survey covers an area of 6.0×10^{7} km^2 with a volume of 2.4×10^{8} km^3 (16% of the area and 18% of the volume of the World Ocean). Since the 1920s, the total heat content has increased by $(11.4 \pm 6.4)10^{22}$ J, corresponding to an average heat uptake of $0.76 \pm 0.43\mathrm{W\ m}^{-2}$. For the layer 0–2000 m, our estimate of the heat uptake of $0.82 \pm 0.28\ \mathrm{W{\cdot}m}^{-2}$ is higher than the *Levitus et al.* [2012] estimates of $0.63\ \mathrm{W{\cdot}m}^{-2}$ for the South Atlantic and of $0.73\ \mathrm{W{\cdot}m}^{-2}$ for the North Atlantic Ocean for 1955–2010. Differences in the estimates can be attributed to differences in geographic areas, time periods, data, and methods. We find that half of the total heat energy gained by the ocean accumulated within the upper 400 m, and 72% within the upper 700 m, with the cooling below 2000 m reducing the full-depth heat content by about 9%.

[18] Generally, changes in salinity (Figures 1 and 2) occurred parallel to those in temperature. Salinification occurred predominantly above 2000–2500m, with a slight decrease below that depth and mostly in the northern part of the survey area. However, the detected changes in the lower half of the water column are well within the uncertainties, due to the possible residual uncertainty in salinity. The total fresh-water loss for the area amounts to -190 ± 10 cm, equivalent to -2.4 ± 0.1 cm per year over the 80 years, which is about a half of the estimate for the latitude 24°N from 1960 to 2000 [*Curry et al.*, 2003]. Dissolved oxygen content measurements were also conducted during the GAE. Since both the reference and the GAE oxygen values are less accurate compared to temperature and salinity, they are not presented here. However, the GAE observations suggest an overall decrease of the oxygen content, which is expected for the warming ocean.

[19] Compared to temperature, the difference patterns of salinity (Figure 1b) are patchier, and we attribute this to the uncertainties in salinity data. Assuming the temporal stability of the salinity-temperature relationship within the lower part of the water column (below 1500 m) (the assumption frequently used to estimate systematic errors in salinity data [*Gouretski and Jancke*, 2001]) and taking modern salinity as an unbiased reference, we find a small overall salinity bias of -1.5×10^{-3} for the GAE data set, with the standard deviation of 1.1×10^{-2}, which agrees with the salinity precision estimate from the expedition report. The removal of individual salinity biases (Figure S3) does not lead to a qualitative change of this study results. The combination of temperature and salinity changes leads to the increase of the mean sea level by about 3.7 ± 0.1 cm (0.46 mm/year). Table S2 provides in situ temperature, salinity, and in situ density data for each *Meteor* station along with the contemporary values and the respective differences.

5. Temperature Changes Detected for the pre-GAE Cruises

[20] To put the GAE data into a broader context, we similarly analyzed the temperature data from the several hydrographic cruises occupied in the South Atlantic before the GAE. The *Challenger* dataset [*Roemmich et al.*, 2012] was extended by the addition of the temperature profiles obtained during the German 1874–1876 *Gazelle* expedition [*Rottok*, 1888], which was designed to be complementary to the *Challenger* cruise and used similar minimum/maximum thermometers. Additionally, four German ships (*Planet* [*Brennecke*, 1909] in 1906 and *Deutschland* [*Brennecke*, 1921], *Möwe* [*Schott et al.*, 1914], and *Stephan* [*Merz*, 1912] in 1911) provided data for the comparison with the GAE (Figure 2a). It is important to note, that observations on all four German cruises were conducted by experienced oceanographers, and descriptions of the data and methods are provided in the respective cruise reports. However, the hydrographic data from the pre-GAE cruises generally exhibit broader temperature ranges both due to the less accurate temperature measurements and due to the uncertainties in the sample depth estimation. For these cruises, temperature deviations from the contemporary values were rejected if they exceeded five standard deviations for the same level from the GAE survey. We also note that the accuracy of the data from the pre-GAE cruises does not allow the similar comparison for salinity.

[21] We find that between the 1906–1911 cruises and the GAE, the ocean warmed by about 0.05–0.2 °C (the layer 500–1500 m), and that there is no discernible warming between the 1870s and 1906/1911 (Figure 2b). However, atmospheric $\mathrm{CO_2}$ was rising during that period as evidenced by the Antarctic ice core data [*Etheridge et al.*, 1996]. Since the thermometric depth measurements were not conducted on other cruises (except for a part of *Deutschland* stations), sample depths for the majority of the pre-GAE temperature profiles are represented through the length of the wire put out, giving a true depth only for the vertical position of the wire in the water. Since usually the wire deviates from the vertical position, the sample depths would mostly overestimate

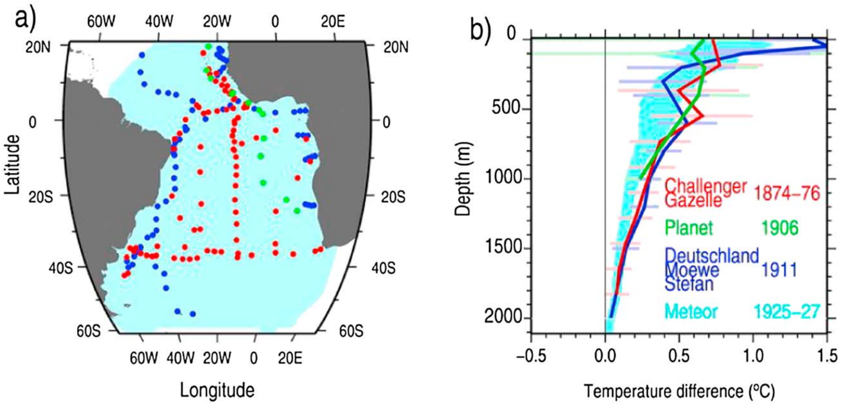

Figure 2. (a) GAE survey domain (light blue). Dots show locations of the temperature profiles obtained during the cruises of *Challenger* and *Gazelle* (red), *Planet* (green), *Deutschland*, *Möwe*, and *Stephan* (blue). (b) Area-averaged Argo era-minus-historical cruise temperature difference for the cruises shown in Figure 2a. Error bars correspond to ± 1 standard error of the mean.

the sample depth. If an average depth overestimation of 5% is assumed for the pre-GAE cruises, the temperature difference relative to the Argo era would increase by about 0.1 °C within the main thermocline. Tables S3–S5 in the auxiliary material provide in situ temperature data for each pre-GAU cruise along with the contemporary mean temperatures and the respective temperature differences.

6. Comparison With Climate Model Simulations

[22] The GAE campaign forms a unique observational data set to quantify large-scale hydrographic changes in the 20th century that can be used to test model simulations and to examine if the observed changes are consistent with the recent evolution of Earth's climate. As part of the Coupled Model Intercomparison Project phase five [*Taylor et al.*, 2012], so-called "historical" (1850–2005) experiments are carried out, with prescribed external drivers such as greenhouse gases, volcanic, and anthropogenic aerosols. Here we choose a three-member ensemble performed with the Max Planck Institute Earth System Model at Mixed Resolution (MPI-ESM-MR, [*Jungclaus et al.* [2013]). This model features relatively high resolution (0.4°) in the ocean model and, compared to its lower-resolution counterpart, reduced biases in the hydrography of the South Atlantic. The three realizations started from different initial conditions in the ocean, which were taken at different time instants from a 1000 year long unperturbed pre-industrial control simulation (PiCtrl). Since we are interested in the almost centennial changes from the early 20th century to now, we compare ocean properties and heat contents averaged over the period 1995–2005 with the respective ones for the decade 1920–1929. To obtain an estimate of internal variability in the absence of external forcing, we calculate standard deviations for 10 year averages of the respective variables from the PiCtrl simulation. We have interpolated the simulated temperature and salinity data to the station network of the GAE. For the upper ocean (0–2000m), the ensemble mean difference between the present period and the GAE decade displays a similar warming magnitude (Figure 1g). While it is reassuring that some features found in the observations, like the maximum warming near 40°S and a reduced warming/slight cooling near 60°S robustly occur in the simulations, there are also intra-ensemble differences (Figure S4). The deeper ocean changes are less consistent in the simulations with two realizations showing a slight warming, and one a slight cooling, both at a similar magnitude as in the observations. Taking the control experiment as reference reveals, however, that only the upper ocean warming significantly and consistently exceeds the unperturbed internal variability (Figure S5).

[23] In terms of quantities integrated over the GAE network box (Figure 1a, Table S1) the simulated ocean (0–5000 m depth) warms between the 1920s to the 2000s by 0.112, 0.148, and 0.066 °C in the three realizations, bracketing the observed value of 0.119 °C. The heat content increases by 10.1×10^{22}, 14.24×10^{22} and 6.37×10^{22} J, respectively, a range that includes the observed value of 11.4×10^{22}J. All values exceed by far the PiCtrl decadal-mean standard deviation of about 1×10^{22} J. The corresponding heat uptakes read 0.713, 0.945, and 0.423 Wm^{-2} in the simulations and 0.758 Wm^{-2} in the GAE data. The relatively large intra-ensemble spread found in the South Atlantic heat uptake can be compared with the more homogeneous values calculated from the simulations for the global ocean: 0.41, 0.43, and 0.40 Wm^{-2}. An additional analysis of advective meridional heat transports at 33°S (not shown), which discriminates between gyre and overturning component, indicates that the more pronounced variations found in the South Atlantic are due to changes in lateral heat transports associated with variations in the meridional overturning circulation, possibly reflecting changes in the inter-ocean exchange from the Indian Ocean to the Atlantic [*Lee et al.*, 2011].

[24] Simulated salinity changes (Figures S4d–S4e) consistently reproduce salinification in the regions of strong heat uptake around 40^{o}S, but are less consistent with the observed upper-ocean salinity increase further to the north. Moreover, salinity changes are largely not significantly different from the control experiment variability in the interior ocean. As has been shown by *Durack et al.* [2012], changes in the hydrological cycle depend on more complicated feedbacks. Their analysis revealed that climate models, compared with ocean observations over the last 50 years, tend to show a weaker amplification of salinity patterns in a warming climate. A more thorough analysis on the simulated heat and fresh water budget of the South Atlantic is presently in preparation.

7. Conclusion

[25] Our comparison of high quality historic data with contemporary Atlantic hydrographic data revealed pronounced full-depth synchronous changes in temperature and salinity reflecting the evolution of 16% of the oceans' surface (18% of its volume) in response to Earth's warming during the 20th and early 21st centuries. The diagnosed warming corresponds to a regional heat uptake of 0.82 ± 0.28 W m^{-2}—a two times larger value compared to *Levitus et al*. [2012] global estimate of 0.39W m^{-2} between 1955 and 2010. These changes in temperature were accompanied by the changes in salinity, which increased by 0.030 ± 0.014 within the upper 2000 m layer. Changes in both parameters jointly contribute to the sea level rise of 3.7 cm. Comparing the observed century-scale changes with the MPI-ESM-MR simulations over the historical period reveals that the upper ocean warming is consistent with anthropogenic climate change. The amount of heat uptake over the last 90 years is consistently simulated in the experiments driven by estimates of anthropogenic aerosols and greenhouse gases in addition to natural forcing. It clearly exceeds the range of internal variability diagnosed from an unperturbed control experiment. On the other hand, the changes in the lower levels do often not exceed the range of internal variability and intra-ensemble differences indicate a prominent role of ocean circulation changes in determining the full-depth heat and fresh water budget. The diagnosed salinification of the upper 2000 m layer can be interpreted as the manifestation of the hydrological cycle intensification [*Curry et al*., 2003], but decadal-scale variations are also prominent in simulations and observations. For example, the global analysis of the surface and near-surface temperatures [*Gouretski et al*., 2012] reveals a reversal in temperature trends in the Southern Ocean, where the warmest temperatures since 1900 (especially in the Atlantic sector) were reached between 1970 and 2000, followed by a cooling. Such decadal scale reversals of the thermal conditions in the Antarctic regions, together with circulation changes, could potentially explain the observed deep and bottom water cooling since the 1920s.

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