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Variability of Thermohaline Characteristics at 26.5 N in Reanalyses and Oceanographic Section Data

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Abstract—The most common methods for studying the variability of ocean parameters are field measurements and numerical modeling. Due to the insufficient availability of ocean measurement data, it is not always possible to verify the reliability of modeling results. Changes in temperature and salinity of the Atlantic Ocean water masses at 26.5 N in the recent 30 and 70 years are estimated. The estimation is based on the data of SODA, ORAS4, ECCO, GECCO reanalyses, EN4 and WOA13 objective analyses, and six regular oceanographic sections. In 1992 to 2016, all reanalyses simulate an increase in temperature and salinity of surface water for the entire section, which is consistent with field data. On average, the reanalyses overestimate temperature by 0.1–0.3 C and salinity by 0.02–0.05 psu. The closest values to field data are reproduced by the ORAS4 reanalysis and EN4 objective analysis. Trends in temperature and salinity coincide best with the EN4 results.

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INTRODUCTION

One of the major problems of ocean studies is the insufficient volume of field data for many ocean areas far from the shore, especially at large depths. Despite a great number of expeditionary and autonomous measurements, the North Atlantic is not an exception, because observations at standard oceanographic sections from the shore to the shore suitable for assessing changes in the deep water characteristics are conducted once a year at best. As the numerical modeling developed, reanalyses became widely used. They provide information on the ocean parameters with various spatial (usually 0.25 –1) and temporal (usually monthly) resolution. The use of different initial data and boundary conditions leads to ambiguous results. Reanalyses are a convenient tool for estimating long-term changes in thermohaline characteristics of water masses; however, there are very few studies (for example, [3, 8]) which compare reanalyses with each other and with the results of field measurements.

The objective of the present paper is to estimate long-term variations in temperature and salinity in the North Atlantic by an example of the transatlantic section along 26.5 N. To achieve the above goal, it is necessary to compare reanalyses with each other and with the data of regular oceanographic sections in order to corroborate the correctness of simulation of potential temperature and salinity by reanalyses for the whole section and for different water masses as well as the direction of their trends.

The North Atlantic was chosen for the study because this is the region with the largest available volume of field data. In particular, the section along 26.5 N was selected due to the presence of regular high-precision measurements from 1992 till now; continuous autonomous measurements have been carried out there in the framework of the RAPID program [11] since 2004. The position of expeditionary sections slightly deviates from the position of the reanalysis section due to a complex trajectory of the section (the difference is to 2 of altitude). Hereinafter, the term "section" is used both for oceanographic sections and for the samples of reanalyses data along ~26.5 N.

Two time periods were chosen for the comparison: 1992–2016 and 1955–2016. The first period coincides with the period of regular field measurements (approximately once in six years), the second period is interesting for studying long-term changes in temperature and salinity; most studies [4, 6, 9, 13, 14] cover the entire time interval.

According to the results of numerous studies since 1955, a trend toward the warming has generally been observed for the upper 3000-m layer of the North Atlantic [4, 9, 13]. The main contribution to the ocean heat content increase is made by surface water; however, the warming trend is observed in deeper layers as well. It should be noted that in most papers [8–10, 14], the explored North Atlantic layers whose boundaries are situated at the depth of 500, 700, 1000, and 3000 m do not correspond to water masses [11]; therefore, it is not always possible to reveal trends in water mass characteristics confidently.

According to data presented in [10], in 1955–1998 a significant increase in the heat content of the upper 3000-m layer of the North Atlantic amounted to 4.8 10^{22} J; this corresponds to the temperature rise by 0.095°C that is two times lower than according to data presented in [4]. The authors of [13] based on measurement data only and made a conclusion about the warming in the upper 3000-m layer of the North Atlantic with the rate of 0.012 0.009 C per decade in 1955–2000.

The authors of [7] studied salinity variations in the Atlantic Ocean using the data of quasimeridional sections averaged over the periods of 1955–1969 and 1985–1999. According to these data, northward of 40 N average salinity decreased by 0.03 psu. At 26 N, in the upper 1000-m layer (surface and intermediate waters) salinity significantly increased by 0.03–0.5 psu with the maximum near the surface, while temperature grew in the upper 2000-m layer to 1 C with the maximum at the depth of 800–1000 m.

According to [10], an increase in the heat content of the upper 700-km layer amounted to 3.6 10^{22} J/100 years or 0.27 C/100 years. In accordance to [9], heat content increase for the whole layer of 0–1450 m exceeding 6 10^{18} J/year was observed at 26 N in 1955–2003. Trends towards the warming that reaches the maximum values close to the surface are observed in the Atlantic Ocean from 10 to 30 N [9].

Paper [8] is one of the few papers dealing with the intercomparison of reanalyses; it studied the North Atlantic heat content variations for the period from 1955 to 2013 based on EN4.0.2, ORAS4, and ECDA reanalyses with the resolution of 1 and on the SODA 2.2.8 reanalysis with the resolution of 0.5 . The SODA, EN4, and ORAS4 reanalyses reproduce a roughly identical increase in the heat content for the upper 700-m layer: ~3 10^{22} J that is slightly smaller than the value presented in [10].

The authors of [14] note the salinization of the upper 500-m layer in the tropical region by 0.07 psu per 40 years (1957–1996). Study [5] indicates the salinization of the layer of 0–1500 m (surface and intermediate water) in the area of 40 N in the North Atlantic in 1955 to 1998, with the linear trend of 0.0005 psu/year. The authors of [6] analyzed variations in temperature and salinity at the section along 24.5 N for 1957–2004. The warming and salinization of the layer of 500–1750 m with the rate of 0.0065 C/year and 0.0004 psu/year, respectively, were registered.

Study [15] described temperature rise in the intermediate and deep layers by 1 C/100 years in 1957–1998 which was calculated from the data of field sections along 24 N in the North Atlantic.

The authors of [2] used oceanographic sections to compute trends in potential temperature for Antarctic intermediate water (AAIW) for 1920–1990. In 1957–1981 temperature rise at 24 N was equal to 0.75 C/100 years in the western part of the Atlantic basin and 0.048 C/100 years in the eastern part of the basin. The respective values for 1981–1992 are 0.3 C/100 years and 1.621 C/100 years. According to [7], AAIW salinity dropped by 0.02 psu in 1969–1999.

In 1957–2004, according to [6], the layer deeper than 1760 m was cooled with a trend of –0.0021 C/year and was desalinated with the rate of –0.0003 psu/year. In opinion of the authors of [13], the warming in the layer of 1000–3000 m by 0.1 0.021 C was also registered during the same time period. Based on measurement data, the authors of [12] detected a trend towards an increase in potential temperature in the core of Antarctic bottom water (AABW) in the South Atlantic in the Vema Channel since 1972 (~0.05 C/100 years). The authors of [1] used data of field measurements at 8 S for the period from 1957 to 1994 to estimate temperature and salinity variations in AABW: by –0.063 C and 0.001 psu per 100 years.

Thus, most authors state the trend towards the warming in the subpolar North Atlantic in the recent 70 years both for the entire layer and for separate water masses.

DATA AND METHODS

Data of four reanalyses and two objective analyses were used for the comparison. Reanalyses utilized data on the fluxes of heat and momentum and freshwater flows on the boundaries, whereas the objective

Table 1. The characteristics of reanalyses and objective analyses (EN and WOA) used in the present study

Parameter	ORAS4	SODA	ECCO	GECCO	EN	WOA
Version	4	2.2.4	GODAE v3.xx	1	4.2	2013v2
Developer	European Centre for Medium-range Weather Forecasts (ECMWF)	University of Maryland	National Oceanographic Partnership Program (NOPP)	National Oceanographic Partnership Program (NOPP)	U.K. MetOffice	National Oceanogra- phic Data Center (NODC/NOAA) –
Model	NEMO 3.0	MOM5	MITgcm	MITgcm	–	1955–2012
Calculation period	1958–2009	1871–2010	1992–2002	1952–2001	1900–2017	–
Reanalysis type	3D	3D	3D	4D	4D	0.25 0.25
Spatial resolution	1 1	0.5 0.5	1 1	1 1	1 1	102
Number of horizons	42	50	23	23	42	5500
Last horizon, m	5350	5375	5450	5450	5350	WOD13
Source of data	EN3v2	WOD09	WOCE climatology, Argo, WOCE	CTD, MBT/XBT, Argo, ToGA/TAO	WOD13 ASBO, GTSPP, Argo	–
Atmospheric fluxes	ERA-40, ERA-Interim	20CRv2	NCEP	NCEP-1	–	–
Assimilation of SST and ice	ERA-40, NCEP OI v2	ICOADS 2.5	Reynolds/TIM/ AMSR-E SST	AMSR/E/TMI SST	–	

analyses were obtained using the spatiotemporal interpolation alone, without consideration of the ocean dynamics. Hereinafter, for ease of presentation, the term “reanalyses” is applied to the objective analysis as well.

The ORAS4, SODA, and ECCO reanalyses utilize different models and different initial thermohaline data and data on atmospheric flows. The GECCO reanalysis uses a model similar to ECCO but based on the four-dimensional computation scheme. This system differs from the three-dimensional one, during calculations it assimilates not only surface values but also bottom profiles of temperature and salinity (Table 1).

To obtain a more detailed pattern of temperature and salinity variations for the entire section as well as to identify reasons for the warming (cooling) and salinization (desalination), the main water masses were analyzed separately. The boundaries of water masses are similar to those used in [11] in the framework of the RAPID project:

—surface water (SW): 0–800 m;

—Antarctic intermediate water (AAIW): 800–1100 m;

—upper North Atlantic deep water (uNADW): 1100–3000 m;

—lower North Atlantic deep water (lNADW): 3000–5000 m;

—Antarctic bottom water (AABW): >5000 m.

Mean temperature and salinity were calculated by the spatial averaging over the section area. The time series of average annual temperature and salinity for 1992–2016 were constructed for the comparison with the data of regular field measurements. The study utilizes CTD measurements at the oceanographic section A05 which were carried out along ~25 N with the six-year periodicity: in August 1992, February 1998, April 2004, February 2010, January 2011, and January 2016. At each section, ~100 stations are located, the average distance between the stations is ~0.5 .

The longer series based on the SODA, ORAS4, EN4, World Ocean Atlas (WOA13) reanalyses for the period from 1955 till now were constructed to compare reanalyses and to estimate changes in the parameters. The WOA13 was applied for the comparison as the most widely used source of initial data for numerical models; it represents the fields of objective analysis of thermohaline data averaged over six decades.

Three corrections were applied for the accurate comparison of temperature and salinity computed from data of reanalyses and sections. It should be noted that the value of corrections is very significant and comparable with the variation range of characteristics.

The correction for the section position was applied only for the data of field sections. To calculate it, the mean values of temperature for the section along 26 N and for the section being maximally close to the real coordinates of the analyzed section were computed using SODA reanalysis data. The correction represents a difference between the obtained values.

The correction for a month when the section was performed, was applied only to the data of field sections. This correction is used for reducing the value for a particular month to the average annual value; it was calculated from the SODA reanalysis data.

The corrections for the entire section are presented below (the numerator gives the correction for the section position, and the denominator provides the correction for a month):

Month	August 1992	February 1998	April 2004	February 2010
Temperature, C	0.1438/–0.0497	0.0638/0.0239	0.0487/0.0444	0.1113/0.0132
Salinity, psu	0.0072/0.0037	0.0054/–0.0056	0.0061/–0.0029	0.0140/0.0035

Only the values which correspond to the horizons of reanalyses were taken from the data of the real section to calculate the correction for irregularity of reanalyses data. Then the whole section was retrieved from the selected values by the bilinear interpolation. This correction is a difference in the average values of temperature and salinity between the real and retrieved sections. For example, in 1992 the correction for irregularity of temperature data for the whole section was 0.037 C.

The value of corrections for surface and intermediate waters reaches 0.4 C and 0.04 psu. The corrections for deep layers do not exceed 0.07 C and 0.02 psu for uNADW, they are by an order of magnitude smaller for deeper layers.

RESULTS AND DISCUSSION

The analysis of temperature and salinity dynamics is presented for two periods. In 1992–2016, the oceanographic section along 26.5 N was performed every six years that allows analyzing trends in thermohaline parameters of water masses during that period and comparing them with reanalyses data (GECCO and ECCO reanalyses cover only a part of this time period). The period of 1958–2016 was interesting for the analysis of long-period changes, this period is covered by most reanalyses.

Temperature and salinity variations in 1992–2016. Surface water (the layer of 0–800 m) is the most variable layer. The maximum range of interannual temperature variations is 0.37 C in reanalyses (EN4) and 0.44 C in field data. The reanalyses demonstrate an intense warming during 2000–2005. The stable warming is observed for the whole analyzed time period (see Fig. 1a), which is corroborated both by reanalyses and measurements: +0.33 C for the EN4 and +0.18 C for the SODA. In terms of absolute values, temperature is the closest to the EN4 and ORAS4 data. This may be associated with the fact that the EN4 is the objective analysis of observational data and the ORAS4 utilizes its previous version EN3.

Besides the direct atmospheric effect, high variability of temperature in the layer of 0–800 m is associated with oscillations in the Atlantic meridional overturning circulation (AMOC) [11]. For example, a significant decrease in the transport in the lower cell of AMOC corresponding to lNADW was observed in 2010. In opinion of the authors of [11], this should cause the strengthening of the eddy transport in surface water, hence, temperature decreases in this layer. This effect is clearly observed in field measurement data obtained in 2010 and 2011; however, it is poorly simulated only by the EN4 reanalysis, which means the absence of the physical relationship between AMOC and the surface layer in the models. Despite high variability of temperature, a high coefficient of correlation between reanalyses is observed in this layer (up to 0.9).

Salinity in this layer is characterized by more complex variations (Fig. 2a), and the correlation between reanalyses is almost absent. However, reanalyses and field data demonstrate salinity growth by 0.2–0.6 psu during the whole analyzed period.

According to field data and ORAS4, EN4, and SODA reanalyses, there is no strongly pronounced trend in temperature variations in AAIW (800–1100 m). An insignificant warming by 0.08–0.12 C is observed during the entire analyzed period, which is however comparable with the amplitude of temperature fluctuations. The GECCO reanalysis in this layer provides significantly overestimated values (by more than 1 C) and the confident warming by 0.3 C during 1992–2002. The ECCO reproduces an insignificant warming

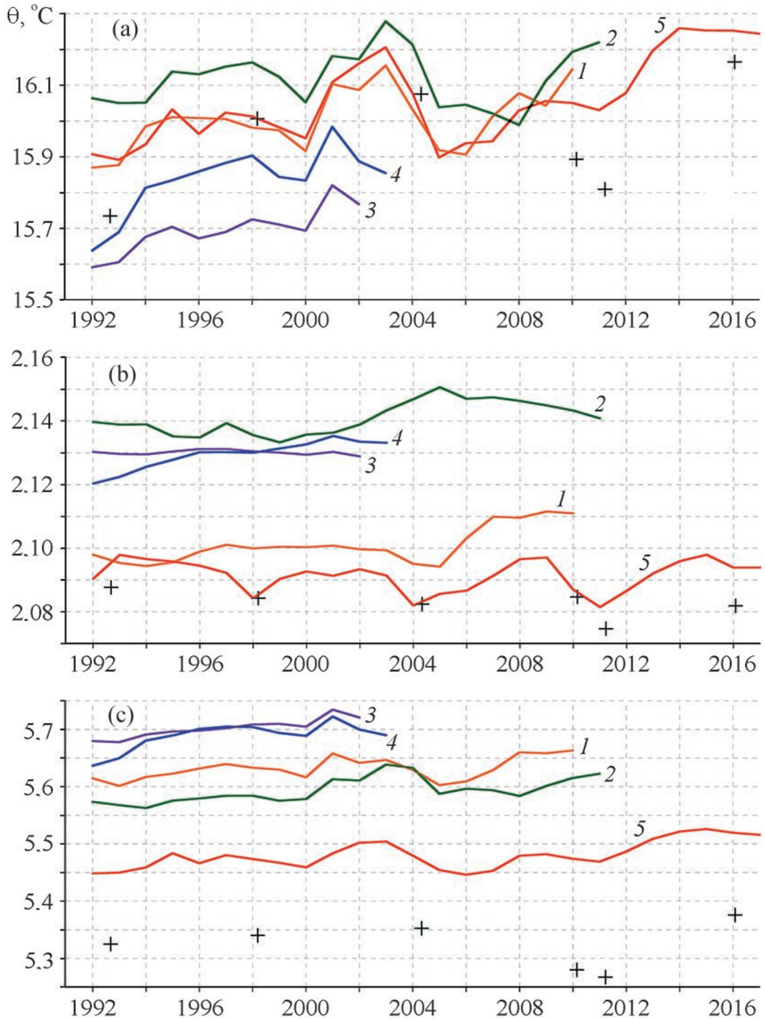

Fig. 1. Average potential temperature of (a) surface water, (b) lower North Atlantic deep water, (c) and the entire section derived from (*1–5*) reanalyses and field data (section A05, the crosses). Reanalyses data here and in Fig. 2: (*1*) ORAS4; (*2*) SODA; (*3*) GECCO; (*4*) ECCO; (*5*) EN4.2.

till 1997; then, temperature drops by 0.2 C till 2003 that contradicts the other reanalyses. The EN4 simulates the lowest values being the closest to field data. Salinity variations in this layer have a similar pattern to temperature variations. Over the entire period, salinization and desalination are observed only from GECCO (till 2002) and ECCO (till 2003), respectively.

In the uNADW layer, all reanalyses overestimate temperature as compared with field data by 0.1 C on average. The significant temperature and salinity variations for the whole time interval are absent both in reanalyses and field data. The GECCO reproduces lower salinity than the other reanalyses but it agrees best with field data.

In the NADW layer, the values of temperature and salinity being the closest to field data are simulated by the ORAS4 and EN4 (Figs. 1b and 2b). The other reanalyses overestimate temperature by 0.04 C and salinity by 0.012 psu on average. The close values of temperature and salinity to field data in the ORAS4 may be caused by the use of the EN3 as initial data. For this layer, the EN4 deserves special attention, because its results demonstrate that the values of temperature and salinity regularly approach field data in the years of regular sections and the values are close to expeditionary data.

In the AABW layer, the EN4 data also approach field data. The ORAS4 reproduces insignificant drops in temperature and salinity over the entire analyzed period, unlike the other reanalyses. The closest values to field data for temperature are simulated by the ECCO and GECCO and those for salinity are reproduced

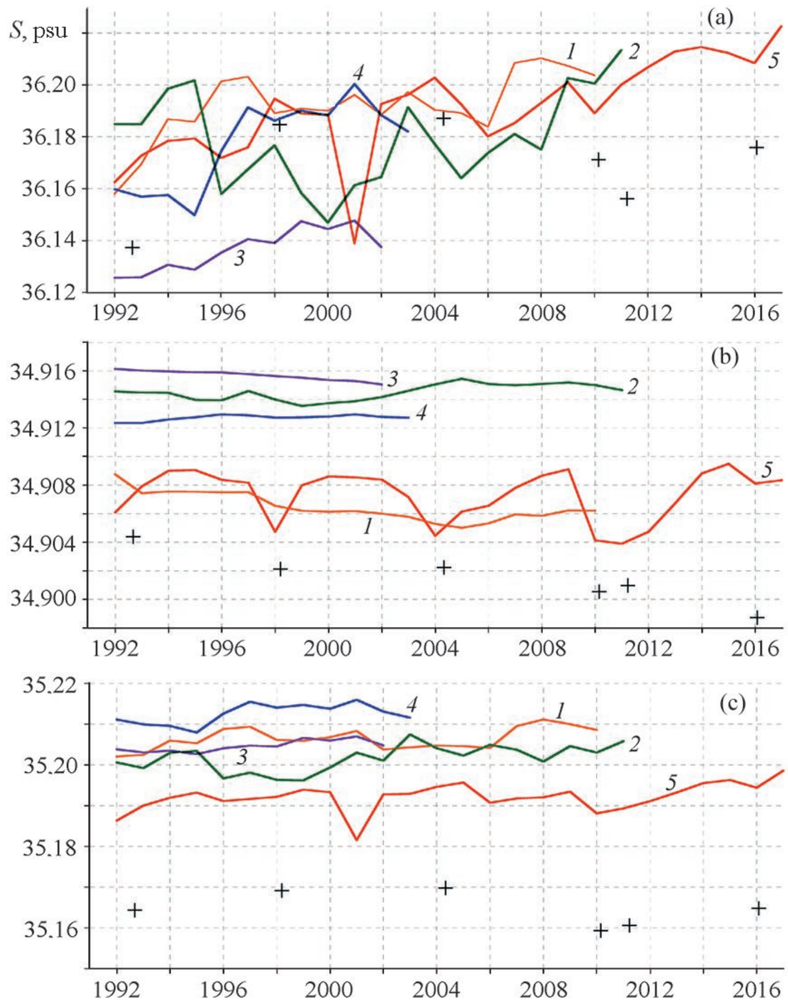

Fig. 2. Average salinity of (a) surface water, (b) lower North Atlantic deep water, (c) and the entire section derived from (*1–5*) reanalyses and field data (section A05, the crosses).

by the ECCO, GECCO, and EN4. In general, observational data demonstrated the 0.015°C warming and insignificant desalination.

The reanalyses results are "separated" from observational data for the whole section (Figs. 1c and 2c). On average, all reanalyses overestimate temperature by 0.1–0.3 C and salinity by 0.02–0.05 psu. The lowest temperature and salinity are reproduced by the EN4 which fits best field data. This is caused by the lower values in deep layers as well as by the described artificial rapprochement of the results to field data in the lNADW and uNADW layers. According to field data, a decrease in temperature and salinity is observed in 2010–2011, which is perhaps associated with the described weakening of AMOC [11]. The EN4, ORAS4, and SODA simulated an increase in average temperature for the entire section by 0.05–0.07 C over the whole analyzed period; according to observational data, the increase amounts to 0.05 C. The salinity growth is 0.005–0.013 psu according to the EN4, ORAS4, and SODA data and 0.001 psu according to observational data.

Besides the analysis of variations in mean temperature and salinity of water masses and the entire section, the objective of the present study is to assess the quality of reanalyses in simulating temperature and salinity trends. The standard deviation of results of reanalyses (in the section year) from field data was calculated to evaluate the simulation of the absolute values of temperature (Table 2). The EN4 data agree best with observational data. The low values of the standard deviation for temperature are observed for the SODA (except SW and lNADW) and ORAS4 (except AABW) reanalyses, and those for salinity are registered for the ORAS4 (except uNADW).

Table 2. Average standard deviations of temperature and salinity for the entire section and different water masses derived from reanalyses and field data

Reanalysis	Entire section	SW	AAIW	uNADW	lNADW	AABW
Potential temperature, C						
ECCO	0.339	**0.100**	0.810	0.120	0.040	**0.015**
GECCO	0.362	0.223	1.397	0.131	0.044	**0.024**
ORAS4	0.314	0.145	0.689	0.129	0.017	0.115
SODA	0.296	0.287	0.756	0.104	0.059	0.084
EN4	**0.157**	0.136	**0.503**	**0.088**	**0.006**	0.050
Salinity, psu						
ECCO	0.046	**0.016**	0.121	0.031	0.009	**0.009**
GECCO	0.038	0.033	0.266	**0.006**	0.013	0.011
ORAS4	0.040	0.020	0.112	0.030	**0.005**	0.015
SODA	0.038	0.036	0.100	0.280	0.013	0.017
EN4	**0.026**	0.027	**0.081**	0.026	**0.005**	**0.009**

Note: The smallest deviations are bolded.

Table 3. The simulation of trends in temperature (numerator) and salinity (denominator) by reanalyses

Reanalysis	Years	Entire section	SW	AAIW	uNADW	lNADW	AABW
SODA	1992–1998	+/–	+	+/–	+/–	–	+
	1998–2004	+	+	+	–	–/+	–/+
	2004–2010	+	–	+/–	+	–/+	–/+
ECCO	1992–1998	+	+	+	+/–	+/–	–
	1998–2004						
	2004–2010						
GECCO	1992–1998	+	+/–	+	+	–	–/+
	1998–2004						
	2004–2010						
ORAS4	1992–1998	+	+	+	–	+	–/+
	1998–2004	–	–/+	+	–	+/–	+/–
	2004–2010	–	+	–	+	+/–	+/–
EN4	1992–1998	+	+/–	+	–/+	+	+
	1998–2004	+	–/+	+	–	+	+/–
	2004–2010	+	–	+	+	+	+

Note: The plus means that trends are reproduced by a reanalysis, the minus means that trends are not reproduced.

The simulation of trends in the analyzed parameters was assessed by comparing temperature and salinity changes for the corresponding water mass during time periods between the regular sections. A trend coincides if the parameter variations derived from reanalysis and field data are of the same sign. Table 3 presents the results of the trend analysis.

The most frequent coincidence of trends is observed for data of the EN4 objective analysis in all layers except for SW and uNADW. According to the SODA results, temperature trends coincide in the upper layers and for the entire section; salinity trends coincide in deep layers. The ORAS4 simulates the trends corresponding to the trends in field data in SW and to the temperature trends in lNADW and AABW.

Long-term variations in temperature and salinity in 1955–2016. Variations were investigated from the EN4, ORAS4, SODA, and WOA13 reanalyses for the period from 1955 to 2016. In the surface layer, the steady growth of potential temperature (from 0.25 to 0.54 C) and salinity (from 0.034 to 0.063 psu) has

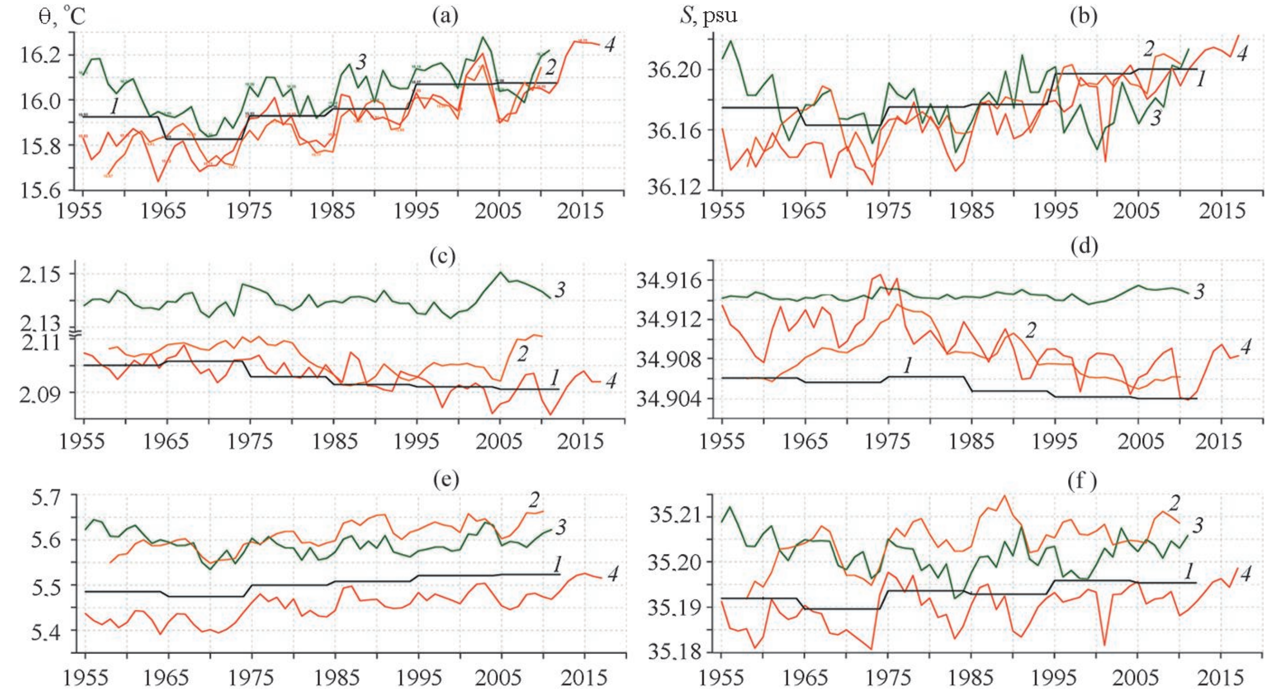

Fig. 3. Average (a, c, e) temperature and (b, d, f) salinity of (a, b) surface water, (c, d) lower North Atlantic deep water, (e, f) and the entire section in (*1*) WOA13, (*2*) ORAS4, (*3*) SODA, and (*4*) EN4.2 reanalyses.

been observed since 1970 and is reproduced by all reanalyses (Figs. 3a and 3b). The similar temperature trend was described in [10], where the temperature rise in the upper 700-m layer was estimated at 0.27 C/100 years. The authors of [14] note the salinization of the upper 500-m layer in the tropical region by 0.07 psu during 1957–1996, the ORAS4 and EN4 simulate the salinity growth by 0.04 psu over the same period. According to the other reanalyses, a decrease in temperature (from –0.1 to –0.27 C) and salinity (from –0.012 to –0.04 psu) was observed till 1970.

The variations in temperature and salinity in AAIW derived from the EN4, ORAS4, and WOA13 are insignificant. The SODA simulates a stable decrease in AAIW temperature by 0.15 C and in salinity by 0.05 psu. A slightly underestimated salinity variation was described in [7], where AAIW salinity in 1969–1999 dropped by 0.02 psu. The authors of [15], on the contrary, describe the temperature rise in the intermediate and deep layers by 1 C/100 years during 1957–1998 calculated from data of field sections along 24 N in the Atlantic Ocean; the authors of [2] made the conclusion on the temperature growth from 1957 to 1992 based on the data of oceanographic sections.

According to the WOA13, EN4, and ORAS4 data, potential temperature in uNADW increases by 0.03–0.076 C, and salinity varies insignificantly except for an increase by 0.02 psu in 1975–1995. The SODA reproduces the temperature drop by 0.027 C and the salinity growth by 0.015 psu in 2000–2011.

The SODA simulates insignificant changes in temperature and salinity of lNADW during the analyzed period; however, the other reanalyses demonstrate an insignificant decrease in both parameters with a certain increase (<0.01 C and <0.008 psu) in 1970–1985. The absolute values of temperature and salinity derived from the SODA are higher than those for the other reanalyses (Figs. 3c and 3d). The trend towards the temperature decrease simulated by the SODA is also described in [6]: the layer below 1750 m was cooled by 0.0021 C/year and was desalinated with the rate of –0.0003 psu/year during 1957–2004.

The values of temperature and salinity of AABW derived from data of all reanalyses are higher than those for the WOA13. The difference in the absolute values of temperature and salinity is caused by difference of the lower layer depth in reanalyses; this directly affects the number of horizons corresponding to AABW. The higher AABW temperature is, the higher the last reanalysis horizon is. The ORAS4 reproduces the temperature rise by 0.02 C being close to the value presented in [12]. The mentioned paper revealed a trend towards an increase in potential temperature in the AABW core in the South Atlantic in the Vema Channel since 1972 (~0.05 C/100 years). It also detected the salinity growth by 0.006 psu till 1997 thus exceeding the value calculated in [1] where the salinity growth is estimated at 0.001 psu per 100 years in 1957–1994.

The ORAS4 and SODA simulate close values for the whole section which are slightly higher than the results of the EN4 and WOA13 being close to each other (Figs. 3e and 3f). In 1955 to 2010, the ORAS4, EN4, and WOA13 simulate an increase in average temperature at the section by 0.03–0.08 C (the highest value is observed for the ORAS4). This is slightly below the values presented in [13], where the authors make the conclusion on the warming in the 3000-m layer of the North Atlantic by 0.012 0.009 C/10 years during 1955–2000 based on measurement data only. The ORAS4 and WOA13 also simulate the salinity growth at the entire section by 0.017 and 0.03 psu, respectively. The EN4 reproduces an insignificant salinity reduction that does not exceed the salinity variation range over the whole time period. The SODA, unlike the other reanalyses, simulates a decrease both in temperature (by 0.08 C) and salinity (by 0.06 psu).

CONCLUSIONS

There is the temperature rise for the entire section by 0.037–0.08 C that agrees with data from [10] and the salinity growth at the section by 0.017–0.03 psu according to all data except the SODA during 1955–2016. The temperature increase for the whole section is especially defined by the warming in the surface layer that corroborates the results of [9].

According to the SODA reanalysis, unlike the ORAS4, WOA13, and EN4, in 1955–2016 there is the decrease in temperature (by 0.08 C) and salinity (by 0.06 psu) for the whole section. The differences of the SODA data are caused by high values in surface and deep water.

In 1992 to 2016, all reanalyses simulate the increase in temperature and salinity of surface water that agrees with field data and reanalyses [8] and, hence, the temperature rise for the entire section. In general, the reanalyses overestimate temperature by 0.1–0.3 C and salinity by 0.02–0.05 psu.

The significant temperature drop in surface water in 2010–2011 observed for field data and described in [11] is poorly simulated from field data and EN4 objective analysis. In deep layers, there is no similarity of the EN4 results to field data, except for the years of regular sections, when temperature and salinity in the EN4 approach field data, which is probably caused by the assimilation of data of these sections.

The closest values to field data are reproduced by the ORAS4 and EN4 reanalyses. The trends in temperature and salinity derived from the EN4 data indicate the trends based on field data better than the other reanalyses.

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REFERENCES

1. E. V. Krayushkin and A. N. Demidov, “Global Change in Thermohaline Characteristics of Intermediate, Deep, and Bottom Water Masses in the South Atlantic,” Vestnik Moskovskogo Un-ta, Ser. 5, Geografiya, No. 2 (2014) [in Russian].
2. B. Arbic and W. Owens, “Climatic Warming of Atlantic Intermediate Waters,” J. Climate, No. 20, **14** (2001).
3. M. Balmaseda, K. Mogensen, and A. Weaver, “Evaluation of the ECMWF Ocean Reanalysis System ORAS4,” Quart. J. Roy. Meteorol. Soc., **139** (2013).
4. P. Barnett, D. Pierce, and R. Schnur, “Detection of Anthropogenic Climate Change in the World’s Oceans,” Science, **292** (2001).
5. T. Boyer, “Linear Trends in Salinity for the World Ocean, 1955–1998,” Geophys. Res. Lett., **32** (2005).
6. S. Cunningham, T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. J.-M. Hirschi, L. M. Beal, C. S. Meinen, and H. L. Bryden, “Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5 N,” Science, **317** (2007).
7. R. Curry, B. Dickson, and I. Yashayaev, “A Change in the Freshwater Balance of the Atlantic Ocean over the Past Four Decades,” Nature, **426** (2003).
8. S. Hakkinen, P. Rhines, and D. Worthen, “Heat Content Variability in the North Atlantic Ocean in Ocean Reanalyses,” Geophys. Res. Lett., No. 8, **42** (2015).

9. S. Levitus, J. Antonov, T. Boyer, O. K. Baranova, H. E. Garcia, R. A. Locarnini, A. V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, and M. M. Zweng, "World Ocean Heat Content and Thermosteric Sea Level Change (0–2000 m), 1955–2010," Geophys. Res. Lett., No. 10, **39** (2012).
10. S. Levitus, J. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli, "Anthropogenic Warming of Earth Climate System," Science, **292** (2001).
11. G. McCarthy, E. Frajka-Williams, W. E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. Roberts, and S. A. Cunningham, "Observed Interannual Variability of the Atlantic Meridional Overturning Circulation at 26.5° N," Geophys. Res. Lett., No. 19, **39** (2012).
12. E. G. Morozov, A. N. Demidov, R. Y. Tarakanov, and W. Zenk, *Abyssal Channels in the Atlantic Ocean* (Springer, 2010).
13. I. Polyakov, A. Beszezynska, E. Carmack, I. A. Dmitrenko, E. Fahrbach, I. E. Frolov, R. Gerdes, E. Hansen, J. Holfort, V. V. Ivanov, M. A. Johnson, M. Karcher, F. Kauker, J. Morison, K. A. Orvik, U. Schauer, H. L. Simmons, O. Skagseth, V. T. Sokolov, M. Steele, L. A. Timokhov, D. Walsh, and J. E. Walsh, "One More Step toward a Warmer Arctic," Geophys. Res. Lett., No. 17, **32** (2005).
14. P. Stott, R. Sutton, and D. Smith, "Detection and Attribution of Atlantic Salinity Changes," Geophys. Res. Lett., No. 21, **35** (2008).
15. M. Vargas-Yanez, G. Parrilla, A. Lavin, P. Velez-Belchi, and C. Gonzalez-Pola, "Temperature and Salinity Increase in the Eastern North Atlantic along the 24.5 N in the Last Ten Years," Geophys. Res. Lett., No. 6, **31** (2004).