DECADAL CHANGES OF THE θ -S RELATIONSHIP OF THE EASTERN NORTH ATLANTIC CENTRAL WATER.

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ABSTRACT

Observations of the eastern North Atlantic mode waters spanning a 20-year period have been assembled; the data set includes previously unpublished observations as well as historical data. The spatial and temporal variations have been investigated. Along 42°N, the freshening of salinity on the isopycnal $\sigma_\theta = 27.1$ is shown to persist until 1990, with an abrupt increase in 1991 to levels not seen since the late 1970s. Some suggestions are made of mechanisms that may be involved in the variability.

INTRODUCTION

When studying global warming and recent regional climate changes, and relating the temperature changes to the existence of large periodic cycles of the thermohaline properties in marine water masses, it is difficult to discern the causes of the more recent changes observed in the North Atlantic (Clarke, 1992). Becker et al. (1992) also show a continuous increase in salinity at surface waters in the English Channel and the Southern North Sea over the last two years. Ellett and Turrell (1992) studied a time series and described the surface saline evolution of the Rockall Trough. They showed that salinity values returned to the maximum values found during the 1960s in late 1989 to early 1990.

Similar changes have also occurred in the Eastern North Atlantic Water, as shown later. Pollard and Pu (1985) analysed the salinity on an isopycnal layer ($\sigma_\theta = 27.1$) along 42°N, and found that between the IGY(1958) and 1977 there was a freshening of approximately 0.1, west of about 15°W, which became reduced towards the Iberian coast. Overplotting the data set from 1989 and 1990 in Pollard and Pu's figure, King (1991) noted the extension of salinity decreases in the last years of the past decade towards the Iberian peninsula.

During 1991 two oceanographic cruises occurred in this area; VIVALDI and GALICIA-XI. The VIVALDI survey (Charles Darwin-58) was designed to resolve features of the subtropical and subpolar circulation. The Spanish cruise Galicia XII studied coastal processes and biological implications in the Iberian coast. In both cruises similar and sudden changes in the thermohaline characteristics of Eastern North Atlantic Central Water (hereafter, ENAW) were identified. These observed saline changes driven us to collect the interannual variability recorded during the two last decades in the Iberian sector of the eastern North Atlantic and to study the spatial variability of these changes with the

aim to assess about what possible mechanism or changes in the thermohaline circulation are involved.

The seasonal changes studies in the thermohaline properties had shown a gradual increase of temperature and salinity from spring to late autumn at a fixed latitude as in open sea as in the shelf during the upwelling season (Rios et al. 1992, Alvarez-Salgado et al, 1993). These thermohaline changes due to the thermohaline circulation are restricted to the Θ -S line which define the annual class of ENAW which is formed or modified each winter. The thermohaline or saline changes (forward) here shown, will relate with the annual variation of the Θ -S line which will define for the saline changes at a fixed density, usually 27.1. These changes is not affected by the seasonal changes because these only increase the length of the segment representative of ENAW or also its salinity maximum at a given position.

Θ -S RELATIONSHIP OF ENAW

The different characteristics of ENAW compared with WNAW have already been described by several authors (Iselin, 1936; Helland-Hanssen and Nansen 1926). Since the last decade, a different definition for these central waters has been used, and is located in different geographic areas of the North Atlantic (Fiuza, 1984 and Emery and Meincke 1986). From IGY data, Harvey (1982) described the formation of several mode waters from south of the subpolar gyre as far as 45°N in the Bay of Biscay. The characteristics are very close to those given by Helland-Hanssen, with maximum values of 35.66 and 12 °C in salinity and temperature respectively. By comparison Fiuza and Halpern (1982) and Pollard and Pu (1985) describe ENAW characteristics east of the Azores, also dominant in water of the Iberian upwelling system, with a lower limit of 35.7 in salinity. Subsequently Ríos et al (1992) summarized both descriptions of ENAW and classified the subpolar and subtropical origin of ENAW, in relation to the salinity being higher or lower than 35.66, and giving its distribution in the Eastern North Atlantic.

The standard Θ -S lines representative of WNAW and ENAW are showed in Table 1. The deviations, usually parallel changes, in the Θ -S distributions in a given area at a given time are due to gradual or abruptly winter modifications of the Central Water, mainly advected from the west (Pollard et Pu, 1985; Sy, 1988) or the south (Frouin et al. 1990).

TEMPORAL VARIATIONS OF θ -S RELATIONSHIP

During the last decade several cruises repeatedly surveyed the North Atlantic with an ongoing interest in the formation, characteristics and circulation of mode water. Figure 1b shows the θ -S relations of 10 profiles from Discovery-132 carried out in February 1983 in a section close to 42°N from 12°W to 21°W. Figure 1a also shows the θ -S ratios of samples taken in the Galicia-VI cruise in an area from 40°N to 47°N and from 9°W to 11°W during December 1983. Both figures show similar thermohaline properties. Practically all of the samples of Central water are situated between the representative curves of ENAW and WNAW. The central water bodies found exhibit a lower salinity and/or higher temperature than expected if the representative ENAW curve is considered, especially its subtropical component which appear to be WNAW.

During 1986 two other cruises surveyed the same area. The CTD profiles of Discovery-162 (November 1986) were taken close to those of Discovery-132, and are parallel with the reference line of ENAW in both the subpolar and subtropical components (Fig. 2b). The sample bottles of the Galicia-IX (September 1986) off the Galician coast show a similar relationship to that given by the ENAW line (Fig. 2a). Also in 1989 the thermohaline characteristics of Central waters found during the French cruise Bord-Est 3 in an area off the Iberian coast (37°-45°N and 9°-13°W) agree with the ENAW line (Fig. 3a). A similar pattern of ENAW was found (Fig. 3b) during 1990 in data collected during Discovery-189 along a section close to 42°N between 9°W and 18°W.

During May 1991, as part of UK WOCE, Charles Darwin Cruises 58 and 59 sampled an area between 39°N and 54°N and 12°W and 28°W. A Spanish cruise, "Galicia-XI", also worked close to the Iberian Peninsula. In this cruise three stations off the continental slope (number 55,74,84) were occupied using a Sea-Bird 9/11. The thermohaline ratios (Fig. 4a) show clear differences from those found in former years, being more saline and colder than the ENAW reference line. Figure 4a also includes a θ -S profile of a CTD cast taken at the closest station (12°W and 42°N) to the Iberian peninsula during Darwin-58. This profile is very similar to those made on the Spanish cruise.

During March 1992, inside the Ria of Vigo (42.1°N and 8.8°W), the highest values of salinity recorded during winter and spring were measured. Figure 4a shows the representative point of the sample of 12 March 1992 at a depth of 40 metres.

The results show that during 1991, there was a strong change in the thermohaline characteristics of ENAW. This phenomenon has also been observed by other researchers of different countries in the same area. The thermohaline characteristics found in the Galicia cruises, in areas closer to the Iberian peninsula, agree with those recorded in other cruises, including more extensive areas towards 22°W.

In the cruise "Galicia I" (Fraga et al., 1982) in September 1974, the central water found was saltier and colder than the reference line (Fig. 4b), and was closer to those values found in 1991.

The all former θ -S plots show that the thermohaline changes observed during the last decade outspread from the Iberian coast to the basin interior about 20°W, and that thus is possible use the long record of thermohaline properties measured off the Galician coast to study the decadal variability.

SPATIAL DISTRIBUTION OF ENAW ANOMALY

Figure 5 illustrates the θ -S ratios of central water sampled with SeaSoar (Pollard et al. 1992) in four meridional sections at 12°W, 16°W, 20°W and 24°W, between 39°N and 50°N. At 24°W there is a clear agreement between the values found and those expected for the reference line of ENAW. However, the sections further to the east are more saline, and a gradual separation appears. Besides this gradual change from east to west, another change in a north-south direction also exists, but is difficult to observe in Fig. 5 at 16° and 12°W. At the same temperature the θ -S ratios observed in the profiles of SeaSoar situated towards the north, have greater separation from the ENAW line than those situated further to the south which are distinguished by higher surface salinity.

The study on the isopycnal level 27.1 carried out by Pollard and Pu (1985) shows a decrease in salinity at 42°N in 1977 (Discovery-81) compared with the IGY sections at 40°N and 43°N; further sections may now be added. Figure 6 shows data sets of ENAW salinity on $\sigma_\theta = 27.1$ obtained along 42°N. The minimum values were found during 1983 and thereafter are higher, showing a strong and rapid increase in 1991, especially in the east. In 1977 the salinity is lower than IGY values between 30°W and 14°W, and maintains the higher values in the area close to the Iberian peninsula. By comparison, in 1991, the sudden increase in salinity seems to be stronger in this last zone. The values of salinity at 27.1 obtained during Darwin-58 are similar to those found during the IGY, although slightly higher.

From data gathered from an area off Vigo and near to the Iberian peninsula (42°N , 10°W), over a period of 20 years, it is possible to follow the temporal evolution of the salinity at the level $\sigma_{\theta} = 27.1$ (Fig. 7). Although this figure has been constructed from various data sets, which were obtained by groups of researchers from several countries, it shows a continuous and coherent shape. High salinity values were found at the beginning of the 70's and from 1991 to 1993, while minimum values were recorded during the 1980's. Between 1990 and 1991 a sudden change in salinity of about 0.12 was experienced at $\sigma_{\theta} = 27.1$. In the first 300 metres of the water column, there is an excessive amount of evaporation over precipitation, of about 1 metre in one year. This high value suggests that the processes involved during the winter mixing cause a decrease of temperature and an increase in salinity.

The table 2 show the cruises and the location of the stations used in the figure 7. The small separations from reference postion (42°N , 10°W) have not mean because the great spatial scale involved such us showed above, besides not station over the continental shelf are included. The seasonal changes made up changes in the salinity maximun of ENAW (Rios et al. 1992) at a given position without significatives changes in the salinity at a 27.1 isopycnic level. From Nov-82 (TTO cruise) to Sept-86 (G-IX cruise) the salinity at 27.1 isopycnic level is practicaly constant without show seasonal evolution when all seasons was practicaly sampled twice.

DISCUSSION

As pointed out previously, different authors have described the surface salinity in different areas of the North Atlantic during the years 1991 and 1992 (Becker et al, 1992; Ellett and Turrell 1992). The salinity changes in the ENAW during this study show similar behaviour, suggesting that a salinity change also occurs in the formation of new mode water in the main thermocline in the North Atlantic and not only in the surface layers.

An increase of salinity during one year, in the superior layer of ENAW in front of the Iberian peninsula, has been described by several authors (Rios at al. 1992; Alvarez-Salgado et al. 1993) in the North Atlantic. The maximum values for salinity in the superior limit of ENAW occur at the end of autumn, coinciding with important currents along the continental coast (Pingree & LeCann, 1988; Frouin et al. 1990). Ellet and Turrell (1992) associate these high values in autumn during the 1980s with a higher frequency of southerly winds over the UK since 1975. The pattern of long term salinity changes at σ_{θ}

$\sigma_{\theta}=27.1$ has a different character to those of the autumn extension of ENAW of subtropical origin as a reinforcement of the poleward current (Frouin et al. 1990, Rios et al. 1992,). Frouin et al. (1990), show that the poleward currents respond to a mechanism of large-scale meridional pressure gradient released or modulated by the annual cycle due to dominance of northerly or southerly winds. **In anyway this intraannual changes in the maximum of salinity do not mean significative modifications of the θ -S relationship, and so, no appreciate seasonal changes in the salinity on $\sigma_{\theta}=27.1$ occurs . However these increasing of salinity maximum must be considered in order to understand what sources are involved in the formation of new annual class of ENAW and in its interannual saline changes.**

The fact the maximum salinity of ENAW and that of the poleward currents occur after summer, suggests that the saline advection northwards could be related to the weather conditions in the latter half of year. Lavin et al (1990) give daily values of the north component of wind stress at 43°N , 11°W , obtained using maps of surface atmospheric pressure following the methodology proposed by Bakun (1973). Figure 7 shows the mean values of the northerly wind for the latter half of the former year. The correlation between the salinity values at $\sigma_{\theta}=27.1$ and the mean values of wind stress is significant ($r^2=0.68$, $n=12$). Using the mean between September and December one year before, the correlation coefficient is rather lower ($r^2=0.43$). During the autumn seasons of the 1980s, due to the relaxation of anticyclonic circulation associated with the Azores High, the dominant winds were southerly and the poleward currents which transport saline and warm water northwards were very important (Pingree & LeCann 1992; Pingree 1994). Conversely, the salinity values on the 27.1 isopycnal were minimum during this period. Instead, there is a correlation between the periods when the northerly winds are dominant and the values of salinity are high on the 27.1 isopycnal. There is not sufficient evidence to show that the poleward currents or the hydrographic processes are the mechanism for the elevation of the salinity in the North Atlantic.

To the east of the Azores, in Fig. 2 of Maillard (1984), a slow flux towards the Iberian peninsula was described. In this area and with IGY data, Pollard and Pu (1985) describe the increase of salinity in meridional sections situated progressively eastwards, on isopycnal levels down to 27.3. Considering the θ -S diagram obtained during 1991 (Fig. 5), this process seems to emphasize the advance to higher latitudes. During the autumn of the 1990 and 1991 a reinforcement of the Azores High appeared normally, accompanied by displacement northwards due to an increase in the northern component of the winds

(see Fig. 7) which are normally dry. This could suggest an increase of the excess of evaporation over precipitation in the areas of formation of new central waters. However, the local record of precipitation did not show any correlation with the salinity values at 27.1.

Other possible causes, could be an increase in the cooling of the upper layers of the ocean during the reinforcement periods of the Azores High (northerly wind). This could cause a reinforcement of the thermohaline circulation and an increase of the advection of saline and warm waters northwards. Finally, the generation of new central water bodies which are more salty and/or colder than the former could occur.

The changes observed during 1991 in the θ -S relation could be explained by a thermal decrease (about 0.5°C) and a salinity increase (about 0.06) at the same time. However a strong saline increase along a set of isopycnals requires a very high increase in evaporation. The decrease of 0.5°C and the increase in 0.06 PSU in a layer 300 m thick, would be equivalent to an increase of 420 mm evaporation and a loss of 15 Kcal/cm^2 ; that is 60% of the heat lost during the evaporation of 420 mm of water.

Recently Pingree (1994) showed a mean January surface temperature range for the years 1967 to 1993 along the north Spanish slope from 8°W to 4°W . The trend shows continuously increasing surface temperature during the 80's, but an abruptly cooling appears between 1990 to 1991, in the same period what we found the suddenly change in the thermohaline ratio in ENAW.

Along 42°N during 1991, the new water masses formed show densities higher than the ones prevailing during the two former years (Table 3). While the 27.1 isopycnal reaches the surface layer at 46°N and 44°N during 1989 and 1990 respectively, in 1991 it reaches the surface in areas south of 42°N . Considering the density of the new mode water, there is a displacement of the isopycnal towards the south during 1991. This gives rise to an increase in salinity of new mode water compared with those formed in previous years and in areas further to the north, because the layers above the 27.1 layer are more salty than this. This increase in the vertical mixing at the same latitude would imply an increase in the horizontal advection to the north.

Read and Gould (1992) describe the saline and thermal changes over the last thirty years, based on data of J.R.N. Lazier and also new data collected during CONVEX-91. They show that a sudden decrease in salinity and a comparative decrease in temperature

occurred during 1972, come back again in 1991. Although the pattern here described involved an increase of salinity in the ENAW, it is possible that decadal changes in the polar and subtropical gyre are coupling in a more general frame involving the climate changes

We have attempted to describe a mechanism that frames these large-scale thermohaline changes, but the oceanographic processes involved are probably more complex and are affected by the history of the water masses. However, the recent data shows a possible coupling between the reinforcement of the Azores High during the autumn, and the formation of new saline bodies of ENAW associated with the subtropical gyre. Further investigation of these effects is likely to be beneficial.

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Table 1. Western North Atlantic Central Water (WNAW) and Eastern North Atlantic Central Water (ENAW) standard thermohaline lines.

WNAW (Iselin, 1936)							
Θ	8.00	10.00	12.00	14.00	16.00	17.00	18.00
S	35.13	35.29	35.54	35.85	36.18	36.35	36.47

ENAW (Ríos et al., 1992)						
	Supolar branch (Harvey, 1982)			Subtropical branch (Fiuza and Halpern, 1982)		
Θ	10.00	12.20	12.50	12.83	13.15	18.50
S	35.40	35.66	35.70	35.75	35.80	36.75

Table 2. Key for identification of data used in this study.

Cruise	Date	Latitude (°N)	Longitude (°W)	Reference
Kane 71	Sep-1971	43.0	12.3	CNEXO/C.O.B
Galicia I	Sep-1974	41.9	10.0	Manríquez <i>et al.</i> (1976)
Galicia II	Aug-1975	42.1	9.9	Fraga (1977)
Galicia III	Jun-1976	42.1	10.0	Franco <i>et al.</i> (1978)
Discovery 81	Jan-1977	42.1	10.1	Saunders (1980)
Galicia IV	Oct-1977	42.2	9.9	Manríquez <i>et al.</i> (1978)
TTO	Aug-1981	42.1	10.2	TTO (1981)
Galicia V	Nov-1982	42.0	9.8	Fraga <i>et al.</i> (1984)
Discovery 132	Feb-1983	42.2	12.3	Pollard (1985)
Galicia VI	Dec-1983	41.9	9.7	Pérez <i>et al.</i> (1985)
Galicia VII	Mar-1984	42.0	9.9	Fraga <i>et al.</i> (1985)
Galicia VIII	Jul-1984	41.9	9.7	Marrasé <i>et al.</i> (1985)
Discovery 162	Nov 1986			Saunders and Cooper (1987)
Galicia IX	Sep-1986	41.9	10.0	Fraga <i>et al.</i> (1987)
ANA	Nov-1988	42.0	9.8	Ríos <i>et al.</i> (1992)
Discovery 181	Apr-1989	42.1	10.3	Read <i>et al.</i> (1991)
Bord-Est 3	May-1989	43.0	10	Arhan <i>et al.</i> (1991)
Discovery 189	Mar-1990	42.1	10.3	King <i>et al.</i> (1991)
Galicia XI	May-1991	41.9	9.6	This paper
Darwin-58	May-1991	42.0	12.4	Griffiths <i>et al.</i> (1992)
ICNOR	Aug-1992	41.9	9.6	Cabanas (pers. com.)
MORENA-0593	May-1993	42.0	10.0	This paper
SEFOS-0694	May-1994	42.5	9.6	Cabanas (pers. com.)

Table 3. Average of salinity and isopycnal depth of 27.1 and 27.2 along 42°N between 10° and 20°W.

	1989	1990	1991
	Discovery-181	Discovery-189	Darwin-58
S(27.1)	35.612 $\pm$ 0.015	35.621 $\pm$ 0.012	35.767 $\pm$ 0.049
S(27.2)	35.522 $\pm$ 0.031	35.522 $\pm$ 0.029	35.575 $\pm$ 0.095
difference	0.090	0.099	0.192
Depth(27.1)	265 $\pm$ 86	253 $\pm$ 78	148 $\pm$ 78
Depth(27.2)	496 $\pm$ 54	470 $\pm$ 45	467 $\pm$ 65
difference	231	217	319

FIGURE CAPTIONS

Figure 1 θ -S scatter plot for data collected in the north-east Atlantic, displayed relative to two standard lines. The inset panels show the location and date of sampling. Table 2 provides a key for cruise identification.

Figure 2 As Figure 1.

Figure 3 As Figure 1.

Figure 4 As Figure 1.

Figure 5 As Figure 1. Data are all from Charles Darwin Cruise 58.

Figure 6 Salinity on $\sigma_\theta = 27.1$ as a function of longitude. Data were collected at latitudes close to 42°N between 1957 and 1991.

Figure 7 Time variation of salinity on $\sigma_\theta = 27.1$ at stations close to 42°N, 10°W (square symbol, left hand axis), and of northward wind stress during the last half year of the former year (plus symbol, right hand axis).

TABLE CAPTIONS

Table 1. Western North Atlantic Central Water (WNAW) and Eastern North Atlantic Central Water (ENAW) standard thermohaline lines.

Table 2. Key for identification of data used in this study.

Table 3. Average of salinity and isopycnal depth of $\sigma_\theta = 27.1$ and 27.2 along 42°N between 10° and 20°W.

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