Universidad de La Laguna

Facultad de Ciencias

Trabajo de Fin de Grado:

“MULTIDECADAL TEMPERATURE AND SALINITY CHANGES AT 24.5ºN”

Realizado por:

Carla Hatamoto Lázaro[1]

SEPTIEMBRE 2017

Supervisado por:

Juan Carlos Guerra García[2] y Pedro Joaquín Vélez Belchí[3]

[1] Grado en Física, Universidad de La Laguna
[2]Departamento de Física, Universidad de La Laguna
[3]Departamento de Medio Marino, Instituto Español de Oceanografía

Resumen

La sección oceanográfica 24.5ºN en el Océano Atlántico Norte ha sido objeto de investigación durante un largo periodo de años. Esto se debe principalmente a que se produce el máximo en el transporte de calor de la MOC (por sus siglas en inglés, Meridional Overturning Circulation) hacia el norte, lo cual supone un 25% del flujo global. La observación, recogida de datos y análisis posterior de los mismos es primordial, pero se hace aún más fundamental el hecho de que sea a lo largo de una escala de tiempo grande. Esto nos permite realizar predicciones y deducir si hay ciertos comportamientos cíclicos en las masas de agua. La tendencia anual es de un incremento de la temperatura a lo largo de las aguas superficiales (Upper Ocean) sin embargo se está produciendo un enfriamiento en las aguas profundas (Deep Water). Entre los datos analizados se ha visto un aumento en torno a 0.3ºC century^{-1}si bien las salinidades no experimentan grandes cambios. Es inevitable cuestionarse si hay una tendencia general o son picos relativos a ciclos que aún están por descubrir o bien ya son conocidos como El Niño. Además de los datos tomados en campañas oceanográficas, la red Argo ha resultado vital para confirmar las tendencias observadas y demostrar su valía como red global.

INDEX

1. INTRODUCTION

The oceans could be considered the thermostat of the Earth. Due to its capacity to storage heat, the weather conditions are determined by the changes in the oceans, their currents and density, that is defined by temperature and salinity.

However, the research of the oceans and specifically the hydrographic section of 24.5ºN in North Atlantic is quite recent. This is an issue due to the absence of continuous data and measurements to see changes in shorter timescales. The section at 24.5ºN represents one of the best observed regions of the world oceans and it offers an opportunity to investigate large-scale decadal changes in the ocean state, so it has become a benchmark in observations used to quantify the variability in temperature and salinity at this latitude. Also, it is used to monitor the nature and causes of climate change.

The first hydrographic cruise took place during the 1957 International Geophysical Year (IGY) and it has continued since then. The next one was in 1981(*Roemmich and Wunsch., 1985*), and it follows the WOCE (World Ocean Circulation Experiment) data in 1992 (*Parrilla et al., 1994*), in 1998 (*Baringer and Molinary., 1999*), in 2004 (*Cunningham and Alderson., 2007*) and in 2010 and 2011 (*Vélez-Belchí et al., 2010*).

The assessment of these measurements across the North Atlantic Ocean has shown that in 1992 and 1998 the temperature tendency was increasing in terms of 0.65ºC century^{-1}(*Vélez-Belchí et al., 2010*).

The aim of this study is to show the changes in temperature and salinity at 24.5ºN from 1957 to 2015 with oceanographic occupations and from 2011 to 2015 with Argo data using *Roemmich and Gilson., 2009*. The Argo data is used to compare the data and verify the useful of this free-drifting profiling floats, known as Argo network.

In this study, we monitories both basins, the eastern one (23º-35ºW) and the western one (65-75ºW), according to *Cunningham and Alderson. (2007)* and we focus on the thermocline (300-800dbar) and intermediate waters(800-1800dbar) due to an increasing in temperature tendency, on the contrary, deep waters cooled and freshened.

Although it is important to describe the tendencies in the past, in this study we compare the changes between the years with the dominant tendency and the last one in 2015. According to the results (*Vélez-Belchí et al., 2010*) it is reported that the thermocline (300-800dbar) showed shifts mainly in eastern basin, in the period of 1992-2002 around 2.7ºC century^{-1} according to *Vargas-Yáñez et al., 2004.*

In addition, we have an interest in how the changes in the ocean properties modifies the dynamics of the Subtropical Gyre in the North Atlantic which has an important role in the overall circulation in the Atlantic. This is the main reason which explains the difference of the weather among Europe and America at the same latitude. It is related with the geostrophic flow so the study is to assess the cycle and possible patterns in a big timescale.

The study is focused on the predominant changes which occurs in upper-ocean and in western basin. Also there is an intention to examine the decadal changes in potential temperature(θ)-Salinity(S) characteristics of these water masses. Hence, the changes and the tendency can show recent trends and may predict cycles and a possible time-evolution in the behaviour of the ocean.

The results presented in chapter 3 confirms the tendency in temperature and salinity and the necessity of a research in long-term variability in properties of the ocean. In chapter 4 these results are discussed and the conclusions are explained.

2. DATA AND METHODS

En este apartado se hace una pequeña descripción de cómo han sido tomados los datos, las variaciones que ha habido a lo largo del tiempo en las campañas oceanográficas, así como las estaciones periódicas en las que se han hecho recogida de datos. Por otra parte, se hace hincapié en el desarrollo matemático seguido, así como la explicación de la interpolación de los datos y el porqué de la necesidad de usar la ecuación de Bindoff.

2.1 DATA

There are eight hydrographic sections which cover from the African continental shelf to the Bahamas. As in figure 1.1 there are two sections that are parallel over the Atlantic, but the others make an angle to the southwestwards at about 28ºN which ends at 23ºW and it continues to the west parallel until 70ºW and they make another angle northwestward at 26.5ºN.

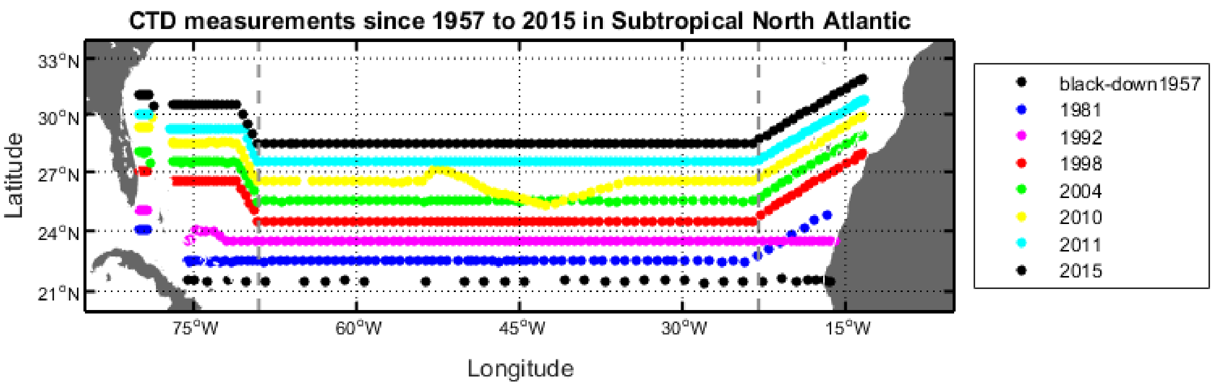


FIG. 1.1. It represents the CTD measurements from East to West since 1957. Notice the difference in each oceanographic cruise, mostly in 1957 where the distance between stations is 230km.

The section 2010 has a deviation in the middle of the cruise, that has been taken into account when the measurements are compared with others. The first section was in 1957 and had 38 stations. It was sampled using Nansen bottles, however, the hydrographic sections after 1981 have been using continuous CTD (Conductivity, Temperature, Depth; conductivity used to determine salinity) measurements and the distance between them was around 70km. To make a more precise comparison, only the measurements between 23º and 70ºW are used, this is due to the difference in the angle about the two different latitudes in African and Bahamas shore. Temperature and salinity have been interpolated linearly in 101 pressure levels from the surface to 2000 dbar to compare the results (Fig. 2.2.1 reaches 6000dbar because it is created with CTD measurements although it is also interpolated linearly in 101 pressure levels). The reason of 2000 dbar is due to the Argo network which takes profiles each 0.5º between 23º and 70ºW.

a)

b)

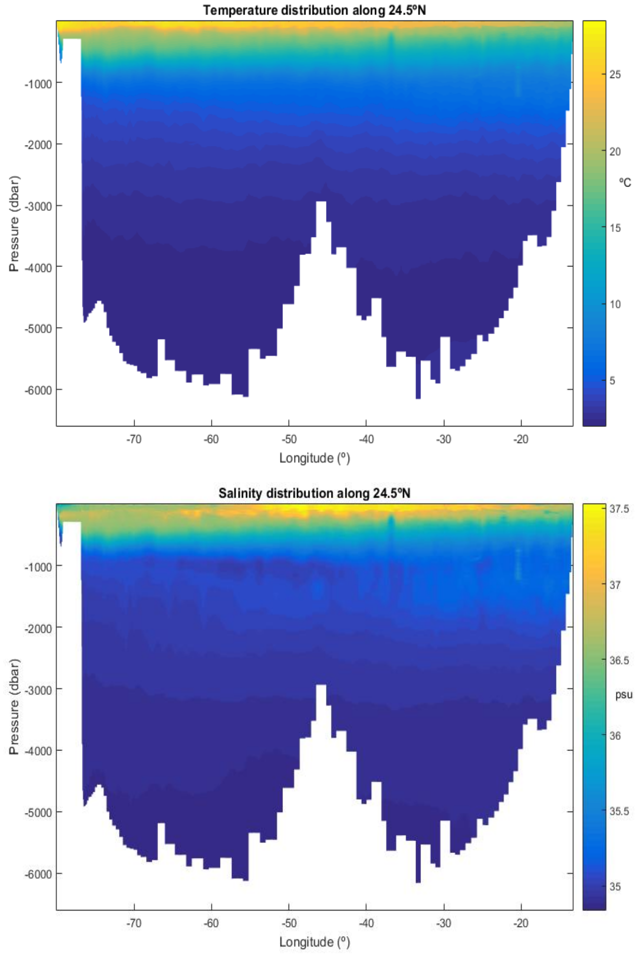


FIG. 2.2.1. a) and b) are images of temperature and salinity data interpolated and referred to pressure levels. The longitude used is from 23º to 70ºW due to the quality of the data. White spaces show the lack of data because of the bottom of the ocean.

Moreover, we are interested in Argo data system due to the property data and the fact that Argo is spread all over the oceans. Although the Argo data has their own control system, *Hernández-Guerra et al., 2009*, developed their own quality control which differs from *Roemmich and Gilson.,2009*, hence with the approximation realized by *Hernández-Guerra et al., 2009* it is shown that Argo section have pretty much less eddy noise instead of hydrographic sections. Thus, there. The main difference is related with the interpolation, that is carried out into a hypothetical section to minimize noise caused by eddies.

2.2 METHODS

Since we want to examine the mechanisms responsible for the trends in temperature and salinity, avoiding the effects of the pressure, we have used potential temperature (considering adiabatic processes and taking a reference pressure). Following the model by *Bindoff and McDougal (1994)* we interpret the variations in a water column, since this method allows to differentiate between the changes in density due to changes either in salinity of potential temperature, and the changes due to pressure variations. At each pressure level the trend is discomposed into water mass property changes on neutral surfaces and changes due to vertical movement of neutral surfaces. Taking a Taylor expansion and assuming that there are no variations in time, so the vertical gradients of temperature are constants, so little changes of potential temperature (θ) can be considered as:

$$\left.\frac{d\theta}{dt}\right|_p = \left.\frac{d\theta}{dt}\right|_{\gamma_n} - \left.\frac{dp}{dt}\right|_{\gamma_n}\frac{\partial\theta}{\partial p} \qquad (1)$$

Where $|_p$ refers to changes along pressure surfaces and $|_\gamma$ denotes changes along neutral surfaces. This equation distinguishes between contribution of adiabatic processes and adiabatic displacements of the water column. The last term of the equation refers to the vertical temperature gradient.

Heaving (*Jackett and McDougall., 1997*) can be due to changes in isopycnal thickness (e.g., remote changes of surface buoyancy fluxes) and changes in the gyre circulation strength (e.g., wind dynamics).

In addition, it has been proved that temperature and salinity changes have different reasons in Western and Eastern basin and they can differ so they are assessed at each side of the Mid-Atlantic Ridge (MAR). Also, it explains some results from the Subtropical gyre and how it contributes in the temperature and salinity changes.

To assess the accuracy between the tendency in temperature and salinity changes two different methods are applied. The first one is linear, and try to make an approximation in linear way. The other is called robusfit which gives the coefficient for a multilinear regression, it incorporates iteratively reweighted least squares with a bi-square weighting function. This method is insensitive to outliers, but the results are very close to the standard linear least squares trends (*Holland and Welsch., 1977*).

The last part of the project focused on dynamic changes such as dynamic height and its relation with velocity, as a proxy for the intensity of the Subtropical gyre. Density is also related with these variations, so if it changes it will modify the dynamic height. The warmer and less salty water, the density is decreased so water mass is elevated on surface. To define and understand the concept of dynamic height, gravity must be mentioned. If we considered the ocean as a static and homogeneous fluid, sea level would be under gravity force laws in a constant way and as consequence the surface would be a kind of sphere but flattened on Poles. The difference between the real surface measurements and theoretical ones defines dynamic height. The main importance of this variable is due to the gradient of pressure created in high levels and low ones. Water flows into low surface but we have to consider Coriolis' Force which diverts the water mass to the right in Northern Hemisphere. Because of the balance among the horizontal component in gradient of pressure and Coriolis, the geostrophic equation results as:

$$2\Omega \sin\Phi \; V_1 = g \tan(i) \qquad (2)$$

where V1 is the speed related with the measurement in the slope i of the isobaric surface. The result is what we know as geostrophical currents. These are perpendicular to the gradient of pressure and the fluid flows around the pressure centres in a constant pressure. So it is possible to see that the gradient of pressure has two contributions, one due to gradient on sea level and the other related with horizontal variations in density in depth. In this line, we can consider that geostrophical velocity could be calculated based on density profiles. Here is where the dynamic height definition comes

$$D = \int_{P_1}^{P_2} \alpha dp \qquad (3)$$

where α refers to a specific volume. This equation combined with geopotential lead us to understand that knowing the density from measurements of temperature and salinity, it is possible to estimate the geostrophical flow in any level p2 relative to the geostrophical flow at level p1.

It has been interesting to assess the data from classical sections to Argo system to have a sight of descriptive and dynamical oceanography.

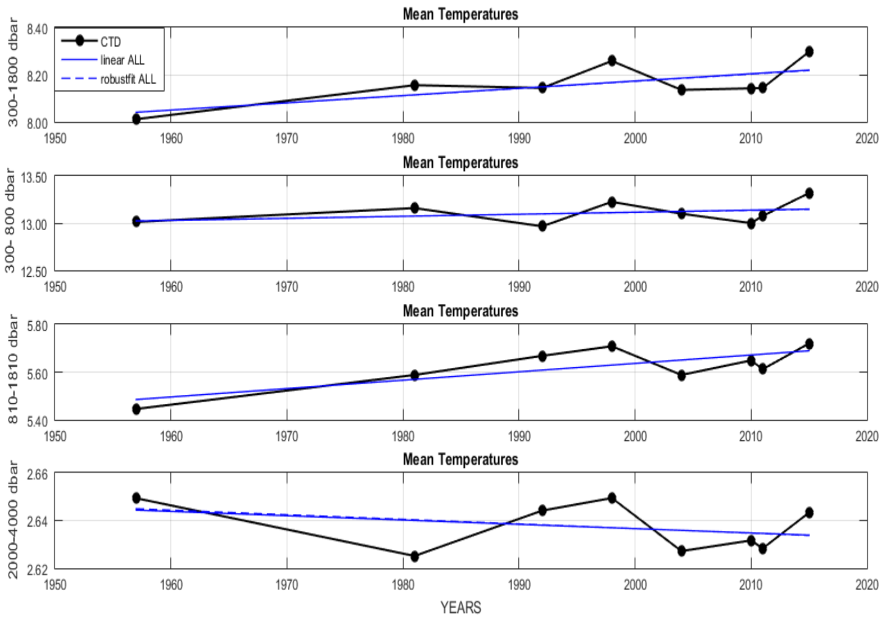
All the graphics and images were done with Matlab.

3. RESULTS

En la sección de resultados, para analizar ese punto de vista descriptivo y dinámico de la oceanografía, diferentes puntos evaluados son presentados. Se ha empezado haciendo un análisis temporal anual desde 1957 a 2015 con los datos clásicos de las expediciones oceanográficas, evaluando distintas posibilidades al presentar los datos. Posteriormente, usando la ecuación (1) se presentan perfiles verticales tanto de temperatura como de salinidad para ver la contribución en los cambios de las masas de agua. Por otra parte, se hacen evaluaciones en cuanto a la presión y un análisis de la densidad mediante diagramas TS. Por último, la parte dinámica incluye gráficas relacionadas con la altura dinámica evaluada en una escala grande de tiempo, velocidades y comparativa con los datos obtenidos por Argo.

3.1 LONG-TERM VARIABILITY AND EL NIÑO

a)



b)

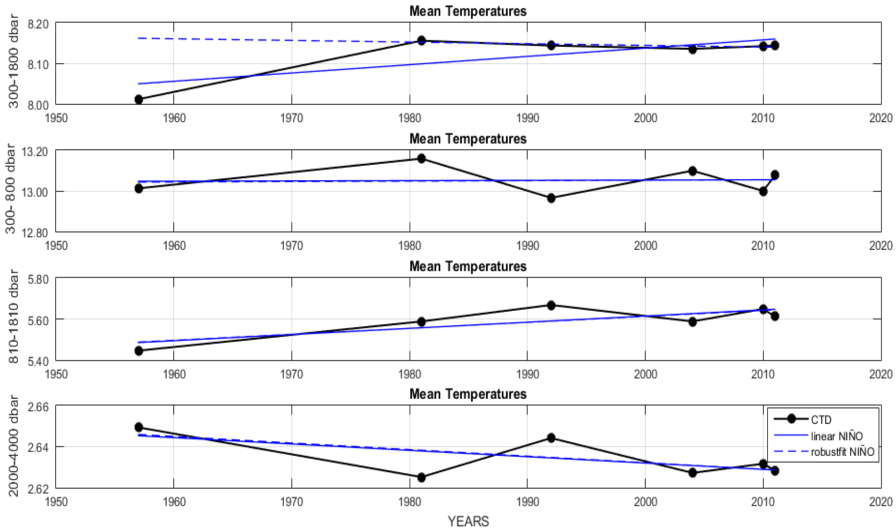


FIG. 3.1.1. Mean temperature differences since 1957 and tendencies are represented. a) Temperature variation is shown taking the years 1957, 1981, 1992, 1998, 2004, 2010, 2011 and 2015, in b) we disregard the years 1998 and 2015. There are two methods represented, the linear and the discontinuous which is the robust multilinear. Note the different *y* scales used.

El Niño is a periodical variation in winds and sea temperature over the tropical eastern Pacific Ocean and it affects especially to the subtropics. Basically, this phenomenon is due to changes from a high pressure system and it results in a pressure gradient force, that is related with the Walker Circulation.

In is interesting to analyze the time evolution of the mean temperature and salinity for the upper ocean taken into account the effects of El Niño in the subtropical North Atlantic.

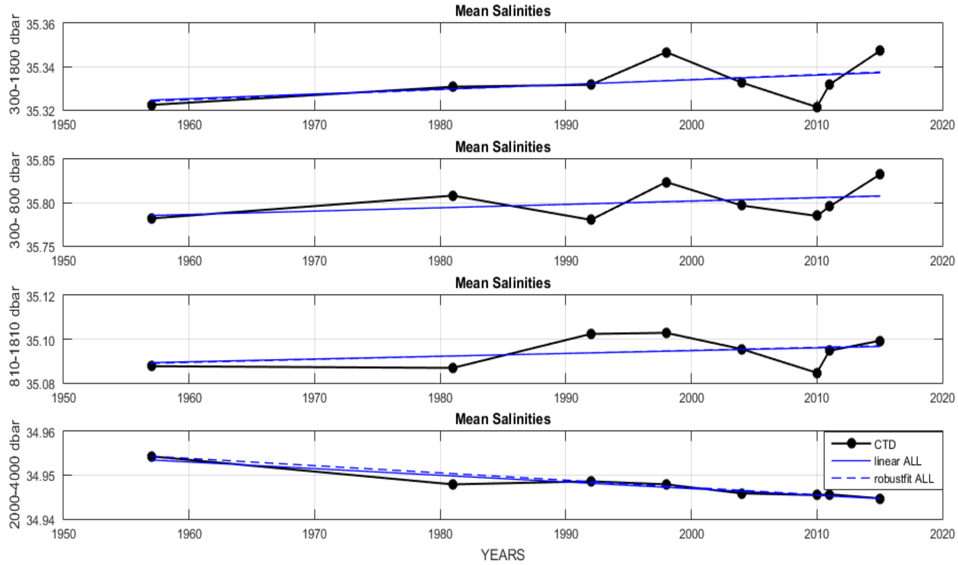
Table 1. Tendency °C century^{-1} for each pressure levels assessing different methods. Column in the center shows the tendency for the years 1957, 1981, 1992, 1998, 2004, 2010, 2011 and 2015. Right column is removing the years of 1998 and 2015.

Pressure (dbar)	Linear (Robust) All data	Linear (Robust) 1998-2015
301-1811	0.31(0.31)	0.20(-0.04)
301-791	0.22(0.21)	0.01(0.02)
811-1811	0.35(0.35)	0.30(0.29)
2001-4001	-0.02(-0.02)	-0.03(-0.03)

The assessment of the long-term changes in temperature and salinity in last decades have been realized using the CTD measurements between 23ºW and 70ºW. The upper ocean temperature and salinity changes show an influence of the years of 1998 and 2015 which matches with the period of El Niño. Thus, there is a relation between this phenomenon and the shifts in thermohaline properties.

Temperature differences shows, in the 41-years period between surveys from WOCE 1998 and IGY 1957 a warming in temperature with a rate of 0.65ºC century^{-1} coherent with the results form *Parrilla et al., 1994*. Fig. 3.1.1.a) represents the time evolution of temperature. In a) we can observe the long-term tendency, and Fig. 3.1.1.b) is the same but eliminating the years of El Niño which are 1998 and 2015.

a)



b)

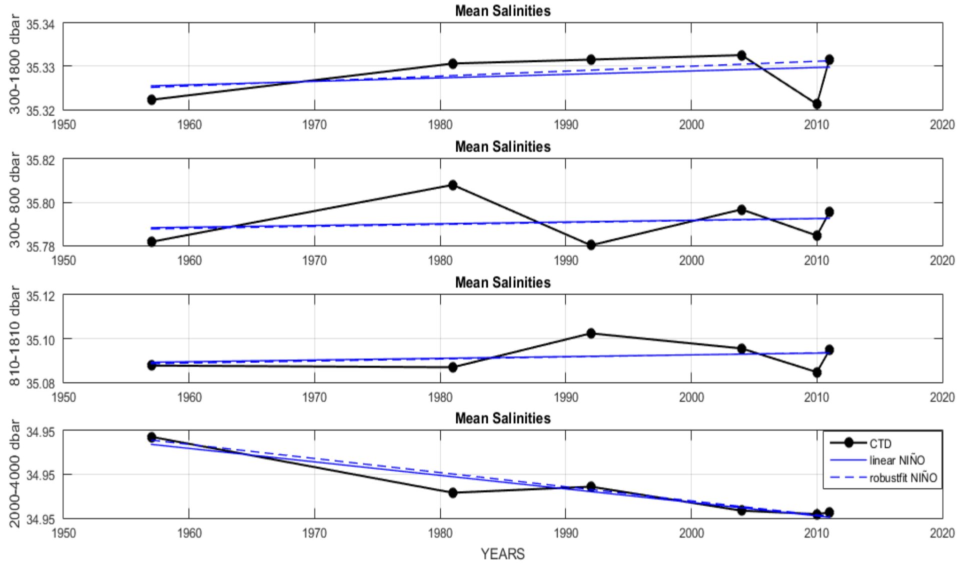


FIG. 3.1.2. Mean salinity differences since 1957 and tendencies are represented. a) Variability in salinities is shown taking the whole year including 1998 and 2015, in b) we disregard these years. As in Fig. 3.1.1, there are two methods represented, the linear and the discontinuous which is the robust multilinear. Note the different y scales used.

The tendencies are represented on both images. We assess the difference between a linear approach or taking into account a robust multilinear regression. The most appreciable difference is in the robust tendency and the linear one in the upper ocean when the years 1998 and 2015 are removed. Table 1. shows the tendencies of temperature with the different methods and the comparison between taking the data from all cruises and deleting the years of 1998 and 2015. The tendency in upper ocean is warming but with the robustfit method, and removing El Niño years, the tendency is slightly negative -0.04ºC $century^{-1}$.

Table 2. Tendency psu century^{-1} assessing different methods. On the left pressure is divided into levels, on the center column we see the results of both methods taking all data since 1957. On the right side, the results are without considering the years of 1998 and 2015.

Pressure(dbar)	Linear (Robust) All data	Linear (Robust) 1998-2015
301-1811	0.02(0.02)	0.01(0.01)
301-791	0.04(0.04)	0.01(0.01)
811-1811	0.01(0.01)	0.01(0.01)
2001-4001	-0.02(-0.02)	-0.02(-0.02)

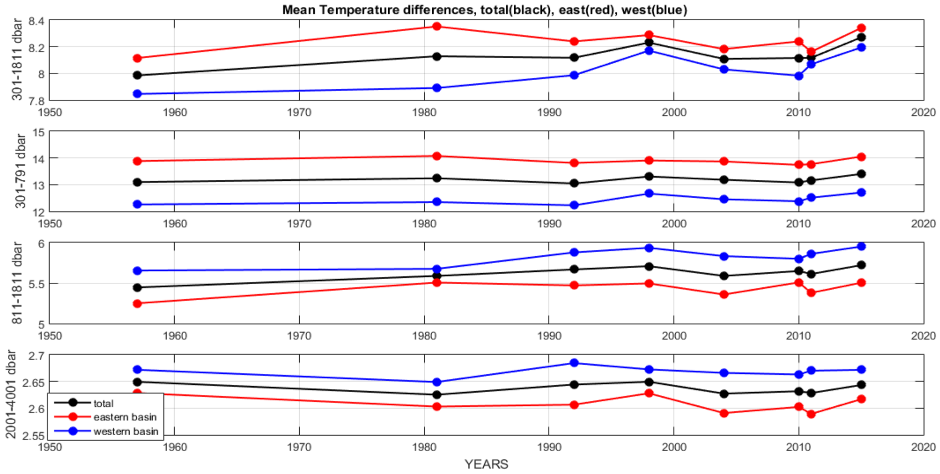
However, the thermocline is where we find the most stunning difference. When the all years are taken, the tendency is about 0.2ºC century^{-1}, but the tendency when we remove 1998 and 2015 is 0.01ºC century^{-1}. The changes in intermediate waters and in NADW are relatively small.

Fig. 3.1.2.a) and 3.1.2.b) represents the tendency in salinities with the pressure. Also, the same method is used to represent the difference in salinities. The years of 1998 and 2015 are disregarded in Fig. 3.1.2.b) to compare the difference in tendencies with Fig. 3.1.2.a). Also in this case, the two approaching methods are used. The continuous line is for linear one and the discontinuous is for the robust multilinear method. As long as in upper ocean the changes are practically similar, we observe a slightly change in the thermocline as well as in temperature differences.

The tendency in thermocline waters taking all data is about 0.04 psu century^{-1} which means it is saltier than removing the years of 1998 and 2015, in this case, the value decreases until 0.01 psu century^{-1}. On the contrary, the results in Table 2, show that the NADW (North Atlantic Deep Water) are getting less salty and both methods agree in the statistics. Intermediate waters do not show any change in salinity and the tendency is closed to zero. In Table 2. the different values for salinity tendencies are shown. As in Fig. 3.1.1 we use two methods to estimate the tendencies in salinity, using the linear one and also comparing it with the robust multilinear regression. There is a difference among the approach of robustfit method in salinity and temperature on the upper ocean. In salinities both methods are pretty closed to each other.

Another value that have been assessed are the contribution of each basin. Temperature and salinity changes are different at both sides of the Middle Atlantic Ridge (MAR), hence Fig. 3.1.3.a shows temperature tendency from 1957 to 2015 in total and also in eastern and western basin. The east greatly contributes in shallower waters as well as in temperature and salinity, however intermediate waters and deep waters have differences and the contribution of the east basin is reduced compare with the west basin. In temperature, the intermediate waters contribution is less in the east basin and the difference between east and west is increasing so finally deep waters show remarkable differences in the west basin in 1992 and 1998. Salinity differences show also the same contribution as temperature in shallower and thermocline waters, however the tendency changes again in the intermediate waters and deep waters. we highlight the bigger differences in west basin and the east one, in this case, the tendency by the year 2015 was that these big differences are separating.

a)



b)

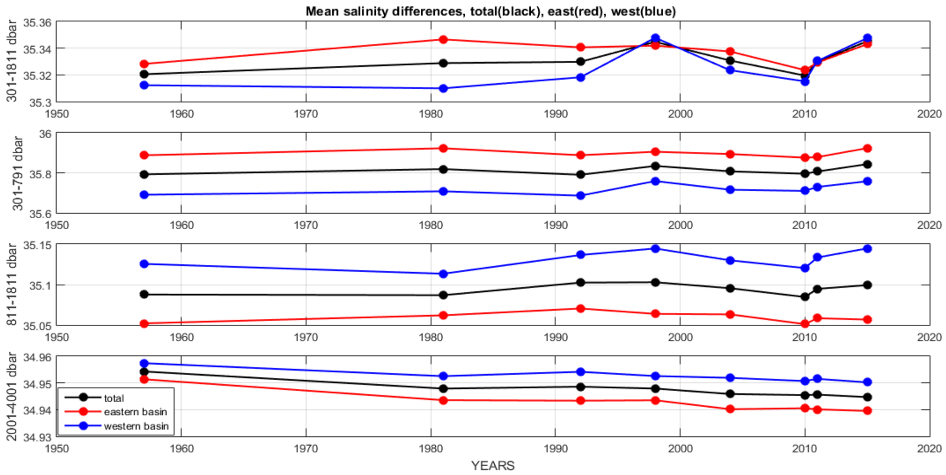


FIG. 3.1.3. Long-term tendency in temperature and salinity a) and b). In black total tendency, in blue western basin and in red eastern basin. The first part refers to Upper Ocean, the second is Thermocline Waters, and the next are Intermediate Waters and Deep Waters.

As it shows the Fig. 3.1.3.a) and 3.1.3.b) the total tendency in black is the same as the Fig. 3.1.1a) and Fig. 3.1.2.a) This differences between basins are mainly due to the MAR and the contribution to the Subtropical gyre is affected by them.

3.2 VERTICAL PROFILES

We plot the average temperature and salinity differences on pressure surface. Due to the trend in temperature and salinity we have shown before, it is interesting to consider the years 1998 and 2015 as we know these are the years of “El Niño”. The data before these years are considered to compare the changes in temperature and salinity between an ordinary year and the ones with this phenomenon.

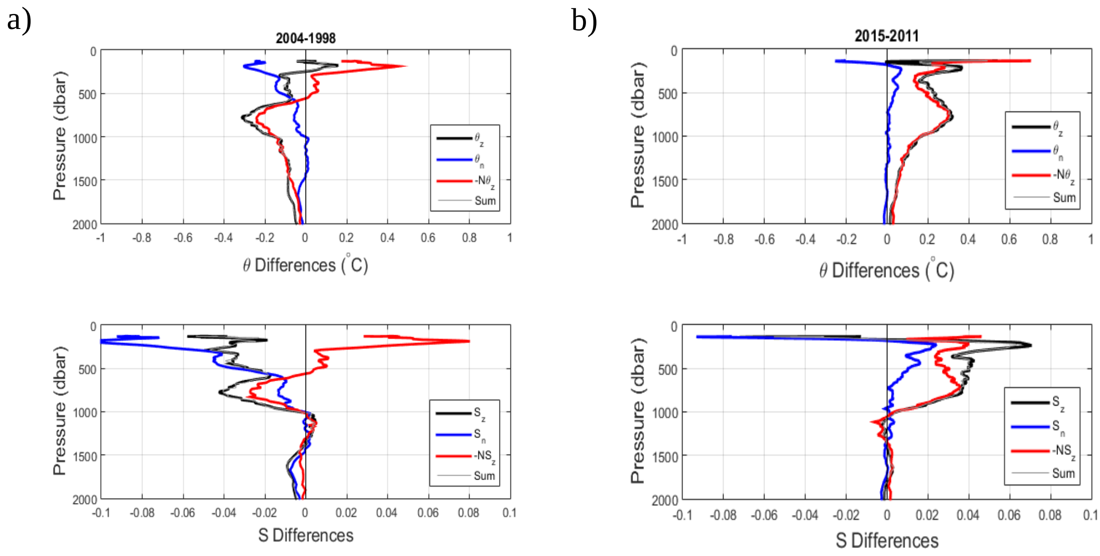


FIG. 3.2.1.a) and b) represents vertical profiles of averaged potential temperature and salinity differences. a) refers to comparison between years 1998 and 2004.b) represents the difference among 2011 and 2015. The black thin line is related with the total and the red, black and blue are the decomposition of the Bindoff's equation (1) on each terms.

Fig. 3.2.1 it is interesting to study due to it is represented the contribution of each terms in the equation of Bindoff (1) and it is possible to see what kind of changes have occurred in the masses of water. The blue lines indicate changes in isoneutral surfaces and the red ones show displacements in the water column (changes in density). Hence the changes in isopycnal surfaces represent changes in the vertical distribution of water density. Fig. 3.2.1 shows that in both comparisons between years of El Niño changes are related with the isopycnal surfaces and vertical masses of water. In the shallower levels, the tendency is not clear due to the mixing and the interaction with the atmosphere. In these first levels of pressure the cooling related with the atmosphere, the effects of wind and the solar radiation have an important role and also the wind-driven turbulence contributes to make more confused the comparison in these data. Therefore, only from 200dbar is considered as a good approximation to the terms of the equation (1). Both years, 1998 and 2015 are compared with the year before and as well as in temperature and salinity changes follow the same tendency. However, as in the period 1998-2004 the ocean was getting cooler and less salty as it is shown in the Fig. 3.2.1.a), in 2011-2015 Fig. 3.2.1.b) a warming temperatures and saltier water are observed. Moreover, these observations agree with the Fig. 3.1.3 shown before in long-term trends. So as *Vélez-Belchí et al., 2010* showed, only the intermediate waters show some contribution from changes along neutral surfaces. This is remarkable due to the importance in the eastern basin of the Mediterranean Outflow Waters at 1200 dbar.

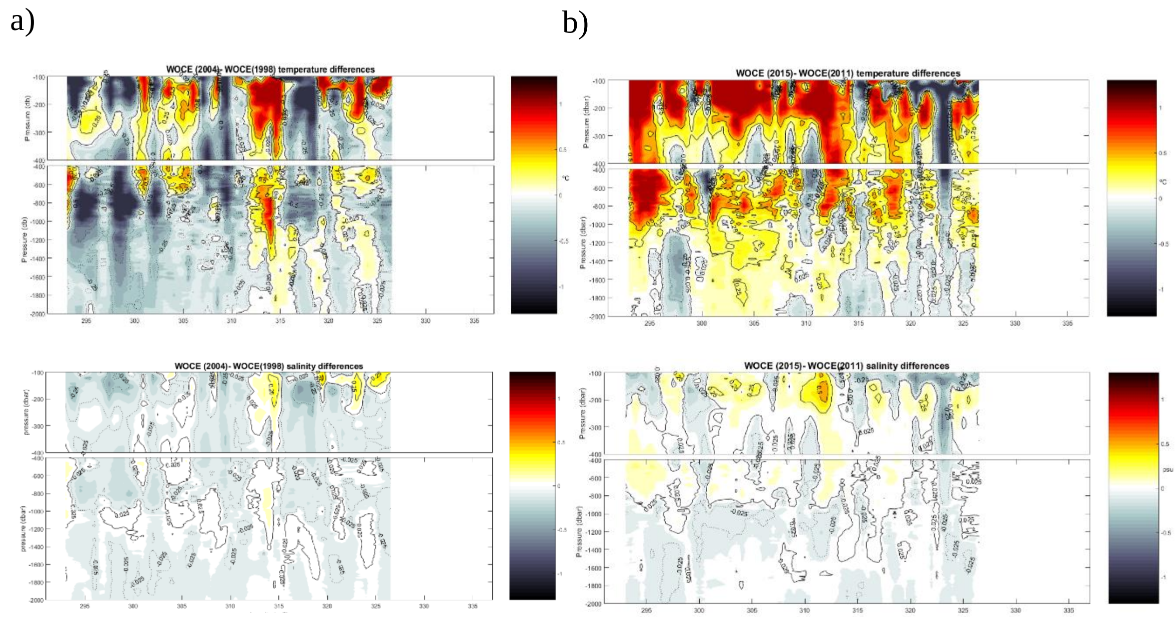


FIG. 3.2.2. Vertical zonal sections, on pressure surfaces, of potential temperature differences at 24.5ºN in North Atlantic. Each one corresponds to the periods: a)2004-1998 up and down and b)2015-2011. On the top, temperature differences and below the salinity differences.

In order to confirm the Fig. 3.2.1, a comparison is presented between the years 2004-1998 and 2015-2011 as well as in temperature and salinity. As it is shown in Fig. 3.2.4 the tendency of temperature in both periods agree with the average temperature differences. In 2004-1998 cooling and refreshing dominates the surfaces and the western basin is clearly more fresh than eastern basin. However, the trends in temperature in period 2015-2011 changes and the western basin shows warming and even a deeper warming than in other cases. Thus, it matches with the vertical profiles shown forward.

Besides, the salinity differences as well as in temperature, show the tendency in both periods. In Fig. 3.2.2.a) below the temperature differences, salinity presents a saltier surface in eastern basin but not a remarkable scale. As in temperature in the second period shown, salinity presents highlight the changes between both periods, as in the last one the ocean is warming and saltier. The effects of El Niño, should be compared with other years, in a bigger scale of time in order to compare the results.

In Fig. 3.2.3 the comparison between the years 1998 and 2015 with 1981 is presented and on the contrary at the Fig. 3.2.1 the changes in water masses are not produced in the vertical displacements.

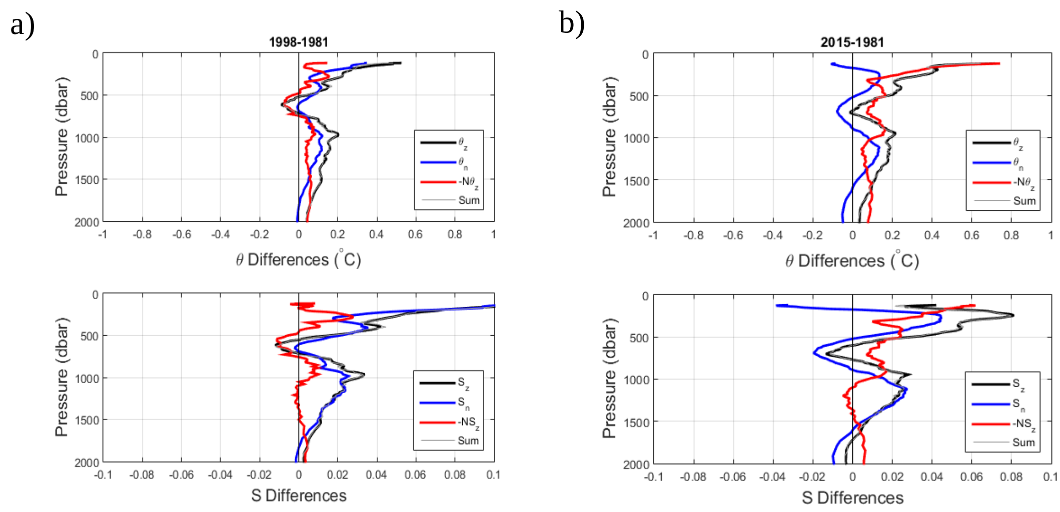


FIG. 3.2.3. a) and b) shows as in Fig. 3.2.1 the average temperature and salinity differences but in this case the comparison is between the years of El Niño, 1998 (a) and 2015(b) with 1981. 1957 is not taken as the first year of data due to the lack of measurements and the distance between stations. Moreover, the CTD measurements started at 1981. The contribution of each term of equation (1) is represented.

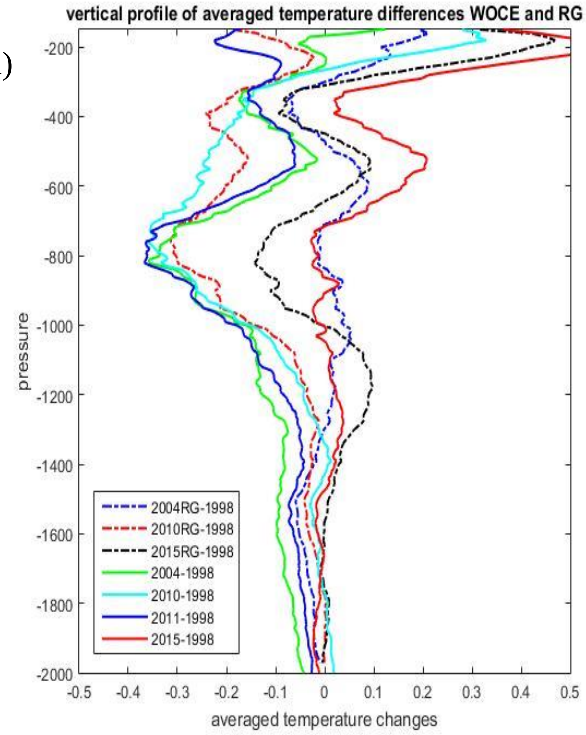
In Fig. 3.2.3.a) which is a period of 34 years it can be observed that salinity differences are produced mainly in changes in neutral surfaces, mainly from 1000dbar where the average salinity differences are close to +0.02 but above 1000dbar the difference is less salty reaching -0.02. In temperature differences is less clear and it is due to isoneutral surfaces but in intermediate waters the tendency is, also, due to isoneutral surfaces. Besides, the Fig. 3.2.3.b) takes the period between 1981 and 1998 which is about 17 years. The average temperature differences in this period in thermocline waters is more about vertical displacements but taking intermediate and deep waters is related more with neutral surfaces. Despite this assessment, the period between 1981 and 1998 does not take so pretty differences, reaching a peak less than ±0.02.

On the contrary, the salinity differences in 1981-1998 are quite clear and the changes are produced by the isoneutral surfaces. The maximum peak exceeds +0.02 psu. More vertical profiles have been taken during the process, though, the more interesting ones related with years of 1998 and 2015 are presented to the discuss after.

Also in Fig. 3.2.4 vertical profiles of average temperature and salinity changes are presented to show the difference between classical CTD measurements and the Argo network.

As we mentioned before, the first year of El Niño in this section with data and measurements is 1998, hence the next years are compared with 1998 so we can obtain vertical profiles of average temperature in case 3.2.4.a) or average salinity in 3.2.4.b).

a)



b)

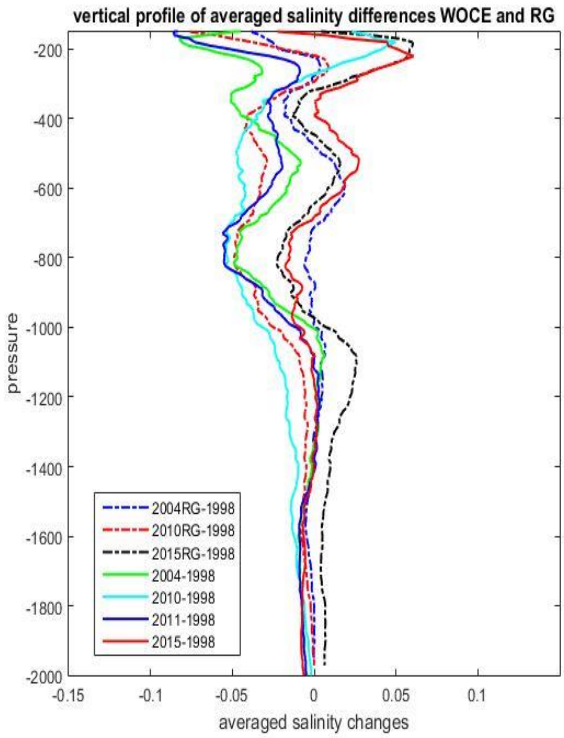


FIG. 3.2.4. Vertical average profiles of temperature a) and salinity b). The comparison between CTD measurements and Argo is presented and all the recent years are presented in based on 1998 and the years after. The dashed lines take the Argo data to compare with WOCE. Note the scale is different in temperature and salinity.

Although the classical data are compared with 1998 also we are interested in data from Argo network to assess the annual variability. In case of temperature we observe that year 2004 Argo (Fig. 3.2.4.a) blue dashed line) is not so close to the WOCE data (green line) and from 300dbar to 800dbar which it is thermocline waters the tendency is a little similar and the trend is negative so with 1998 is cooling. However, 2010 Argo data (Fig. 3.2.4.a red dashed line) and 2010 WOCE (light blue) are pretty similar, avoiding the mixed or upper ocean. Moreover, from 800dbar the lines are very close and the tendency in intermediate waters tends to zero. 2011 has no comparison due to the lack of data from Argo, but in 2015 it is remarkable the similar tendency in upper ocean and also in the last part of intermediate waters, although from 800dbar to 1300dbar the lines are a little bit different. Taking a look within the Fig. 3.2.4 it is clear that as based on 1998, the tendency in temperature is about cooling and refreshing, with a maximum peak in 2011 where the difference reaches almost -0.04.

Fig. 3.2.4.b) shows the average salinity changes and as in temperature changes, it is compared the Argo data and the WOCE ones. Also, the dashed lines represent the Argo data. In the comparison of the year 2004-1998 the data from Argo (blue dashed line) and WOCE (green) tends a similar way from 400dbar to 800dbar so we call the thermocline waters, afterwards, intermediate waters tend to zero. The total trend in salinity in this period was less salty.

Taking the period of 2010-1998 we observe that Argo data (red dashed lines) and the classical measurements (light blue) are pretty similar avoiding the upper ocean where the initial data are not so reliable and other variables affects the measurements. Despite this first tendency, from 600dbar to 2000dbar the lines are closed and tend to zero at the end. The maximum peak is reach close to -0.05 which means less salty in the ocean.

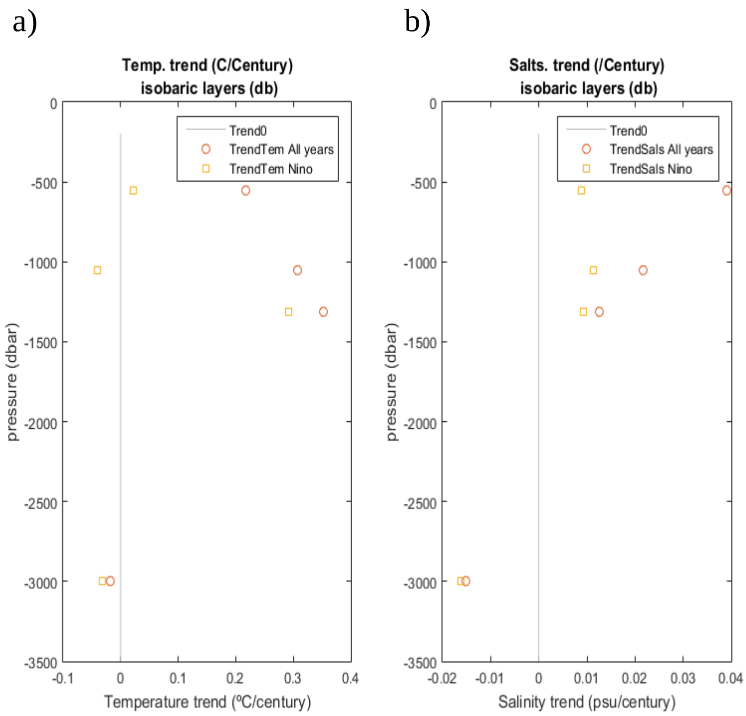


FIG. 3.2.5a) and b). Temperature a) and salinity b) trends are represented in a vertical profile following the isobaric layers. Both data are taken to make an assessment between the all years and refusing the years of 1998 and 2015.

As in temperature, the Argo did not take data in year 2011 hence only WOCE data are represented. Though, the last year 2015 is presented for both, Argo (black dashed lines) and WOCE (red line). This period 2015-1998 is remarkable due to these are the years of El Niño, so in a long-term assessment of the temperature and salinity, we are analyzing these two peaks. We highlight the fact that in this case the two lines from both data are pretty similar also in the shallower waters. These profiles are interesting to compare the useful of Argo method to observe the long term changes.

In addition, the trends can be also assessed taking into account the isobaric layers. In Fig. 3.2.5 both trends are presented temperature and salinity. Moreover, in order to compare the effects of El Niño and the changes between the years, the data of these years are represented as well as the classical ones.

It is remarkable the fact that excepting the deep layers, the trend in both properties as temperature and salinity, in shallower waters, thermocline and intermediate waters the trend is positive. However, there are differences between the way we consider the data. As we have mentioned before, the years 1998 and 2015 correspond to El Niño and it results interesting to remove them from the data to see the trend without this phenomenon.

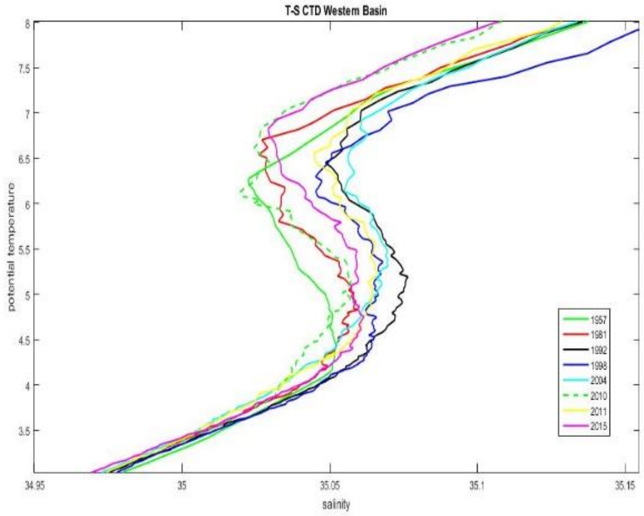
The squares represent the data refusing these years to see the trends and the circles considering all the years. In temperature trends there is big difference in the upper ocean where the trend in all years is closed to 0.2ºC/Century and without 1998 and 2015 temperature tends to zero. In thermocline waters, this difference is getting bigger and even when the years of El Niño are not considered, the temperature trend is negative. Thus make an important question to discuss. In the deep ocean as in intermediate waters, the trend is similar in both data, thus, the removal of the years does not mean a relevant shift.

In Fig. 3.2.5 on the right side, salinity trend is represented as in temperature taking the isobaric layers. A similar trend in temperature occurs, in deep ocean and intermediate waters, the trend in both data is similar, although, in deep waters the trend is negative. Despite this agreement in these layers, the thermocline and shallower waters show a difference between the way we consider the data. In shallower waters is where the distance between the results is bigger. Considering all years, the trend is located about 0.04psu/century but removing 1998 and 2015, the trend changes and results closed to zero. In thermocline waters there are diverges but no in the way before.

Another interesting result in Fig. 3.2.5.b) is the fact that removing the years of 1998 and 2015, salinity trend in the first layers as in intermediate waters remains the same, and the change occurs when we see the deep waters where the trend is negative. In temperature case, the change happens at first layers.

3.3 CHANGES IN WATER MASS CHARACTERISTICS

a)



b)

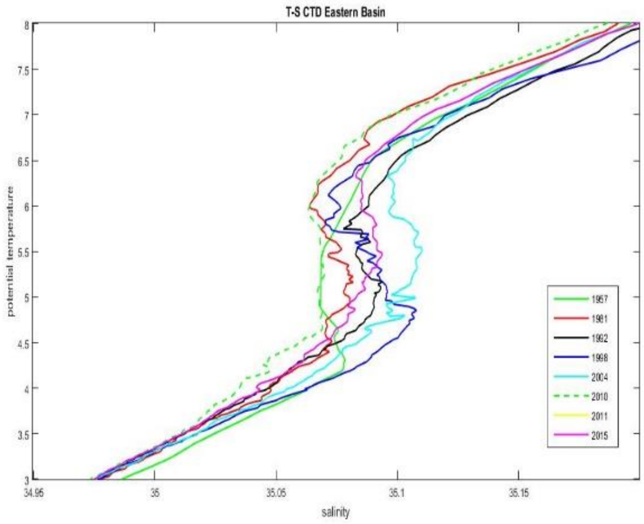


FIG. 3.3.1. Averaged potential temperature-salinity relationships (θ-S) divided into both basins. Western basin a) and eastern basin b) are represented with all years of classical sections. Notice different scale in each one.

Bryden et al., 1996, appoints the fact that temperature and salinity at constant pressure can change in two ways so it also changes the density defined by the relation along θ-S: changes in water mass characteristics due to the movements in vertical of a water mass column, or changes locally defined density surfaces. In this case, we are interested in the first case where the slope of θ-S is related with the changes of temperature and salinity. *Bindoff and McDougall., 1994* called it "heaving", and they distinguish into warming components and refreshing ones. Where there are strong θ-S relationships is in Thermocline Waters and Deep Waters. However, as we have mentioned before, in the Intermediate Waters there are variations associated with the Mediterranean Waters.

In Fig. 3.3.1 this relationship θ-S is very useful to identify the water masses. The pressure is used as vertical coordinate and excepting the surface or shallower waters where the heat and the salinity depends on other variables, without mixing water masses, potential temperature and salinity are conserved. Based on this principle, we can see in Fig. 3.3.1.b) how the Mediterranean Waters (*López-Jurado at el., 2005*) can affect the relationship θ-S as we see in the years of 1998 and 2004 where there are some peaks on the right side.

3.4 DYNAMIC EVOLUTION

To introduce the concept of dynamics in the ocean, we know the geostrophic current and its effects in the ocean. The geostrophic current is a flow related with the pressure gradient and the balance produced by the Coriolis' force. In the Northern Hemisphere the current is clockwise. In the geostrophic currents the forces are influenced by the displacements of water masses which has its own reasons such as solar radiation or winds. The forces are distinguished into three main ones: Coriolis, flow's direction and the gravity which turns into pressure gradient.

Also, the Ekman transport plays an important role in the dynamics of the gyre and it is pretty related with the wind's effect and Coriolis' force. The wind's effect on shallower waters origins movements in this layer. The deeper the ocean, the less velocity and the current's direction shifts and the angle regarding the wind is about 45º. The mean transport in all layers is a net movement in angle of 90º in relation with wind's direction. In subtropical gyres, Ekman transport which is produced by the trade winds, the flow is towards the poles and west winds heads to the Intertropical convergence zone. This is the main reason to explain the convergence in the middle of the gyre. Thus, the water is accumulated in the center of the gyre. This creates a difference of height in relation with the edges. The pressure is bigger in the center than in edges hence a pressure gradient is originated and the water flows from the center to the edges. In North Atlantic, the subtropical gyre is displaced to the west and due to the superficial convergence, water mass flows to the edge.

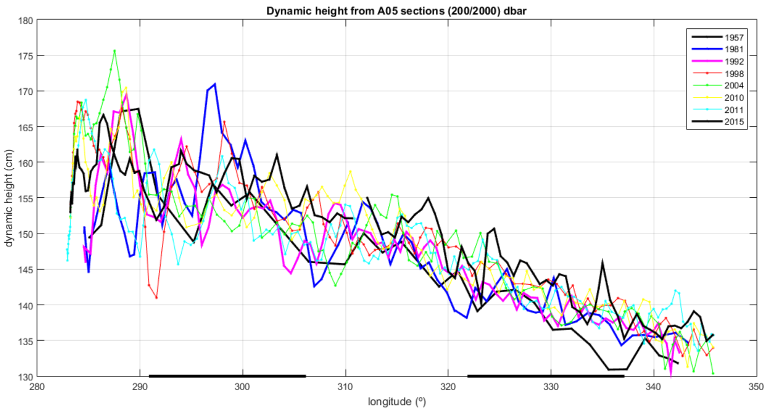
Dynamic height evolution through longitude

Whereas, the dynamic height is explained, it is important to understand in what we have presented in descriptive part that in Western basin, changes have been more highlighted. This agrees with the displacement in the center of the gyre.

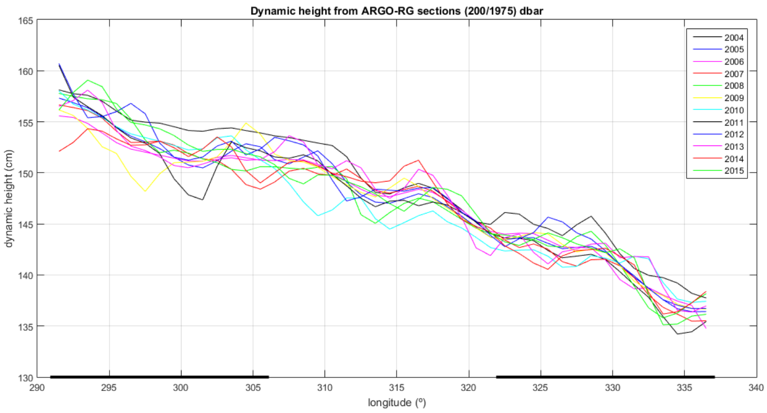
In Fig. 3.4.1, it can be seen the dynamic height for CTD sections Fig. 3.4.1.a) and Argo ones Fig. 3.4.1.b) (*Roemmich and Gilson, 2009*). Remarkable longitudes are represented to see the difference between Western and Eastern basin. Also, it is clearly noticed that dynamic height from 1998 is represented in more than 23º-69ºW due to the approaching method followed by Argo data.

We notice the different scale in a) and b) due to the data from Argo network and the classical sections. Moreover, we highlight the height between the west basin and the east. This agrees with the center of the gyre which is displaced to the west. However, years of 2004, 2005 and 2006 have not enough points of measurements to make a valid contrast. Indeed, minimum closed to 2011 can be said that is quite similar the one in CTD data but points referred to 2015 are not as nearly close as we would have expected. To see this difference in Fig. 3.4.1a) and Fig. 3.4.1b) year 2015 from classical sections is compared with the years from RG which has also its equal in CTD system. What results interesting is the gap in the CTD sampling the last year (2015) as we observe in Fig. 3.4.1.c) which was the result of lack of measurements and data in hydrographic cruise.

a)



b)



c)

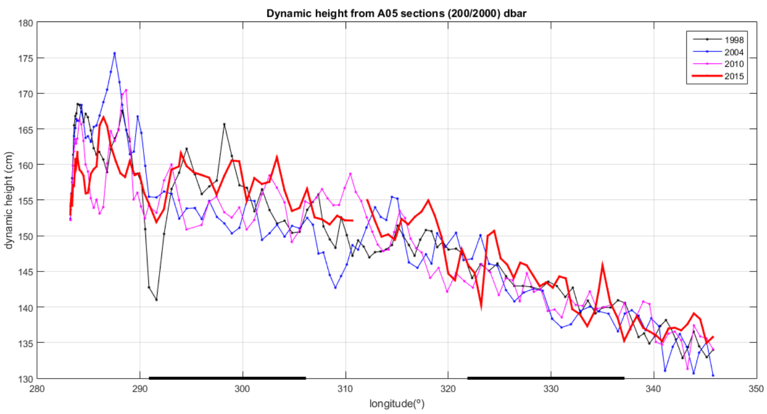


FIG. 3. 4.1. Dynamic height from west to east basins. a) classical sections are taken and the all years since 1957 until 2015, in case b) Argo data are represented since 2004 until 2015. Notice the different scale x due to difference between Argo data and hydrographic sections and the period between years in each group. c) Dynamic height between 2015 A05 sampling and the years from 2004, 2011 and 2015 in Argo network.

But in general, the tendency in dynamic height is quite similar between the CTD sampling and the Argo data. These graphics confirm the geostrophic flow at the subtropical gyre in the North Atlantic and the direction of its. Also in Fig. 3.4.2 we see the mean dynamic height evolution from all years in CTD measurements and the Argo ones.

It is divided into basins but in the middle the total mean of dynamic height is presented also with the Argo data and making mean values in the basins. Here, it is represented the mean dynamic height over the years and how contributes the West part to the total. It is included the dynamic height for Argo data from 2004 to 2015. The tendency in original sections has been increasing since 1957 and it continuous as far as we know. However, there are values from Argo data that differ from the CTD samplings, mainly the first years of Argo.

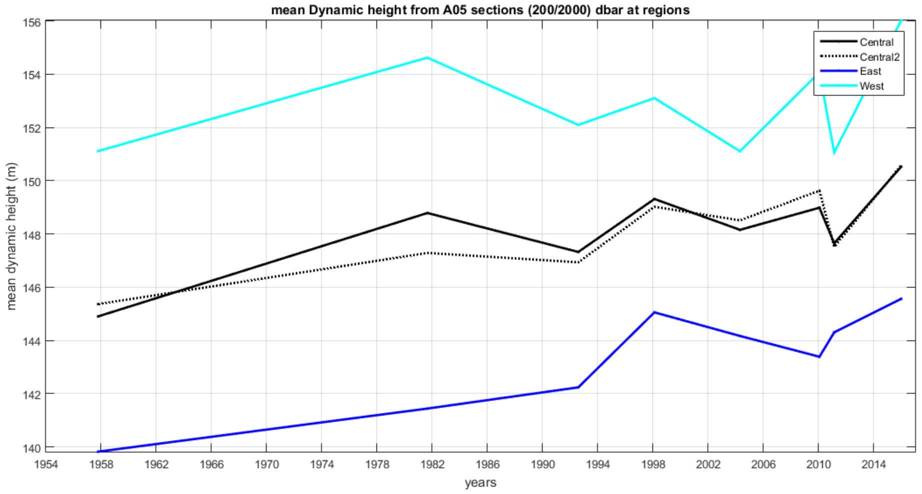


FIG. 3.4.2. Mean dynamic height evolution is represented. Above, in light blue the east evolution of dynamic height, in the middle in black, there are two approximations each one to the mean dynamic height in Argo data and A05 data. Below these, in dark blue mean dynamic height in west basin is represented.

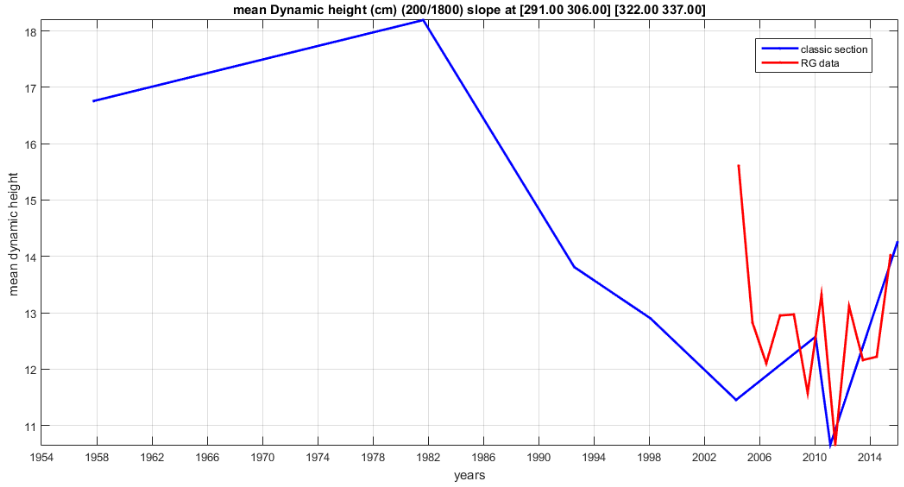


FIG. 3.4.3. Mean dynamic height represented in slopes which indicates the velocity of the subtropical gyre in the North Atlantic through the years. In blue, it is represented the velocity for A05 sections and in red, we calculate the same but taking the Argo network since 2004 to 2015.

Geostrophic velocity

After seeing dynamic height, a relation between the geostrophic equation allow us to calculate the speed by measuring the slope on surfaces with constant pressure. But in reality, we cannot determine pressure directly so we use the difference between levels in dynamic height and make an approach to the slope. The results are represented in Fig. 3.4.3.

In the period from 1957 to 1981 is clearly increasing but after that, until 2004 the intensity of the flow was dropping in a drastic rate. However, from 2011 to 2015 it can be observed how the tendency is growing and intensifying and concurs with Argo data from 2015. On the other hand, Argo data from 2004, 2005 and 2006 as we have written, could be discount and although the minimum in 2011 almost matches with CTD data, it should be recommendable to make an averaged in months for Argo data instead of calculating the mean by years

4. DISCUSSION AND CONCLUSIONS

En este último apartado, se hace una revisión de los resultados presentados anteriormente, así como una interpretación de los mismos. Si bien todo está sujeto a la revisión por parte de la comunidad científica, se presentan unas posibles hipótesis para su discusión además de una estimación en predicción de futuro.

4.1 DISCUSSION

If we see a general view and take a century-scale, the subtropical North Atlantic is warming, mostly in the upper ocean and thermocline waters, but on the contrary, the tendency in deep waters is cooling. *Vélez-Belchí et al., 2010,* presented a rate of 0.25ºC century^{-1} and in this case, it does not differ a lot but it has changed the tendency from the years of 1992 when *Parrilla et al., 1994* presented their rate. The results show a tendency of 0.35ºC century^{-1} in Intermediate Waters and salinity tendency in this case is about 0.01psu century^{-1}. We must distinguish between layers due to the different densities we find in them. On the other hand, it has been proved the importance of making layers and understand the distribution of the depth of isopycnals and changes in properties on the isopycnals.

Assessing the changes at fixed pressure into changes on isopycnals and heave of the vertical movements due to temperature or salinity gradients we can consider as *Cunningham and Alderson., 2007* that gyre circulation could be the consequence of changes in wind forcing, mostly in upper layers and second maybe the isopycnal layers can change its thickness because of the new rates.

These results the difference between the upper ocean, thermocline intermediate waters and deep waters. Since 1957 the tendency in temperature and salinity is increasing whereas the deep waters, which were cooling. However, the trend in temperature in the first layers in the period between 1998 and 2004 show a decreasing in rates.

It is thought as in *Bryden et al.,1996* salinities from 1981 to 1998 in intermediate waters have a positive trend and it may be explained due to first the difference between basins, the Mid-Atlantic Ridge has an important role and the salinity suffers shifts between basins and second and related with this oceanographic crest the influence of AAIW (Antarctic Intermediate Waters), but in case of deep waters we must understand the role of AABW (Antarctic Bottom

Waters) which takes part in western basin. Moreover, the east basin has influence of Mediterranean Waters and it affects also the trends in salinity as it is shown. From 2010, the tendency in both, temperature and salinity increases and it may result from the long cycle period but it would be necessary more long-term scales and data.

Afterwards an assessment in temperature and salinity tendencies, it is shown the phenomenon El Niño may cause the shifts in tendencies and affects the trends during long periods. We know the years of 1998 and 2015 are remarkable due to this warming of the ocean in periods that vary between 3 and 8 years. We have checked the difference in tendencies if we take the years of El Niño and without them and the results show there is a big contribution in trends in temperature and salinity, due to both approximations show that defeating these years the tendency is closed to zero. Although we consider these results, the temperature and salinity trend is positive in mostly ocean layers and cooling and saltier in deep waters.

This agrees with results from temperature and salinity trends in South Pacific Ocean, which have an increasing in temperature and salinity as well as in 2004 to 2012 and explained in *Zhang and Qu., 2014*. Certainly, the changes in water mass characteristics are determined using density and vertically continuous CTD measurements, which has a standard since 1992. Thermohalines properties define a surface density and it is proportional to salinity but on the contrary to the temperature. Following Argo network, we find its credibility agrees with results from CTD stations, but the approximation depends on the method used (i.e. *Roemmich et al., 2005, Vélez-Belchí et al., 2010*).

Vertical profiles of average temperature and salinity differences calculated using the decomposition of *Bindoff and McDougall., 1994*, we observe that both temperature shifts through neutral surfaces and vertical displacements are important in temperature trends. No more than 2000dbar are taken to take the same scale as in Argo data. These vertical profiles are useful to compare the changes in temperature and salinity and to know why they have been originated. In our case, the years chosen are related with El Niño, because we compare the year before in case of 1998 and 2015 with 2011 (there are not data available longer than 2015). The results in this case reflects that almost temperature and salinity differences are due to changes along isoneutral surfaces, however, taking a based year as 1981 where the first CTD were taken, we compare again 1998 and 2015 with this year. If 2015 is taken with 1981 we find that the changes in temperature and salinity are mainly caused by vertical displacements of water masses which contrasts with the results from 2011-2015. This agrees with the results shown between 1998 and 1981 which also confirms vertical displacements as reason of this changes in thermohaline properties. When vertical zonal sections are presented in a WOCE comparison between the years 1998-2004 and 2011-2015 it is remarkable the warming in upper ocean in both periods but mainly in the first one. In second case, the western basin shows an important increase in temperature differences and saltier ocean and moreover we highlight the warming in thermocline and intermediate waters.

Taking a look to vertical profiles of average temperature and salinity and comparing them with the trends in isobaric layers we find an agreement. All vertical profiles are presented in based on 1998 WOCE.2004-2010-2015 are used to compare them between Argo data and classical sections, excepting 2004 we may say that Argo approximation is clearly useful because there is not much variation between CTD data and Argo. We understand the difference between the year of 2004 due to the first treatment of this kind of data and the method was not so much approximated. Average temperature differences show a negative trend between 1998 but it changes in 2015, equally in salinity differences. Although both years, 1998 and 2015 are periods of El Niño, the trend from the last years is warming and saltier, with peaks and maximum in thermocline and intermediate waters; the upper ocean is not taken in importance as much as next layers due to more variables as wind-forcing. These matches with trends presented distributed in isobaric layers and taking a difference between all years and removing 1998 and 2015. Thus, it is possible to see the warming around 0.2ºC century^{-1} and the increase of salinity about 0.02 psu century^{-1} in thermocline and intermediate waters, this is a difference between upper ocean and deep waters where the trend is cooling and less salty which was also presented by *Desbruyères et al., 2014* as a possible influence by AABW (Antarctic Bottom Water). However, we see a difference when we consider again to defeat the years of El Niño, though deep waters do not present variations in these terms. This could be explained by the cooling in mid-1990s of the LSW (Labrador Sea Water) which extends to Iceland and was spreading to the eastern basin (*Yashaev et al., 2007 and Bersh., 2002*). we know that the arrival of LSW (*Molinari et al., 1998*) at subtropical regions takes around 10 years it serves to confirm the idea of this cooling and less salty in deep waters.

The lower core of NADW (North Atlantic Deep Water) could decrease as well as LSW the salinities and temperatures, this is also related with the Mid-Atlantic Ridge, due to between 65º and 75ºW the isopycnals slope down to the west so NADW reduces its southward transport (*Bryden et al., 2005b*). This is also confirmed with T-S relationships which are divided into basinwides to see the different contributions of each kind of water masses. T-S diagrams give us densities relations and it allows to define water masses, so it is possible to see that Mid-Atlantic Ridge, North Atlantic Current and Mediterranean Waters influence in the basins and how affects the distribution of water masses.

However, we also take into account the dynamic processes in subtropical gyre. Hence, *Atkinson et al., 2012* reported the transport variability and the changes in strength and velocity at 25ºN and also related the shifts in velocity of NADW with the changes in temperature and salinity at this latitude. As we observe, the dynamic height matches with the center of the gyre and the distribution of the forces but in 2015 there are more oscillations in dynamic height in contrast with years of 2011 or 2010. Besides, Argo network confirms is useful approximation with hydrographic sections which was also used in South Pacific Subtropical Gyre by *Zhang and Qu., 2015*. The main differences in mean dynamic height are in eastern basin in 2004 but we have considered this year as the first in using approximation method with Argo. Although the mean dynamic height in east and west are different in terms of slopes we agree that the general tendency in dynamic height is increasing.

Hence, it is interesting to see the velocity changes through these years and as we can observe the tendency from 1981 to 2010 was decreasing reaching a minimum in 2010 that matches with Argo data, since then there is speeder velocity in subtropical gyre and it is difficult to discern the variability as we need a bigger long-time scale. In *Roemmich et al., 2005* they related the changes of velocity in South Pacific Subtropical Gyre and find that these shifts were mainly responsible of the warming ocean at 40ºS so this can be extrapolated with the North Atlantic Subtropical Gyre.

4.2 CONCLUSION

As one cause of the increasing temperature and salinity is global warming, we wonder the importance of phenomenon as El Niño o La Niña as well as the changes in North Atlantic Ocean's internal variability in the global warming hiatus (*Cheng and Tung., 2014*). Here, we highlight the importance analyzing of temperature and salinity changes and their causes. The heaving and the vertical displacement of a water mass column are already discussed in the energy budget of the climate system (modeling community *Meehl et al., 2011; Palmer and McNeall., 2014*) so we should understand the origins of these changes in temperature and salinity which allow us to predict in future some kind of behavior and patterns in ocean.

It also is remarkable to not forget to relate the thermohaline properties and their changes with changes in dynamic parts of the ocean and observe the velocity changes or Ekman's currents which have an important relation with wind-forcing. Interaction ocean-atmosphere should be taken into account as well as long-scale time to be able to make predictions and observe. Upper ocean and thermocline are highly influenced by wind and exchange ocean-atmosphere so results should be observed taking these variables which complicate the assessment of ocean climate change (*Keenlyside et al., 2008*).

Moreover, the hydrographic sections are quite recent and in long time scales, 50 years are not enough to predict or make models about ocean so this should encourage to follow the assessment. It is also related with the periods of each phenomenon as El Niño which occurs between 3-8 years once. Thus, it is not possible to say if more than climate change and global warming, there is a cycle related with this effect, but the results provide a different view of global warming and the interannual variability in MOC.

In addition, we remark the Argo network which confirms its utility for the future and that it is needed to keep the system due to the facility of getting real-time and regular data. North Atlantic has an interesting number of Argo floats and it allows to measure continuously large-scale fields of density, dynamic height and mid-depth velocity. This is an extraordinary way for better understanding of ocean climate variability and change.

REFERENCES

Atkinson, C.P., H.L. Bryden, S.A. Cunningham, and B.A. King, 2012: Atlantic transport variability at 25ºN in six hydrographic sections. *Ocean Science*, **8,** 513-521.

Baringer, M.O., and R. Molinari, 1999: Atlantic Ocean baroclinic heat flux at 24 to 26ºN. *Geophys. Res. Lett*., **26**, 353-356.

Bindoff, N.L., and T.J. McDougall, 1994: Diagnosing climate change and ocean ventilation using hydrographic data. *J. Phys. Oceanogr*., **24**, 1137-1152.

Bersh, M, 2002: North Atlantic Oscillation-induced change and ocean ventilation using hydrographic data. *J. Phys. Oceanogr*., **107(C10)**, 3156, doi:10.1029/2001JC000901.

Bryden, H.L., M.J. Griffiths, A.M. Lavin, R.C. Millard, G. Parrilla, and W.M Smethie, 1996: Decadal changes in water mass characteristics at 24ºN in the subtropical North Atlantic Ocean. *J. Climate*, **9**, 3162-3186.

——H.R. Longworth, and S.A. Cunningham, 2005: Slowing of the Atlantic Meridional Overturning Circulation at 26.5ºN. *Nature.*, **438**, 655-657.

Chen, X., and K.-K. Tung, 2014: Varying planetary heat sink led to global-warming slowdown and acceleration. *Science*., **345**, 897-903, doi:10.1126/science.1254937.

Cunningham, S.A., and S. Alderson, 2007: Transatlantic temperature and salinity changes at 24.5ºN from 1957 to 2004. *Geophys. Res. Lett*., **34**, L14606, doi:10.1029/2007GL029821.

Desbruyères, D.G., E.L. McDonagh, B.A. King, F.K. Garry, A.T. Blaker, B.I. Moat, and H. Mercier, 2014: Full-depth temperature trends in the northeastern Atlantic through the early 21st century. *Geophys. Res. Lett.*, **41**, 7971-7979 doi:10.1002/2014GL061844.

Hernández-Guerra, A., T.M. Joyce, E. Fraile-Nuez, and P. Vélez-Belchí, 2009: Using Argo data to investigate the meridional overturning circulation in the North Atlantic. *Deep-Sea Res. I*, **56**, 317-333.

Holland, P.W., and R.E. Welsch, 1977: Robust regression using iteratively reweighted least-squares. *Comunication in Statistics: Theory and Methods.*, **A6**, 813-827.

Jackett, D.R., and T.J. McDougall, 1997: A neutral density variable for the world's oceans. *J. Phys. Oceanogr*., **27**, 237-263.

Keenlyside, N.S., M.Latif, J. Jungclaus, L. Kornblueh, and E. Roeckner, 2008: Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature.*, **453**, 84-88, doi:10.1038/nature06921.

López-Jurado, J.-L., C. González-Pola, and P. Vélez-Belchí, 2005: Observation of an abrupt disruption of the long-term warming trend at the Balearic Sea, western Mediterranean Sea, in summer 2005. *Geophys. Res. Lett.*, **32**, L24606, doi:10.1029/2005GL024430.

Meehl, G.A., J.M. Arblaster, J.T. Fasullo, A. Hu, and K.E. Trenberth, 2011: Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nat. Clim. Change*., **1**, 360-364, doi:10.1038/NCLIMATE1229.

Molinari, R.L., R.A. Fine, W.L. Wilson, R.G. Curry, J. Abell, and M.S. McCartney, 1998: The arrival of recently formed Labrador Sea Water in the Deep Western Boundary Current at 26.5ºN. *Geophys. Res. Lett*., **25**, 2249-2252.

Palmer, M.D., and D.J. McNeall, 2014: Internal variability of Earth's energy budget simulated by CMIP5 climate models. *Environ. Res. Lett.*, **9**, 034,016, dooi:10.1088/1748-9326/9/3/034016.

Parrilla, G., A. Lavin, H. Bryden, M. Garcia, and R. Millard, 1994: Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years. *Nature.*, **369**, 48-51.

Roemmich, D., and C. Wunsch, 1985: Two transatlantic sections: Meridional circulation and heat flux in the subtropical North Atlantic Ocean. *Deep-Sea Res.*, **32**, 619-664.

——R. Davis, P. Sutton, S. Wijffels, and S. Riser, 2005: Decadal Spinup of the South Pacific Subtropical Gyre. *J. Phys. Oceanogr*., **37**, 169-173, doi:10.1175/JPO3004.1.

——and, J. Gilson, 2009: The 2004-2008 mean and annual cycle of temperature, salinity and steric height in the global ocean from the Argo program. *Progress in Oceanography.,* **82**, 81-100, doi:10.1016/j.pocean.2009.03.004

Vargas-Yáñez, M., G. Parrilla, A. Lavin, P. Vélez-Belchí, and C. González-Pola, 2004: Temperature and salinity increase in the eastern North Atlantic along the 24.5ºN in the last ten years. *Geophys. Res. Lett.*, **31**, L06210, doi:10.1029/2003GL019308.

Vélez-Belchí, P., A. Hernández-Guerra, E. Fraile-Nuez, and V. Benítez-Barrios, 2010: Changes in temperature and salinity tendencies of the upper subtropical North Atlantic Ocean at 24.5ºN. *J. Phys. Oceanogr*., **40**, 2546-2555, doi:10.1175/2010JPO4410.1.

Yashayaev, I., M. Bersh, and H.M. van Aken, 2007: Spreading of the Labrador Sea Water to the Irminger and Iceland basins. *Geophys. Res. Lett.*, **34**, L10602, doi: 10.1029/2006GL028999.

Zhang, L., and T. Qu, 2014: Low-frequency variability of South Pacific Tropical water from Argo. *Geophys. Res. Lett.*, **41**, 2441-2446, doi:10.1002/2014GL059490.

——,2015: Low-frequency variability of the South Pacific subtropical gyre as seen from satellite altimetry and Argo. *J. Phys. Oceanogr*., **45**, 3083-3098, doi:10.1175/JPO-D-15-0026.1.