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Contribution to the ICES Working Group on Oceanic Hydrography

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*Fabienne Gaillard, Ifremer Researcher at Labioratoire d’Océanography Physique et Spatial, Brest, France, has pasted away after a courageous battle against illness. For years, she has contributed consistently to produce and gather the French contributions to ICES-IROC annual report on the North Atlantic State of the Ocean. One of her major contribution is the production of the high quality in situ data product ISAS, from temperature and salinity in situ quality controlled profiles. For a decade, she has developed these tools and products, which is now acknowledged and wildly used in the oceanographer’s scientific community. Fabienne was a scientist recognized for its scientific rigor and enthusiastic investment with its collaborators and in scientific community.

Rapport : LOPS-WGOH-2017-01

Summary

1 Argo gridded temperature and salinity field

The ARGO network of profiling floats has been set up to monitor the large-scale global ocean variability (http://www.argo.ucsd.edu/). Argo data are transmitted in real time and hastily made available by the two Global Data Assembly Centres (Argo-GDAC). Delayed mode data undergo expert calibration processes and are delivered later. In the North Atlantic, the temperature and salinity conditions of the upper 2000 m are adequately described since 2002. This dataset is thus suitable for an overview of the oceanographic conditions in this basin, giving the general context for the repeat stations and sections collected mostly at the periphery of the basin by the partners of the ICES Working Group on Ocean Hydrography (WGOH). Note that, in this Section, the temperature and salinity anomalies are compute using WOA-05 climatology (World Ocean Atlas-2005; https://www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html), that mainly reflects the mean oceanic conditions of the pre-Argo period, *i.e.* before 2000's. Thus, temperature and salinity anomalies reflect change in comparison to this period.

1.1 ISAS: gridded temperature and salinity fields

Temperature and salinity fields are estimated on a regular half degrees (Mercator scale) grid using the In Situ Analysis System (ISAS), (*Gaillard et al.*, 2016). The dataset is downloaded from the Coriolis Argo GDAC (http://www.coriolis.eu.org/). It should be noted that Coriolis assembles many types of data transmitted in real time, merging the ARGO data set with data collected by the GTS such as mooring data, marine animals, CTDs. However, the ARGO dataset remains the main contributor in the open ocean. The last years of the analyzed series uses the Near Real Time dataset prepared by Coriolis at the end of each month from real time data. Delayed mode data are progressively taken into account for the previous years, replacing the NRT data.

Data are pre-processed before entering the analysis. First we perform a climatological test to detect outliers then we vertically interpolate the profiles on 152 standard levels between the surface and 2000m. The analysis to produce gridded fields is performed at each standard level independently. The method is based on optimal estimation principles and includes a horizontal smoothing through specified covariance scales. The results presented here were produced with version 6 of ISAS (*Gaillard*, 2012). The reference state was computed as the mean of a 2004-2010 analysis (D2CA1S2) and the a priori variances were computed from the same dataset. The period 2002-2012 was fully reprocessed to take into account new delayed mode data and flags. Near-Real Time (NRT) temperature and salinity fields provided by Coriolis Center (Ifremer) are used to complete the time series from 2013 to 2016. Over this period, data are interpolated using ISAS v6 including only Real Time mode data (i.e. only from automatic QC processing).

1.2 Surface layers

During winter 2016, the near surface waters were anomalously cold and fresh in the middle of subpolare gyre and in the Labrador Sea (Fig. 1.1). Further South, waters were extremely warm and salty in the western basin south of 40°N, indicating a northward shift of the Gulf Stream. A warmer than normal subtropcial gyre is also observed.

This subpolar cold anomaly persists but decreases throughout the year 2016 (Fig. 1.1), and eventually re-increases during fall 2016. Summer 2016 has been anomalously warm in the northern subpolar basin, north of 55°N, including Labrador Sea and Irminger basin. South of 55°N, a slight cool anomaly is persistent over the northern subtropical gyre.

During summer fresh salinity anomalies north of 40°N is however intensified throughout the year 2016. Waters were very fresh in the Greenland Sea/Norvegian Sea and along the East Greenland coast, while they are saltier in the Labrador Sea along the Canadian coasts; and in the Greenland Sea, north of Island.

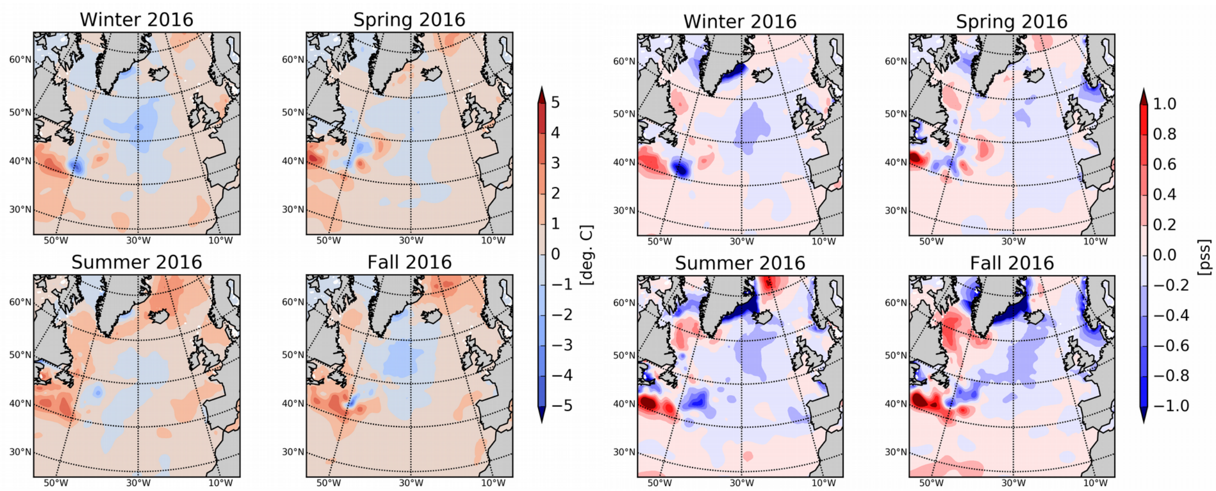


Figure 1.1: Near surface (10 meter) temperature (left) and salinity (right) averaged over Winter (JFM), Spring (AMJ), Summer (JAS) and Autumn (OND) 2016. The anomalies are shown relative to the World Ocean Atlas (WOA-05).

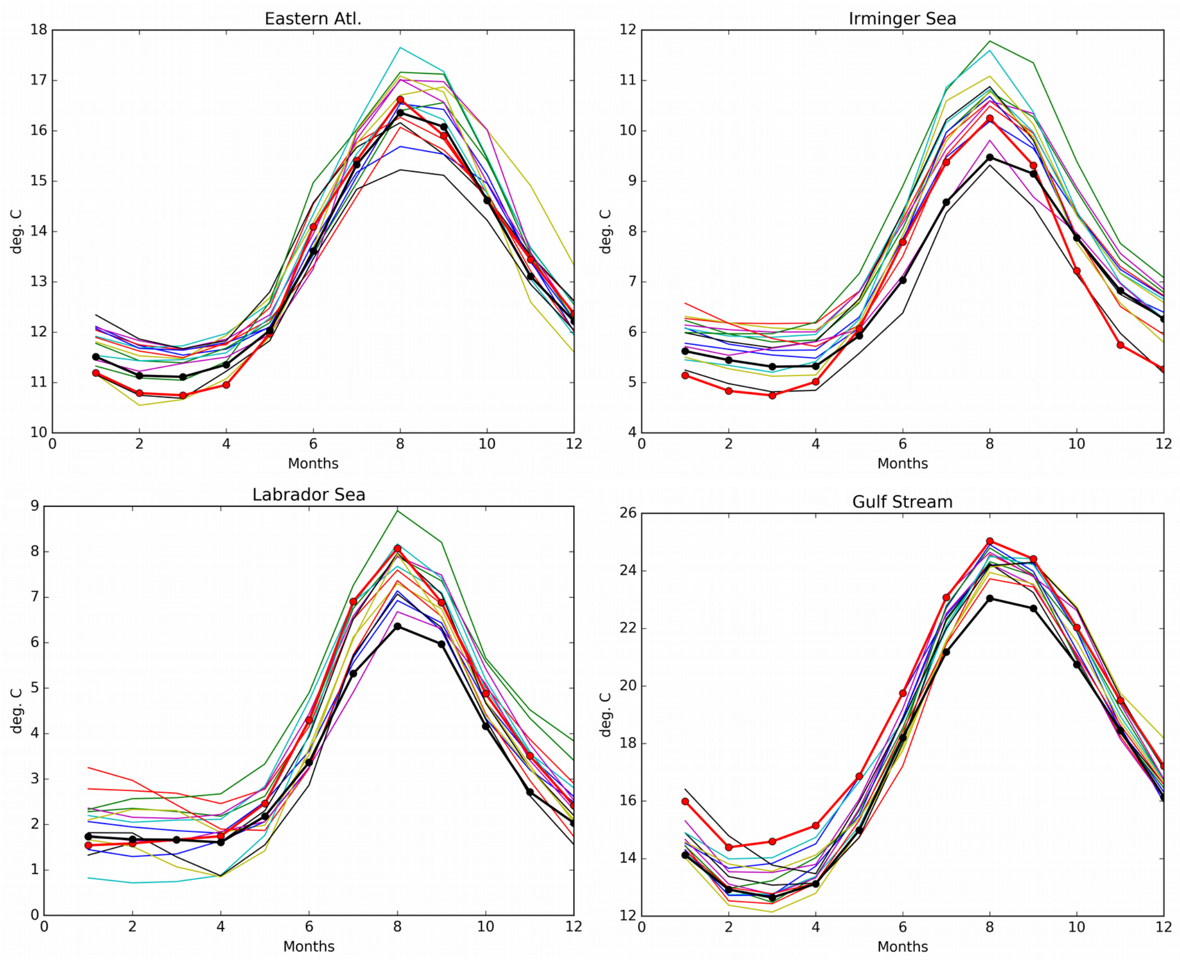
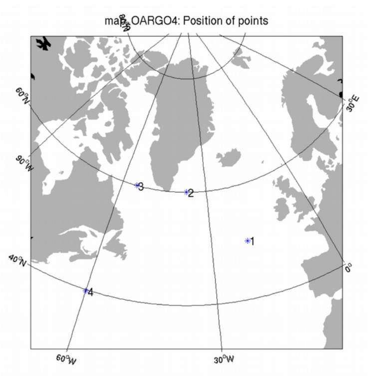


Figure 1.2: Seasonal cycle for near surface temperature at 4 points in the North Atlantic basin (see the map below), i.e. : a) Eastern Atlantic; b) Irminger Sea; c) Labrador Sea and d) Gulf Stream region. In heavy red the year 2016, in dashed black the WOA05 climatology, other curves show the years 2002-2015.



In the eastern North Atlantic, i.e. in the Irminger Sea and off the European coasts, the winter 2016 (as for winter 2015) appears to be one of the extreme cold winter over the 2002-2016 decade, (Fig. 1.2ab) where temperatures went well below the climatological mean (1° lower in the Irminger Sea). These conditions contrast with the general trend of warmers condition (than WOA05 climatology) observed over the 2002-2015 decade in winter and summer in the south-west part of the basin (Fig. 1.2d). One of the last decade warmest summer is observed in Labrador Sea (Fig. 1.2c).

Winter surface temperature and salinity determine the mixed layer properties (e.g. density, depth, ...). In order to compare all areas over the decade, we adopt a simple definition for the mixed layer depth, using the level at which density changes by more than 0.03 kg.m^{-3} with respect to the 10 meter depth. The criteria on density is more accurate because is sensitive to both temperature and salinity stratification. Nevertheless, it may slightly overestimate the mixed layer depth in region of temperature/salinity density compensation. The month of March is selected as the common period for maximum mixed layer depth. This is not perfectly true since the time of the deepest mixed layer may vary from year to year at a single location and does not occur at the same time over the whole basin (between February and March in North Atlantic).

In the North of the basin extending from the Labrador Sea to the Irminger Sea, in spite of the exceptional winter 2015, during late winter 2016 the area covered by a deep mixed layer (deeper than 1000 m) is the second most extended (Fig. 1.3). This deep mixed layer may reflect strong winter convection in both Labrador and Irminger basin. Unusual deep mixed layer is also observed in the eastern side of the basin off Scotland and Ireland coasts. In the South-East of the basin, the deep mixed layer extension stops around 48/50°N such that only moderate mixed layer depths are observed along the shelf in the Bay of Biscay contrary to the 2011, 2014 and 2015 winters.

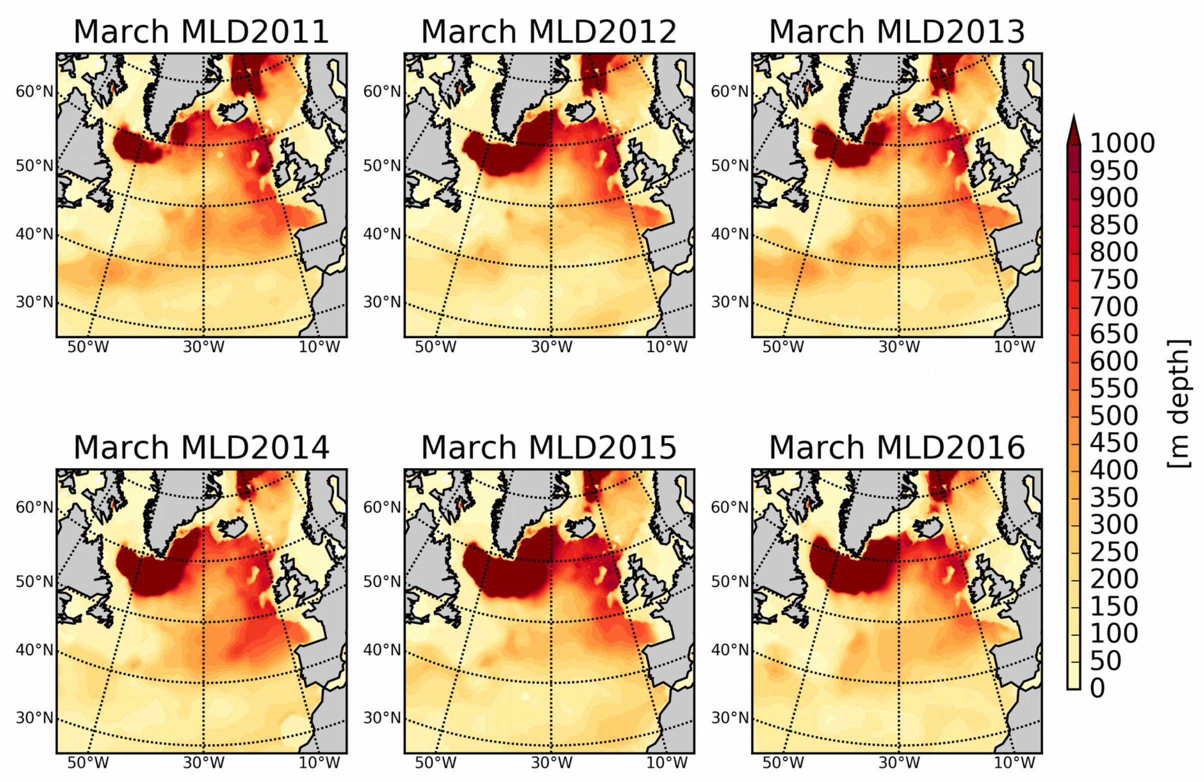


Figure 1.3: North Atlantic mixed layer depth in March from 2011 to 2016.

The most salient feature of the 2016 annual mean temperature anomaly (using WOA05 as reference climatology) is an intense cold anomaly, persistent and increasing since 2013) over the subpolar basin from the tip of Greenland to 40°N and the persistence and increase of a warm anomaly over the Greenland Sea and along the East Greenland coast (Fig. 1.4a).

In 2011, a salinity anomaly is observed in the western North Atlantic basin around 45°N, then the fresh near surface water anomaly translates toward the eastern North Atlantic entering the Irminger Sea in 2016 (Fig. 1.4b). In the Irminger Sea, fresher near surface water may explain the smaller than 2015 extend of deep mixed layer (Fig. 1.3), because of stratification effect of fresh water. Around the Greenland coast, strong fresh anomaly is also observed increasing since 2014. In Greenland Sea persistent warm/salty anomaly is observed since 2011. In contrast, in 2016 Labrador Sea is saltier than usual, likely favoring convection during winter.

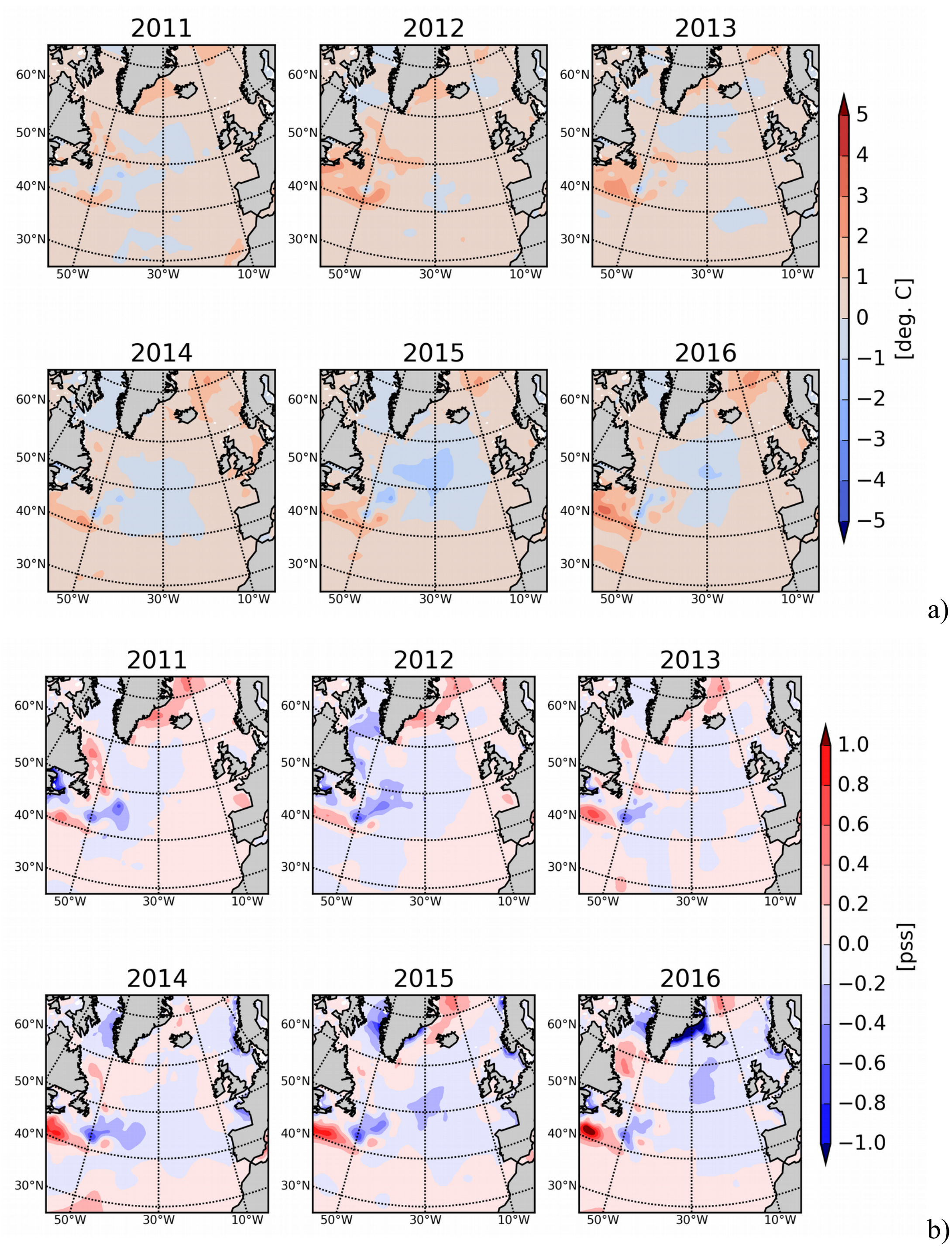


Figure 1.4: Annual average temperature (a) and salinity (b) anomalies at 10 m depth during 2011-2016

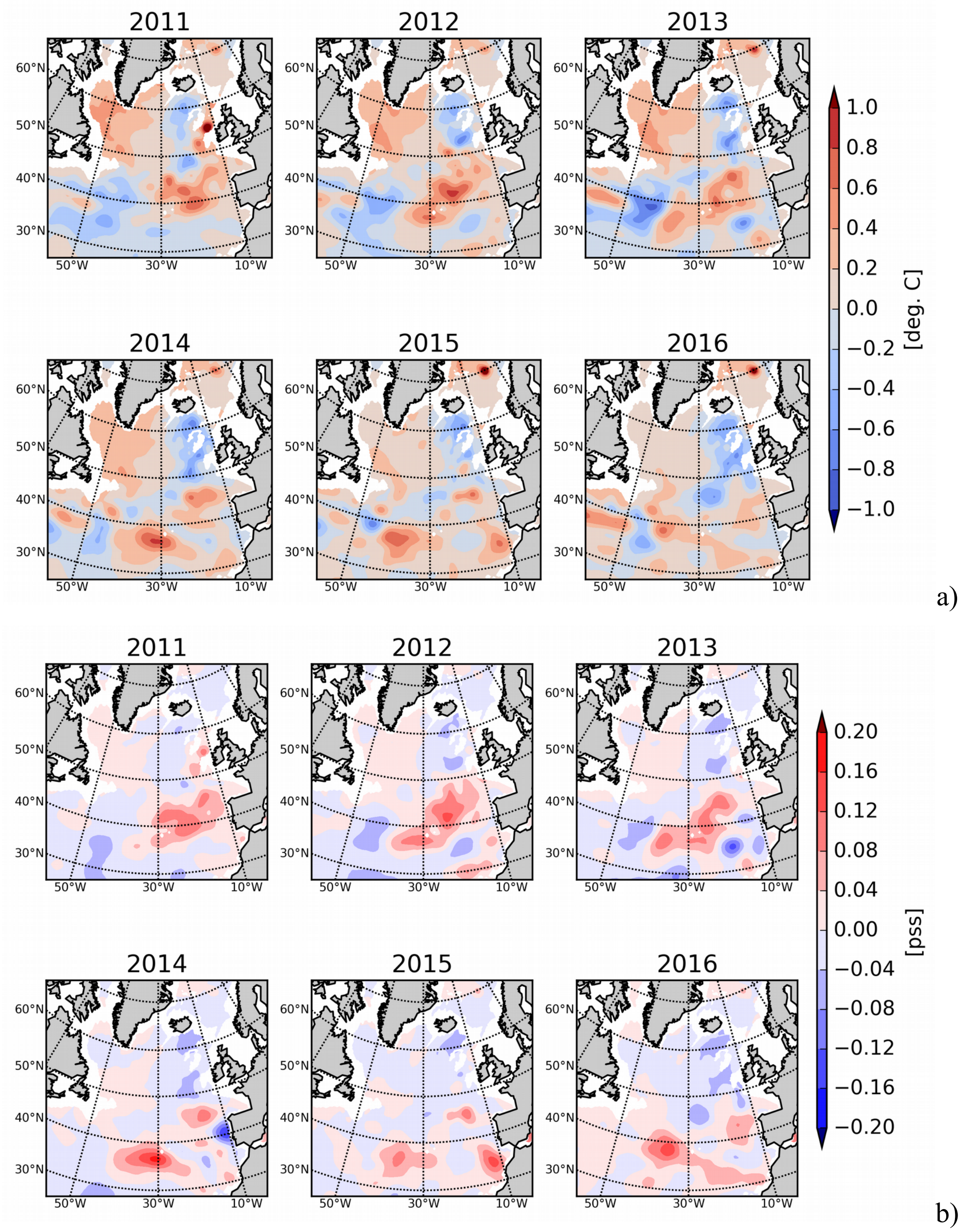


Figure 1.5: Annual average temperature (a) and salinity (b) anomalies at 1000 m depth during 2011-2016.

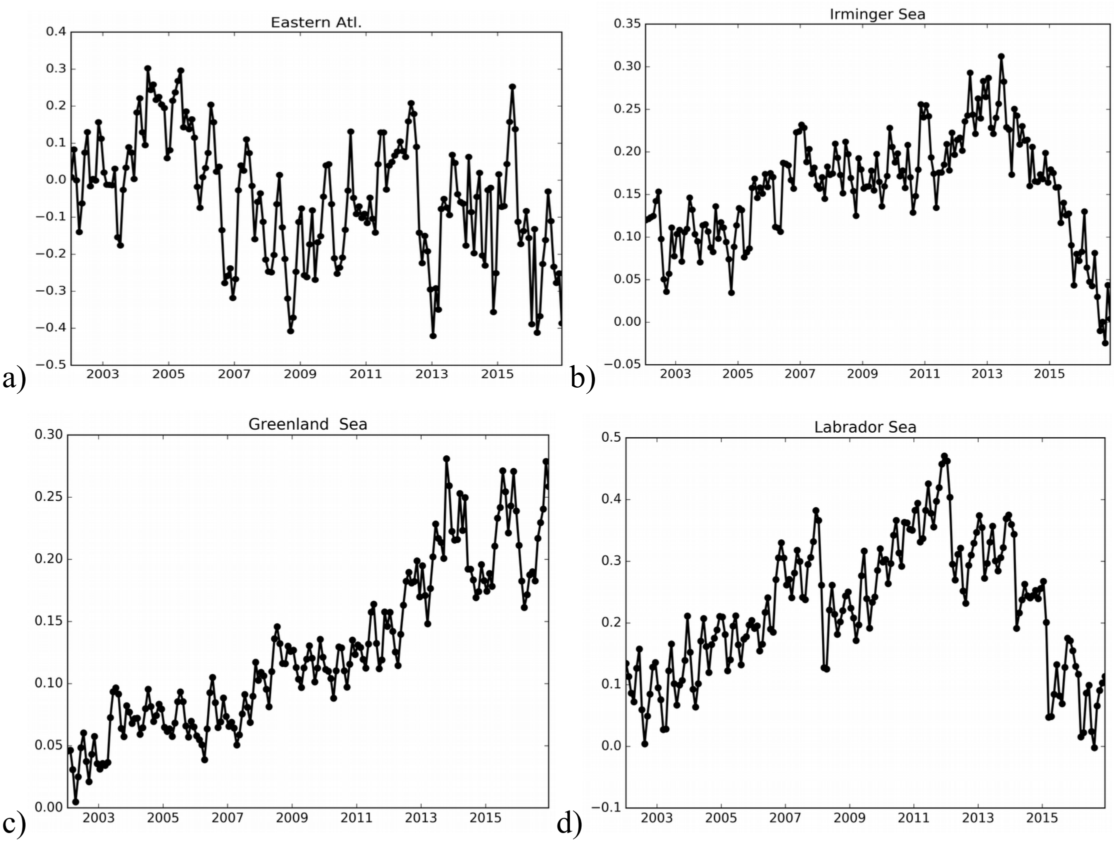


Figure 1.6: Time series of temperature anomalies (using WOA05 as reference) averaged over the 800-1200m layer over 2002-2016 period in a) Eastern Atlantic region; b) Irminger Sea; c) Greenland Sea and d) Labrador Sea.

1.3 Deep layers

At 1000 m (Fig. 1.5), the Labrador Sea and the Irminger Sea are warmer than normal, but the warming tendency observed since 2002 is interrupted since 2012 as seen in the time series (Fig. 1.6bd). This may likely reflect the return to deep winter convection in this both basin since 2012.

The Greenland sea warming reaches a maximum in 2014. Then, it remains stable during 2015-2016 (Fig. 1.6c).

The Mediterranean Outflow water is warmer and saltier south of 40°N and off Gibraltar straight. The salt increase seems to extend westward in the subtropical basin and northward off the Portuguese coasts (Fig. 1.5).A cold and fresh anomaly stands from the South of Iceland down to Rockall Trough, and is intensified in 2016 (Fig. 1.5). A warm and salty anomaly is observed south of the Gulf-Stream and Azores current (subtropical gyre; Fig. 1.5).

1.4 References

Gaillard, F., 2012. ISAS-Tool Version 6: Method and configuration. Rapport LPO-12-02, http://archimer.ifremer.fr/doc/00115/22583/

Gaillard, F., T. Reynaud, V. Thierry, N. Kolodziejczyk and K. von Schukmann , 2016 : In Situ–Based Reanalysis of the Global Ocean Temperature and Salinity with ISAS: Variability of the Heat Content and Steric Height, *J. Clim.,* 29, 1305-1323.

2 Surface sampling along AX1 and AX2 (North Atlantic subpolar gyre)

The two shipping routes along which surface sampling was continued were (Fig. 2.1) lines AX2 (since mid-1993; in 2015/mid-2016, MV Skogafoss) between southern Newfoundland and Reykjavik; and AX1 (since mid-1997; mostly from MV Nuka Arctica) between Denmark and west Greenland. Both ships were equipped with thermosalinograph and XBT launchers, and are part of a concerted multi-disciplinary effort, including the measurement of the current with a ship-ADCP on Nuka Arctica (Univ. Bergen) and pCO2 measurements on Skogafoss (NOAA/AOML) and Nuka Arctica (Univ. Bergen). Because of large sea ice extent in late winter and early spring, as well as numerous winter storms in the winter and early spring 2015 or 2016, the nominal AX2 route was not often followed during these seasons. Regular sampling on AX2 has stopped in mid-2016, and the update in 2016 will not be presented. For AX1 (Nuka Arctica), there were different issues with the instrumentation from August to November 2016, and the Hovmüller is only presented until early August 2016 for the part of the section between the shelf break off Cape Farewell and the approaches of Scotland is presented.

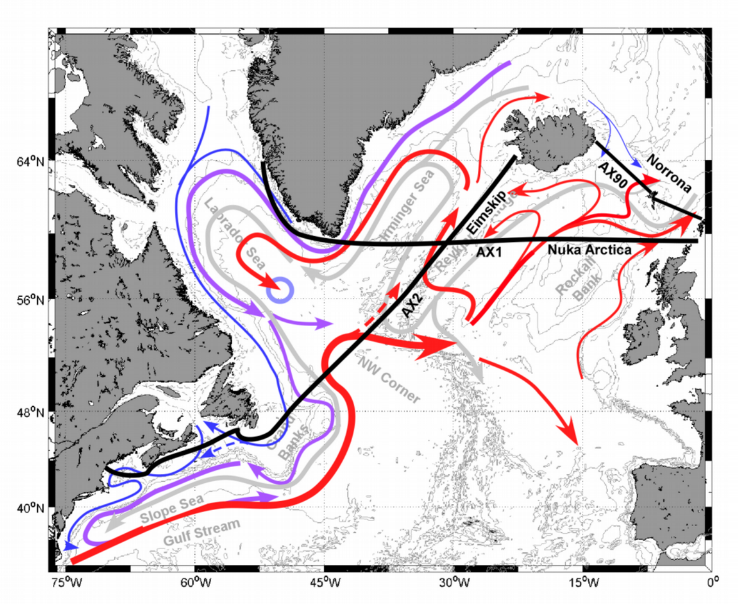


Figure 2.1 : AX1 and AX2 ship of opportunity lines equipped with Thermosalinograph and XBT launcher. Surface (red arrows) and deep (bleu and purple arrrow) main currents are indicated.

We will now comment the AX1 zonal section (Nunka Arctica. Most of the data originate along 59°N, the most sampled latitude band) (Fig. 2.2), but to fill gaps at times, we have also combined with data a little further south (near 58°N) or north (near 60°N). These three latitude bands indeed present rather coherent variability except at the eastern end, when combining data based on bathymetry (that is in a north-east to south-west direction, parallel to the Reykjanes Ridge). First, monthly anomalies are computed with respect to an average seasonal cycle, then a 1-2-1 running mean filter is applied over successive monthly anomalies. Isolated data gaps over more tan 3 months have also been interpolated linearly (mostly in 1993-1997). On this section, salinity anomalies can be rather different east of the Reykjanes Ridge in the Iceland Basin (15-30°W) than west of it. For example the low SSS anomaly in 1994-1996 was more pronounced in the Irminger Basin than to its east, whereas the low salinity anomaly in 2015-2016 was more pronounced in the Iceland

Basin between 15°W and 30°W. Also, it seems that anomalies close to the Scotian slope/eastern Faroe Channel end of the section follow by a little over 1 year the anomalies in the central Iceland Basin (although correlation is not very high). Also, it seems that anomalies are a little weaker near 10°W than to its east or west. The 2015-2016 negative SSS anomalies in the Iceland Basin are the largest anomalies recorded so far in this surface sampling program. Comparison with data compilation since 1896 indicate that they rival with the largest negative anomalies recorded in the late 1970s.

In comparison, SST anomalies that were also very large and negative in 2015 have returned to near normal (slightly negative) in early/mid 2016. The largest negative SST anomalies remain those found in the west (Irminger Basin) in 1993-1994. On a seasonal to interannual basis, SST anomalies tend to be much more zonally homogeneous than SST anomalies, and don't present much coherence with SSS anomalies (see also Reverdin, 2012). On multi-year to decadal time scales, there is more coherence between the SST and SSS anomalies, with a tendency for maximum SSS anomalies to lag the SST anomalies.

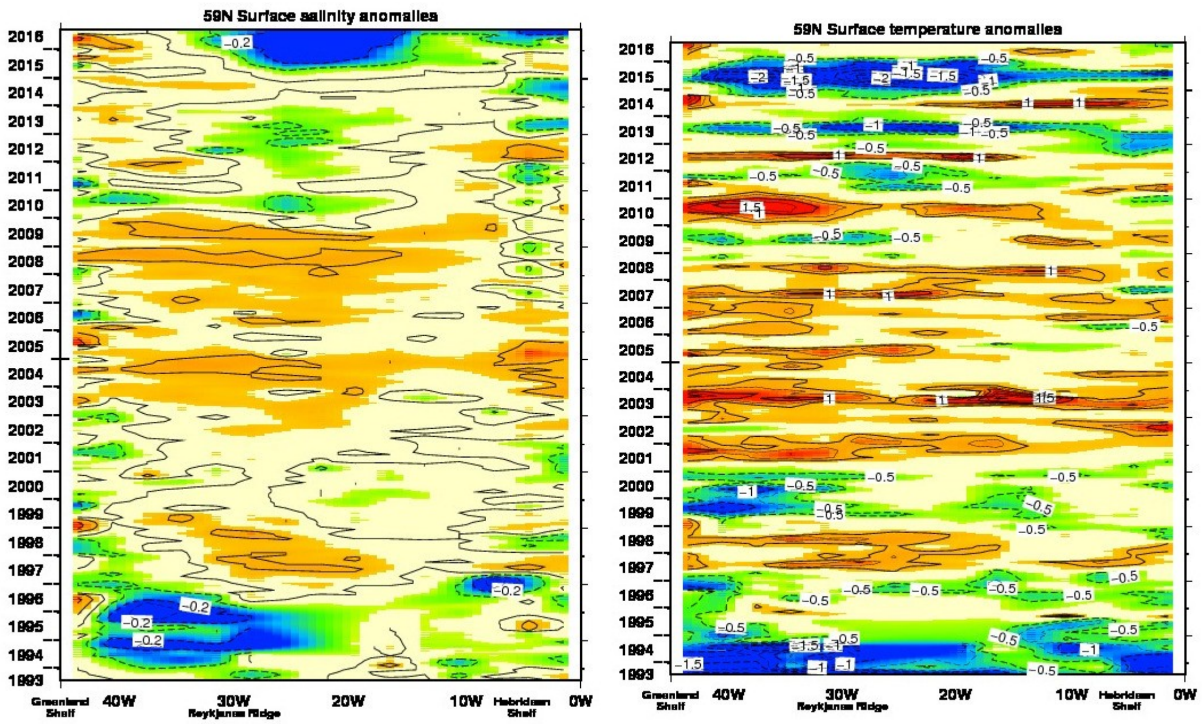


Figure 2.2: Monthly salinity (left panel) and temperature (right panel) anomalies from the Nuka Arctica along 59°N from the shelf break south-east of Cape Farewell to the north-west of Scotland between 1993 and August 2016.

3 South western Channel: Astan and Estacade time series

3.1 The year 2016 vs Climatology

Here, we present measurements collected twice a month at two stations located on the north coast of Brittany in France. The Estacade site is located at the end of a pier (3°58’58°W and 48°43’56°N) (Figure 3.1) in the city of Roscoff (France) where the bottom depth varies from 3 to 12 m depending on the tides. Measurements began in 1985 and are collected at 1 m depth. The Astan site (3°56’15°W; 48°46’40°N) is located 3.5 kilometers offshore from the Estacade site (Figure 3.1) and measurements began in 2000. Seawater biogeochemical properties at this site are typical of the Western Channel waters. Bottom depth is about 60 m depth and the water column is well mixed for most of the year. More details can be found at http://somlit.epoc.u-bordeaux1.fr/fr/ and http://www.sb-roscoff.fr/en/coastal-observatory/marine-system-hydrological-parameters-offshore-roscoff. The Western Channel is connected to the eastern boundary current and linked to the North Atlantic drift. The climatic conditions are impacted by the westerlies blowing over the Atlantic basin which transport heat and moisture towards the Western Europe. These conditions explain the typical weather conditions observed in the Roscoff area: Winter precipitations generate intensive weathering of the soils loaded with important nutrients amounts from intensive agriculture. River discharges contribute to influence the salinity cycles and to feed the stocks of nutrients in coastal waters. Salinity of this coastal waters remained close to 35.5, a typical value of the waters adjacent to the North Atlantic Ocean. This system can be considered as a coastal system.

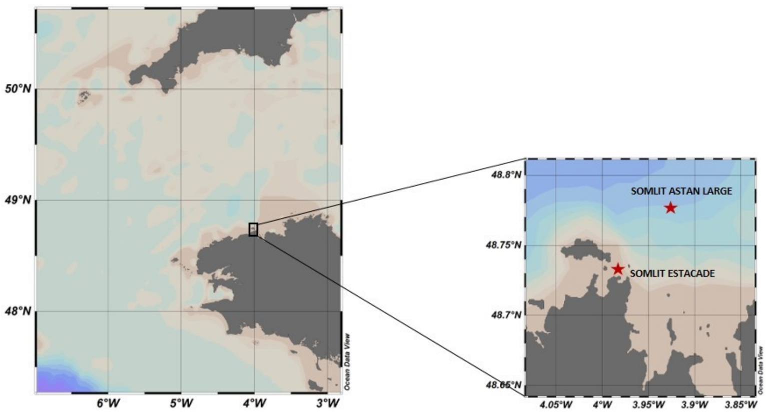


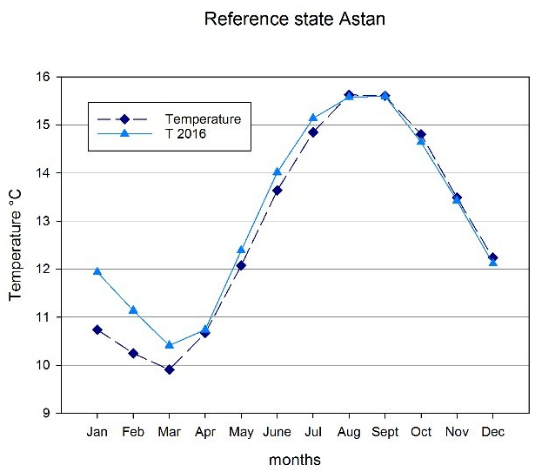
Figure 3.1: Localisation of Estacade and Astan large sites.

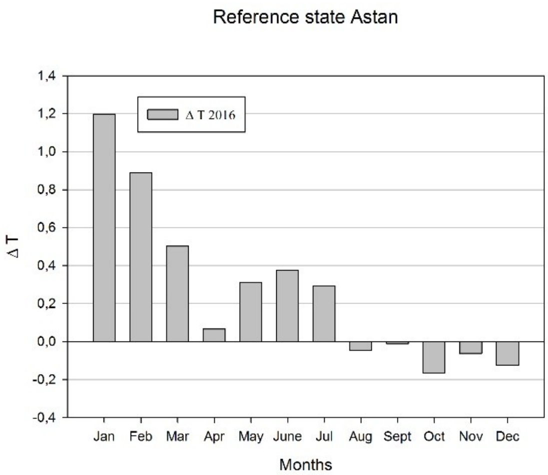
Figures 3.2 and 3.3 display the 2016 cycles of temperature, salinity and nitrate in relation to the mean annual cycle at the Astan and Estacade stations. The temperature cycles show similar dynamics between the 2 studied stations: At Astan station, for the year 2016, temperatures are higher than the climatology values for the winter, spring, summer (from 1.20°C to 0.07°C) and lower from august to december (from -0.17 °C and -0.01°C). At Estacade station, temperatures are higher than climatology values for the winter and at the beginning of spring (from +1.38°C to

+0.20°C) but become lower in summer and the beginning of fall with a maximum deviation equal to -0.44°C in october. In the two stations, except in winter, we can observe that the temperature values are close to the climatology The annual average and global values are given in tables 3.1 and 3.2.

The mean Salinity cycles at the two stations are characterized by an important seasonality with minimum values in spring and maximum in fall. The salinity seasonal cycle is starts one month earlier at the Astan station compared to the Estacade station. In 2016, the salinity cycle is atypical in comparison with the global average cycle. Indeed, there are no low values in winter and spring except in February and march at Estacade station and we can observe a constant increase all along the year (we observed a maximum deviation in salinity equal to +0.166 at Estacade and +0.122 at Astan, in December). Salinity values are just lower than the average for summer. Minimum salinity values weren't observed in 2016, especially at Astan station, because of a dry winter with low water precipitations reducing the river inputs in the Western Channel. We 've observed the same kind of cycle with no spring salinity low values in 2005, 2007, 2012 and 2015. At Estacade, we can observe a minimum salinity value. This event is just located in the shore station and didn't affect the deep sea station. We can link this low salinity value at Estacade with the very high nitrate (11.4 µM) value observed in March. This value corroborates an episodic discharge of fresh water from soil weathering.

During 2016, at Astan station, nitrate concentrations were significantly lower than the averaged values excepted from August to september where they are above the mean values. At the Estacade station, we observed a different evolution than in the Astan station. Nitrate concentrations were almost totally exhausted at Estacade contrary to Astan where the nutrients stock is spread over the well-mixed water column and not totally consumed by the phytoplankton development. The low levels of nitrate concentrations are linked to the high levels of salinity for 2016, especially at Astan station in winter and spring as in 2015. The weaker river inputs contributed less to the nutrients supplies.





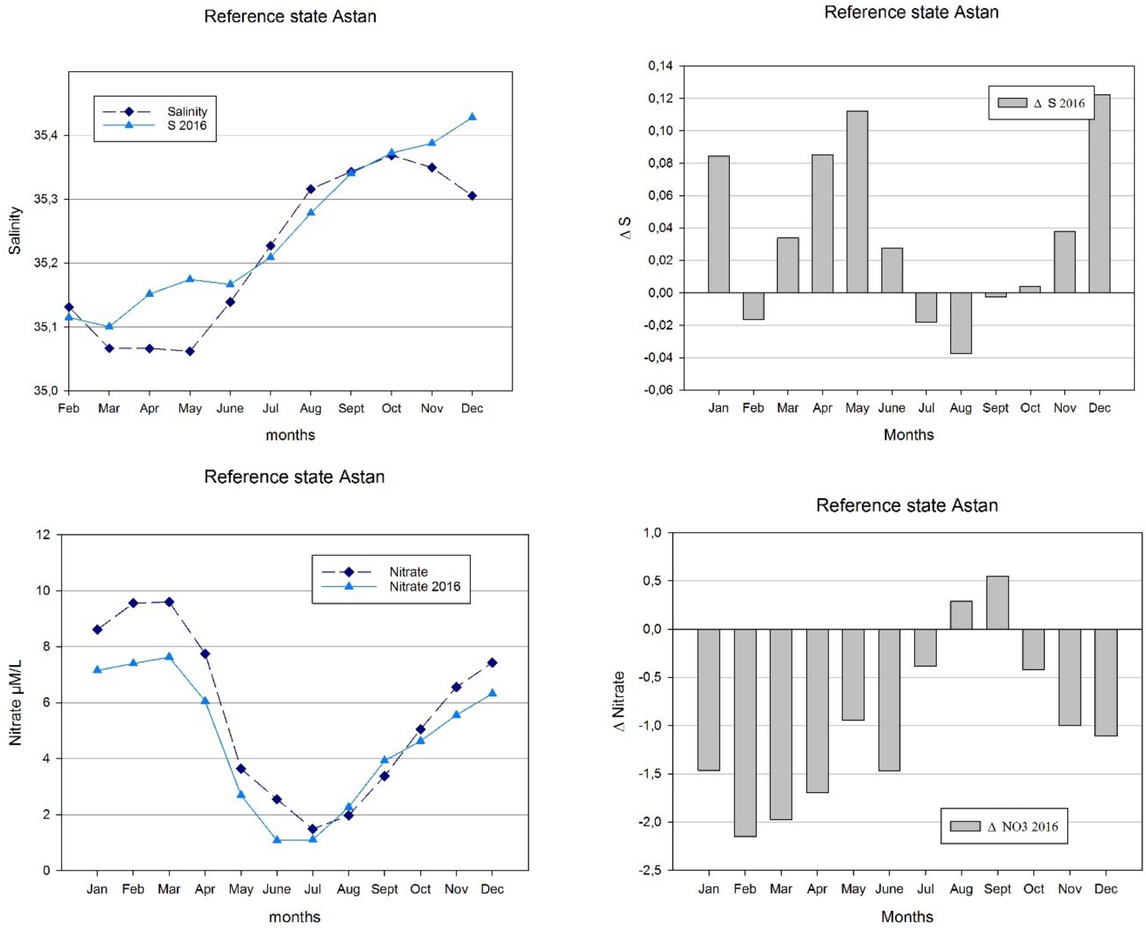
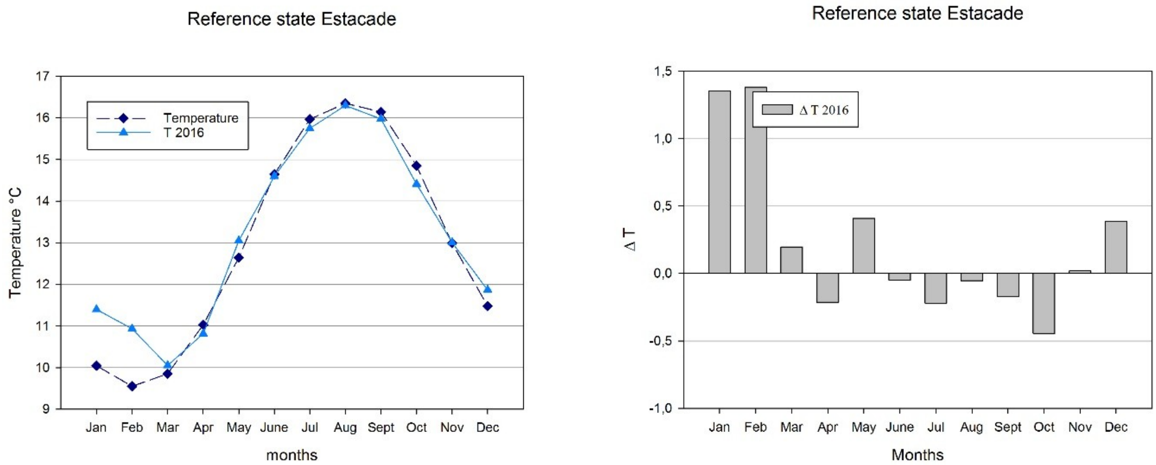


Figure 3.2: comparison between time series of temperature (upper), salinity (middle) and nitrate (lower) at Astan site in 2016 with the climatological cycle (average over the 2000-2016 period). (Left panels) Dark blue line represents the mean annual cycle and the light blue line represent 2016 data. (Right panels) 2016 deviation to mean values.



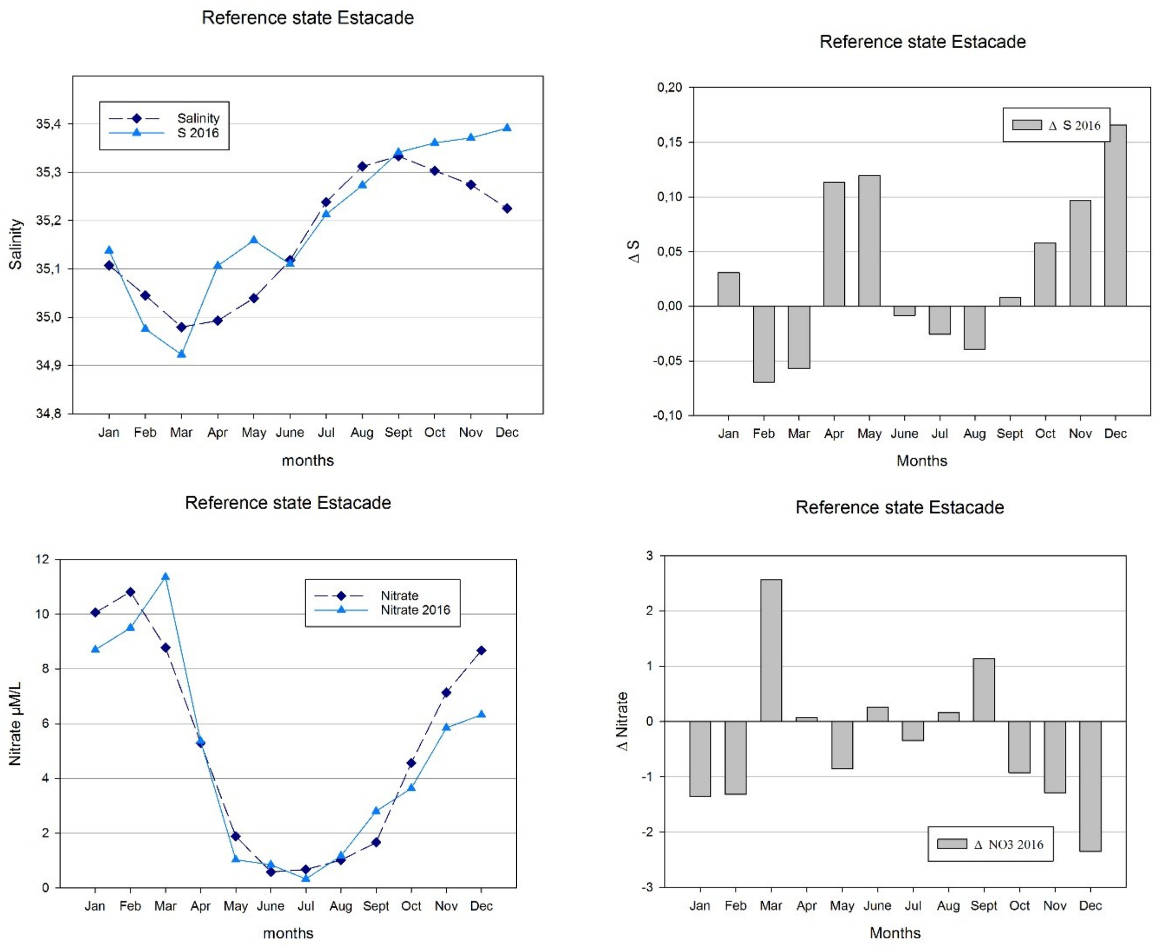


Figure 3.1: comparison between time series of temperature (upper), salinity (middle) and nitrate (lower) at Estacade site in 2016 with the climatological cycle (average over the 2000-2016 period). (Left panels) Dark blue line represents the mean annual cycle and the light blue line represent 2016 data. (Right panels) 2016 deviation to mean values.

Estacade	Temperature (°C)	Salinity	Nitrate (µmole/l)
Global average	12.94	35.172	5.1
2016	12.95	35.190	4.9

Table 3.1: Global mean for the period 1985-2015 and 2015 values at Estacade station.

Astan	Temperature (°C)	Salinity	Nitrate (µmole/l)
Global average	12.84	35.213	5.5
2016	13.00	35.246	4.7

Table 3.2: Global mean for the period 2000-2016 and 2016 values at Astan station.

3.2 Water column properties

As usually observed in this area, the Western Channel waters were well-mixed over the entire water column during the whole year with no significant gradient observed between the surface and the bottom (Figure 3.4). The low vertical temperature gradient observed episodically in late summer (late august- early September) during low wind-neap tides period was not observed in 2016. As for temperature Western Channel waters were generally well-mixed over the entire water column since no salinity differences between surface and bottom waters were observed even during the late summer surface heating.

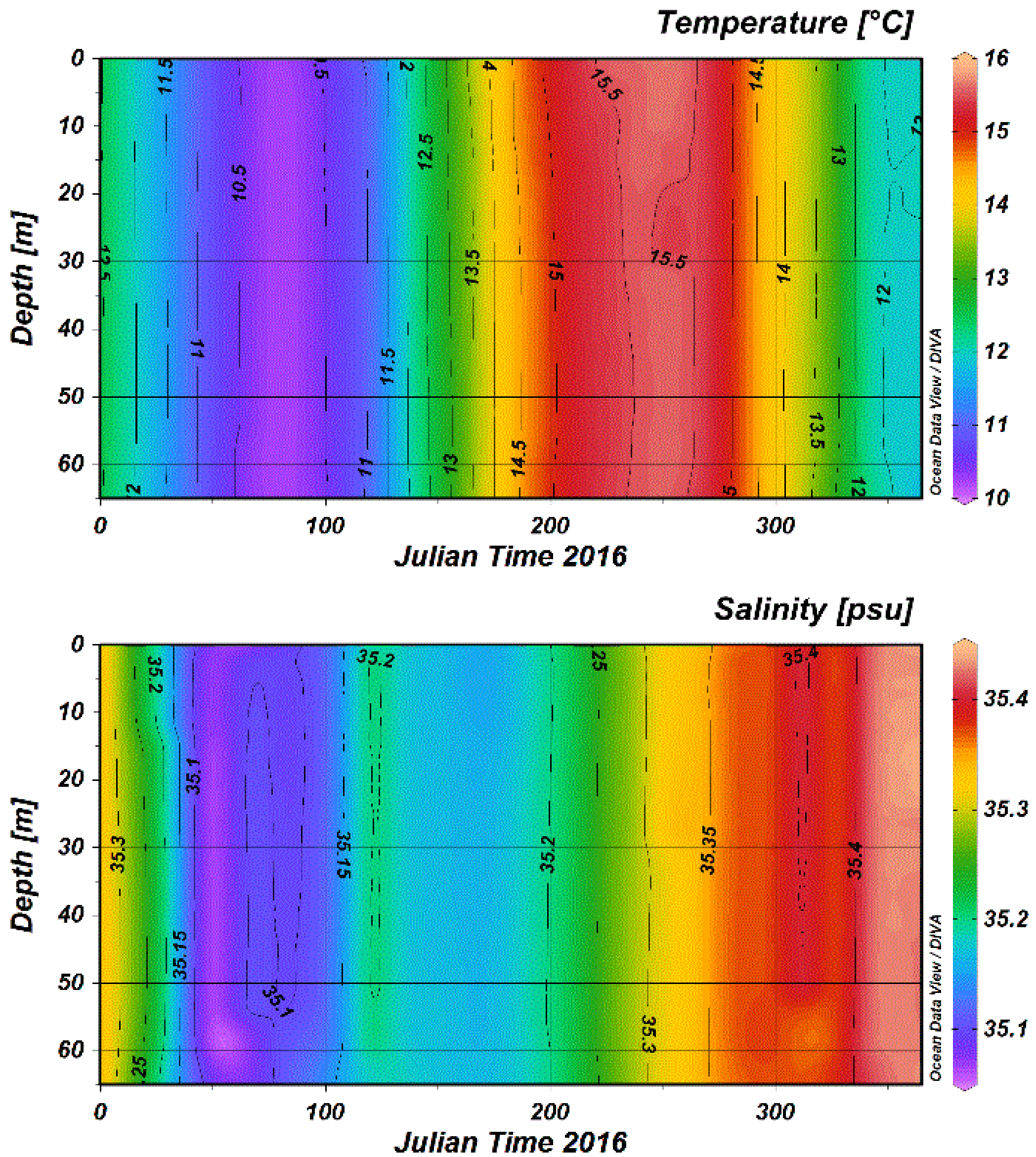


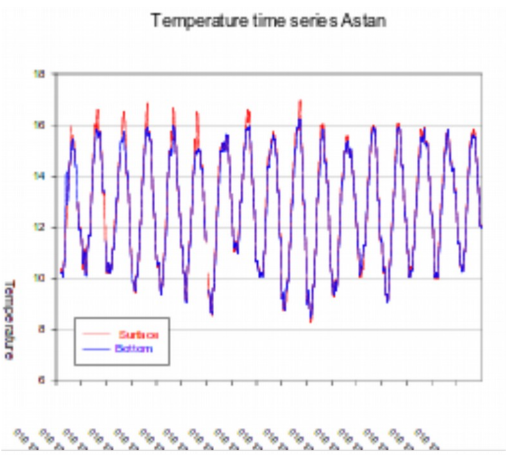
Figure 3.4: vertical distributions of temperature (top) and salinity (bottom) at Astan site during 2016 (bimonthly CTD profiles). Well-mixed waters were observed during the whole year due to an enhanced vertical mixing by tidal currents.

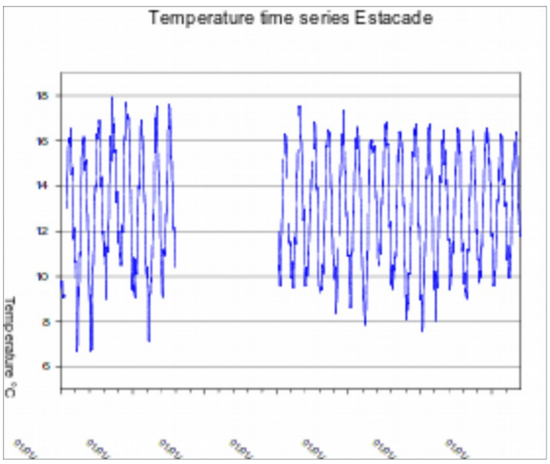
3.3 Long-term trends

Figure 3.5 shows the time series of temperature, salinity and nitrate at Astan over the period 2000-2016 and at Estacade over the period 1985-2016 with a large gap from 1992 through 2000 for temperature, salinity and nitrate measurements. At the Astan and Estacade sites, winter 2016 minimum temperature were significantly higher than the global mean calculated over the time series.

In 2016, salinity cycle is characterized, as mentioned above, by higher values than those usually observed in this area, especially in winter. Annual salinity Means at Astan and Estacade are slightly higher than the global average values. The differences are more important during winter explaining the low values of nitrate in the first part of the year, except for March at Estacade. Usually, nitrate concentrations, as salinity and temperature, present a large interannual variability particularly in the winter maximum values which is linked to the interannual variability in the oceanic influence in the Channel waters. Maximum nitrate winter concentration (7.6 µM/l at Astan) was significantly lower than average winter values due to the reduced influence of the low salinity waters in the Western Channel. At Estacade, the hydrological cycle shows a different evolution, particularly in winter with a 2016 nitrate maximum above the average values (11.4 µM in 2016 vs 10.8 µM for the maximum average value).

The winter (January to March) mean nitrate concentrations was the third minimum concentrations observed between January and April since 2000 at Astan. Nitrate winter and early spring stock for the spring phytoplankton development was reduced in 2016 when compared to the previous years but not in the lowest values measured since 2000 at the two stations.





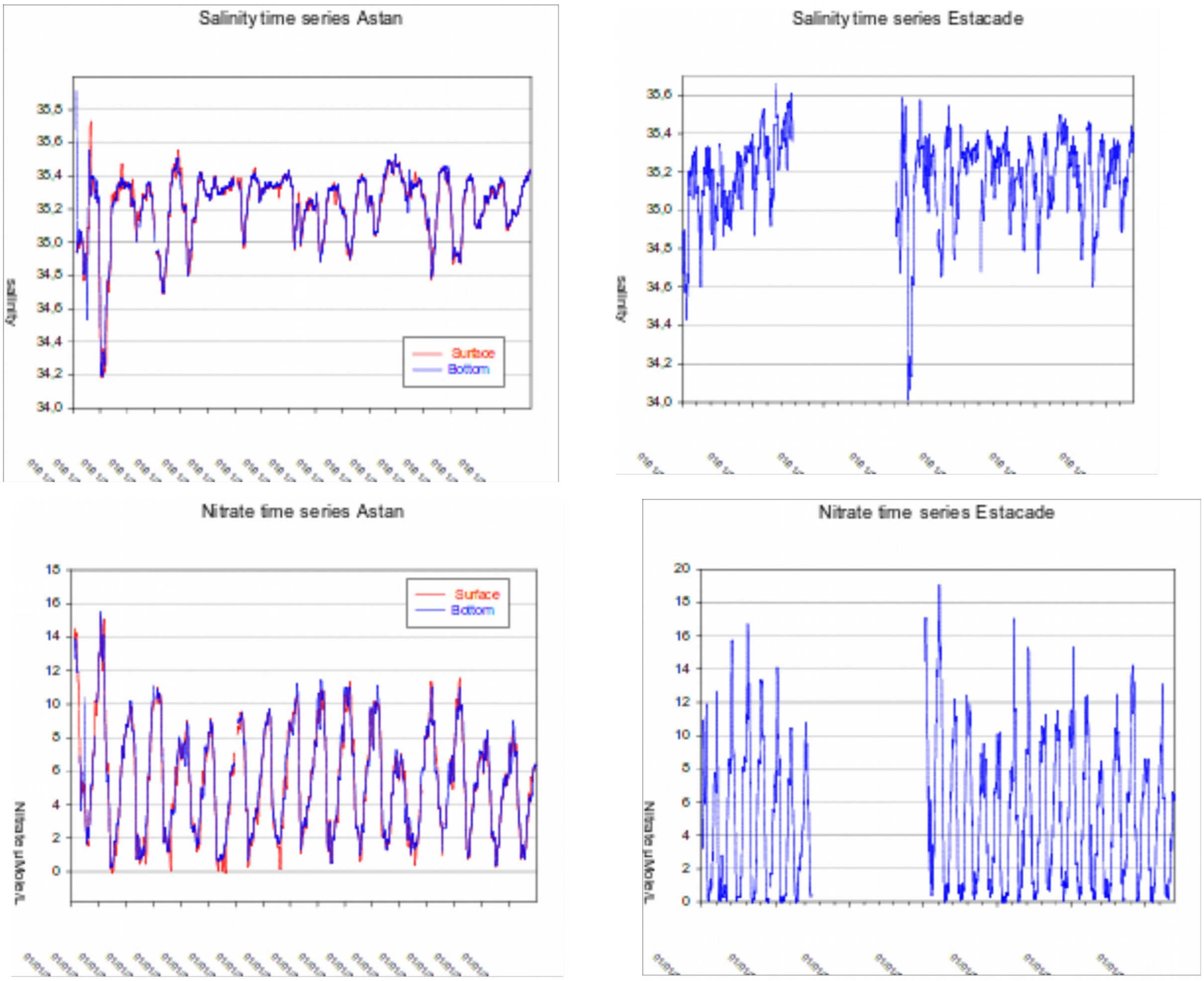


Figure 3.5: Interannual variability of the temperature, salinity and nitrate at Astan site over 2000-2016 (left panels) and at Estacade site over 1985-2016 (right panels).

We calculated the trends over the time series for the 2 periods mentioned above: At Astan station, we observed a decrease of SST (-0.002°C/year), an increase of the SSS (+0.007 pss/year) associated to a decrease of the nutrient concentrations (-0.06 µmole/year).

At Estacade station, on the same period (from 2000 to 2016), we observed an increase of SST (+0.002°C/year), an increase of the SSS (+0.007 pss/year) and a decrease of the nutrient concentrations (-0.07 µmole/year). There is a slight difference between the two sites in the temperature trend with a decrease in the open sea station (Astan) and an increase at the coastal point (Estacade).