Laboratoire d'Océanographie Physique et Spatiale

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Contribution to the ICES Report on Ocean Climate : North Atlantic Ocean in 2019

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Table of Content

1 Argo gridded temperature and salinity field

1.1 ISAS: gridded temperature and salinity fields

The ARGO network of profiling floats has been set up to monitor large-scale global ocean variability (http://www.argo.ucsd.edu). Argo data are transmitted in real time and rapidly made available by the two Global Data Assembly Centres (Argo-GDAC). Delayed-mode data undergo expert calibration and are delivered later. In the North Atlantic, temperature and salinity conditions have been adequately described over the upper 2000 m since 2002. The dataset is thus suitable for an overview of oceanographic conditions in this basin and provides the general context for the data collected at stations and sections, mostly located at the periphery of the basin.

Temperature and salinity gridded fields are estimated on a regular 0.5° grid using the *In Situ* Analysis System (ISAS; Gaillard *et al.*, 2016). The dataset used for generating ISAS gridded fields is downloaded from the Coriolis Argo GDAC1. It should be noted that Coriolis assembles many types of data transmitted in real time, merging the Argo dataset with data collected by the Global Telecommunications System[1] (GTS), such as data from moorings and CTDs, and data on marine animals. However, the Argo dataset remains the main contributor to the ISAS gridded fields in the open ocean. The optimal interpolation (OI) procedure is as follows: the *in-situ* temperature and salinity profiles are vertically interpolated on 152 standard levels between the surface and 2000 m depth. The horizontal mapping to produce gridded fields is performed at each standard level independently. The mapping method is based on an optimal estimation algorithm and includes a horizontal smoothing through specified covariance scales. The results presented here were produced with the last version of ISAS. The reference state used in the OI process was computed as the mean of a 2005–2012 analysis (using ISAS13; Gaillard *et al.*, 2016) and the *a priori* variances were computed from the same dataset. Two ISAS gridded temperature and salinity products are used:

- For the period 2002–2015, ISAS15 product is used (Kolodziejczyk *et al.*, 2017). For this period, only delayed mode *in situ* data are used, and ISAS15 product is the highest quality product in Delayed Mode. Moreover, data are preprocessed, and extra quality control is applied to *in situ* profiles before they are included in the analysis.
- The last years of the analysed series, i.e. 2016–2019, use the Near Real Time (NRT) dataset prepared by Coriolis at the end of each month from real-time data. For this period, data are interpolated using ISAS v6 including only real-time mode data (i.e. only from automatic QC processing). Because Argo salinity data require advanced quality checks and validation, NRT salinity fields have to be used with caution. Therefore, time-series of monthly salinity anomalies are not considered herein, and the focus is rather made on their seasonally averaged and annually averaged patterns.

1 https://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html

The ISAS interpolated fields are used to compute seasonal to interannual maps of temperature and salinity anomalies averaged within an upper layer (0–100 m depth) and an intermediate layer (800–1200 m depth). Note that the temperature and salinity anomalies throughout this section are computed using the climatological ISAS15 fields (2006–2015). This approach differs from the

Argo sections of previous IROC reports, which described anomalies referenced to the long-term pre-Argo era (World Ocean Atlas, 2005). In order to compute temperature and salinity anomalies, the climatological monthly temperature and salinity fields are removed from each monthly ISAS field over the period 2002–2019. Note that the temperature and salinity fields are blanked in regions with water depths exceeding 1000 m, where the Argo coverage is either too sparse or unavailable. A criterion of > 80% of explained variance provided by the objective analysis was chosen to further discard the undersampled grid points, which are mostly found within shallow shelf regions. The seasonal time-windows are defined as winter (December–March), spring (April–June), summer (July–September), and autumn (October–December)

1.2 Highlight of 2019

In the North Atlantic sector, the surface layer (0–100 m) of the subtropical ocean, subpolar ocean, and the Nordic seas had been trending warmer, cooler, and warmer, respectively since 2002. In the most recent years (2018–2019), those trends have reversed, presumably simultaneously, and a cooling – warming – cooling latitudinal pattern is now being observed by the array of Argo profiling floats (Fig. 1).

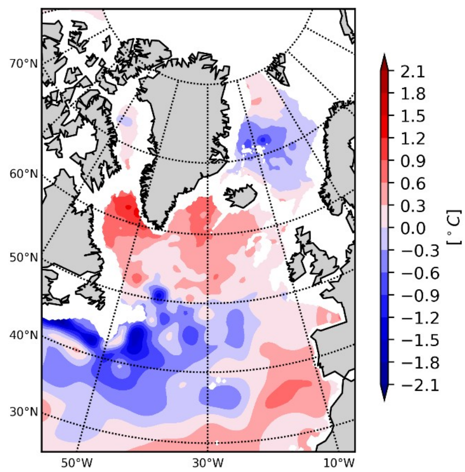


Figure 1: 2019 minus 2018 temperature difference in the upper layer (0–100 m).

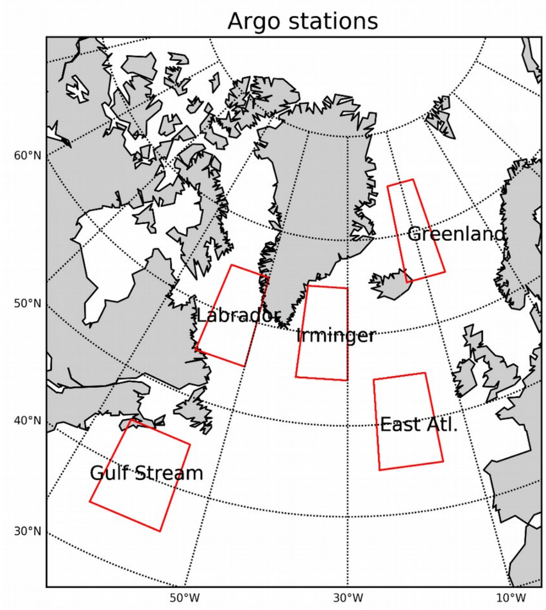


Figure 2: Location of five boxes in the North Atlantic basin: Eastern Atlantic, Irminger Sea, Labrador Sea, Gulf Stream region, and Greenland Sea. Those areas are used for temperature and salinity diagnosis (time-series).

1.3 Surface layers

Seasonal cycle

The broad pattern of temperature and salinity anomalies in 2019 (with respect to the 2006–2015 climatological mean) shows a relatively warm and salty subtropical region, a relatively cold and fresh subpolar region, and relatively warm and salty Nordic seas. However, there were significant subregional and intra-annual changes in each of these regions (Fig. 3). The warm subtropical anomalies appear to originate in winter in a confined area encompassing the Gulf Stream path south of the Grand Banks. They subsequently spread eastward and southward in the subsequent seasons following the general anticyclonic circulation of the gyre. A similar, although less marked, pattern is observed for salinity. In the subpolar region, negative temperature anomalies were significant within two centres of action, the Irminger Sea and the Newfoundland area, and peaked in both regions in spring, after which the former faded away, while the latter started to propagate eastward toward the Iceland Basin. Interestingly, a warm and salty anomaly gradually developed in the northern Labrador Sea, reaching a peak amplitude in autumn while being advected southward by the Labrador Current along the upper North American US continental slope. In the Nordic seas, warm anomalies primarily developed within the western portion of the domain (Iceland and Greenland seas), while cold anomalies developed along the eastern margin (Norwegian Sea). This asymmetric pattern is less visible for salinity, but still present (salty in the west and fresh in the east). The 2019 seasonal cycles of temperature and salinity, averaged within five boxes representative of the main area of the North Atlantic domain, are put into context relative to the long-term 2002–2019 context in Figure 4.

- In the Eastern Atlantic (Fig. 2 and Fig. 4), the 2019 surface layer temperature exhibited a seasonal cycle similar to the 2006–2015 average, while, during the previous period (2014–2018), the surface layer was consistently cooler than normal throughout the year.
- In the Irminger Sea (Fig. 2 and Fig. 4), the surface layer temperature was cooler than normal throughout the seasonal cycle, especially during winter season. Nevertheless, during summer, temperatures were warmer than during the 2014–2018 period
- The surface layer temperatures in the Labrador Sea (Fig. 2 and Fig. 4) were warmer than normal over the whole seasonal cycle.
- The surface layer in the Greenland Sea (Fig. 2 and Fig .4) was also warmer than normal throughout the year, comparable to the period 2015–2018.
- The surface layer of the Gulf Stream region (Fig. 2 and Fig. 4) was warmer than normal. However, the warming tendency appears to decline in comparison with four previous warmest years (2015–2018).

In conclusion, the observed 2019 seasonal cycle supports the reversal of the warming–cooling–warming pattern observed in the subtropical-subpolar-Nordic seas region (Gulf Stream, and Irminger and Greenland seas), towards a more average situation (referred to the 2006–2015 climatology).

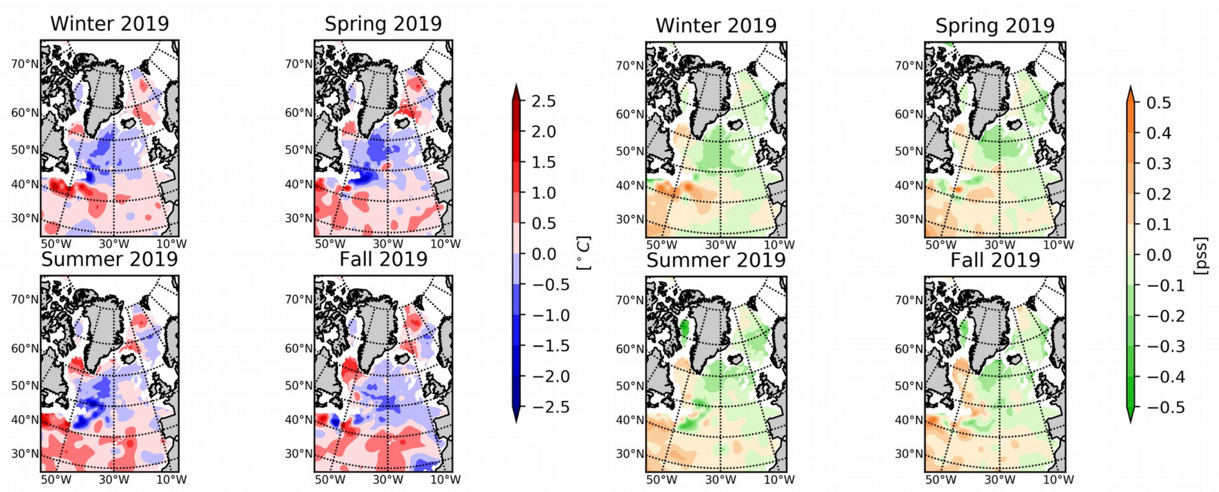


Figure 3: Near surface (10 m depth) temperature (left) and salinity (right) averaged over Winter (JFM), Spring (AMJ), Summer (JAS) and Autumn (OND) 2019. Anomalies are the differences between the ISAS monthly mean values and the reference climatology ISAS15 2006–2015. The colour-coded scale is the same in all panels. Data prepared from the Coriolis, ISAS monthly analysis of Argo data.

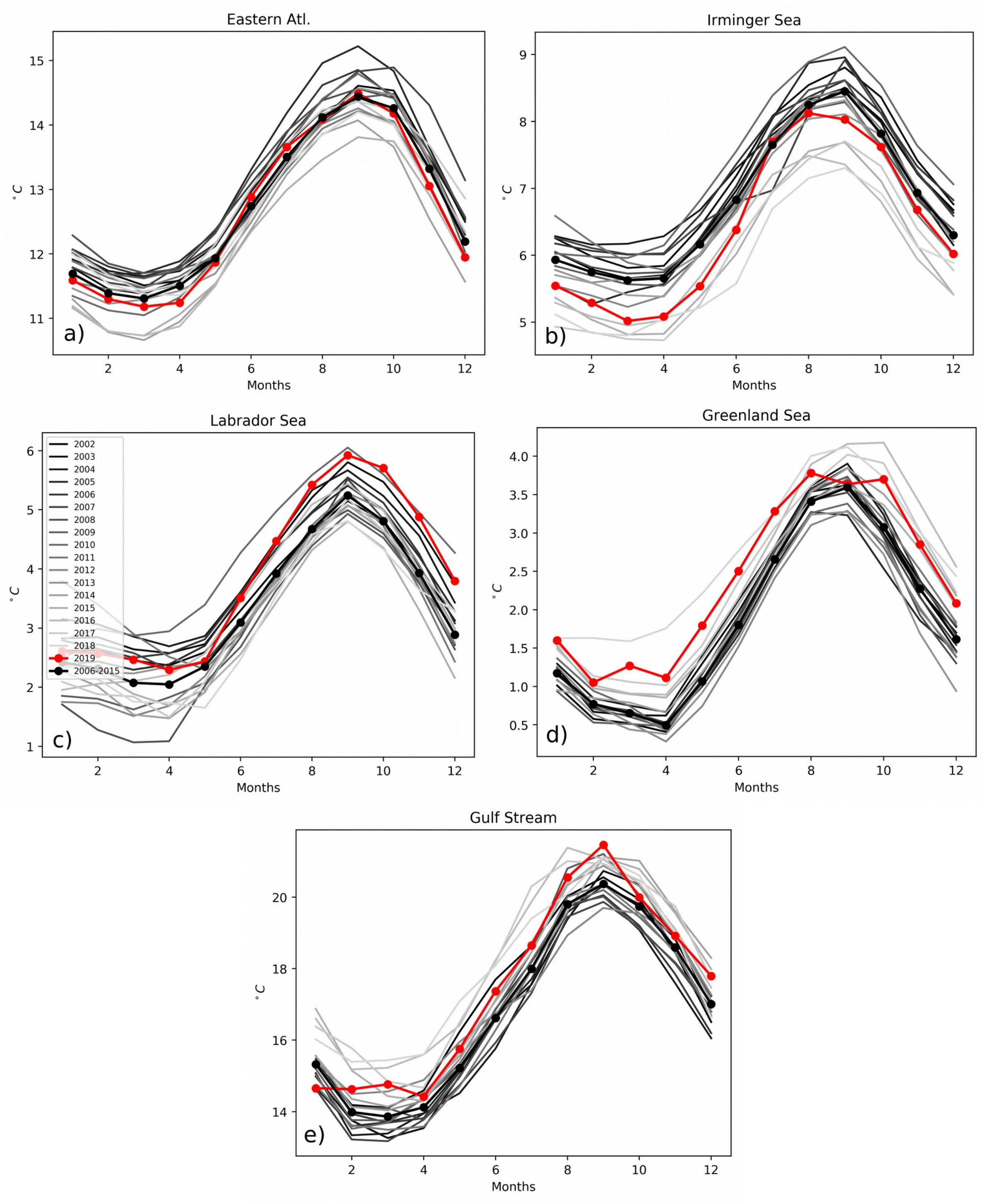


Figure 4: Seasonal cycle for upper temperature (0–100 m layer) as averaged within five boxes in the North Atlantic basin (see stations in Figure 2.3). (a) Eastern Atlantic; (b) Irminger Sea; (c) Labrador Sea; (d) Greenland Sea, and (e) Gulf Stream region. The year 2019 is shown in thick red, the 2006–2015 climatology in thick black, and other curves show the individual years 2002–2018.

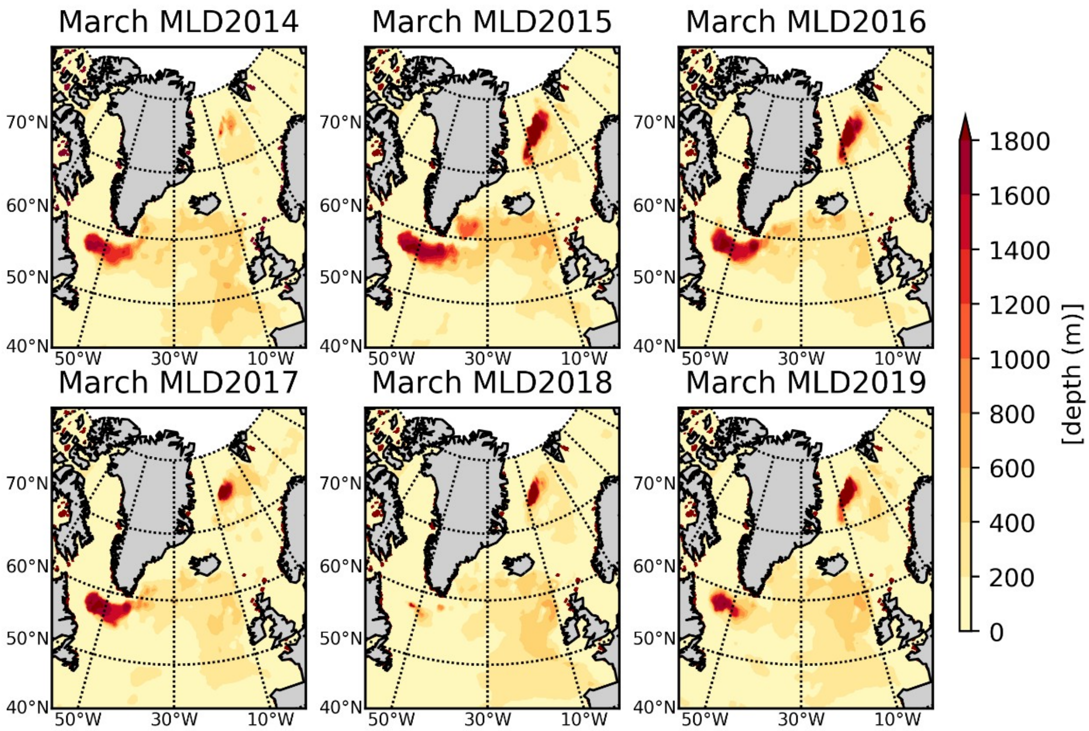


Figure 5: Maps of North Atlantic winter (March) mixed-layer depths (MLD) for 2014–2019. From the ISAS monthly analysis of Argo data. The mixed-layer depth is defined as the depth at which the density has increased by more than 0.03 kg m^{-3} from the density at 10 m depth. This criterion is able to represent MLD in areas where there are both effects of temperature and salinity (ice melting).

Interannual variability

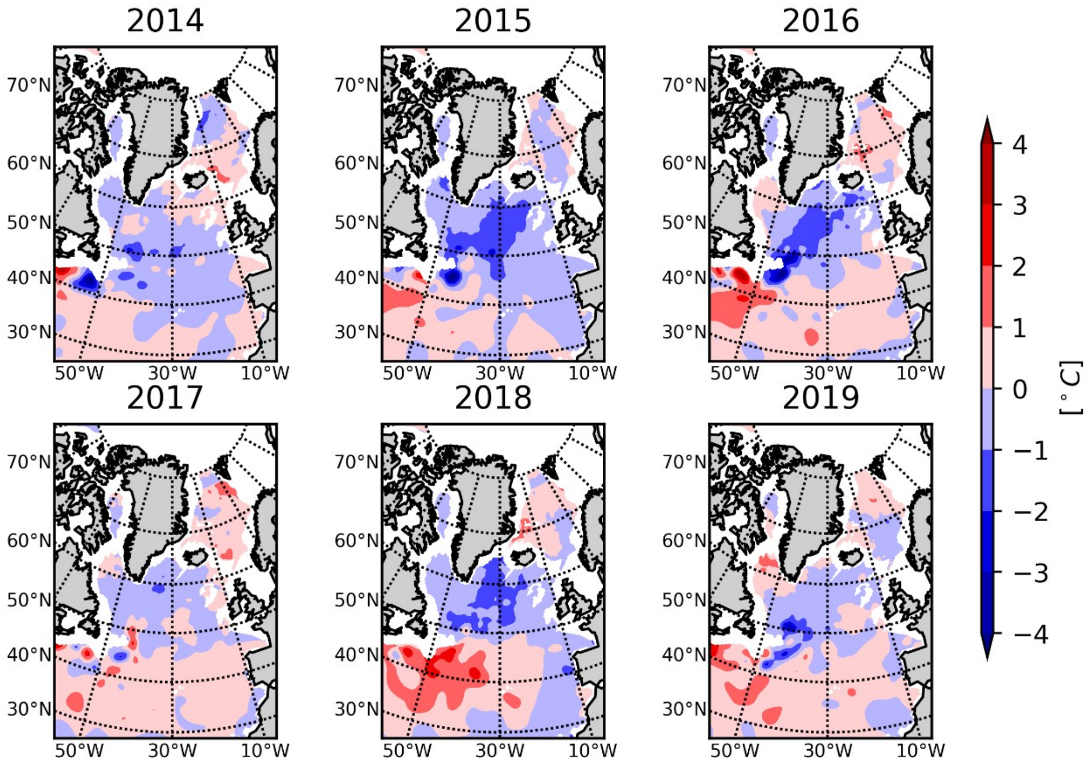
The interannual variability of upper layer (0–100 m) temperature in the North Atlantic is illustrated by annual maps of temperature anomaly (Fig. 6) and regional average time-series (Fig. 7). When compared to the long-term 2006–2015 mean, the subtropical region was generally warmer during recent years, with anomalies increasing in intensity and being particularly strong over the Gulf Stream / North Atlantic Current (NAC) path (Newfoundland basin) in 2016 and 2018. On average, the subpolar region was colder than the long-term mean in recent years, with anomalies peaking in 2015, 2016, and 2018 over the NAC pathways towards the eastern basins.

The most noticeable large-scale change occurred between 2018 and 2019 when the anomalous subtropical–subpolar–Nordic seas tripole weakened from its 2018 peak. This significant change characterizing the most recent years (2018/2019) is best illustrated through the time-series of regional-average upper temperatures (Fig. 7), where a clear transition to cooling, warming, and cooling trends has taken place in the subtropical (Gulf Stream panel), subpolar (Irminger Sea panel), and Nordic seas (Greenland Sea panel) regions, respectively. This reversal event is also evident for salinity, although it is less striking. The spatial pattern associated with this trend reversal is shown in Figure 1.

Mixed layer depth

The mixed-layer depth is an indicator of winter convection intensity in the North Atlantic and Nordic seas. Winter heat and freshwater fluxes control the buoyancy loss (increase of density) of the ocean surface layers and trigger deep convection. In order to compare all areas throughout the decade, the mixed-layer depth is defined here as the level at which density changes by more than 0.03 kg m^{-3} with respect to the 10-m depth value. This is a common criterion used for the global ocean (de Boyer Montegut *et al.*, 2004). Given the stratification in the North Atlantic and Nordic seas, it is probably not the optimal criterion to define the mixed layer in this region. However, adopting this definition allows the comparison of the relative winter mixed-layer depth across multiple years. The month of March has been selected as being the common period for maximum mixed-layer depth, is at the end of the winter season, and comes before spring re-stratification. However, this is not always true, since the time-point when the deepest mixed layer occurs can vary from year-to-year at a single location and might not occur at the same time of year across the whole basin (between February and March in the North Atlantic).

The 2019 winter (Fig. 5) was characterized by a noticeable increase in mixed-layer depths in both the Labrador and Greenland seas (> 1600 m). This reflects both an important recovery of atmospherically driven convective mixing in those regions since the 2018 winter and its very shallow mixed layers. The spatial extent of 2019 mixed layers was still relatively small when compared to those observed during the highly convective period of 2014–2016.



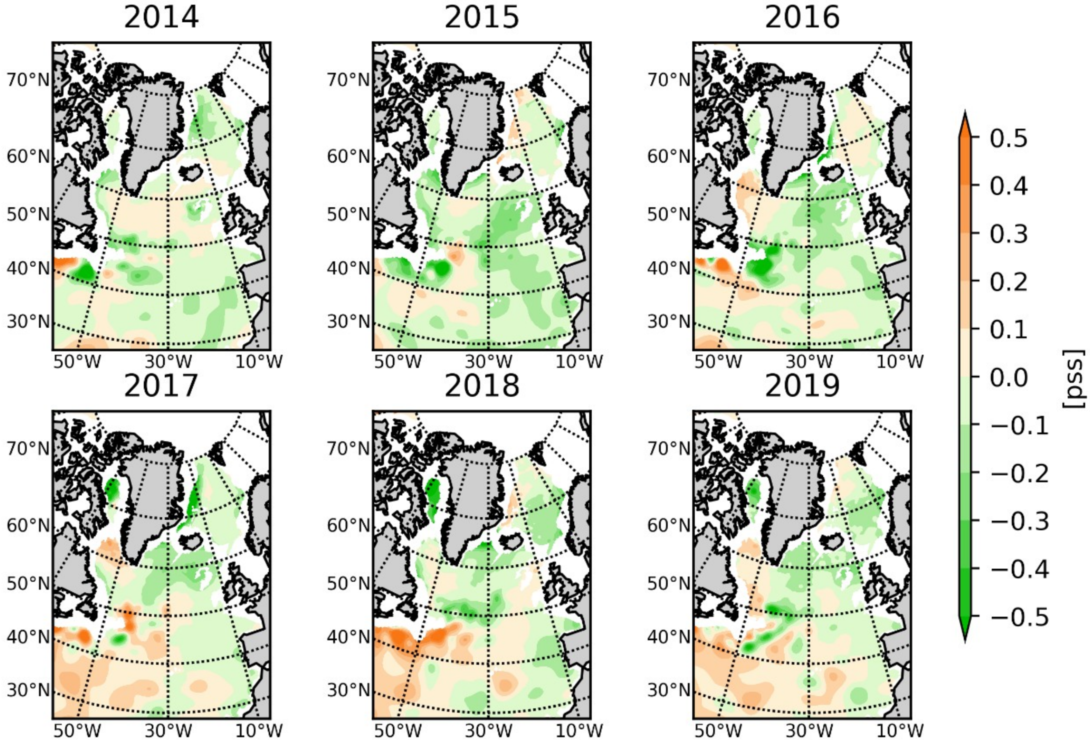


Figure 6: Maps of annual temperature (upper) and salinity (lower) anomalies averaged within 0–100 m in the North Atlantic for the period 2014–2019. Anomalies are the differences between the ISAS monthly mean values and the reference climatology ISAS15 2006–2015. The colour-coded scale is the same in all panels. Data prepared from the Coriolis, ISAS monthly analysis of Argo data.

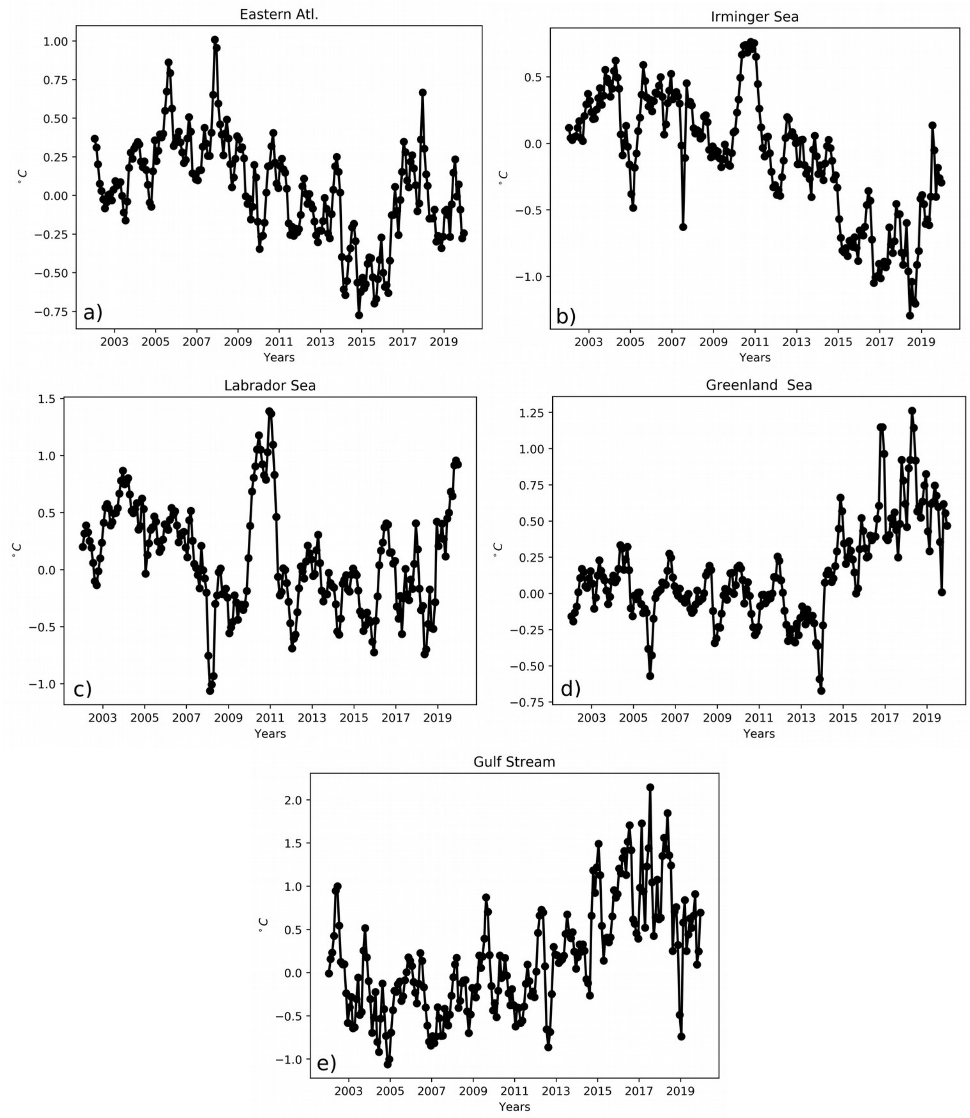


Figure 7: Time-series of temperature anomalies (using 2006–2015 as reference) averaged over the 0–100 m layer and in (a) Eastern Atlantic, (b) Irminger Sea,(c) Labrador Sea, (d) Greenland Sea, and (e) Gulf Stream region over the period 2002–2019.

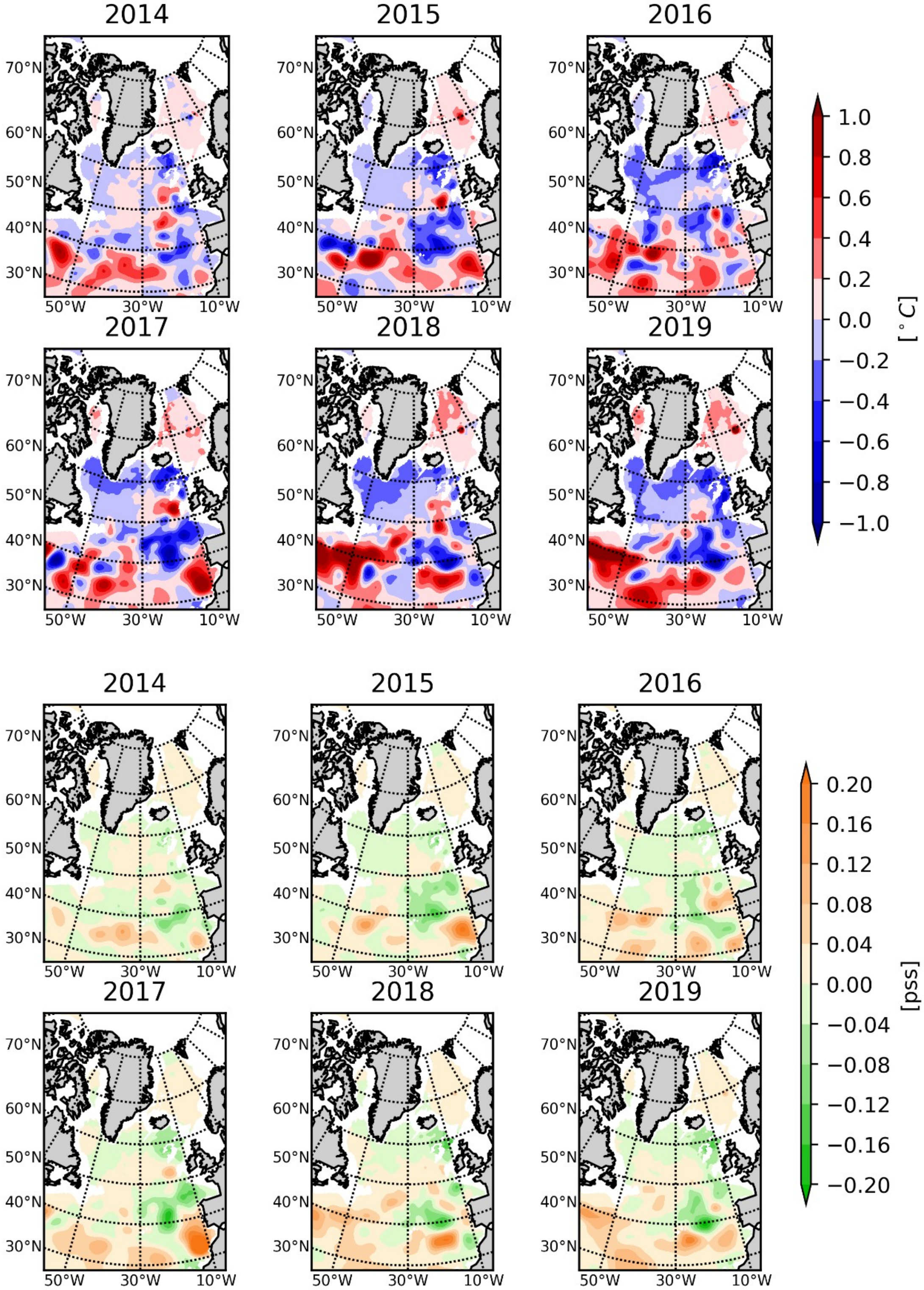


Figure 8: Maps of annual temperature (upper) and salinity (lower) anomalies at 1000 m depth in the North Atlantic for the period 2014–2019. Anomalies are the differences between the ISAS monthly mean values and the reference climatology, World Ocean Atlas 05 (WOA5). The colour-coded scale is the same in all panels. Data prepared from the Coriolis, ISAS monthly analysis of Argo data.

1.4 Deep layers

The interannual variability of temperature anomalies in the intermediate layer (800–1200 m) during 2014–2019 is provided in Figure 8 as maps for the years 2014–2019 and in Figure 9 as time-series for the period 2002–2019. In this layer, the gross spatial pattern in recent years is for a relatively warm subtropical region, a relatively cold subpolar region, and relatively warm Nordic seas (when compared to the 2006–2015 climatological period). This tripole pattern characterizing the intermediate layer has progressively intensified over the years and has a reached its current peak in amplitude in 2018/2019. The strongest centres of action are located in the western Subtropical Gyre, where the Gulf Stream/NAC area are found, in the Irminger and Labrador seas, and in the Greenland Sea. The contrasting behaviour of temperature in those regions is striking (Fig. 9). Since 2012, the Gulf Stream area has warmed nearly 0.1°C, and the subpolar area (Labrador and Irminger seas) has cooled nearly 0.4°C. In contrast to those two latter regions, temperatures in the intermediate layer of the Greenland Sea have been characterized by a long-term positive trend (increase of about 0.25°C since 2002). A similar intensifying tripole pattern can be seen in the salinity fields in recent years, with a relatively salty subtropical region, fresh subpolar region, and salty Nordic seas, although the picture is less clear than for temperature.

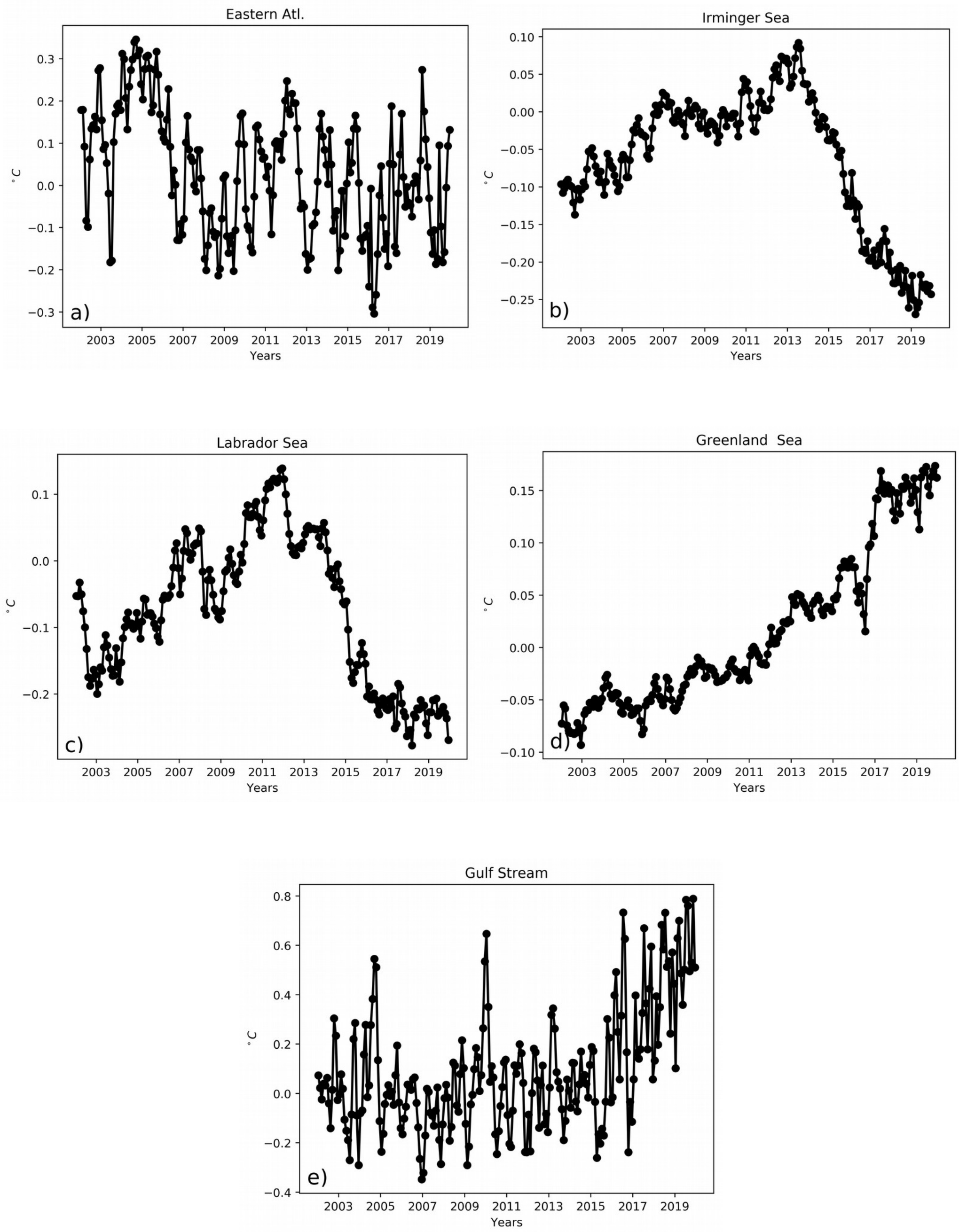


Figure 9: Time-series of temperature anomalies (using 2006–2015 as reference) averaged over the 800–1200 m layer and in (a) Eastern Atlantic, (b) Irminger Sea, (c) Labrador Sea, (d) Greenland Sea, and (e) Gulf Stream region over the period 2002–2019.

2 References and dataset

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