

Dear Gilles,

Thank you very much for your comments.

We have modified the 2 lines you proposed:

1. "In agreement with Grist et al. (2015), we found that the air-sea heat flux is ~~the main~~ responsible for **most of** the cooling observed in the surface-intermediate layers. "

2. "Dutchez" by "**Duchez**".

We have carefully revised all the abbreviations in the reference list. Concerning Frakjan-Williams et al., 2017, it was published in Scientific Reports (Sci. Rep.).

All the best,

Patricia Zunino

1 **The GEOVIDE cruise in May-June 2014 reveals an intense Meridional**
2 **Overturning Circulation over a cold and fresh subpolar North Atlantic**

3

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12

13 **Abstract**

14 The GEOVIDE cruise was carried out in the subpolar North Atlantic (SPNA), along the
15 OVIDE section and across the Labrador Sea, in May–June 2014. It was planned to clarify the
16 distribution of the trace elements and their isotopes in the SPNA as part of the GEOTRACES
17 international program. This paper focuses on the state of the circulation and distribution of
18 thermohaline properties during the cruise. In terms of circulation, the comparison with the
19 2002–2012 mean state shows a more intense Irminger current and also a weaker North
20 Atlantic Current, with a transfer of volume transport from its northern to its central branch.
21 However, those anomalies are compatible with the variability already observed along the
22 OVIDE section in the 2000s. In terms of properties, the surface waters of the eastern SPNA
23 were much colder and fresher than the averages over 2002–2012. In spite of negative
24 temperature anomalies in the surface waters, the heat transport across the OVIDE section,
25 estimated at 0.56 ± 0.06 PW, was the largest measured since 2002. This relatively large value
26 is related to the relatively strong Meridional Overturning Circulation measured across the
27 OVIDE section during GEOVIDE (18.7 ± 3.0 Sv). Analyzing the air-sea heat and freshwater
28 fluxes over the eastern SPNA in relation to the heat and freshwater content changes observed
29 during 2013 and 2014, we concluded that, at short time-scale, these changes were mainly
30 driven by air-sea heat and freshwater fluxes rather than by ocean circulation.

31 1. Introduction

32 The subpolar North Atlantic (SPNA) is a key area for studying the effect of climate change in
33 the ocean. The deep convection processes there behave as a driving mechanism for the
34 Meridional Overturning Circulation (Kuhlbrodt et al., 2007; Rhein et al., 2011; Sarafanov et
35 al., 2012), which transports heat to high latitudes in the North Atlantic and is predicted to
36 slow down at the end of the present century (IPCC, 2007). Additionally, the SPNA presents
37 the highest anthropogenic CO₂ storage rate of all oceans (Khatiwala et al., 2013), due to both
38 the advection of surface waters enriched with anthropogenic CO₂ in the subtropical North
39 Atlantic (Pérez et al., 2013; Zunino et al., 2015) and their deep injection in the subpolar gyre
40 (Pérez et al., 2010). In addition, the SPNA is one of the few oceanic regions where significant
41 cooling was detected over 1955–2010 while the rest of the world oceans was warming
42 (Levitus et al., 2012). For all these reasons, the SPNA has been the target of several projects
43 and broadly sampled by oceanographic cruises. As part of the OVIDE project
44 (<http://www.umr-lops.fr/Projets/Projets-actifs/OVIDE>), the OVIDE section has been sampled
45 biennially in summer since 2002 to collect data related to the circulation and the carbon cycle.
46 Its path between Greenland and Portugal is shown in Fig. 1 along with a schematic view of
47 the upper, intermediate and deep circulations in the SPNA adapted from Daniault et al.
48 (2016), which will be referred to as D2016 hereafter.

49 The international GEOTRACES program (<http://www.geotraces.org/>) aims to characterize the
50 trace elements and their isotopes (TEIs) in the world ocean. These TEIs are Fe, Al, Zn, Mn,
51 Cd, Cu, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, $^{231}\text{Pa}/^{230}\text{Th}$, Pb and Nd in the dissolved phase as well as in particles and
52 aerosols. TEIs provide constraints and flux estimates that can be used to reconstruct the past
53 environmental conditions. The GEOVIDE project is a French contribution to the
54 GEOTRACES program. It is dedicated to measure the large-scale distributions of TEIs in the
55 SPNA for the first time. The GEOVIDE cruise was carried out in May–June 2014 and was
56 composed of two sections: one along the OVIDE line (its 7th repetition) and another one
57 crossing the Labrador Sea, from Cape Farewell (Greenland) to St John's (Canada). The
58 expertise gained on water mass properties and circulation across the OVIDE section (García-
59 Ibáñez et al., 2015; D2016) first helped to determine the optimal geographic distribution of
60 the TEI sampling. However, the ocean is not steady, and the present study shows how
61 anomalous, in terms of thermohaline properties and circulation, the eastern SPNA was in
62 summer 2014 compared with the previous decade, and thus provides guidance for the
63 interpretation of the measured distribution of TEIs.

64 The ocean has taken up 90% of the heat accumulated in the climate system since 1971 (Riser
65 et al., 2016). In this context, it is striking to note the absence of a significant warming trend in
66 between 50 °N and 60 °N in the Atlantic Ocean between 1955 and 2010 (Levitus et al., 2012;
67 Sgubin et al., 2017). In fact, an important variability in the heat and freshwater content occurs
68 in the SPNA at the decadal or longer time-scales. Since 1960, different periods of cooling
69 (warming) or freshening (salinification) in the SPNA have been detected. Negative salinity
70 anomalies were observed in the SPNA surface waters during the 1970s, and referred to as the
71 Great Salinity Anomaly event. They were explained by a large pulse of freshwater getting into
72 the SPNA through the Denmark Strait (Dickson et al. 1988; Robson et al., 2014).
73 Concurrently, the subpolar gyre (SPG) started a cold phase that persisted up to the beginning
74 of the 1990s. Later, from mid-1990s to mid-2000s, positive anomalies of temperature and
75 salinity in the surface waters of the SPNA were observed, coinciding with the contraction and
76 weakening of the SPG (e.g. Bersch, 2002; 2007; Sarafanov et al., 2008; Häkkinen et al.,
77 2011). Many works analyzed the causes of the observed decadal to multi-decadal variability
78 in ocean heat content in the SPNA by analysis of both observations and model outputs (e.g.
79 Deshayes and Frankignoul, 2008; Lohmann et al., 2009; Robson et al., 2012; 2014; Barrier et
80 al., 2015). They concluded that the heat content anomalies in the SPNA at long time-scale are
81 mainly controlled by changes in the lateral advection, linked to changes in the intensity of the
82 Atlantic Meridional Overturning Circulation (AMOC). At shorter period of time, the air-sea
83 flux causes significant heat and freshwater changes, by intensifying or buffering the effect of
84 the anomalies caused by the lateral advection (Barrier et al., 2015; Desbruyères et al., 2015;
85 Grist et al., 2015).

86 Recently, Hermanson et al. (2014) and Robson et al. (2016; 2017), analyzed outputs of
87 coupled climate models, and identified a new cooling and freshening period from the mid-
88 2000s. Their results coincide with observations: Johnson et al. (2016) documented a SPNA
89 region cooler in 2014 than in 1993-2014 climatology, this cooling intensified in 2015 and
90 2016 (Yashayaev and Loder, 2016; 2017). Over the eastern SPNA, Grist et al. (2015)
91 analyzed the winter 2014 anomalous air-sea fluxes and their imprint on the ocean. Based on
92 EN4 ocean reanalysis, they detected negative temperature anomalies in the surface waters,
93 which they related to anomalous air-sea heat fluxes. Conversely, Holliday et al. (2015), who
94 found evidence of similar cooling and also of freshening in the Iceland basins from 2010–
95 2011 to 2014, privileged the hypothesis of a remote source of those anomalies, writing that

96 “the eastern SPNA is once again being influenced by cold, fresh western subpolar water”. We
97 will discuss both hypotheses in this study.

98 In this article, we first contextualize the physical background of the GEOVIDE cruise to help
99 for the interpretation of distribution of TEIs in the eastern SPNA. The works dealing with
100 TEIs distribution will be published in this Biogeoscience GEOVIDE special issue: Cossa et
101 al. (2017), Lemaître et al. (2017), García-Ibáñez et al., (2017), and other manuscripts are in
102 preparation. Subsequently, by the analysis of the GEOVIDE cruise data along with altimetry,
103 oceanic database and air-sea flux data, we disentangle the causes of the anomalous
104 thermohaline properties of the surface and intermediate layers of the eastern SPNA in May–
105 June 2014. The paper is organized as follows. Data and methodology are described in section
106 2. Section 3 displays the main results on the large and mesoscale patterns of the circulation
107 and thermohaline anomalies in 2014, settling the GEOVIDE TEIs stations in this context.
108 These results are discussed in section 4. Finally, section 5 presents the main conclusions.

109

110 **2. Data and Methods**

111 **2.1. GEOVIDE data**

112 The GEOVIDE cruise was the French contribution to the GEOTRACES program
113 (<http://www.geotraces.org/>) in the North Atlantic. It was carried out on board the French R/V
114 *Pourquoi Pas?* from 15 May 2014 to 30 June 2014. A total of 78 stations were measured and
115 sampled along two hydrographic sections: i) the 7th repetition of the OVIDE section (from
116 Portugal to Greenland) and ii) a section across the southern Labrador Sea, between Cape
117 Farewell and Newfoundland. In this paper we only deal with data from the OVIDE section.
118 Because this cruise was inserted in the GEOTRACES project, a large number of parameters
119 were measured, some of them present in the ocean in very low concentration. Therefore,
120 several rosette casts (up to 9) had to be done at some stations; the full-depth cast with salinity
121 and oxygen samples was always used as reference for physical characterization of water
122 masses and currents. Stations were named according to the parameters to be measured and the
123 different number of casts to be carried out: Short, Large, XLarge and Super stations. Nearly
124 all the TEIs required by the GEOTRACES program were sampled at Xlarge and Super
125 stations, which positions were selected to be representative of the different hydrographic
126 regions, as detailed in section 3.4. Because the ship time was limited to 45 days, the number

127 of stations along the OVIDE section was reduced compared with previous cruises, with 60
128 stations within 6 weeks during GEOVIDE compared with 95 stations usually sampled within
129 about 3 weeks in previous OVIDE cruises.

130 Conductivity, temperature, pressure and dissolved oxygen were measured using a CTD
131 SBE911 equipped with an SBE-43. The rosette was also equipped with 22 bottles for
132 collecting seawater. For calibration purposes, salinity and oxygen were determined on board
133 from seawater samples, using a salinometer and titration, respectively. The final accuracy was
134 0.001 °C, 0.002, and 2 $\mu\text{mol kg}^{-1}$ for temperature, salinity and oxygen, respectively. Figure 2
135 shows the calibrated temperature, salinity and oxygen measured during CTD-O₂ down casts
136 of the OVIDE section. For more details about the water mass properties and their distributions
137 along the OVIDE section between 2002 and 2012, see García-Ibáñez et al. (2015) and D2016.
138 Finally, the velocities of the upper waters were measured continuously with two ship-mounted
139 ADCP (Ocean Surveyors) at a frequency of 38 Hz and 150 Hz, measuring down to 1000 m
140 and 300 m with vertical resolutions of 24 m and 8 m, respectively.

141 The winter mixed layer depth (WMLD) was estimated along the OVIDE section by visual
142 inspection of the individual potential density and Apparent Oxygen Utilization (AOU)
143 profiles measured during the GEOVIDE cruise. Because the cruise was conducted in summer,
144 the seasonal mixed layer was disregarded and the WMLD was defined as the depth where the
145 slope of the density profile accentuated and the AOU was larger than 0.6 $\mu\text{mol kg}^{-1}$. The latter
146 value was chosen because it was the best fit with the density criteria at most stations.

147 **2.2. Inverse model**

148 The absolute geostrophic field orthogonal to the section was estimated by a box inverse model
149 using the hydrographic profiles measured at each station, current measured by the ship ADCP
150 (S-ADCP) and a volume conservation constraint of 1 Sv northward (Lherminier et al., 2007).
151 For inversion constrain, the S-ADCP data were averaged between stations in layers where the
152 shear of the velocity profile was consistent with geostrophic velocity profiles. The inverse
153 model is based on the thermal wind equation and the least-squares formalism following the
154 method described in Mercier et al. (1986) and Lux et al. (2001). Additionally, the Ekman
155 velocities were added to the inverse model: the Ekman transport was estimated from NCEP
156 winds (Kalnay et al., 1996) and equally distributed over the first 30 m. The velocity errors
157 were given by the resulting covariance matrix from the box inverse model. For more details
158 about the inverse model configuration specific to OVIDE, see Lherminier et al. (2007, 2010)
159 and Gourcuff et al. (2011). The volume transports were computed by multiplying velocities

160 by the distances between two stations. Their errors were obtained from the full covariance
161 matrix of velocities, taking into account error correlations, as explained in Mercier (1986).
162 For the computation of transport across the OVIDE section from GEOVIDE data, the first
163 challenge was to determine the proper spatial sub-sampling. In order to select the station
164 positions and minimize the error associated with the sub-sampling, a sensitivity analysis was
165 performed with the data from the 2010 OVIDE cruise before the GEOVIDE cruise was
166 carried out. The chosen compromise was efficient to represent all the main water masses and
167 gave similar AMOC amplitude and consistent transports of the currents crossing the section,
168 although the errors on the 2010 regional features increased when subsampled. However, in
169 2014, we used a more precise S-ADCP, reducing the S-ADCP error contribution to the
170 inverse model solution. Consequently, the final errors of the dynamical structures in 2014 are
171 of the same order of magnitude than the errors estimated in previous OVIDE cruises.

172 The velocities measured by the S-ADCP and those resulting from the inverse model are
173 compared in Fig. 3 (note that the vertical scale differs between the subplots). We see that the
174 inverse model results reproduce the main features of the large-scale circulation captured by
175 the S-ADCP. As expected, mesoscale and ageostrophic structures of horizontal sizes smaller
176 than the distances between stations are visible on the S-ADCP section but are not resolved in
177 the inverse model solution (e.g. between stations 45 and 38 or between stations 32 and 27).
178 However, because the geostrophic velocity is an average between stations, this does not imply
179 any bias in the transports. This outcome is also supported by Gourcuff et al. (2011) who,
180 comparing altimetry and S-ADCP data, showed that the contributions of ageostrophic motions
181 tend to cancel out when averaged over the distance between stations.

182 The inverse model estimates the absolute geostrophic transport and the transport of heat and
183 other tracers. The under-sampling of the GEOVIDE cruise notably increases the errors
184 associated with the transport of tracers, because the horizontal gradients of those tracers are
185 less well resolved. The tracer considered in this work is temperature. By applying the
186 GEOVIDE sub-sampling to the inversion of the OVIDE 2010 data, we estimated a
187 supplementary and independent sampling error of 0.04 PW for heat transport.

188 **2.3. Oceanic database**

189 We used the In Situ Analysis System (ISAS) analysis (Gaillard et al., 2016), which, based on
190 Argo profiles and other qualified *in situ* observations (cruises, fixed-point time series, ships of
191 opportunity, etc.), produced monthly gridded fields of temperature and salinity profiles by

192 optimal interpolation for the period since 2002. We also used EN4 reanalysis. Similar to
 193 ISAS, EN4 reanalysis is an optimal interpolation that incorporates *in situ* data measured since
 194 1900, filling gaps by extrapolation from the observational data using covariances from the
 195 Hadley Centre model (Good et al., 2013). We also used the temperature and salinity analysis
 196 developed by JAMSTEC (Hosoda et al., 2008), which is also an optimal interpolation based
 197 on Argo profiles, Triangle Trans-Ocean Buoy Network (TRITON) and other *in situ*
 198 observations.

199 First, we evaluated the temporal and horizontal extension of the potential temperature (θ) and
 200 salinity (S) anomalies detected in the surface layer from ISAS: both properties were averaged
 201 between 20 and 500 m at each ISAS grid point in the North Atlantic, and monthly anomalies
 202 were then estimated with respect to the 2002–2012 mean values. Second, ISAS, EN4 and
 203 JAMSTEC databases were used to evaluate the heat and freshwater content changes in the
 204 upper 1000 m in the region delimited by 40–60 °N and 45–10 °W: for each month the heat
 205 content (HC_{month}) and the freshwater content (FWC_{month}) of the volume of water in the box
 206 previously defined was estimated following eq. 1 and eq. 2, respectively:

$$207 \quad HC_{month} = \sum_{z=1}^{z=n} \sum_{i=1}^{i=n} \theta_{z,i} * Cp_{z,i} * \rho_{z,i} * V_{z,i} \quad \text{eq. 1}$$

$$208 \quad FWC_{month} = \sum_{z=1}^{z=n} \sum_{i=1}^{i=n} \frac{(35 - S_{z,i}) * V_{z,i}}{35} \quad \text{eq. 2}$$

209 where z and i are the depth levels and grid points of the database, and $Cp_{z,i}$, $\rho_{z,i}$ and $V_{z,i}$ are the
 210 heat content capacity, density and volume of each depth level and grid point of the database.

211 **2.4. Air-sea flux data**

212 In order to evaluate the role of atmospheric forcing on the θ and S anomalies observed during
 213 the GEOVIDE cruise, re-analyzed ERA-Interim data (Berrisford et al., 2011) and NCEP data
 214 (Kanamitsu et al., 2002, <http://www.esrl.noaa.gov/psd/>) were processed. In particular, we
 215 estimated seasonal anomalies of net air-sea heat flux (and its components: sensible heat, latent
 216 heat, net longwave radiation and net shortwave radiation) and freshwater flux (and its
 217 components: precipitation and evaporation) as follows. Firstly, seasonal means were
 218 computed defining winter as DJF, spring as MAM, summer as JJA and autumn as SON.
 219 Secondly, seasonal anomalies were calculated relative to the mean seasonal cycle of 2002–
 220 2012. Finally, the anomalies of winter–spring 2014 that preceded the GEOVIDE cruise were
 221 estimated.

222 Furthermore, the monthly time series of net air-sea heat and freshwater fluxes were used to
223 evaluate the contribution of the atmospheric forcing to the observed heat and freshwater
224 content changes in the box defined in section 2.3. Specifically, we integrated net air-sea heat
225 and freshwater fluxes, given every 12h/6h in ERA-INTERIM/NCEP, from January 16, 2013
226 to December 15, 2014. The resulting time series were compared with the monthly time series
227 of heat/freshwater content change between one month and the previous month, accumulated
228 from January 2013 to December 2014.

229

230 **3. Results**

231 **3.1. Circulation across the OVIDE section in 2014**

232 The OVIDE section is intersected by permanent currents and gyres that are described by
233 D2016 using the average measurements from the first 6 OVIDE cruises (2002 – 2012). This
234 section presents the intensity, location and extension of these dynamical structures during the
235 GEOVIDE cruise. The results showed hereafter are based on the solution of the inverse model
236 (see Fig. 3b). Despite the mesoscale structures typical of a single occupation of the section,
237 we can identify and quantify all the main patterns described by D2016.

238 Near Greenland, the water flowing southwestward guided by the continental slope is the
239 Western Boundary Current (WBC): it has two components, the East Greenland-Irminger
240 Current (EGIC $\sigma_0 < 27.8 \text{ kg m}^{-3}$) and the Deep Western Boundary Current (DWBC, $\sigma_0 > 27.8$
241 kg m^{-3}). During the GEOVIDE cruise, the extension of the DWBC towards the central
242 Irminger Sea at depths $> 2000 \text{ m}$ (see Fig. 3b) is marked by a bottom mesoscale feature
243 typical of the plume structure of the overflow (Spall and Price, 1997). The total intensity of
244 the WBC was estimated at $30.3 \pm 2.1 \text{ Sv}$ southward.

245 The cyclonic gyre defined as the Irminger Gyre (IG) by Väge et al. (2011) can be seen in the
246 western part of the central Irminger Sea. Following their definition, we quantified the
247 intensity of the IG by integrating the northward transport above the isotach 0 m s^{-1} (Fig. 3b),
248 which amounted to $6.8 \pm 3.0 \text{ Sv}$.

249 The Irminger Current (IC) flows northeastwards along the western flank of the Reykjanes
250 Ridge. In 2014, its top to bottom integrated transport amounted to $17.5 \pm 7.3 \text{ Sv}$, which

251 accounts for both, the northward and the southward currents east of the IG. Considering only
252 the northward velocities brings the IC intensity to a value of 22.7 ± 6.5 Sv.

253 The Eastern Reykjanes Ridge Current (ERRC) flows southwestward east of the Reykjanes
254 Ridge. In 2014, its top-to-bottom integrated transport, between the Reykjanes Ridge and
255 station 34 (Fig. 3), amounted to 13.6 ± 6.0 Sv southward.

256 The North Atlantic Current (NAC) at the OVIDE section consists of meandering branches
257 flowing northeastward between the center of the Iceland Basin and the Azores-Biscay Rise
258 (D2016). To determine its horizontal extension, we used the top-to-bottom volume transport
259 accumulated from Greenland to each GEOVIDE station (the barotropic stream function, Fig.
260 4) and the AVISO altimetry data (Fig. 5). The NAC intensity was quantified as the
261 accumulated transport from the relative minimum of the barotropic stream function in the
262 central Iceland Basin up to the maximum of the barotropic stream function in the Western
263 European Basin (D2016). In the Iceland Basin, we found two relative minima of the stream
264 function (Fig. 4) due to the presence of an anticyclonic eddy, which was considered as part of
265 the NAC, as justified in the next section. The limits of the NAC along the OVIDE section are
266 indicated by white circles in Fig. 5, between which the different branches of the NAC appear
267 as energetic northeastward currents. The top to bottom intensity of the NAC in 2014
268 amounted to 32.2 ± 11.4 Sv. Following D2016, three different branches of the NAC can be
269 differentiated: the northern branch (NNAC), the subarctic front (SAF) and the southern
270 branch (SNAC). The SAF is identified as the concomitant intense northward transport and
271 salinity increase around 22.5° W (Fig. 4). In 2014, top-to-bottom transport of the different
272 NAC branches was -0.1 ± 6.4 Sv, 25.0 ± 3.0 Sv and 7.3 ± 4.9 Sv, respectively. Note that the
273 net transport in the northern branch is quasi null with a large associated error and, by contrast,
274 the SAF bears a very intense central branch. This point is discussed in section 4.

275 The easternmost dynamical feature of the OVIDE section is the NAC recirculation. Its
276 intensity of 10.1 ± 6.4 Sv southwestward is determined as the top-to-bottom accumulated
277 transport between the southern limit of the NAC and the easternmost station of the OVIDE
278 section.

279 The intensity of the AMOC across the OVIDE section, referred as MOC hereafter, was
280 defined from the velocities given by the inverse model as the maximum of the surface to
281 bottom integrated stream function computed in vertical coordinates of potential density
282 referenced to 1000 m (σ_1). During the GEOVIDE cruise, it amounted to 18.7 ± 2.7 Sv and

283 was found at $\sigma_1 = 32.15 \text{ kg m}^{-3}$. Additionally, using the independent monthly MOC index
284 created by Mercier et al. (2015), which is based on altimetry and Argo data, the intensity of
285 the MOC across the OVIDE section amounted to the compatible value of $21.3 \pm 1.5 \text{ Sv}$ in
286 June 2014, while the 2014 annual mean value of the MOC index was 18.2 Sv .

287 Heat transport during the GEOVIDE cruise was estimated at $0.56 \pm 0.06 \text{ PW}$. Following the
288 Bryden and Imawaki (2001) methodology adapted by Mercier et al. (2015) in isopycnal
289 coordinates (see their equation 1), we found 0.50 PW transported by the overturning
290 circulation, 0.04 PW by the horizontal or gyre circulation and 0.02 PW by the net transport
291 across the section.

292 **3.2. Fronts and eddies**

293 Together with the above-mentioned permanent circulation features, we observed some
294 remarkable eddies during the GEOVIDE cruise that could modify the “typical” patterns of
295 properties defined by D2016 or García-Ibáñez et al. (2015), and they can affect the
296 distribution of tracers measured during the GEOVIDE cruise.

297 The identification of eddies and fronts was based on the analysis of surface velocities
298 provided by AVISO (see Fig. 5), the velocity profiles given by both the S-ADCP and the
299 inverse model (Fig. 3) and the vertical distribution of properties (Fig. 2). In Fig. 5, we identify
300 clearly that the most energetic currents crossing the OVIDE section are the WBC, close to
301 Greenland, and the NAC with its different branches. Moreover, all the energetic eddies
302 intersecting the OVIDE section were observed in the NAC (Fig. 6) and identified on Fig. 3.
303 From north to south, the first eddy intersecting the section, referred to as the northern eddy, is
304 detected at 56.5° N , 27° W (Fig. 5). This eddy lies between stations 34 and 32 (Fig. 3; Fig. 6),
305 extending from the surface to the bottom but intensified in the upper 600 m. From Fig. 6, we
306 inferred that this eddy was generated in April at approximately 56.5° N , 26° W from the
307 meandering of the NAC north of the OVIDE section; its position is marked by yellow squares
308 in Fig. 6. In May 2014, the eddy was totally formed and intersected the section between 55.5°
309 N and 57° N . In June 2014, the eddy moved southwestward, in agreement with the general
310 displacement of anticyclonic eddies in the SPNA. The core of the northern eddy, between
311 stations 34 and 32 in Figs. 2a and 2b, shows properties warmer and saltier than the
312 surrounding water, confirming the NAC origin of this eddy; this is why this anticyclonic eddy
313 has been considered as part of the northern branch of the NAC. Note that in May–June, the

314 net transport of this eddy, from surface to the bottom, is almost 0 Sv (see Fig. 4 between
315 stations 34 and 32).

316 A large anticyclonic eddy, the central eddy, is observed at 53 °N, 26 °W, at a tangent to the
317 OVIDE section between stations 30 and 29 (red squares in Fig. 6). However, no signal was
318 detected in the barotropic stream function (Fig. 4) since the northward and southward
319 velocities (Fig. 3a) compensated once integrated between the two stations (Fig. 3b). It is
320 noteworthy that, contrary to the previous anticyclonic eddy, this one is stationary south of the
321 OVIDE section between March and June (Fig. 6) and was found to be quasi-permanent in the
322 altimetry data since 1993 (figure not shown). Hydrographic properties measured at stations 29
323 and 30 showed cold and fresh water between 350 m and 500 m depth, typical of the Subarctic
324 Intermediate Water (SAIW), which is most likely **trapped** by this anticyclonic eddy.

325 The most remarkable front present on the OVIDE section is the SAF, associated with the
326 central branch of the NAC. Along the OVIDE section, it is situated between 49.5 °N and
327 51°N in latitude and 23.5 °W and 22 °W in longitude (red points in Fig. 5 and 6). This front
328 separates cold and fresh water of subpolar origin from warm and salty water of subtropical
329 origin; it is identifiable in Fig. 2 at station 26 by the steep slope of the isotherms and
330 isohalines. The position of this front is known to vary spatially (Bersch 2002; Bower and Von
331 Appen, 2008; Lherminier et al., 2010), creating anomalies of salinity and temperature that will
332 be discussed later.

333 Finally, also in Fig. 5, we identified the southern branch of the NAC with a maximum in the
334 eastward velocities found at 46.5 °N, 22 °W, west of GEOVIDE superstation 21. Despite a
335 very rich mesoscale activity we can distinguish in Fig. 5 that the southern NAC splits into two
336 sub-branches before crossing the OVIDE section, in agreement with D2016. The
337 northernmost sub-branch cuts the section between stations 23 and 24 at 48.5 °N, 21 °W. The
338 southernmost sub-branch evolves into a cyclonic eddy (the southern cyclonic eddy, light
339 green square in Fig. 6) that intersects the OVIDE section south of station 21. This eddy is also
340 observed in the velocity profiles (Fig. 3) between stations 21 and 19, as well as by the
341 uplifting of isotherms and isohalines in Fig. 2. To its southeast, an anticyclonic eddy (orange
342 square in Fig. 6), centered on station 18, marks the southern limit of the NAC and the
343 beginning of the southwestward recirculation. On the OVIDE section, the southern
344 anticyclonic eddy also marks the northwest limit of the presence of Mediterranean Water at
345 about 1000 m depth (Fig. 2b), consistently with its slow westward advection since March

346 (Fig. 6). Note that while the southern anticyclonic eddy (orange square in Fig. 6) looks stable
347 over time, the southern cyclonic eddy (light green square in Fig. 6) seems more transitory
348 since it is not clearly visible in April.

349 **3.3. Thermohaline anomalies in 2014**

350 The anomalies of potential temperature (θ), salinity (S) and dissolved oxygen along the
351 OVIDE section in 2014 were computed on pressure levels (Fig. 7), with respect to the average
352 of the six repetitions of the OVIDE section (summers 2002, 2004, 2006, 2008, 2010 and
353 2012). Only anomalies larger than one standard deviation from the mean are represented in
354 Fig. 7. In the following, S and θ anomalies were quantified as the mean values of the anomaly
355 patches represented in Fig. 7. We identified 4 different types of anomalies along the OVIDE
356 section. First, negative anomalies in surface-intermediate waters were observed above the
357 WMLD over the Reykjanes Ridge (in the IC and the ERRC) and east of 20° W (in the SNAC
358 and its recirculation). In the former, the S and θ anomalies were quantified at -0.08 and -1.04
359 $^\circ\text{C}$, respectively. In the latter, the negative anomalies of S and θ amounted to -0.11 and -0.70°
360 $^\circ\text{C}$. In the ERRC, negative S and θ anomalies also appeared below the WMLD amounting to $-$
361 0.06 and -0.80 $^\circ\text{C}$, respectively. It concerns a water mass that is different from the one in the
362 WMLD; both water masses are separated by a negative anomaly of oxygen (Fig. 2c) and a
363 maximum of potential vorticity (not shown). The cooling and freshening of the surface-
364 intermediate waters were not compensated in density: the cooling dominated and the water
365 was significantly denser (Fig. not shown). Concurrently, a positive oxygen anomaly was
366 observed.

367 In both the Irminger Sea and the Iceland Basin, positive anomalies of S and θ were observed
368 in waters deeper than 1000 m. In the Irminger Sea, the S and θ anomalies amounted to 0.017
369 and 0.122 $^\circ\text{C}$, respectively. In the Iceland Basin, they reached similar values, i.e. 0.014 and
370 0.125 $^\circ\text{C}$. In both basins, these anomalies coincided with significant negative oxygen
371 anomalies up to -20 $\mu\text{mol kg}^{-1}$, suggesting that this water mass was not recently ventilated.

372 In the Iberian Abyssal Plain (IAP), negative anomalies of S (-0.12) and θ (-0.67 $^\circ\text{C}$) were
373 observed at the level of the Mediterranean Water (MW), above and below the isopycnal 32.15
374 kg m^{-3} . Although remarkable, those anomalies are difficult to interpret because of the high
375 variability of the Meddy distribution in this area.

376 The displacement of fronts or eddies already identified in the previous section generated other
377 occasional anomalies. The salty and warm anomaly found at 27.4 °W, above isopycnal 32.15
378 kg m^{-3} , is explained by the anticyclonic eddy (the northern eddy), which advected water from
379 the NAC. The fresh and cold anomaly localized at 25 °W is a consequence of the SAIW
380 brought by the anticyclonic eddy (the central eddy) located at 53 °N, 26 °W and touching the
381 OVIDE section between stations 30 and 29. Finally, the southeastward displacement of the
382 SAF created a fresh and cold anomaly between 23 °W and 22 °W because warm and salty
383 North Atlantic Central Water (NACW) usually found in this area was replaced by subpolar
384 water.

385 In Fig. 7c, we found an increase in the ventilation in the first 1000 m, while the deeper waters
386 are less oxygenated when compared to the 2002–2012 period. The anti-correlation between
387 the oxygen anomalies and the θ -S anomalies will be discussed in section 4.2.

388 **3.4. Settling the special GEOVIDE stations in the framework of the large-scale and** 389 **mesoscale circulation**

390 As part of the GEOTRACE program, seven superstations and three XLarge stations were
391 carried out along the OVIDE section in 2014 for sampling TEIs in the SPNA. The TEIs
392 results will be published in this Biogeoscience GEOVIDE Special Issue (e.g. Cossa et al.,
393 2017, about mercury; Lemaître et al., 2017, about particulate barium; Le Roy et al., in prep.,
394 about radium 226; Tonnard et al., in prep., about dissolved iron). In order to facilitate the
395 interpretation of the TEIs distribution, here, we contextualize the superstations and XLarge
396 stations (red and green numbers, respectively, in Figs. 2, 3 and 4, and pink stars in Fig. 5) in
397 the physical framework described above. Apart from station 26, which was specifically
398 selected in real-time in the middle of the SAF, and station 38 over the Reykjanes Ridge, all
399 the other special stations are representative of relatively large hydrographic domains since
400 they are not strongly affected by the peculiar mesoscale features described in section 3.2.

401 Specifically, from Greenland to Portugal, these stations were located in: the East Greenland
402 Coastal Current (EGCC, station 53), the East Greenland-Irminger Current (EGIC, station 60,
403 same position than 51), the Irminger Gyre (station 44, same position than station 46), in the
404 middle of the Iceland Basin (being part of the NNAC, station 32), in the SNAC (station 21),
405 in the center of the southward recirculation in the IAP (station 13), on the Iberian Peninsula
406 slope (station 8) and, finally, on the Portuguese continental shelf (station 2). Importantly for
407 the GEOTRACES community, although the superstations and XLarge stations are

408 representative in terms of circulation, the large-scale $S-\theta$ anomalies detailed in section 3.4
409 need to be taken into account when comparing GEOVIDE data with data from the previous
410 decade.

411

412 **4. Discussion**

413 **4.1. State of the circulation during the GEOVIDE cruise with respect to the mean state**

414 We will first discuss the circulation patterns seen during the GEOVIDE cruise in comparison
415 with the mean position, extension and intensity of the main currents intersecting the OVIDE
416 section defined by D2016. Despite the coarse resolution of the GEOVIDE stations, all the
417 circulation structures are identified in the inverse model solution (Table 1). The intensity of
418 the WBC and the IG are similar to the mean state with a quite high reliability (low relative
419 error). The transports of the ERRC and the southwestward recirculation in the IAP are also
420 very similar to the mean state, but remained to a large degree uncertain. Conversely, the IC
421 and NAC are different from the mean state, but not significantly.

422 When defining the IC as in D2016, we saw an increase in the IC intensity in 2014, but within
423 the observed variability (Table 1). However, the such-defined IC encompasses a warm and
424 salty northward transport and a cold and fresh southward transport. So, to go further in the
425 analysis of IC, we compared its northward component near Reykjanes Ridge with its
426 equivalent from the 2002–2012 mean data (not shown in D2016). In this case, the IC
427 amounted to 22.7 ± 6.5 Sv, which is significantly larger than the northward IC computed from
428 D2016 data: 11.0 ± 3.4 Sv. Our result is similar to the estimate of Väge et al. (2011) who
429 quantified the IC at 19 ± 3 Sv (1991–2008). Therefore, we conclude that the thus-defined IC
430 was strengthened in 2014 with respect to the 2002–2012 mean value. Note that the northward
431 component of the IC, between stations 38 and 41, transports water masses that are warmer and
432 saltier than those advected southward, between stations 41 and 45, (Fig. 2); so, the
433 intensification of the Irminger Current is meaningful in terms of transport of warm and salty
434 water to the north, and actually contributes to the upper limb of the MOC (Fig. 4, dotted line).

435 Concerning the NAC, its 2014 intensity, 32.2 ± 11.4 Sv, is weaker although within the limits
436 of the observed variability (41.8 ± 3.7 Sv). By the decomposition of this wide current, it is
437 very likely that the difference comes from the change in the intensity of the northern branch
438 of the NAC: -0.1 ± 6.4 Sv was computed in GEOVIDE, while 11.0 ± 3.0 Sv was estimated by

439 D2016. However, the weakening of the northern branch of the NAC in 2014 was partially
440 compensated by the doubling of transport of the NAC central branch, when compared with
441 the 2002–2012 mean (25 ± 3 Sv vs. 14 ± 6 Sv), suggesting there was a partial transfer of
442 transport from the northern to the central branch of the NAC.

443 The SAF, that bears the central branch of the NAC, shows also a remarkable southeastward
444 displacement in 2014 with respect to the mean circulation pattern (station 26 in Fig. 1), of
445 about 100 km. A careful study of the ADT streamlines (Fig. 8) showed that this displacement
446 was not due to a peculiar meandering of the front and that the SAF was actually narrower and
447 located more to the southeast in 2014, when compared to the 2002–2012 mean. Bersch et al.
448 (2007) linked the northwestward displacement of the SAF in the eastern North Atlantic in the
449 late 1990's to a shift from positive to negative values in the index of the North Atlantic
450 Oscillation (NAO), which is the dominant mode of atmospheric variability over the North
451 Atlantic. After a decade of neutral values, the winter NAO index turned positive in 2011 and
452 continued positive in 2013 and 2014 (Hurrell et al., 2017). The southeastward displacement of
453 the SAF is thus symmetric to Bersch et al. (2007) and consistent with their observations.

454 Along the OVIDE section, some permanent circulation features were observed by D2016,
455 where the velocity was found to be in the same direction for all repeated measures over the
456 2002–2012 period (see their Fig. 4). In our Fig. 3, we found most of these permanent
457 circulation features: the WBC, IC, ERRC, two deep southward veins transporting the Iceland-
458 Scotland Overflow Water (ISOW) in the Iceland Basin, and the northward transport over
459 Eriador Seamount in the intermediate layer. Only the “permanent” anticyclonic eddy marking
460 the southern limit of the NAC moved: it was expected between station 20 and 21 according to
461 the mean circulation (Fig. 1), but was instead found at station 18, i.e. more to the southeast,
462 during the GEOVIDE cruise (and called the southern anticyclonic eddy previously).

463 The inverse model solution also provides a robust estimate of both the intensity of the MOC
464 and the heat transport. We observed a heat transport of 0.56 ± 0.06 PW. To compare it with
465 the 2002–2010 average, we used the data of Mercier et al. (2015), without data from 1997,
466 because it did not belong to our reference period, and obtained 0.47 ± 0.05 PW. Even if the
467 2014 value is not statistically different from the mean, it is surprising to find such a high heat
468 transport considering the cold anomaly observed in the NAC surface waters (Fig. 7). To
469 determine the role of the MOC in this result, we first looked at the 2014 MOC (18.7 ± 2.7 Sv),
470 which is 2.5 Sv higher than the 2002–2010 average (16.2 ± 2.4 Sv). Note that including 2012

471 data (15 Sv and 0.39 PW, not published) in the mean increases the difference with 2014. This
472 result is in line with the observation of Rossby et al. (2017), who found that the MOC
473 intensity at 59.5 °N was larger for the period from late-2012 to early-2016 than the average
474 over 1993–2016. To improve our quantification of the influence of the MOC on heat
475 transport, we used the heat transport proxy HT^* built by Mercier et al. (2015), which
476 evaluates the heat transport only driven by the diapycnal circulation, known to be the
477 dominant term of heat transport for all the OVIDE cruises. The proxy (eq. 3) is based on the
478 MOC intensity (MOC_σ) and the temperature difference between the upper and lower limbs of
479 the MOC (ΔT):

$$480 \quad HT^* = \rho \cdot c_p \cdot \Delta T \cdot MOC_\sigma \quad (\text{eq. 3})$$

481 where HT^* , ρ and c_p are the heat transport proxy, the *in situ* density and the specific heat
482 capacity, respectively. During GEOVIDE, HT^* amounted to 0.49 PW, with $MOC_\sigma = 18.7$ Sv
483 and $\Delta T = 6.40$ °C. The 2002–2010 mean values of HT^* , MOC_σ and ΔT were 0.43 PW, 16.2
484 Sv and 6.79 °C, respectively. So, the heat transport index and MOC_σ were larger in 2014 than
485 the mean values, while the ΔT was smaller, which is consistent with the cold anomaly. These
486 results show that the larger MOC_σ measured during GEOVIDE was enough to compensate for
487 the heat transport decrease due to the cooling of the surface waters. This result might be the
488 effect of a short-term variability since it contrasts with the study of Desbruyères et al. (2015),
489 who argued that the long-term variability of the ocean heat transport at the OVIDE section is
490 dominated by the advection by the mean velocity field of temperature anomalies formed
491 upstream rather than the velocity anomalies acting on temperature.

492 **4.2. Negative anomalies of θ and S in surface-intermediate layers explained by the local** 493 **atmospheric forcing.**

494 The long-term evolution of heat content anomaly with respect to the 2002–2012 mean (Fig. 9)
495 was calculated in the upper 1000m over the SPNA region delimited by 40–60 °N latitude and
496 45–10 °W longitude (green square in Fig. 11). As shown by Robson et al. (2016), the SPNA
497 started a new long-term cooling period since the mid-2000s. By analyzing outputs of coupled
498 climate models, Robson et al. (2017) argued that this new cooling period is led by the reduced
499 ocean heat transport convergence resulting from a long term slow-down of the AMOC.
500 Within this long-term cooling period, we will focus hereafter on the pronounced heat content
501 drop that happened between 2013 and 2014.

502 The negative anomalies of θ and S in the surface-intermediate layers along the OVIDE
503 section in May–June 2014 with respect to the mean 2002–2012 were actually present over the
504 whole of the year 2014 and the whole SPNA (Fig. 10). θ and S anomalies in the ocean can be
505 caused by changes in the lateral advection of water masses with different properties, and/or by
506 anomalous net air-sea fluxes. Considering the high ocean heat transport observed during
507 GEOVIDE, we analyzed the air-sea flux anomalies. The mean winter–spring (W-S 2014)
508 anomalies of air-sea heat flux presented strong negative anomalies over the whole SPNA (Fig.
509 11a), i.e. the ocean lost more heat than the 2002–2012 average, with contribution of both
510 sensible and latent air-sea heat fluxes (Fig. 11b and 11c). The spatial repartition of the
511 freshwater budget is mainly driven by the patterns of the precipitation anomalies, with a net
512 freshwater loss southwest of the region and a clear gain in the eastern side. When the net
513 freshwater flux was integrated over our region (Fig. 12), the net freshwater gain (Fig. 11d)
514 shows that high precipitation rates (Fig. 11f) overcame the freshwater loss by evaporation
515 (Fig. 11e). These anomalous air-sea heat and freshwater fluxes in the eastern SPNA suggest
516 that the negative θ and S anomalies observed in the surface-intermediate waters during
517 GEOVIDE were mainly formed locally by atmospheric forcing.

518 The heat/freshwater content changes in the upper 1000 m of the ocean during the 2013–2014
519 period were evaluated together with the air-sea heat/freshwater fluxes in the region delimited
520 by 40–60 °N latitude and 45–10 °W longitude. In agreement with Grist et al. (2015), we
521 found that the air-sea heat flux is ~~the main~~ responsible for most of the cooling observed in the
522 surface-intermediate layers. Exactly, we estimated the accumulated air-sea heat loss from
523 summer 2013 to summer 2014 at $6.8 \cdot 10^{21}$ J, while the accumulated ocean heat loss for the
524 same period amounted to $4.8 \cdot 10^{21}$ J (averaged of ISAS, EN4 and JAMSTEC estimates). This
525 result is also in agreement with the findings of Dutchez et al. (2016), who argued the 2013–
526 2015 intense air-sea heat fluxes drove water masses transformation, which is an irreversible
527 process. Recently, Frajka-Williams et al. (2017) explained that such short-term cooling is
528 mainly caused by the atmospheric forcing since the hypothetical slow-down of the AMOC
529 would take longer to generate a cooling of this magnitude. Concerning the freshwater, we
530 detected that, despite the variability in freshwater content change at intra-seasonal and
531 seasonal time-scales (Fig. 12), there is a good agreement between the trends shown by the
532 ocean freshwater content and the air-sea freshwater flux over the 2013–2014 period. We are
533 aware of the large uncertainty associated with the air-sea freshwater flux (Josey and Marsh,
534 2005; Dee et al., 2011) and the ocean freshwater content. Therefore, we estimated both

535 variables from two and three databases, respectively. The difference between the ERA-
536 Interim and NCEP estimates of accumulated air-sea freshwater flux over the two years
537 amount to $0.4 \times 10^{12} \text{ m}^3$, while the ocean freshwater content estimates differ by $0.3 \times 10^{12} \text{ m}^3$
538 (Fig. 12). We conclude that between 70 % and 100 % of the freshening observed in the
539 considered volume of the SPNA is caused by air-sea freshwater inputs. These results support
540 our conclusion that the negative θ and S anomalies observed in the surface-intermediate
541 waters during the GEOVIDE cruise were locally formed by atmospheric forcing.

542 More evidence for the important role of air-sea fluxes is provided by the distribution of θ , S
543 and oxygen anomalies in the water column. Indeed, the WMLD along the OVIDE section east
544 of 20° W coincided with the deep limit of the anomalies (Fig. 7). It is somewhat more
545 complex in the ERRC, where the WMLD crosses the anomaly separating subpolar mode
546 water (SPMW) and upper Labrador Sea Water (LSW), see Fig. 2b; both water masses were
547 advected together by the ERRC, but probably issued from different ventilation regions.
548 According to de Boissésón et al. (2012), the SPMW is formed by air-sea interactions on its
549 way around the Iceland basin. The sign of all the anomalies described above is consistent with
550 vertical mixing in the winter before the GEOVIDE cruise, transferring the cold, fresh and
551 oxygenated anomalies imprinted locally by the atmosphere into the whole mixed layer. In the
552 Irminger Sea, the WMLD in Fig. 7 reaches 1200 m although deep convection did not exceed
553 700 m in winter 2014 in the central Irminger Sea (Piron, 2015; Duchez et al., 2016). It most
554 likely results from the advection in the depth range 700–1200 m of high-oxygen intermediate
555 water with densities slightly denser than the water above and possibly formed south of
556 Greenland, as suggested by Fig. 5.3 of Piron (2015).

557 Below the orange line in Fig. 7, we observed mainly warming, salinification and
558 deoxygenation. This is in agreement with the tendencies observed since 2002 along the
559 OVIDE section. Deep waters below 1300 m depth in the Irminger Sea were obviously not
560 recently renewed, apart from the plume of DSOW. Kieke and Yashayaev (2015) showed the
561 evolution of S and θ in the LSW measured in the Labrador Sea: below 1300 m, the positive
562 tendencies of S and θ were similar to those observed in the Irminger Sea, and concerned the
563 dense LSW formed in the 1990s.

564 **5. Summary and conclusions**

565 This paper addresses two main issues: first, under the umbrella of the GEOTRACES program,
566 it contextualizes the physical background of the GEOVIDE cruise carried out in May–June
567 2014, which is essential for the interpretation of distribution of TEIs in the eastern SPNA.
568 Second, it elucidates the cause of the cold and fresh anomaly detected in the surface waters of
569 the eastern SPNA in May–June 2014.

570 Concerning the circulation across the OVIDE sections, the most important difference between
571 the GEOVIDE state and the 2002–2012 mean state defined by D2016 is a strengthened
572 Irminger Current and a weaker North Atlantic Current, with a possible transfer of volume
573 transport from its northern branch to its central branch. The intensity of the MOC was the
574 highest measured at the OVIDE section since 2002, 18.7 ± 3.0 Sv, and was high enough to
575 compensate the negative temperature anomaly detected in the surface waters, resulting in a
576 high heat transport across the OVIDE section, 0.56 ± 0.06 PW.

577 The special GEOVIDE stations where the trace elements were measured were indeed
578 representative of the targeted hydrographic regions, away from the core of the main advected
579 eddies identified along the sections. Nevertheless some precautions should be taken when
580 comparing with previous years since temperature, salinity and oxygen of the SPNA winter
581 mixed layer in 2014 were significantly different from the 2002–2012 mean.

582 Finally, we demonstrated that the cold and fresh anomalies in the 2014 mixed layer induced
583 consistent changes in heat and freshwater content of the SPNA. This strong 2013–2014
584 cooling is inserted in a long-term cooling in the SPNA that started in mid-2000s. Our results
585 elucidate the important role of air-sea flux in the θ -S changes in this region at short time-
586 scale, overcoming the warming induced by the increase in the MOC amplitude and associated
587 heat transport in May–June 2014.

588

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609

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611 **References**

612 *Barrier, N., Deshayes, J., Treguier, A. M. and Cassou, C.: Heat budget in the North Atlantic subpolar*
613 *gyre: Impacts of atmospheric weather regimes on the 1995 warming event, *Progress in**
614 *Oceanography*, 130, 75-90, doi:10.1016/j.pocan.2014.10.001, 2015.

615 *Berrisford, P., Kallberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A.J., Poli, P., Sato, H.:*
616 *Atmospheric conservation properties in ERA-Interim, *Q. J. R. Meteorol. Soc.* 137, 1381–1399.*
617 *DOI:10.1002/qj.864, 2011.*

618 *Bersch, M., North Atlantic Oscillation-induced changes of the upper layer circulation in the northern*
619 *North Atlantic Ocean, *J. Geophys. Res.-Oceans*, 107(C10), 3156, doi:10.1029/2001JC000901, 2002*

620 *Bersch, M., Yashayaev, I., Koltermann, K. P.: Recent changes of the thermohaline circulation in the*
621 *subpolar North Atlantic, *Ocean Dynamics*, 57:223–235, doi:10.1007/s10236-007-0104-7, 2007.*

622 *de Boisséson, E., Thierry, V., Mercier, H., Caniaux, G., and Desbruyères, D.: Origin, formation and*
623 *variability of the Subpolar Mode Water located over the Reykjanes Ridge, *Journal of Geophysical**
624 *Research-Oceanography*, 117, C12005, doi:10.1029/2011JC007519, 2012.

625

626 *Bower, A. S. and von Appen, W.J.: Interannual variability in the pathways of the North Atlantic current*
627 *over the Mid-Atlantic Ridge and the impact of topography, *J. Phys. Oceanogr.*, 38(1), 104–120,*
628 *doi:10.1175/2007JPO3686.1, 2008.*

629 *Bryden, H. and Imawaki, S.: Ocean heat transport, in: *Ocean Circulation and Climate*, edited by:*
630 *Siedler, G., Church, J., and Gould, J., Academic Press, 2001.*

631 *Cossa, D., Heimbürger, L-E., Pérez, F. F., García-Ibáñez, M.I., Sonke, J. E., Planquette, H., Lherminier,*
632 *P., Sarthou, G.: Mercury distribution and transport in the North Atlantic Ocean along the Geotraces-*
633 *GA01 transect, *Biogeosciences Discuss.*, doi:10.5194/bg-2017-467, 2017.*

634 *Danialt, N., Mercier, H., Lherminier, P., Sarafanov, A., Falina, A., Zunino P., Pérez, F. F., Rios, A. F.,*
635 *Ferron, B., Huck, T., Thierry, V., Gladyshev, S.: The northern North Atlantic Ocean mean circulation in*

636 | the early 21st Century, *Prog.ress—in Oceanogr.aphy*, 146, 142–158,
637 | doi:10.1016/j.pocean.2016.06.007, 2016.

638 | Desbruyères, D., Mercier, H., Thierry, V.: On the mechanisms behind decadal heat content changes in
639 | the eastern subpolar gyre, *Prog.ress—in Oceanogr.aphy*, 132, 262–272,
640 | doi:10.1016/j.pocean.2014.02.005, 2015.

641 | Deshayes, J., and Frankignoul, C.: Simulated variability of the circulation in the North Atlantic from
642 | 1953 to 2003. *J. Climate*, 21, 4919–4933, doi:10.1175/2008JCLI1882.1, 2008.

643 | Dickson, R.R., Meincke, J., Malmberg, S.A., Lee, A.J.: The “great salinity anomaly” in the northern
644 | north Atlantic 1968–1982, *Prog. Oceanogr.*, 20 (2), 103–151, doi: 10.1016/0079-6611(88)90049-3,
645 | 1988.

646 | Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., McCarthy, G. D., Sinha,
647 | B., Berry, D. I., and Hirschi, J. J-M: Drivers of exceptionally cold North Atlantic Ocean temperatures
648 | and their link to the 2015 European heat wave, *Environ. Res. Lett.*, 11, doi:10.1088/1748-
649 | 9326/11/7/074004, 2016.

650 | Frajka-Williams, E., Beaulieu, C., Duchez, A.: Emerging negative Atlantic Multidecadal Oscillation
651 | index in spite of warm subtropics, *Sci.entific Rep.orts*, doi:10.1038/s41598-017-11046-x, 2017.
652 |

653 | Gaillard, F., Reynaud, T., Thierry, V., Kolodziejczyk, N., Von Schuckmann, K.: In Situ–Based Reanalysis
654 | of the Global Ocean Temperature and Salinity with ISAS: Variability of the Heat Content and Steric
655 | Height, *J.ournal-of Climate*, doi:10.1175/JCLI-D-15-0028.1, 2016.

656 | García-Ibáñez, M. I., Pardo, P. C., Carracedo, L. I., Mercier, H., Lherminier, P., Ríos, A. F., and Pérez, F.
657 | F.: Structure, transports and transformations of the water masses in the Atlantic Subpolar Gyre, *Prog.*
658 | *Oceanogr.*, 135, 18–36, doi:10.1016/j.pocean.2015.03.009, 2015.

659 | García-Ibáñez, M. I., Pérez, F. F., Lherminier, P., Zunino, P., Tréguer, P.: Water mass distributions and
660 | transports for the 2014 GEOVIDE cruise in the North Atlantic, *Biogeosciences*
661 | *Discuss.*, doi:10.5194/bg-2017-355, 2017.
662 |

663 | Good, S.A., Martin, M.J. and Rayner, N. A.: EN4: quality controlled ocean temperature and salinity
664 | profiles and monthly objective analyses with uncertainty estimate,. *J Geophys. Res.*, 118, 6704– 6716,
665 | doi:10.1002/2013JC009067, 2013.

666 | Gourcuff, C., Lherminier, P., Mercier, H., and Le Traon, P. Y.: Altimetry Combined with Hydrography
667 | for Ocean Transport Estimation, *J. Atmospheric Ocean. Technol.*, 28(10), 1324–1337,
668 | doi:10.1175/2011JTECHO818.1, 2011.

669 | Grist, J. P., Josey, S. A., Jacobs, Z. L., Marsh, R., Sinha, R., Sebille, E. V. : Extreme air–sea interaction
670 | over the North Atlantic subpolar gyre during the winter of 2013–2014 and its sub -surface legacy,
671 | *Clim Dyn*, doi:10.1007/s00382-015-2819-3, 2015.

672 | Häkkinen, S., Rhines, P. B., and Worthen, D. L.: Warm and saline events embedded in the meridional
673 | circulation of the northern North Atlantic. *J. Geophys. Res.*, 116, C03006, doi:10.1029/2010JC006275,
674 | 2011.

675 Hátún, H., Sandø, A.B., Drange, H., Hansen, B., and Valdimarsson, H.: Influence of the Atlantic
676 subpolar gyre on the Thermohaline circulation. *Science*, 309, 1841–1844,
677 doi:10.1126/science.1114777, 2005.

678 Hermanson, L., Eade, R., Robinson, N. H., Dunstone, N. J., Andrews, M. B., Knight, J. R., Scaife, A. A.,
679 and Smith, D. M.: Forecast cooling of the Atlantic subpolar gyre and associated impacts, *Geophys.*
680 *Res. Lett.*, 41, 5167–5174, doi:10.1002/2014GL060420, 2014.

681 Holliday, N. P., Cunningham, S. A., Johnson, C., Gary, S. F., Griffiths, C., Read, J. F., and Sherwin, T.:
682 Multidecadal variability of potential temperature, salinity, and transport in the eastern subpolar
683 North Atlantic, *J. Geophys. Res. Oceans*, 120, 5945–5967, doi:10.1002/2015JC010762, 2015.

684 Hosoda, S., Ohira, T. and Nakamura, T.: A monthly mean dataset of global oceanic temperature and
685 salinity derived from Argo float observations, *JAMSTEC Rep. Res. Dv.*, 8, 47–59, 2008.

686
687 Hurrell, James & National Center for Atmospheric Research Staff (Ed). Last modified 06 Oct 2017.
688 “The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)”.
689 [https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-stationbased)
690 [stationbased](https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-stationbased).
691

692 IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the*
693 *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M.
694 Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University
695 Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

696
697 Johnson, G. C., Lyman, J. M., Boyer, T., Domingues, C. M., Ishii, M., Killick, R., Monselesan, D., and
698 Wijffels, S. E.: Ocean heat content [in “State of the Climate in 2015”]. *Bull. Amer. Meteor. Soc.*, 97 (8),
699 S64–S65, 2016.

700 Josey, S. A., and Marsh, R.: Surface freshwater flux variability and recent freshening of the North
701 Atlantic in the eastern subpolar gyre, *Journal of Geophysical Research*, VOL. 110, C05008,
702 doi:10.1029/2004JC002521, 2005.

703
704 Kalnay, E., Kanamitsu, M., Kistler, R.: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the*
705 *American Meteorological Society* 77, 437–470, 1996

706
707 Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J. J., Fiorino, M., and Potter, G.L.: NCEP–
708 DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society* 83:1631–1643, 2002.

709 Kieke, D. and Yashayaev, I.: Studies of Labrador Sea Water formation and variability in the subpolar
710 North Atlantic in the light of international partnership and collaboration, *Progress in Oceanography*,
711 132, 220–232, doi:10.1016/j.pocean.2014.12.010, 2015.

712 Khatiwala, S., Tanhua T., Mikaloff Fletcher S., Gerber M., Doney S.C., Graven H. D., Gruber N.,
713 McKinley G.A., Murata A., Rios A.F. and Sabine C.L.: Global ocean storage of anthropogenic carbon.
714 *Biogeosciences*, 10, 2169–2191, doi:10.5194/bg-10-2169-2013, 2013.

715 Kuhlbrodt, T., Griesel, A., Montoya, M., Levermann, A., Hofmann, M., and Rahmstorf, S.: On the
716 driving processes of the Atlantic meridional overturning circulation, *Rev. Geophys.*, 45, RG2001,
717 doi:10.1029/2004RG000166, 2007.

Code de champ modifié

718 Lemaître, N., Planquette, H., Planchon, F., Sarthou, G., Jacquet, S., García-Ibáñez, M.I, Gourain, A.,
 719 Cheize, M., Monin, L., André, L., Laha, P., Terryn, H., Dehairs, F. : Particulate barium tracing significant
 720 mesopelagic carbon remineralisation in the North Atlantic, *Biogeosciences*
 721 Discuss., doi:10.5194/bg-2017-400, 2017

722

723 Lherminier, P., Mercier, H., Gourcuff, C., Alvarez, M., Bacon, S., and Kermabon, C.: Transports across
 724 the 2002 Greenland-Portugal OVIDE section and comparison with 1997, *J. Geophys. Res.*,
 725 112(C07003), doi:10.1029/2006JC003716, 2007.

726 Lherminier, P., Mercier, H., Huck, T., Gourcuff, C., Pérez, F. F., Morin, P., Sarafanov, A., and Falina, A.:
 727 The Atlantic Meridional Overturning Circulation and the subpolar gyre observed at the A25-OVIDE
 728 section in June 2002 and 2004, *Deep-Sea Res. Part -Oceanogr. Res. Pap.*, 57(11), 1374–1391,
 729 doi:10.1016/j.dsr.2010.07.009, 2010.

730 Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., Mishonov, A. V.,
 731 Reagan, J. R., Seidov, D., Yarosh, E. S., and Zweng, M. M.: World ocean heat content and
 732 thermosteric sea level change (0–2000 m), 1955–2010, *Geophysical Research Letters*, 39, L10603,
 733 doi:10.1029/2012GL051106, 2012.

734 Lohmann, K., Drange, H., and Bentsen, M.: Response of the North Atlantic subpolar gyre to persistent
 735 North Atlantic Oscillation like forcing, *Climate Dyn.*, 32, 273–285, doi:10.1007/s00382-008-0467-6,
 736 2009.

737 Lux, M., Mercier, H., and Arhan, M.: Interhemispheric exchanges of mass and heat in the Atlantic
 738 Ocean in January–March 1993, *Deep-Sea Res. Pt. I*, 48, 605–638, 2001.

739 Marsh, R., Josey, S. A., de Cuevas, B. A., Redbourn, L. J. and Quartly, G. D.: Mechanisms for recent
 740 warming of the North Atlantic: Insights gained with an eddy-permitting model, *J. Geophys. Res.*, 113,
 741 C04031, doi:10.1029/2007JC004096, 2008.

742 Mercier, H.: Determining the general circulation of the ocean: a non linear inverse problem, *J.*
 743 *Geophys. Res.*, 91, 5103–5109, doi:10.1029/JC091iC04p05103, 1986.

744 Mercier, H., Lherminier, P., Sarafanov, A., Gaillard, F., Daniault, N., Desbruyères, D., Falina, A., Ferron,
 745 B., Gourcuff, C., Huck, T., Thierry, V.: Variability of the meridional overturning circulation at the
 746 Greenland–Portugal OVIDE section from 1993 to 2010, *Prog. Oceanogr.*, 132, 250–261,
 747 doi:10.1016/j.pocean.2013.11.001, 2015.

748 Pérez, F. F., Mercier, H., Vázquez-Rodríguez, M., Lherminier, P., Velo, A., Pardo P. C., Rosón, G. and
 749 Ríos, A. F.: Atlantic Ocean CO₂ uptake reduced by weakening of the meridional overturning
 750 circulation. *Nat. Geosci.*, doi:10.1038/NGEO1680, 2013.

751 Pérez, F. F., Vázquez-Rodríguez, M., Mercier, H., Velo, A., Lherminier, P. and Ríos, A.F.: Trends of
 752 anthropogenic CO₂ storage in North Atlantic water masses. *Biogeosciences*, 7, 1789 – 1807,
 753 doi:10.5194/bg-7-1789-2010, 2010

Code de champ modifié

754 Piron, A.: Observation de la convection profonde en mer d'Irmingier sur la période 2002-2015 par les
755 flotteurs Argo, PhD Thesis, Université de Bretagne Occidentale.
756 <http://archimer.ifremer.fr/doc/00313/42434/>, 2015.

757 Piron, A., Thierry, V., Mercier, H., and Caniaux, G.: Gyre-scale deep convection in the subpolar North
758 Atlantic Ocean during winter 2014–2015, *Geophys. Res. Lett.*, 44, 1439–1447,
759 doi:10.1002/2016GL071895, 2017.

760 Rhein, Monika., Kieke, D., Hüttl-Kabus, S., Roessler, A., Mertens, C., Meissner, R., Klein, B., Böning,
761 CW., Yashayaev, I.: Deep water formation, the subpolar gyre, and the meridional overturning
762 circulation in the subpolar North Atlantic, *Deep-Sea Research II*, 58, 1819–1832,
763 doi:10.1016/j.dsr2.2010.10.061, 2011.

764 Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbeoch, M., Gilbert, D., Xu,
765 J., Poulouen, S., Ann, T., Le Traon, P. Y., Maze, G., Klein, B., Ravichandran M., Grant, F., Poulain, P.
766 M., Suga, T., Lim, B., Sterl. A., Sutton, P., Mork, K. A., Velez-Belch, J. P., Ansorge, I., King, B., Turton, J.,
767 Baringer, M., Jayne, S. R.: Fifteen years of ocean observations with the global Argo array. *Nature*
768 *Clim. Change*, 6(2), 145-153. doi:10.1038/NCLIMATE2872, 2016.

769 Robson, J., Sutton, R., Lohmann, K., Smith, D., and Palmer, M.: Causes of the Rapid Warming of the
770 North Atlantic Ocean in the Mid-1990s, *Journal of Climate*, doi:10.1175/JCLI-D-11-00443.1, 2012.

771 Robson, J., Sutton, R. and Smith, D.: Decadal predictions of the cooling and freshening of the North
772 Atlantic in the 1960s and the role of ocean circulation, *Clim. Dyn.*, 42, 2353–2365,
773 doi:10.1007/s00382-014-2115-7, 2014.

774 Robson, J., Ortega, P., Sutton, R.: A reversal of climatic trends in the North Atlantic
775 since 2005, *Nature Geo.*, DOI: 10.1038/NCEO2727, 2016.

776 Robson, J., Polo, I., Hodson, D. L. R., Stevens, D. P., Shaffrey, L. C.: Decadal prediction of the
777 North Atlantic subpolar gyre in the HiGEM high-resolution climate model, *Clim. Dyn.*, DOI:
778 10.1007/s00382-017-3649-2, 2017.

779
780 Rossby, T., Reverdin, G., Chafik, L., and Sjøland, H.: A direct estimate of poleward volume, heat, and
781 freshwater fluxes at 59.58N between Greenland and Scotland. *Journal of Geophysical Research: Oceans*,
782 doi:10.1002/2017JC012835, 2017.

783
784 Sarafanov, A., Falina, A., Sokov, A., and Demidov, A.: Intense warming and salinification of
785 intermediate waters of southern origin in the eastern subpolar North Atlantic in the 1990s to mid-
786 2000s, *J. Geophys. Res.*, 113, C12022, doi:10.1029/2008JC004975, 2008.

787 Sarafanov, A., Falina, H., Mercier, A., Sokov, P., Lherminier, C., Gourcuff, S., Gladyshev, F., Gaillard, and
788 N. Danaïault (2012), Mean full-depth summer circulation and transports at the northern periphery of
789 the Atlantic Ocean in the 2000s, *J. Geophys. Res.-Oceans*, 117(C01014), doi:10.1029/2011JC007572,
790 2012.

791 Sgubin G., Swingedouw D., Drijfhout S., Mary Y. and Bennabi A.: Abrupt cooling over the North
792 Atlantic in modern climate models, *Nature Communications*, 8, 14375, doi: 10.1038/ncomms14375,
793 2017.

Code de champ modifié

Code de champ modifié

794 Spall, M. A. and Price, J. F.: Mesoscale Variability in Denmark Strait: The PV Outflow Hypothesis,
795 *Journal of Physical Oceanography*, 1997.

796 Väge, K., Pickart, R. S., Sarafanov, A., Knutsen, O., Mercier, H., Lherminier, P., van Aken, H. M.,
797 Meincke, J., Quadfasel, D., and Bacon, S.: The Irminger Gyre: Circulation, convection, and interannual
798 variability, *Deep-Sea Res. Part -Oceanogr. Res. Pap.*, 58(5), 590–614, doi:10.1016/j.dsr.2011.03.001,
799 2011.

800 Williams, R., Roussenov, V., Smith, D., Lozier, S.: Decadal evolution of ocean thermal anomalies in the
801 North Atlantic: The effects of Ekman, Overturning, and Horizontal Transport, *Journal of Climate*, 27,
802 doi:10.1175/JCLI-D-12-00234.1, 2014.

803 Yashayaev, I., and Loder, J. W.: Recurrent replenishment of Labrador Sea Water and associated
804 decadal scale variability, *J. Geophys. Res. Oceans*, 121, 8095–8114, doi:10.1002/2016JC012046, 2016.

805 Yashayaev, I., and Loder J. W.: Further intensification of deep convection in the Labrador Sea in 2016,
806 *Geophys. Res. Lett.*, 44, 1429–1438, doi:10.1002/2016GL071668, 2017.

807 Zunino, P., Pérez, F. F., Fajar, N. M., Guallart, E. F., Ríos, A. F., Pelegrí, J. L., and Hernández-Guerra, A.:
808 Transports and budgets of anthropogenic CO₂ in the tropical North Atlantic in 1992–1993 and 2010–
809 2011, *Global Biogeochem. Cycles*, 29, 1075–1091, doi:10.1002/2014GB005075, 2015.

810

811 **TABLES**

812 Table 1. Intensity (top-to-bottom integrated) of the different dynamical structures defined in
813 section 3.1 for 2014 and the mean values (2002–2012) estimated by Daniault et al. (2016).
814 Note that the errors given for the GEOVIDE estimates come from the covariance matrix
815 resulting from the inverse model. Otherwise, the errors given with the mean values are the
816 standard deviation of the six estimates of each current.

Units: Sv	WBC	IG	IC		ERRC	NAC	Recirculation
			as D2016	Northward transport			
GEOVIDE	-30.3 ± 2.1	6.8 ± 3.0	17.5 ± 7.3	22.7 ± 6.5	-13.6 ± 6.0	32.2 ± 11.4	-10.2 ± 6.4
MEAN (2002–2012)	-33.1 ± 2.6	7.7 ± 2.1	9.5 ± 3.4	11.0 ± 3.4	-12.1 ± 1.1	41.8 ± 3.7	-13.0 ± 2.0

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820

821 **FIGURE CAPTIONS**

822 **Fig. 1.** Schematic diagram of the 2002–2012 mean large-scale circulation adapted from
823 Daniault et al. (2016). Bathymetry is plotted in color with color changes at 100 m, 1000 m
824 and every 1000 m below 1000 m. The locations of the GEOVIDE hydrographic stations are
825 indicated by black dots along the OVIDE section and across the Labrador Sea. Red dots, and
826 associated numbers, along the OVIDE section show the stations delimiting the regions used in
827 this paper for the transport computations of the different currents crossing the OVIDE section.
828 The names of the main currents are indicated in the figure: East Greenland-Irminger Current
829 (EGIC), Deep Western Boundary Current (DWBC), Irminger Current (IC), Eastern Reykjanes
830 Ridge Current (ERRC), Northern branch of the North Atlantic Current (NNAC), Subarctic
831 Front (SAF) and Southern branch of the North Atlantic Current (SNAC). Superstations and
832 XL stations carried out during GEOVIDE are represented by pink stars. The main
833 topographical features of the Subpolar North Atlantic are labeled: Azores-Biscay Rise (ABR),
834 Bight Fracture Zone (BFZ), Charlie–Gibbs Fracture Zone (CGFZ), Faraday Fracture Zone
835 (FFZ), Maxwell Fracture Zone (MFZ), Mid-Atlantic Ridge (MAR), Iberian Abyssal Plain
836 (IAP), Northwest Corner (NWC), Rockall Trough (RT), Rockall Plateau (Rockall P.) and
837 Maury Channel (MC). The main water masses are indicated: Denmark Strait Overflow Water
838 (DSOW), Iceland–Scotland Overflow Water (ISOW), Labrador Sea Water (LSW),
839 Mediterranean Water (MW), and Lower North East Atlantic Deep Water (LNEADW).

840
841 **Fig. 2.** Vertical section of potential temperature ($^{\circ}\text{C}$), salinity and oxygen ($\mu\text{mol kg}^{-1}$) along
842 the OVIDE section measured during the GEOVIDE cruise. The horizontal grey lines in the
843 three plots represent the isopycnal layers ($\sigma_1 = 32.15 \text{ kg m}^{-3}$, $\sigma_0 = 27.80 \text{ kg m}^{-3}$ or $\sigma_2 = 36.94 \text{ kg}$
844 m^{-3} , $\sigma_4 = 45.85 \text{ kg m}^{-3}$) indicated in the upper plot. The vertical grey lines in the three plots are
845 the limits between the different circulation components crossing the OVIDE section: Western
846 Boundary Current (WBC), Irminger Gyre (IG), Irminger Current (IC), Eastern Reykjanes
847 Ridge Current (ERRC), northern branch of the North Atlantic Current (NNAC), SubArctic
848 Front (SAF), southern branch of the North Atlantic Current (SNAC) and the recirculation in
849 the Iberian Abyssal Plain (RECIR.). The main water masses are indicated in the central plot:
850 Denmark Strait Overflow Water (DSOW), Iceland–Scotland Overflow Water (ISOW),
851 Labrador Sea Water (LSW), Sub-Polar Mode Water (SPMW), Sub-Arctic Intermediate Water
852 (SAIW), North Atlantic Central Water (NACW), Mediterranean Water (MW) and North East
853 Atlantic Deep Water (NEADW). The main topographic features are indicated in the bottom

854 plot: Reykjanes Ridge (RR), Eriador Seamount (ESM), Western European Basin (WEB),
855 Azores-Biscay Rise (ABR) and Iberian Abyssal Plain (ABP). Ticks at the top of the upper and
856 central plots indicate the positions of all the stations measured during GEOVIDE, along the
857 OVIDE section, with some station numbers given above. In the bottom plot, the red and green
858 numbers indicate the position of the superstations and XLarge stations, respectively.

859

860 **Fig. 3.** Velocities (m s^{-1}) orthogonal to the OVIDE section measured during the GEOVIDE
861 cruise. Positive/negative values indicate northeastward/southwestward velocities. a)
862 Velocities measured by the ship-ADCP. b) Geostrophic velocity obtained by the inversion
863 model plus Ekman velocities in the upper 30 m. The vertical black lines are the limits between
864 the different circulation components crossing the OVIDE section as defined in the main text
865 and at the bottom of Fig. 2a. The horizontal discontinuous black line delimits the 800 dbar for
866 comparison of Fig. 3a and 3b. The horizontal black continuous lines are the isopycnals $\sigma_1 =$
867 32.15 kg m^{-3} , $\sigma_0 = 27.80 \text{ kg m}^{-3}$ or $\sigma_2 = 36.94 \text{ kg m}^{-3}$ and $\sigma_4 = 45.85 \text{ kg m}^{-3}$. Bold numbers
868 inside the figure are the volume transports (in Sv) estimated for each region and vertical layer,
869 with errors in parentheses. The only exception is the estimation of the IG transport, which,
870 following Väge et al. (2011) was computed as the northward transport (the 0 m s^{-1} isotach is
871 indicated as a thin black line in Fig. 3b in the western Irminger Sea). Station numbers at the
872 top of the figure are color-coded: black for regular stations, blue for large stations, green for
873 XLarge stations and red for superstations. The eddies described in section 3.2 are indicated at
874 the top of the plots.

875

876 **Fig. 4.** Upper panel: Stream function or volume transport horizontally accumulated from
877 Greenland to each GEOVIDE station, down to Portugal, and vertically accumulated in the
878 upper limb of the MOC (red discontinuous line) and in the whole water column (red
879 continuous line). The mean salinity in the upper limb of the MOC is also shown by the blue
880 line and labeled on the right-hand axis. Acronyms in the top of the figure indicate the different
881 components of the circulation crossing the OVIDE section as defined in Fig. 2. See Fig. 3 for
882 station numbers and bathymetry legend. Lower panel: bathymetry along the OVIDE section;
883 acronyms as in Fig. 2

884

885 **Fig. 5.** Surface velocities (m s^{-1}) derived from AVISO data: arrows indicate current direction
886 and colors indicate current intensity. The white line represents the OVIDE section. The red
887 and white points indicate the extension of the different dynamical structures crossing the
888 OVIDE section in 2014. The white points delimit the extension of the NAC. The pink stars
889 indicate the position of the GEOVIDE superstations and XLarge stations. The bathymetry
890 contours, every 1000 m, are indicated by light white lines.

891

892 **Fig. 6.** Surface velocities derived from AVISO data, as in Fig. 5, but zooming in on the NAC
893 region in March 2014, April 2014, May 2014 and June 2014. The yellow, red, clear green and
894 orange squares indicate the position of the northern, central and southern eddies, respectively,
895 discussed in section 3.2. The numbers of the GEOVIDE stations are indicated in all the plots:
896 pink for the superstations and XLarge stations, and yellow for regular stations. The red and
897 green points delimitate the position of the SAF and the NAC, respectively, at the period of the
898 GEOVIDE cruise. The bathymetry contours, every 1000 m, are indicated by light white lines.

899 **Fig. 7.** Anomalies of potential temperature (upper panel, in $^{\circ}\text{C}$), salinity (middle panel) and
900 oxygen (bottom panel, in $\mu\text{mol kg}^{-1}$) in 2014 with respect to the OVIDE 2002–2012 mean.
901 Only anomalies larger than one standard deviation of the 2002–2012 values are colored in the
902 figure. Station numbers follow the color code of Fig. 2. The orange line indicates the winter
903 mixed-layer depth (WMLD); in the Irminger Sea, the dotted line indicates the WMLD that
904 was not formed locally (see section 4.2). The acronyms in the bottom plot are as in Figs. 2 and
905 3.

906 **Fig. 8.** Contours of the Absolute Dynamical Topography (ADT) averaged over 2014 (in thin
907 lines), contours are every 0.05 m. Thick contours correspond to the levels encompassing the
908 SAF front during OVIDE cruises: red for the mean 2002–2012 and black for 2014. Note that
909 the temporal trend on the mean ADT over the whole box (2.8 mm yr^{-1}) was removed.
910 Bathymetry (1000 m step contours) and the OVIDE section are plotted in white. Colors
911 represent the absolute velocity of the current (yellow for velocities stronger than 0.3 m s^{-1}).

912

913 **Fig. 9.** Heat content anomalies with respect to the mean heat content for the period 2002 –
914 2012 in the upper 1000 m of the region $40\text{--}60^{\circ}\text{N}$ and $45\text{--}10^{\circ}\text{W}$: the monthly time series in
915 grey and the 2-year running mean in black. Data source: EN4 database (Good et al., 2013).
916 The red square highlights the short-term cooling event analyzed in this paper.

917

918 **Fig. 10.** Annual mean anomalies of potential temperature (left panel) and salinity (right panel)
919 in the surface waters (20–500 m) in the North Atlantic, estimated from ISAS database. The
920 reference period for estimating the anomalies was 2002–2012. The OVIDE section is
921 represented by a black line. Only anomalies larger than one standard deviation are colored in
922 the figure.

923

924 **Fig. 11.** 2014 Winter–Spring (DJFMAM) mean anomalies. The anomalies were calculated in
925 with respect to the period 2002–2012. A, B and C are the total heat, sensible heat and latent
926 heat air-sea flux, respectively, in W m^{-2} ; positive/negative values indicate ocean heat
927 gain/lost. D, E and F are net gain of freshwater, evaporation and precipitation; the unit is 10^{-4}
928 m; positive/negative values indicate ocean freshwater gain/loss. The contours of anomalies 0
929 W m^{-2} (in a, b and c) and of 0 m (in d, e and f) are represented by a white line. Data source:
930 ERA-Interim. The green square represents the area for which the changes of heat/freshwater
931 content, and the integrated air-sea heat/freshwater flux represented in Fig. 12 were evaluated.

932

933 **Fig. 12.** Monthly time series of the freshwater content change between one month and the
934 month before (in m^3), accumulated since February 1, 2013 in the upper 1000 m of the box
935 delimited by 40–60 °N and 45–10 °W computed from three datasets: EN4 (blue), ISAS (red)
936 and JAMSTEC (green). Integrated air-sea freshwater flux, or precipitation minus evaporation,
937 over the same box, and accumulated from January 16, 2013, from ERA-Interim (continuous
938 black line) and from NCEP (discontinuous black line) databases.