<u>Reply to reviewer #1</u>

We would like to thank the reviewer #1 for his/her helpful minor comments, which we followed as can be seen below in bold.

Sarthou and coworkers introduce the special issue with a well-written overview of the GEOVIDE expedition. The manuscript clearly describes the motivation for following the OVIDE line for the GEOTRACES study, including the benefits for interpreting trace element and isotope distributions by having the wealth of complementary data from multiple occupations of the section by the OVIDE program. Sarthou et al. entices readers to read the remaining papers in the issue by describing the primary features of many of the trace element and isotope distributions, giving just enough information to motivate readers to seek the remainder of each account in the original publication. Quality control of the data has been a hallmark of the GEOTRACES program, so it is reassuring to see the essential information about nutrient and hydrographic data in the supplementary material.

I recommend publication with just a few minor editorial changes:

1) Line 90: The delta before 14C should be capitalized,

Done

2) Line 93: Correct the Th in 234Th,

Done

3) Lines 291 – 301: Give the approximate depth range of each water mass described here,

The approximate depth range was given for each water mass, and the sentence was changed as followed:

The increase in the MOC intensity from 2002–2010 to 2014 was shown to be related to the increase in the northward transport of the Central Waters in its upper limb (from the surface to 1000 m in the south-eastern part of the section), and in the southward flow of both the Subpolar Mode Water of the Irminger Basin (SPMW, 200 to 1500 m) and the Iceland–Scotland Overflow Water (ISOW, between 1800 and 3000 m) in its lower limb (García-Ibáñez et al., 2018).

4) Lines 358-359: If there are specific references that present results pertaining to nepheloid layer sources of trace elements then please cite them here.

The reference Gourain et al. (2018) was added in the text.

Reply to reviewer #2

We would like to thank the reviewer #2 for his/her helpful minor comments, which we followed as can be seen below in bold.

This paper serves as introductory paper for the GEOVIDE special issue and provides a summary of the scientific motivation and objectives for the cruise, as well as an overview of the major findings, presented in detail in the individual papers. The manuscript emphasizes the need for a combined analysis of the physical and biogeochemical processes (currents and water masses on one side, biological production, particle remineralization, particle adsorption/desorption, and fluxes from the atmosphere as well as from/to sediments on the other), and makes the point that the long history of previous OVIDE observations along the same track clearly benefits the interpretation of the present GEOVIDE data.

The manuscript is well written and provides a good context for the other papers. I recommend publication with only minor modifications, as described below.

Line 90f: This sentence is very general and can be hard to understand. Please provide examples for the "specific mechanisms".

We agree that this sentence is very general and four examples were given in the following sentence, with the associated TEIs. The cited mechanisms were atmospheric deposition, mixing rates of deep waters or shelf-to-open ocean, boundary exchange processes, downward flux of organic carbon and/or remineralisation in deep waters.

Line 283: Please describe briefly, on what evidence the finding of "a weaker North Atlantic Current" is based on. I understand this is included in the Zunino, 2017 paper, but a short explanation will help readers.

In order to help the readers in understanding the weaker NAC, the following sentence was added:

"The distribution of the volume transport in the three branches of the NAC (Figure 1) has changed: no transport was found in the northern branch, although 11 Sv were found in the mean of the previous decade, and the central branch, that marks the limit between the subpolar and the subtropical regions, nearly doubled in 2014."

Line 292ff: Please explain how the meridional heat transport can be "largest" despite the lower-than-average temperatures in and the weaker flow of (line 283) its main contributor, the North Atlantic Current. Also please explain how the MOC can be strong (line 293) when the NAC transport is relatively small.

To make it clearer for the readers, the text has been modified as followed:

"Remarkably, despite the negative temperature anomalies in the surface waters, the heat transport across the OVIDE section estimated during GEOVIDE was the largest measured

since 2002. This was attributed to the relatively strong MOC measured across the OVIDE section during GEOVIDE (Zunino et al., 2017) and, more particularly, to the strong transport of central water in the central and southern branch of the NAC (García-Ibáñez et al., 2018) that compensates the cold anomaly of the surface layer. The relatively strong MOC and heat transport were confirmed by Holliday et al. (2018) across a nearly simultaneous section (June-July 2014) between Labrador and Scotland."

Typos:

line 184: achieve

Done

line 194: TEI

Done

line 210: have

Done

Introduction to the French GEOTRACES North Atlantic Transect (GA01): GEOVIDE cruise

Sarthou Géraldine [1], Lherminer Pascale [2], Achterberg Eric P. [3], Alonso-Pérez Fernando [4], Bucciarelli Eva [1], Boutorh Julia [1], Bouvier Vincent [5], Boyle Edward A. [6], Branellec Pierre [2], Carracedo Lidia I. [4], Casacuberta Nuria [7], Castrillejo Maxi [7,8], Cheize Marie [1,9], Contreira Pereira Leonardo [10], Cossa Daniel [11], Daniault Nathalie [2], De Saint-Léger Emmanuel [12], Dehairs Frank [13], Deng Feifei [14], Desprez de Gésincourt Floriane [1,2], Devesa Jérémy [1], Foliot Lorna [15], Fonseca-Batista Debany [13,16], Gallinari Morgane [1], García-Ibáñez Maribel I. [4,17], Gourain Arthur [1,18], Grossteffan Emilie [19], Hamon Michel [2], Heimbürger Lars Eric [20], Henderson Gideon M. [14], Jeandel Catherine [5], Kermabon Catherine [2], Lacan François [5], Le Bot Philippe [2], Le Goff Manon [1], Le Roy Emilie [5], Lefèbvre Alison [2], Leizour Stéphane [2], Lemaitre Nolwenn [1,~~7,~~13, 21], Masqué Pere [8,~~21~~22,23], Ménage Olivier [2], Menzel Barraqueta Jan-Lukas [3,24], Mercier Herlé [2], Perault Fabien [12], Pérez Fiz F. [4], Planquette Hélène F. [1], Planchon Frédéric [1], Roukaerts Arnout [~~12~~13], Sanial Virginie [5,~~22~~25], Sauzède Raphaëlle [~~23~~26], Shelley Rachel U. [1, ~~24~~27], Stewart Gillian [~~25,26~~28,29], Sutton Jill N. [1], Tang Yi [~~26,25~~28,29], Tisnérat-Laborde Nadine [15], Tonnard Manon [1,~~27,28~~30,31], Tréguer Paul [1], van Beek Pieter [5], Zurbrick Cheryl M. [6], Zunino Patricia [2]

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Mis en forme : Exposant

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Mis en forme : Interligne : simple

Mis en forme : Interligne : simple

Abstract

The GEOVIDE cruise, a collaborative project within the framework of the international GEOTRACES programme, was conducted along the French-led section in the North Atlantic Ocean (Section GA01), between 15 May and 30 June 2014. In this Special Issue, results from GEOVIDE, including physical oceanography and trace element and isotope cyclings, are presented among seventeen articles. Here, the scientific context, project objectives and scientific strategy of GEOVIDE are provided, along with an overview of the main results from the articles published in the special issue.

1. Scientific context and objectives

Understanding the distribution, sources, and sinks of trace elements and isotopes (TEIs) will improve our ability to understand the past and present marine environments. Some TEIs are toxic (e.g. Hg), while others are essential micronutrients involved in many metabolic processes of marine organisms (e.g. Fe, Mn). The availability of TEIs therefore constrains the ocean carbon cycle and affects a range of other biogeochemical processes in the Earth system, whilst responding to and influencing global change (de Baar et al., 2005; Blain et al., 2007; Boyd et al., 2007; Pollard et al., 2007). Moreover, TEI interactions with the marine food web strongly depend on their physical (particulate/dissolved/colloidal/soluble) and chemical (organic and redox) forms. In addition, some TEIs are diagnostic in allowing the quantification of specific mechanisms in the marine environment that are challenging to measure directly. Few examples include: (i) atmospheric deposition (e.g. ^{210}Pb, Al, Mn, Th isotopes, ^{7}Be; Baker et al., 2016; Hsieh et al., 2011; Measures and Brown, 1996), (ii) mixing rates of deep waters or shelf-to-open ocean (e.g. ^{231}Pa/^{230}Th, Δ^{14}C, Ra isotopes, ^{129}I, ^{236}U; van Beek et al., 2008; Casacuberta et al., 2016; Key et al., 2004), (iii) boundary exchange processes (e.g. ε_{Nd}, Jeandel et al., 2011; Lacan and Jeandel, 2001, 2005), and (iv) downward flux of organic carbon and/or remineralisation in deep waters (e.g. ^{234}Th/^{238}U, ^{210}Pb/^{210}Po, Ba_{xs}; Buesseler et al., 2004; Dehairs et al., 1997; Roca-Martí et al., 2016). In such settings, TEIs provide chemical constraints and allow the estimation of fluxes which was not possible before the development of their analyses. Finally, paleoceanographers are wholly dependent on the development of tracers, many of which are based on TEIs used as proxies, in order to reconstruct past environmental conditions (e.g. ocean productivity, patterns and rates of ocean circulation, ecosystem structures, ocean anoxia; Henderson, 2002). Such reconstruction efforts are essential to assess the processes involved in regulating the global climate system, and possible future climate change variability.

Despite all these major implications, the distribution, sources, sinks, and internal cycling of TEIs in the oceans are still largely unknown due to the lack of appropriate clean sampling approaches and insufficient sensitivity and selectivity of the analytical measurement techniques until recently. This last point has improved very quickly as significant improvements in the instrumental techniques now allow the measurements of concentrations, speciation (physical and chemical forms), and isotopic compositions for most of the elements of the periodic table which have been identified either as relevant tracers or key nutrients in the marine environment. These recent advances provide the marine geochemistry community with a significant opportunity to make substantial contributions to a better understanding of the marine environment.

In this general context, the aim of the international GEOTRACES programme is to characterize TEI distributions on a global scale, consisting of ocean sections, and regional process studies, using a multi-proxy approach. The GEOVIDE section is the French contribution to this global survey in the North Atlantic Ocean along the OVIDE section and in the Labrador Sea (Fig. 1) and complements a range of other international cruises in the North Atlantic. GEOVIDE leans on the knowledge gained by the OVIDE project during which the Portugal-Greenland section has been carried out biennially since 2002, gathering physical and biogeochemical data from surface to bottom (Mercier et al., 2015; Pérez et al., 2018).

Rationale for the GEOVIDE section:

i) The North Atlantic Ocean plays a key role in mediating the climate of the Earth. It represents a key region of the Meridional Overturning Circulation (MOC) and a major sink of anthropogenic carbon (C_{ant}) (Pérez et al., 2013; Sabine et al., 2004; Seager et al., 2002). Since 2002, the OVIDE project has contributed to the observation of both the circulation and water mass properties of the North Atlantic Ocean. Despite the importance of the MOC on global climate, it is still challenging to assess its strength within a reasonable uncertainty (Kanzow et al., 2010; Lherminier et al., 2010). The MOC strength estimated from *in-situ* measurements on OVIDE cruises has thus helped to validate a time series for the amplitude of the MOC (based on altimetry and ARGO float array data) that exhibits a drop of 2.5±1.4 Sv (95% confidence interval) between 1993 and 2010 (Mercier et al., 2015), consistent with other modelling studies (Xu et al., 2013). This time series, along with the *in situ* data, shows a recovery of the MOC amplitude in 2014 at a value similar to those of the mid-1990s, confirming the importance of the decadal variability in the subpolar gyre. During OVIDE, the contribution of the most relevant currents, water masses and biogeochemical provinces have been localized and quantified. This knowledge was crucial for the establishment of the best strategy to sample TEIs in this specific region.

In addition to the OVIDE section, the Labrador Sea section offered a unique opportunity to complement the MOC estimate, to analyse the propagation of anomalies in temperature and salinity (Reverdin et al., 1994), and to study the distribution of TEIs along the boundary current of the subpolar gyre, coupling both observations and modelling.

Moreover, recent results provided evidences that CO_2 uptake in the North Atlantic was reduced by the weakening of the MOC (Pérez et al., 2013). The most significant finding of this study was that the uptake of C_{ant} occurred almost exclusively in the subtropical gyre, while natural CO_2 uptake dominated in the subpolar gyre. In light of these new results, one issue to be addressed was the coupling between the C_{ant} and the transport of water, with the aim to understand how the changes in the ventilation and in the circulation of water masses affect the C_{ant} uptake and its storage capacity in the various identified provinces (Fröb et al., 2018).

Finally, as the subpolar North Atlantic forms the starting point for the global ocean conveyor belt, it is of particular interest to investigate how TEIs are transferred to the deep ocean through both ventilation and particle sinking, and how deep convection processes impact the TEI distributions in this key region.

ii) A better assessment of the factors that control organic production and export of carbon in the productive North Atlantic Ocean, together with a better understanding of the role played by TEIs in these processes are research priorities. Pronounced phytoplankton blooms occur in the North Atlantic in spring in response to upwelling and water column destratification (Bury et al., 2001; Henson et al., 2009; Savidge et al., 1995). Such blooms are known to trigger substantial export of fast-sinking particles (Lampitt, 1985), and can represent a major removal mechanism for particulate organic carbon, macronutrients, and TEIs to the deep ocean.

iii) In the North Atlantic, TEI distributions are influenced by a variety of sources including, for the most important, the atmosphere and the margins (Iberian, Greenland, and Labrador margins).

Atmosphere: Atmospheric inputs (e.g. mineral dust, anthropogenic emission aerosols) are an important sources of TEIs to the North Atlantic Ocean due to the combined effects of anthropogenic emissions from industrial/agricultural sources and mineral dust mobilized from the arid regions of North Africa (Duce et al., 2008; Jickells et al., 2005). Model and satellite data for the GEOVIDE section suggested that an approximately tenfold decrease in the atmospheric concentrations of mineral dust was expected from south to north (Mahowald et al., 2005). As there had been relatively few aerosol TEI studies in the northern North Atlantic compared to the tropical and subtropical North Atlantic prior to GEOVIDE, constraining atmospheric deposition fluxes to this region had been identified as a research priority (de Leeuw et al., 2014). During the GEOVIDE campaign, a multi-proxy approach (e.g. aerosol trace element concentrations, dissolved and particulate Al and Mn, seawater ^{210}Pb, Fe, Nd and Th isotopes, ^{7}Be) was taken to ~~acheive~~achieve the objective of better constraining the atmospheric deposition fluxes of key trace elements.

Margins: The continental shelves can act as a filter for TEIs supplied from shelf sediments, submarine groundwater discharge (including the discharge of fresh groundwater into the coastal seas and recirculation of seawater through the sediment), and rivers. While some TEIs are removed on the continental shelves, others are thought to be mobilized from the solid phase at the land-ocean interface (e.g. Fe and likely other micro- and macro-nutrients, such as Cu, Ni, Mn, and Si; Chase et al., 2005; Jeandel and Oelkers, 2015). The cruise track intersected several margins, thus allowing for the characterization of continental sources and quantification of TEI~~s~~ fluxes associated with these sources in various shelf regimes.

iv) It is obviously needed to further validate the use of paleo-proxies. For example, in recent years, the potential of the ^{231}Pa/^{230}Th ratio for identifying past rates of ocean circulation, and of the isotopic composition of neodymium (ε_{Nd}) as a tracer of thermohaline circulation have led to many paradigm-changing results for the reconstitution of the Atlantic Ocean circulation (McManus et al., 2004; Montero-Serrano et al., 2013; Negre et al., 2010). However, there is an ongoing debate about the interpretation of ^{231}Pa/^{230}Th paleo-records in the Atlantic (Hayes et al., 2015; Keigwin and Boyle, 2008) focused on the effects of particle fluxes versus those of water circulation. Only one single ^{231}Pa profile in the Subpolar North Atlantic has been published before GEOVIDE (Moran et al., 2002). Regarding Nd isotopes, although several profiles of dissolved (and total) Nd isotopes are available in the boundary currents of Greenland and the Labrador Sea, there are very few profiles for the ocean interior of the GEOVIDE region (Copard et al., 2011; Filippova et al., 2017; Lacan and Jeandel, 2004; Lambelet et al., 2016). In addition, the importance of dissolved/particle interactions in the control of the isotopic composition of Nd is becoming increasingly apparent. To our knowledge, particulate ε_{Nd} data have~~s~~ not been published yet for the Subpolar North Atlantic. For these reasons, documenting these tracers in both dissolved and particulate phases is needed to provide new constraints and significantly advance our understanding of the cycles of these tracers and their use in the modern and past oceans.

Furthermore, proxies of nutrient utilization, such as the silicon stable isotopes ($\delta^{30}Si$) from diatom silica, provides a means of reconstructing the behaviour of past geochemical cycles and the past strength of the biological pump, and its influence on atmospheric concentrations of CO_2. However, successful application of $\delta^{30}Si$ in diatoms accumulating in sediments for reconstruction of past silica cycling requires a thorough understanding of $\delta^{30}Si$ of dissolved Si ($\delta^{30}Si_{DSi}$) and of the processes that control its distribution throughout the modern ocean. Combining studies in the Southern Ocean (De La Rocha et al., 2011; Fripiat et al., 2011) and North and Equatorial Pacific (De La Rocha et al., 2000) with a global circulation model (Wischmeyer et al., 2003) has revealed the roles that ocean circulation and biogeochemical cycling play in controlling the distribution of silicon isotopes within the ocean. Largely missing from this dataset was the North Atlantic Ocean (De La Rocha et al., 2011).

In this general context, the main scientific objectives of GEOVIDE were to (i) better understand and quantify the MOC and the carbon cycle carbon cycle in the context of decadal variability, adding new tracers to this end, (ii) map the TEI distributions, including their physical and chemical speciation, along this full-depth high resolution ocean section, (iii) investigate the links between TEIs and the production, export, and remineralisation of particulate organic matter, (iv) identify TEI sources and sinks, and quantify their fluxes at the ocean boundaries, and (v) better understand and quantify the paleoproxies $^{231}Pa/^{230}Th$, ε_{Nd}, and $\delta^{30}Si$.

2. Strategy

To achieve the objectives of the GEOVIDE project, a 47-day multidisciplinary cruise was carried out on board R/V Pourquoi Pas? in the North Atlantic Ocean along the OVIDE section, from Lisbon to Greenland, and in the Labrador Sea (Fig. 1). The Labrador section was chosen according to the OSNAP (Overturning in the Subpolar North Atlantic Programme) recommendations because it transects the export route of the Labrador Sea Water downstream of its formation site. Therefore, the properties of the North Atlantic Deep Water (NADW) at 53°N are likely to be representative of NADW further south and a 15-year time series of currents and hydrographic properties is available in the Western Boundary Current at this latitude (Fischer et al., 2010). The GEOVIDE cruise took place from 15 May to 30 June 2014, during the same season as the previous OVIDE cruises (2002-2012). The cruise timing helped to minimize seasonal variations and maximize the representativeness of inter-annual variability of the physical parameters investigated in this specific region. Furthermore, this period of the year corresponds to the bloom/post-bloom period of the subpolar gyre and post-bloom period in the sub-tropical gyre (Henson et al., 2005), thus allowing for the study of the complexity of the biological pump and the links between production, export of organic matter, and TEIs.

A high resolution hydrographical section that includes the *in-situ* measurements of the currents by doppler profilers was performed and, as recommended by GEOTRACES, a multi-proxy approach was used. In total, 78 stations were occupied (plus one test station). Station naming depended on the number of casts that were conducted: Short (47 one-cast stations), Large (17 three-cast stations), XLarge (5 five-cast stations), and Super (10 multi-cast stations). A total of 341 on-deck operations were carried out during GEOVIDE.

In total, (i) the standard stainless steel rosette was deployed 163 times, (ii) the trace metal clean rosette, 53 times, (iii) *in-situ* pumps, 25 times, (iv) the mono-corer, with or without *in-situ* pumps clamped on the cable, 11 times and (v) the plankton net, 9 times. We also collected 140 surface seawater samples using a fish towed from the ship's starboard side and deployed at 1–2 m depth, 18 aerosol samples, and 10 rainwater samples. In addition, we deployed: 60 eXpendable BathyThermographs (XBTs), 17 ARGO profiling floats (8 ARVOR, 2 ARVOR-deep, 2 PROVOR-DO, 2 PROVBIO, 1 ARVOR double DO, and 2 APEX), and 12 weather buoys.

3. Summary of the main results published in this special issue

In this special issue, seventeen publications present results of the GEOVIDE project. Six other manuscripts have already been published in other journals (Benetti et al., 2017; Cossa et al., 2018b; Le Reste et al., 2016; Pérez et al., 2018; Shelley et al., 2017; Zunino et al., 2015). Due to the long time required for some analyses, other articles related to this project are to be expected for publication at a later date.

The articles in this special issue are linked to four general research themes: (i) hydrographic and physical characteristics, (ii) links between water masses and TEIs, (iii) external sources and sinks of TEIs, and (iv) biogeochemical tracers of community structure, export and remineralisation.

3.1. Hydrographic and physical characteristics

In terms of circulation, the comparison with the 2002–2012 mean state shows a different repartition of the northward warm currents that compose the upper limb of the MOC, with a more intense Irminger Current (station 39-41) and a weaker North Atlantic Current (NAC) in the Western European Basin, these anomalies being compatible with the variability previously observed along the OVIDE section in the 2000s (Zunino et al., 2017). The distribution of the volume transport in the three branches of the NAC (Fig. 1) has changed: no transport was found in the northern branch, although 11 Sv were found in the mean of the previous decade, and the central branch, that marks the limit between the subpolar and the subtropical regions, nearly doubled in 2014.

The main hydrographic properties along the GEOVIDE section are shown on Fig. 2 for potential temperature, salinity, dissolved oxygen, nitrate + nitrite, and silicic acid. The surface waters of the eastern SPNA, down to about 500 m, were much colder and fresher than the average values observed over 2002–2012 (Zunino et al., 2017). In the context of the ocean heat loss observed in the subpolar gyre since 2005, the year 2013-2014 was indeed particularly intense. Remarkably, despite the negative temperature anomalies in the surface waters, the heat transport across the OVIDE section estimated during GEOVIDE was the largest measured since 2002. This was attributed to the relatively strong MOC measured across the OVIDE section during GEOVIDE (Zunino et al., 2017) and more particularly to the strong transport of central water in the central and southern branch of the NAC (García-Ibáñez et al., 2018) that compensates the cold anomaly of the surface layer. The relatively strong MOC and heat transport were confirmed by Holliday et al. (2018) across a nearly simultaneous section (June-July 2014) between Labrador and Scotland.

The water mass properties of the GEOVIDE cruise were used to perform an extended Optimum MultiParameter (eOMP) analysis and to assess the water mass distribution (García-Ibáñez et al., 2018). The eOMP analysis together with the absolute geostrophic velocity field determined using a box inverse model allowed the evaluation of the relative importance of each water mass to the MOC. The increase in the MOC intensity from 2002–2010 to 2014 was shown to be related to the increase in the northward transport of the Central Waters in its upper limb (from the surface to 1000 m in the south-eastern part of the section), and in the southward flow of both the Subpolar Mode Water of the Irminger Basin (SPMW, 200 to 1500 m) and the Iceland–Scotland Overflow Water (ISOW, between 1800 and 3000 m) in its lower limb (García-Ibáñez et al., 2018).

In addition, the precise determination of different water masses (García-Ibáñez et al., 2018) and ventilation processes are crucial for the interpretation of the TEIs whose distributions are, for many of them, strongly related to water masses.

3.2. Links between water masses and TEIs

The concentrations of TEIs are strongly influenced by water mass distribution, age, and circulation/mixing. For instance, this is the case of ^{230}Th and ^{231}Pa, high concentrations of both tracers were observed in the old water of North East Atlantic Deep Water (NEADW), and low values in young waters, particularly in Denmark Strait Overflow Water (DSOW) (Deng et al., 2018). The low values of ^{230}Th and ^{231}Pa in water near the seafloor of the Labrador and Irminger Seas are related to the young waters present in those regions (Deng et al., 2018). This study reports systematic increase of ^{230}Th activities with water age but a more complex relationship between age and ^{231}Pa which challenges some approaches to the use of sedimentary $^{231}Pa/^{230}Th$ ratios to assess past rates of oceanic circulation. The application of this proxy at a basin scale to constrain the overturning circulation is, however, supported by GEOVIDE data which now allows a complete nuclide budget for the North Atlantic to be constructed (Deng et al., 2018).

Long-lived artificial radionuclides were also very useful to assess the circulation in the SPNA, namely ^{129}I and ^{236}U, and the origin of water masses in a dual tracer approach (i.e. $^{129}I/^{236}U$ and $^{236}U/^{238}U$ atom ratios) (Castrillejo et al., 2018). These transient tracers, originating from La Hague (France) and Sellafield (UK) nuclear reprocessing plants and the atmospheric nuclear weapon tests, helped investigating the shallow western boundary transport and the ventilation processes. For example, the ^{129}I concentrations validate the ISOW transport pathways in the Western European basin. The time series of ^{129}I in the Labrador Sea revealed two circulation loops of the Atlantic Waters carrying the signal from the European reprocessing plants: i) a short loop through the Nordic Seas into the central Labrador Sea of about 8-10 years, and; ii) a longer loop which includes about 8 additional years of recirculation in the Arctic Eurasian Basin before entering back to the Atlantic Ocean (Castrillejo et al., 2018).

Some other TEIs were also strongly linked to water mass distribution: Within GEOVIDE, silicon isotopes (Sutton et al., 2018), lead (Pb) (Zurbrick et al., 2018), mercury (Hg) (Cossa et al., 2018a), and particulate and dissolved Fe and Al (Gourain et al., 2018; Menzel Barraqueta et al., 2018a; Tonnard et al., 2018), as examples. For instance, the Labrador Seawater (LSW) is characterized by a relatively high silicon stable isotope composition for dissolved silicon ($\delta^{30}Si_{DSi}$) whose signature can be seen not only in the region where it is formed, but also throughout the mid-depth zone of the North Atlantic Ocean (Sutton et al., 2018). The $\delta^{30}Si_{DSi}$ distribution thus provides information on the interaction between subpolar/polar water masses of northern and southern origin, and indicates the extent to which local signatures are influenced by source waters (Sutton et al., 2018). In LSW, the concentrations of Pb (Zurbrick et al., 2018) and Hg (Cossa et al., 2018a) provided evidence for a decrease in the anthropogenic inputs of these two elements over the last decade, since the values are lower in the recently formed LSW between Greenland and Newfoundland than in the older LSW of the Western European basin.

The Mediterranean Water (MW), meanwhile, was characterised by higher concentrations of trace metals, such as Pb, Hg, and Al (Cossa et al., 2018a; Menzel Barraqueta et al., 2018a; Zurbrick et al., 2018). It reflects the importance of Saharan and anthropogenic atmospheric inputs to the Mediterranean region, which are much higher than in our studied area (see below), as well as enhanced remineralisation as indicated by the correlation between total mercury concentrations and the apparent oxygen utilisation (Cossa et al., 2018a).

3.3. TEI sources and sinks

Different methods/TEIs were used to estimate atmospheric input fluxes: aerosol concentrations in aerosol and rainwater samples were compared with estimates derived from the measurement of beryllium-7 (^{7}Be) in aerosols, rainwater and seawater (Shelley et al., 2017). Taking a different approach, Menzel Barraqueta et al. (2018b) used dAl in the surface waters to estimate the atmospheric input flux. All these methods allowed concluding that the atmospheric inputs of total trace elements were low in our study area, and the soluble input was even lower, based on their fractional solubility (Shelley et al., 2018).

One of the main sources of TEIs during GEOVIDE was sediment input (i) within the benthic nepheloid layers in the Iceland, Irminger and Labrador Basins (Gourain et al., 2018), and (ii) above the Iberian, Greenland and Canadian margins, as well as fluvial and meteoric inputs (Benetti et al., 2017). This is notably the case for some dissolved TEIs, such as Fe (Tonnard et al., 2018), Al (Menzel Barraqueta et al., 2018a), and radium-226 (^{226}Ra) or barium (Ba) (Le Roy et al., 2018), as well as for particulate trace elements (Gourain et al., 2018). Overall, enhanced concentrations of TEIs close to the bottom suggest that continental shelves and margins acted as a source to adjacent waters. In the case of the Iberian margin, advection of particulate Fe (pFe) was visible over a distance of more than 250 km from the source (Gourain et al., 2018).

However, some results provide evidence that occasional removal of dFe or dAl by particles can be a dominant process rather than partial dissolution from resuspended sediments, but this is likely dependent on the nature of particles (Menzel Barraqueta et al., 2018a).

Additional sources for particulate elements and sinks for dissolved ones are biological uptake and scavenging. Evidence for a biogenic influence on the pFe/pAl ratios within the Irminger and Labrador Basins was found by Gourain et al. (2018). Almost all the stations displayed dFe minima in surface waters, in association with the chlorophyll maxima. The abundance of diatoms exerted a significant control on the surface concentrations of Fe and Al (Menzel Barraqueta et al., 2018b; Tonnard et al., 2018). Remineralisation processes were also highlighted for some TEIs (see also section 3.4). Dissolved Al concentrations generally increased with depth and the net release of dAl at depth during remineralisation of sinking biogenic opal containing particles was generally larger than the net removal of dAl through scavenging.

3.4. Production, export, and remineralisation

The main biogeochemical features of the GEOVIDE cruise in terms of biogenic silica (BSi), particulate organic carbon (POC), and particulate organic nitrogen (PON) are reported on Fig. 3 and supplementary material. The higher BSi concentrations were observed in the Irminger and Labrador Seas. POC and PON were also high in these regions, but also show high values in the Iceland and Western European Basins.

On the Iberian margin and in the Western European Basin, an unexpectedly high heterotrophic nitrogen fixation activity was reported, likely sustained by the availability of phytoplankton-derived organic matter (dissolved and/or particulate), resulting from the on-going to post spring bloom conditions, while dissolved iron supply relied on atmospheric deposition and surface waters advection from the subtropical region and the shelf area (Fonseca-Batista et al., 2018).

In terms of particulate organic carbon (POC) export, thorium-234 (^{234}Th) was used to provide estimates of POC export fluxes, with the highest values near the Iberian margin where a phytoplankton bloom was declining, and the lowest values in the Irminger Basin where the bloom was close to its maximum (Lemaitre et al., 2018a). The proxy $^{210}Po/^{210}Pb$ was also used to assess the export of particles (Tang et al., 2018). The prominent role of small particles in sorption was confirmed, suggesting that particulate radionuclide activities and export of both small (1-53 µm) and large (> 53 µm) particles should be considered to account for the observed surface water 210Po/210Pb disequilibria (Tang et al., 2018).

In the subpolar and subtropical regions, the mesopelagic POC remineralisation fluxes, estimated from the particulate biogenic barium (excess barium; Ba_{xs}) proxy, were found to be equal to and occasionally higher than the upper ocean POC export fluxes (Lemaitre et al., 2018b). These results highlighted the strong impact of the mesopelagic remineralisation on the biological carbon pump with a very low carbon sequestration efficiency at the time of our study (Lemaitre et al., 2018b).

Conclusion

The main GEOVIDE results have helped to improve our understanding of the TEI cycles in the North Atlantic. The strong physical oceanography background of the GEOVIDE project is a strength for interpreting our data. For many TEIs, a strong link was observed between their distributions and water masses. On the other hand, TEIs also helped to constrain oceanic circulation, notably in the subpolar gyre and Labrador Sea. Important sources (sediments, fluvial, and meteoric) and sinks (biological uptake and scavenging) of TEIs were highlighted. The biological carbon pump was studied and showed different efficiencies in the various studied regions.

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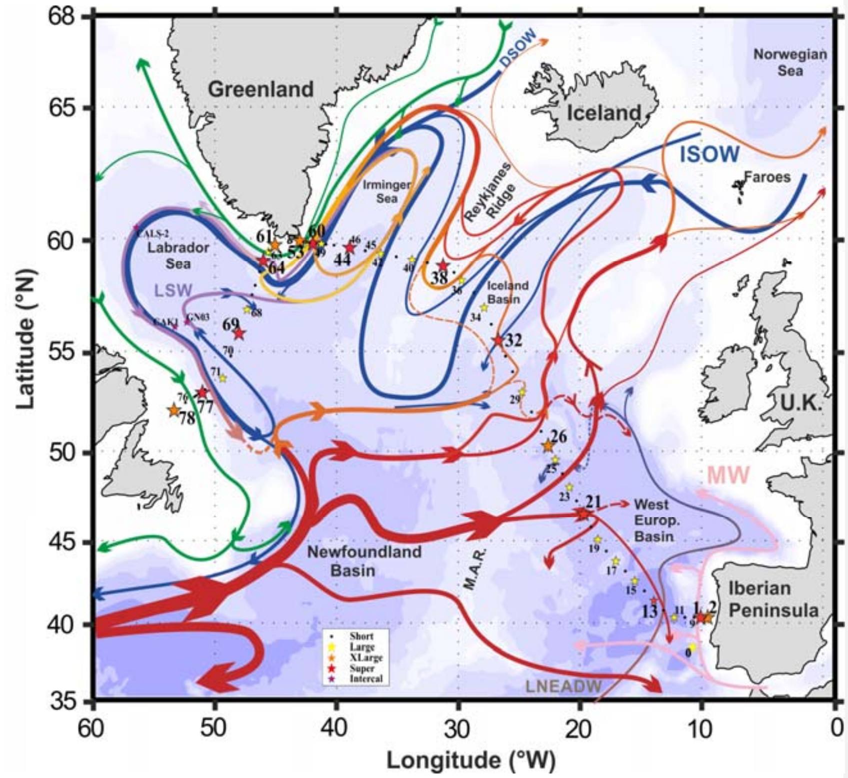
Figure captions

Figure 1: Schematic diagram of the mean large-scale circulation adapted from Daniault et al. (Daniault et al., 2016) and Zunino et al. (Zunino et al., 2017). Bathymetry is plotted in color with color changes at 100 and 1000m and every 1000m below 1000 m. Black dots represent the Short station, yellow stars the Large ones, orange stars the XLarge ones, and red stars the Super ones. The main water masses are indicated: Denmark Strait Overflow Water (DSOW), Iceland–Scotland Overflow Water (ISOW), Labrador Sea Water (LSW), Mediterranean Water (MW), and lower Northeast Atlantic Deep Water (LNEADW).

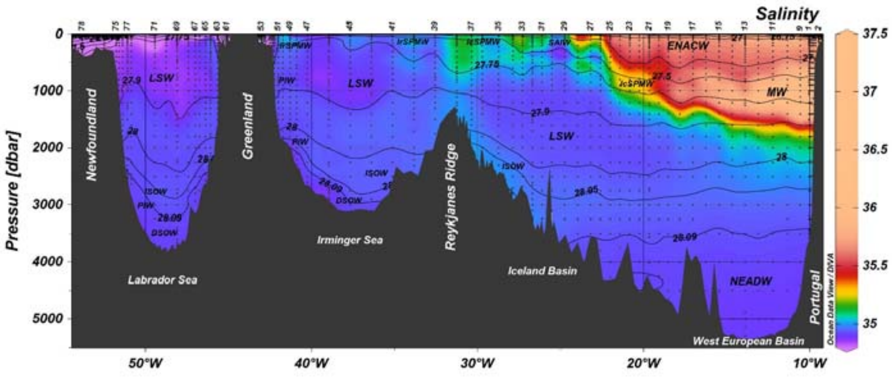
Figure 2: Section plots for (a) salinity, (b) potential temperature (°C), (c) dissolved oxygen (µmol kg^{-1}), (d) nitrate + nitrite (µmol L^{-1}), and (e) silicic acid (µmol L^{-1}) during the GEOVIDE cruise. Water masses are indicated in black, MW: Mediterranean Water; ENACW: North Atlantic Central Water; NEADW: North East Atlantic Deep Water; LSW: Labrador Sea Water; ISOW: Iceland-Scotland Overflow Water; SAIW: Sub-Arctic Intermediate Water; IcSPMW: Iceland Sub-Polar Mode Water; IrSPMW: Irminger Sub-Polar Mode Water. Station locations are indicated by the numbers on top of the panel. These plots were generated by Ocean Data View (Schlitzer, 2017).

Figure 3: Section plots for (a) biogenic silica (BSi, µmol L^{-1}), (b) particulate organic carbon (POC, µmol L^{-1}), and (c) particulate organic nitrogen (PON, µmol L^{-1}), during the GEOVIDE cruise. Station locations are indicated by the numbers on top of the panel. These plots were generated by Ocean Data View (Schlitzer, 2017).

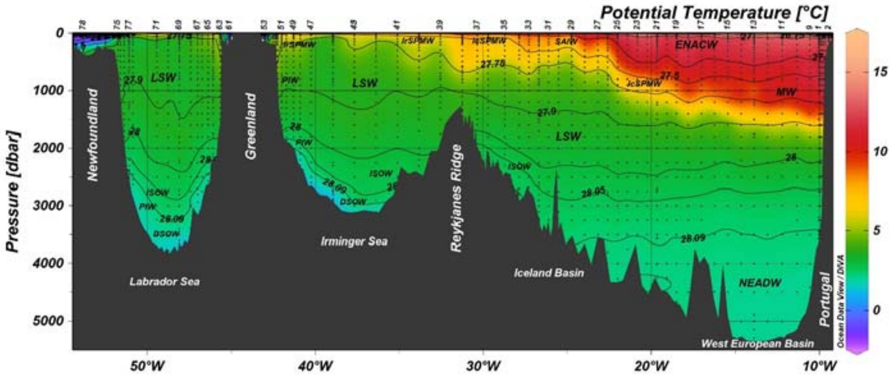


Greenland
Iceland
Norwegian Sea
DSOW
ISOW
Faroes
Irminger Sea
Reykjanes Ridge
Labrador Sea
LSW
Iceland Basin
U.K.
MW
West Europ. Basin
Newfoundland Basin
M.A.R.
Iberian Peninsula
LNEADW
Short
Large
XLarge
Super
Intercal
Latitude (°N)
Longitude (°W)

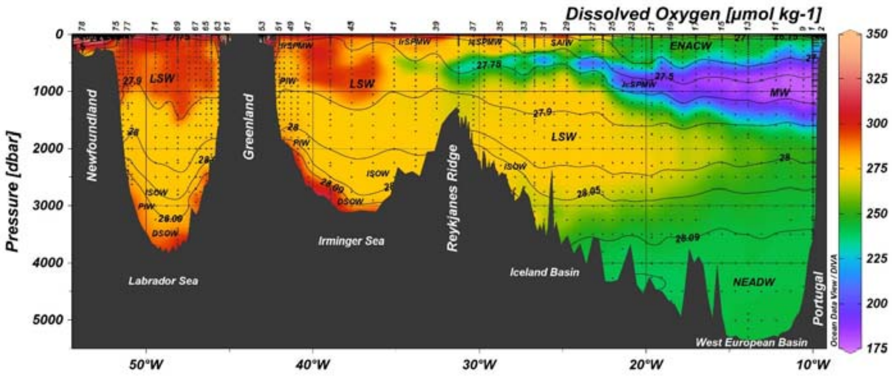
Figure 1


Salinity
Pressure [dbar]
Newfoundland
Greenland
Reykjanes Ridge
Portugal
Labrador Sea
Irminger Sea
Iceland Basin
West European Basin
LSW
PIW
ISOW
DSOW
IrSPMW
SAIW
ENACW
IcSPMW
MW
NEADW
50°W
40°W
30°W
20°W
10°W
Ocean Data View / DIVA

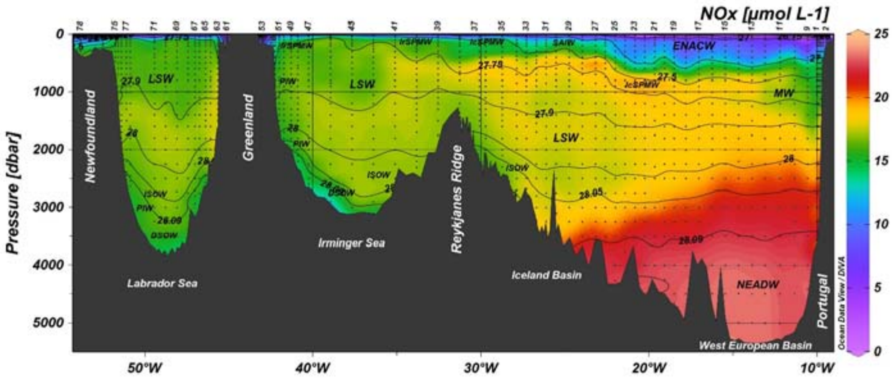
(a)


Potential Temperature [°C]
Pressure [dbar]
Newfoundland
Greenland
Reykjanes Ridge
Portugal
Labrador Sea
Irminger Sea
Iceland Basin
West European Basin
LSW
PIW
ISOW
DSOW
IrSPMW
SAIW
ENACW
IcSPMW
MW
NEADW
50°W
40°W
30°W
20°W
10°W
Ocean Data View / DIVA

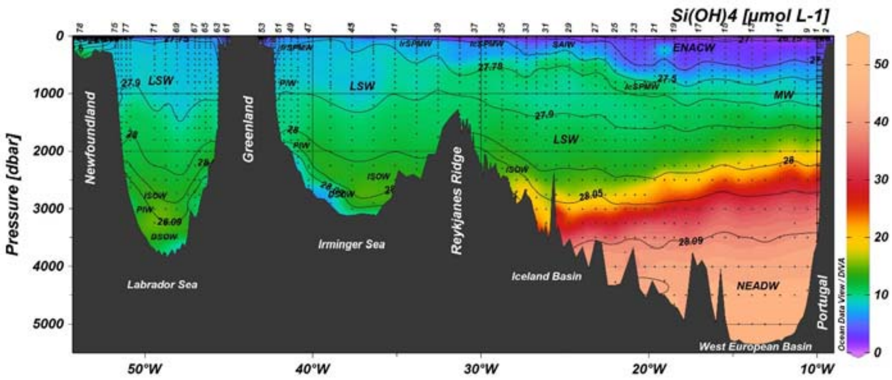
(b)


Dissolved Oxygen [μmol kg-1]
Pressure [dbar]
Newfoundland
Greenland
Reykjanes Ridge
Portugal
Labrador Sea
Irminger Sea
Iceland Basin
West European Basin
LSW
PIW
ISOW
DSOW
IrSPMW
SAIW
ENACW
IcSPMW
MW
NEADW
50°W
40°W
30°W
20°W
10°W
Ocean Data View / DIVA

(c)

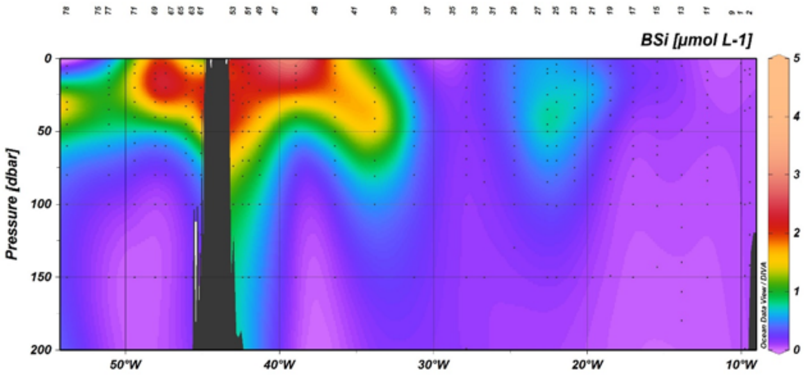

NOx [µmol L-1]
Pressure [dbar]
0
1000
2000
3000
4000
5000
50°W
40°W
30°W
20°W
10°W
Newfoundland
Greenland
Reykjanes Ridge
Portugal
Labrador Sea
Irminger Sea
Iceland Basin
West European Basin
LSW
ISOW
PIW
DSOW
ENACW
MW
NEADW
27.9
28
28.05
28.09
27.78
27.5
Ocean Data View / DIVA
25
20
15
10
5
0

(d)

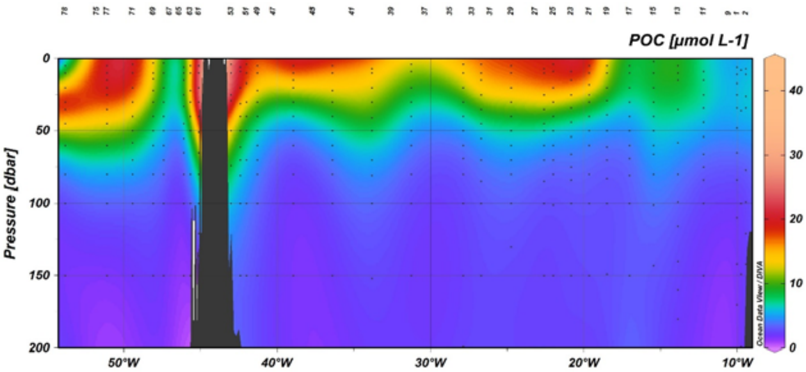

Si(OH)4 [µmol L-1]
Pressure [dbar]
0
1000
2000
3000
4000
5000
50°W
40°W
30°W
20°W
10°W
Newfoundland
Greenland
Reykjanes Ridge
Portugal
Labrador Sea
Irminger Sea
Iceland Basin
West European Basin
LSW
ISOW
PIW
DSOW
ENACW
MW
NEADW
27.9
28
28.05
28.09
27.78
27.5
Ocean Data View / DIVA
50
40
30
20
10
0

(e)

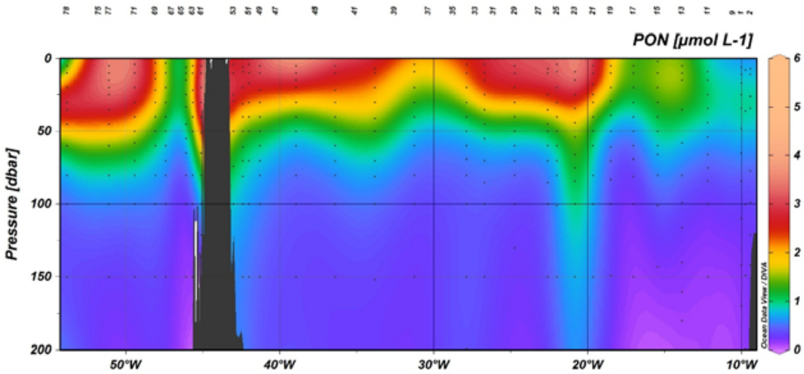
Figure 2


BSi [µmol L-1]
Pressure [dbar]
0
50
100
150
200
50°W
40°W
30°W
20°W
10°W
5
4
3
2
1
0
Ocean Data View / DIVA

(a)


POC [µmol L-1]
Pressure [dbar]
0
50
100
150
200
50°W
40°W
30°W
20°W
10°W
40
30
20
10
0
Ocean Data View / DIVA

(b)


PON [µmol L-1]
Pressure [dbar]
0
50
100
150
200
50°W
40°W
30°W
20°W
10°W
6
5
4
3
2
1
0
Ocean Data View / DIVA

(c)

Figure 3