

***Interactive comment on* “The GEOVIDE cruise in May–June 2014 reveals an intense Meridional Overturning Circulation over a cold and fresh subpolar North Atlantic” *by* Patricia Zunino et al.**

Patricia Zunino et al.

pzuninor@ifremer.fr

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Dear editor and referees,

We were grateful to receive the very constructive reviews of our paper “The GEOVIDE cruise in May–June 2014 reveals an intense Meridional Overturning Circulation over a cold and fresh subpolar North Atlantic”. Thank you very much to the 3 anonymous referees. We will incorporate in the manuscript the majority of their comments and we think the scientific results will be better exposed than in the first submission. Before dealing with the referee comments in detail, we wrote an answer to a concern that is common to the three reviews: the misunderstanding about the timescales dominating

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the cooling and freshening of the subpolar North Atlantic. Following, we answer point by point each comment of the three referees.

One result of our paper is the co-existence in May – June 2014 of the cooler and fresher eastern subpolar North Atlantic (SPNA) in relation to the mean 2002 – 2012, and the relative intense Meridional Overturning Circulation and heat transport across the OVIDE section. In the region delimited by 40°N – 60°N, 45°W – 10°W, the evolution of both (i) ocean heat and freshwater content in the upper 1000 m and (ii) air-sea fluxes of heat and freshwater since 2013 reveals that the atmospheric forcing is mostly responsible for the strong TS anomalies of 2014. However, as pointed by the three reviewers, we did not discuss the decadal context of our observations and missed to refer to Robson et al. (2016; 2017) who identified a new cooling period in the subpolar North Atlantic starting in mid-2000, a cooling period affecting at decadal time-scale.

In our revision, we will include a new figure showing the evolution of heat content in the upper 1000m of the region 40°N – 60°N, 45°W – 10°W (see Figure 1 in this document). Based on this figure, that shows a long term heat content decrease starting in the mid-2000s, we will be able to illustrate Robson et al. (2016; 2017). We also observe intensification in heat content decrease from 2013 to 2014, just the episode we discuss in our paper. Thus, the 2013-2014 cooling episode is inserted in the cooling at longer period of time detected by Robson et al. (2016; 2017). We show in our paper that the former was dominantly produced by the local atmospheric forcing over the 2013-2014 winter. Our results are in agreement with a recent paper, Frajka-Williams et al., (2017, in Scientific Reports): they exposed that the rapid cooling registered between 2013 and 2015 in the subpolar North Atlantic was explained by the atmospheric forcing since the effects of a MOC slow-down at 26°N is too slow to explain the observed rapid cooling.

Following this explanation, the third paragraph of the introduction will be restructured and the references to Robson et al. (2016-2017) added. The discussion 4.2 will also be expanded in order to place our observations in the context of a longer time scale. The figure 1 in this document will be inserted in the new ms.

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We copied the referee comments in this document in blue font followed by our answers in black font.

Anonymous Referee 1

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One of the main findings in this paper is that despite the ongoing cooling/freshening anomaly in the SPNA, the authors measure stronger heat transport across the OVIDE section during the GEOVIDE cruise in May-June 2014. The authors further conclude by strongly stating that air-sea (heat and freshwater) fluxes were the dominant factor for the observed changes and that ocean circulation played a minor role. The authors seem to have ignored the fact that the subpolar gyre (SPG) cooling/freshening is part of a decadal trend most likely initiated by ocean advection and circulation. There are evidence that the SPG temperature and salinity reversed already in 2005 (e.g. Robson et al. 2016, Nature Geoscience), and that the NAO shifted more to the positive state later on around 2011. The 2014 cooling/freshening thus may have been enhanced by air-sea fluxes (not locally formed), but it is important to keep in mind that the cooling as well as the freshening did not start in 2014 as the authors mention. It was well underway! Nevertheless, I think the paper is good and taking into account what I have mentioned above as well as my comments below will help improve the paper, which I recommend for publication after these issues have been resolved.

Major comments

I think the authors need to focus on the 2014 event as being part of the (multi-)decadal cooling/freshening rather than the instigator of it. A robust discussion along these lines is therefore strongly recommended.

Yes, we agree that the 2014 event was not the instigator; it appears to add to the decadal cooling started in 2005 and linked by Robson et al. (2016; 2017) to ocean circulation and heat transport. This point will be clarified in the discussion.

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Furthermore, I wonder also how the authors reconcile the fact that there are numerous studies (see e.g. Robson et al. 2017, Clim Dyn, and references therein) demonstrating that the western SPG is dominated by surface fluxes, while the eastern SPG is dominated by ocean advection.

We agree with the reviewer this applies on the decadal time scales. Our study focuses on an inter-annual event dominantly forced by local air-sea fluxes that appears to add to the decadal signal.

How do you explain the large-scale salinity anomaly in Fig. 8 that spans both the SPNA and the region of the Gulf Stream? there is very little discussed about this basin-scale feature.

Your comment is very interesting and further investigations in the Gulf Stream region would be necessary to determine whether it is a coherent basin-scale feature especially because the negative salinity anomaly is associated with a positive temperature anomaly in the Gulf Stream Region but to a negative temperature anomaly in the SPNA. Our objective is to understand what was observed during the cruise in 2014. In order to interpret the large-scale salinity anomaly, we estimated the freshwater content change in the box $40^{\circ}\text{N} - 60^{\circ}\text{N}$, $45^{\circ}\text{W} - 10^{\circ}\text{W}$ using the ISAS data shown on Figure 8, data from other data sources (EN4 and JAMSTEC), as well as air-sea freshwater flux (ERA-interim and NCEP), see Figure 10 in the initial ms. The surface freshwater fluxes in the eastern SPNA were found to be important in the observed salinity anomaly.

Comments I think the calculations and results are straightforward, but I have some comments that can help to further improve the paper: Using the inverse model the authors and thereby identify all main flows, and show that the ship-ADCP velocities are largely similar, at least in structure, to those based on the inverse modelling. I suggest to compare your transport numbers, whenever possible, to other studies for a complete picture.

We understand your suggestion. In fact, comparing transport numbers with previous

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studies was extensively done by Danialt et al. (2016), D2016 hereafter, who described the mean state of the circulation in the SPNA based on OVIDE data and the existing literature (e.g. Rossler et al. (2015), Sarafanov et al. (2008; 2012), Väge et al. (2008; 2011)). In this study, we only compare with results in other works when significant differences with D2016 were found (for example Väge et al., 2011).

Weaker NAC during 2014 is an interesting finding. The top-to-bottom transport of $0 \pm 6\text{Sv}$ as compared to the $11 \pm 4\text{ Sv}$ estimated by D2016 is large. I believe it is possible to show this large-scale shift from altimetry along the eddy-blockage and the doubling of the intensity of the SAF, which the authors are briefly mentioning in lines 404-412. Please elaborate also on the transfer of transport from the northern to the central branch, it is not clear to me how this occur!

We found your idea very good, and we plotted the mean ADT contours for 2002-2012 and for 2014 after removing the trend in the sea-level rise (2.8mm/yr in our region), see Fig. 2 and 3, respectively, in this document. The colors show the current velocity and highlight the energetic areas. Then we plotted the stream lines encompassing the SAF in bold; they have the same ADT values in both figures (Fig 2. and Fig. 3 in this document) and represent a slope of 15 cm in the ADT. We also plotted in both figures a red circle at the 2014 SAF position (station 26 of GEOVIDE). To interpret this figure, we assume that the bold streamlines delimit the travel of the surface waters crossing the OVIDE section at the SAF position. For comparison, we added in Fig. 3 the 2002 – 2012 mean stream lines encompassing the SAF in red. We see that along the OVIDE section, the SAF is quite narrow and located more to the southeast in 2014, when compared to the 2002-2012 mean. But more important, the NAC transport seems to be dispatched on a larger area in the mean, encompassing the permanent eddy characteristic of the northern branch of the NAC. So in the mean, the NAC transport is shared among both branches, while in 2014, it is concentrated in the SAF. Finally, note that those lines end up at the same position between Iceland and Scotland, so in both cases, the surface water included in the SAF (as defined here) feeds the Atlantic inflow

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to the Nordic Seas.

To conclude, it seems that we were wrong in suggesting an eddy blocking of the northern branch. We now see that the frontal zone moved to the south, leaving no transport for the northern branch identified during the previous decade.

Note that Fig. 2 will not be included in the new ms.

Furthermore, as the authors mention (lines 520-527), they expected an expansion of the SPG. Could you better discuss what the displacement of the SAF actually means?

We agree that this subject requires more discussion, so we will displace the part of the last paragraph of the discussion about the expansion of the SPG to the fourth paragraph of the discussion where we indicated the southeastward displacement of the SAF in 2014. There, we will better explain that the “displacement of the SAF” is the southeastward displacement of the front along the OVIDE section in 2014 as compared with the 2002-2012 average. In fact, Bersch et al. (2002) interpreted that in the eastern SPNA, during the warming period from mid-1990s, there was a northwestward displacement of the SAF coinciding with a contraction of the SPNA. Following Bersch et al. 2002, we proposed that the SAF southeastward displacement suggests a new expansion of the SPNA, consistently with the persistently positive winter NAO index since 2011 (except in 2012). However, both the meandering of the NAC in the eastern SPNA and the lack of distance in time make difficult a strong assessment involving decadal variability as in Bersch et al. (2002).

The green box in Fig. 9 seems very large to me to be considered as the eastern North Atlantic. It is rather peculiar that in the net freshwater field you are averaging over an area that almost symmetrically includes positive and negative net FW.

Surely, the referee is right and the box is somehow large to name it the “eastern sub-polar North Atlantic”. However, our intention was to define a box containing the whole OVIDE section, including upstream and downstream anomalies. We were also greatly

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surprised when we saw the almost symmetrically pattern of the air-sea freshwater flux, with the OVIDE section as the diagonal of the green box separating the negative and positive net FW. It is actually an interesting subject for our future research. It necessarily has a physical explanation, but it can also be fortuitous. In spite of the symmetry, the integrated net FW is positive, which is in agreement with the fact that the eastern SPNA is getting fresher. Diminishing the box (to the northeast) reinforces our conclusion.

The eddy part of the paper is clear, although full of details, it completes the picture well. It is however not easy from a visualization point view to see the eddies and the colors in the figure. Suggest to improve this and make it as clear as possible to the readers, perhaps similar to Fig. 6 of D2016.

We understand your concern. We did different figures representing AVISO information (ADT, and surface velocity) when preparing the first version of the manuscript, and we thought that the representation we propose is more intuitive for our colleagues in biogeochemistry who are interested in the velocity information. We plotted the same way than D2016 but even if the eddies are visible, reading the ADT contours requires some skills typical of the physical community. Therefore, we prefer to keep our presentation, but, to guide the reader, we will introduce more information about the colors of the squares in the next version of the ms.

Consider adding a reference to a recent paper by Rossby et al. (2017, JGR) on the fluxes across 59.5N. Their MOC transport estimate is in line with yours.

Thank you, we will add this reference to reinforce our result.

Minor comments

Please replace 'Hydrological' with 'Hydrographic' throughout.

Ok, totally agree.

Figure 1 is busy and therefore making an effort to explain all the signs is important. For example, you should indicate what the stars represent early on. You may also want to

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add the names of the different NAC branches here.

Yes, we agree Figure 1 is busy and with a lot of information necessary to understand the paper. The meaning of the stars is already indicated in the Figure caption of Fig. 1. We will add NNAC, SAF, SNAC and IC (Irminger C.) in the figure.

lines 251: Please keep it consistent with the decimal throughout the paper.

Ok, thank you, we will add one decimal to be consistent throughout the paper.

The bathymetry can hardly be seen in the AVISO figures.

Right, we will draw the bathymetry with thicker gray lines.

lines 505: Define the SPG acronym. And no need for the SPG acronym in the last paragraph of the discussion.

Right, in any case that part of the discussion will be rewritten, and the definition of the SPG will be done in the introduction.

Caption Fig. 9; It is not clear in the text that the anomalies are for 2014.

The referee is right, we will explicitly indicate that it is the 2014 anomaly.

Interactive comment on Biogeosciences Discuss., <https://doi.org/10.5194/bg-2017-292>, 2017.

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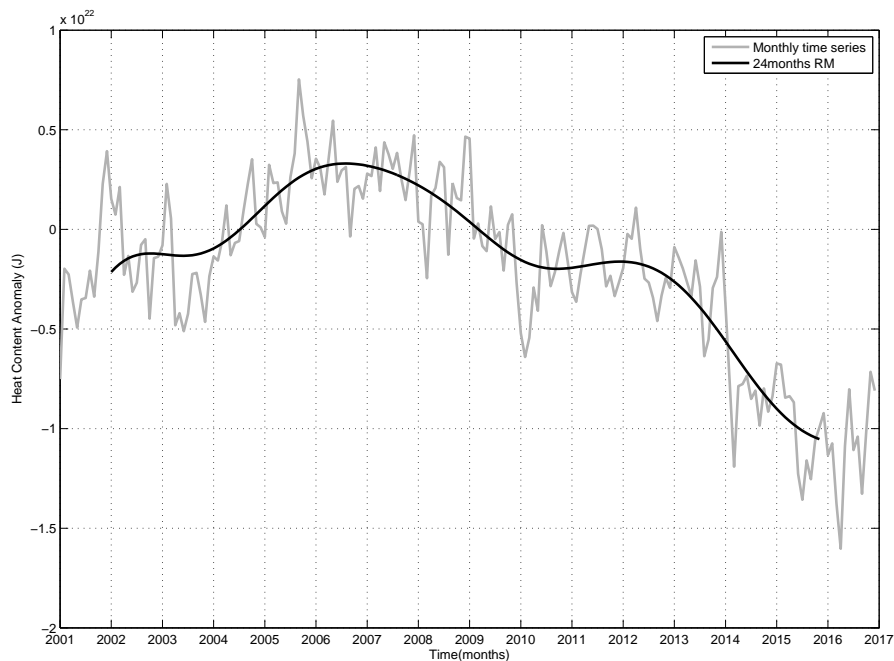


Figure 1: Heat content anomalies in relation to the mean heat content for the period 2002 - 2012 in the upper 1000m of the region 40°N-60°N and 45°W-10°W. Grey line is the monthly time series; black line is the 2-year running mean of the monthly time series. Data source: EN4 database (Good et al. 2013).

Fig. 1.

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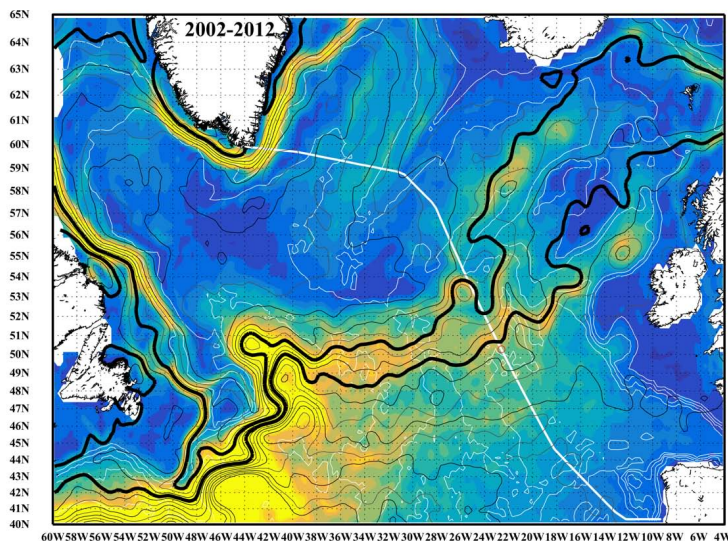


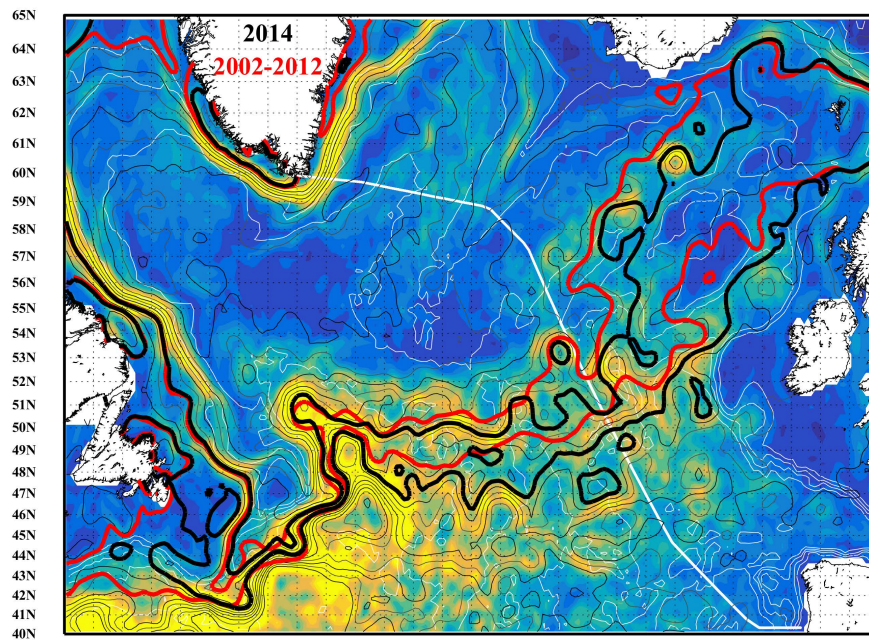
Fig. 2: Contours of the Absolute Dynamical Topography averaged over 2002-2012 (in black and grey), after removing the overall trend of 2.8mm/yr. Contours are every 0.05m. Thick contours correspond to the levels encompassing the SAF front during OVIDE cruises.

Fig. 2.

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60W 58W 56W 54W 52W 50W 48W 46W 44W 42W 40W 38W 36W 34W 32W 30W 28W 26W 24W 22W 20W 18W 16W 14W 12W 10W 8W 6W 4W

Figure 2: Contours of the Absolute Dynamical Topography averaged over 2014 (in thin lines). Contours are every 0.05m. Thick contours correspond to the levels encompassing the SAF front during OVIDE cruises: bold red lines for the mean 2002 – 2012 and bold black lines for 2014. Note that the temporal trend on the mean ADT over the whole box (2.8mm/yr) was removed. Bathymetry (1000m step contours) and the OVIDE section are plotted in white. Colors represent the absolute velocity of the current (yellow for velocities stronger than 0.3m/s). This figure will be added to the new ms.

Fig. 3.

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