Biogeosciences Discuss.,
https://doi.org/10.5194/bg-2017-292-AC1, 2017

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.

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Received and published: 2 October 2017

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

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.

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

Anonymous Referee 2

Received and published: 16 August 2017

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. This paper discusses the physical background of the GEOVIDE cruise in 2014. It highlights changes in transport as well as heat and freshwater content compared to the 2002-2012 mean state. The most interesting conclusion is that the large scale cooling seen in the SPG is (more then) compensated by a strengthened circulation in the net heat transport.

One comment on the structure of the paper. Although the TEI measurements do not feature in the abstract there are discussed several times in the introduction and elsewhere in the paper. It therefore reads like the discussion of the TEI measurements will be discussed later in the paper, but this never happens. It is also never mentioned where (in which other paper) these measurements will be shown. This does not improve the overall clarity of the paper. The authors should rephrase the text as to make it more clear what the focus of this paper is, why it is presented in Biogeosciences and where the other data from the GEOVIDE cruise is (or will be) presented.

We understand that it can be somehow uncommon to publish a physical paper in Biogeoscience. However, our paper is part of a special issue in Biogeosciences with all the papers resulting from the GEOVIDE cruise. This is why our paper, which defines the physical background of the GEOVIDE cruise, has been submitted to Biogeoscience. In order to make it clearer, we will introduce some references at the end of the introduction and at the beginning of the section 3.4 in the new version of the manuscript.

The discussion section can be improved. Where increases and decreases are dis-

cussed (for example the second paragraph) the authors should mention whether this increase is statistically significant or fall with the observed variability.

Ok, we think that we did not introduce enough the ideas in each paragraph, so we will always begin the paragraph with a description of the transport anomaly, including its significance. Actually, we only discussed the NAC and Irminger C. that showed a significant variability in their different components, although their overall transport did not. Paragraph 2 of the discussion (line 392) could begin by: "When defining the IC as in D2016, we saw an increase in the IC intensity in 2014, but within the observed variability (table 1). However, the such-defined IC encompasses a warm and salty northward transport and a cold and fresh southward transport. So, to go further [...]".

At the beginning of paragraph 3 (line 402), we propose: "Concerning the weaker NAC, its 2014 intensity, 32.2 $\pm$ 11.4 Sv, is weaker although in the limits of the observed variability (41.8 $\pm$ 3.7 Sv) in 2014. By the decomposition of this wide current, it is very likely [...]"

In the discussion on the origin of the cooling of the SPG, advection versus surface fluxes, it is important to consider the time scale that both are acting on. The changes in advection are thought to act on longer (decadal) time scales while the surface forcing has a more direct effect. In fact, the warming trend in the western SPG was halted much earlier than 2014 and much has been explained by surface forcing (Piron, 2015; de Jong and de Steur, 2016; Yashayaev and Loder, 2017). I would encourage the authors to put the 2014 anomalies into context of the recent interannual variability rather than focusing on a comparison with the mean.

This is the general critique done by the three reviewers. We agree that the changes in the lateral advection affect the heat and freshwater content changes at decadal timescale. We also agree that the air-sea flux is thought to cause heat and freshwater changes in the ocean at shorter period of time, buffering or intensifying the effect of the lateral advection. A more detailed answer is given in the introduction of this document.

We will reorganize and expand the third paragraph introduction and discussion of the ms in order to be clearer in the timescales of both processes creating thermohaline anomalies in the SPNA (see also answers to reviewer 1 comments).

Comments

- Suggest to replace MOC with AMOC (Atlantic MOC) throughout the paper since it is more appropriate in the context of the North Atlantic circulation discussed here.

We agree that the MOC is a general term for the Meridional Overturning Circulation affecting all the oceans. So we will use "AMOC" in the introduction, but keep "MOC" in the result for consistency with other references (Mercier et al. 2015 and Daniault et al. 2016). Actually, we should even call it OVIDE MOC in the results but we prefer to keep it simple.

- Line 63: "the ocean has taken up 90% of the heat accumulated".

Right, we will modify it.

- Line 74: not sure what is meant by durable.

It means persistent in time. In any case we will rewrite that sentence as: "Robson et al. (2012) found that the rapid warming of the SPNA was primarily caused by a relative long period of high northward ocean heat transport associated with the strengthening (...)".

- Lines 139-141: this criterion seems to lead to unexpected values near the shelf of Greenland. The waters in the IC and EGC are very stratified, but the orange line shows WMLD as deep as in the central Irminger Sea.

It was a mistake, there should have been no value here, Actually, the WMLD cannot be determined west of station 48 because of the strong layering in the East Greenland/Irminger Current.

- Line 221: This current system is not commonly known as the WBC. Elsewhere the

authors refer to the East Greenland (Coastal) Current and the Irminger Current which is more appropriate.

The "western boundary current" is used in many papers referring to the currents over whole water column in the western side of the oceans (see for exemple "Moored Observations of Western Boundary Current Variability and Thermohaline Circulation at 26.5° in the Subtropical North Atlantic" of Lee et al. (1996) or "The western boundary current of the seasonal subtropical gyre in the Bay of Bengal" of Shetye et al. (1993). In our region, we have referred to this dynamic structure as WBC following Daniault et al. (2016). The Western Boundary Current was defined as the sum of the East Greenland Irminger Current and the Deep Western Boundary Current. The former is composed by three components: the East Greenland Current, the spill jet and the adjacent IC that usually cannot be separated at 60°N. In our paper we were referring to the water flowing southward at the western side of the Irminger Sea, west and below the Irminger Gyre. Furthermore, when we talked about the Irminger Current, we were specifically referring to the water flowing northeastward west of the Reykjanes Ridge, although it is true that it recirculates in the East Greenland/Irminger Current (Pickart et al., 2005). In any case, we will rewrite this part of the manuscript to be clearer, but we consider that WBC is the appropriate term here.

- Line 252: "Note that the net transport in the northern branch is null".

Thank you, we will simplify this sentence.

- Line 274: "as well as it can" is not very readable. Even though I understand that the author is not a native English speaker I think the readability would improve if the authors took another critical look at the grammar of some of the sentences in this manuscript.

Ok, we will change "as well as it can ..." by "and they can ... ". Yes, we are not English speaker, this is why our ms was already revised by a professional native English speaker.

- Line 297: the section just seems to miss (cut south off) the high energy signal of the Irminger Current on the RR.

We do not understand what the referee refers to. In this paragraph, we are discussing about the large eddy near Eriador Seamount. The Irminger Current is quite far away to the northwest.

- Regarding the paragraphs between lines 284 and 325. The red squares in Figure 6 are mention, but the others are not. It would be easier to follow the eddy description if the yellow, green and orange squares were also denoted here.

Totally right. Actually, the colored squares were introduced in the figure to make easier the eddy identifications. In the new version of the manuscript we will better indicate all of them.

- Lines 359-361: not clear which anomalies are referred to here. If it is the cooling/freshening in the western SPG (caused by ventilation) it is not surprising to see it linked to an oxygen increase.

Maybe the term “zooming out” was misunderstood. When we talked about ventilation, we were indeed referring to the oxygen positive anomaly, so we will precise Figure 7c. This paragraph was written to give a general view of the link between temperature, salinity and oxygen anomalies. So we will slightly modify this sentence to make it clearer.

- Lines 371-380: Please let the reader know where the data from these other measurements will be presented if not here.

We will include references to the other papers of the Geovide special issue in Biogeoscience in the introduction and in section 3.4.

- Line 430: Briefly mention why is 1997 excluded.

We modified the sentence as “To compare it with the 2002-2010 average, we used the

data of Mercier et al. (2015), without data from 1997 because it did not belong to our reference period, [. . .]”.

- In the discussion on freshwater surface fluxes it would be good to mention something about the uncertainties of these fields over the ocean.

Right, we already thought about this complex issue, because uncertainties in evaporation and precipitation products are very difficult to assess (Dee et al., 2011). So Josey and Marsh (2005) made an estimate by comparing NCEP and ERA-40 products. We did the same in our case. The difference between monthly freshwater fluxes over the region 40°N-60°N, 45°W-10°W estimated with NCEP and ERA-INTERIM is about 10% of the absolute values. Over 2002-2015, no clear bias stands out between both products and accumulating fresh water fluxes over years does not increase the relative difference of 10%. The accumulated air-sea freshwater flux of 2 x 10^{12} m^3 from 2013 to 2014 that was shown in Figure 10 (ERA-IN) is different by 2 x 10^{11} m^3 from the NCEP estimate; we will discuss about these errors for the period 2013 to 2014 in the new version of the ms and add the NCEP estimate in Figure 10.

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

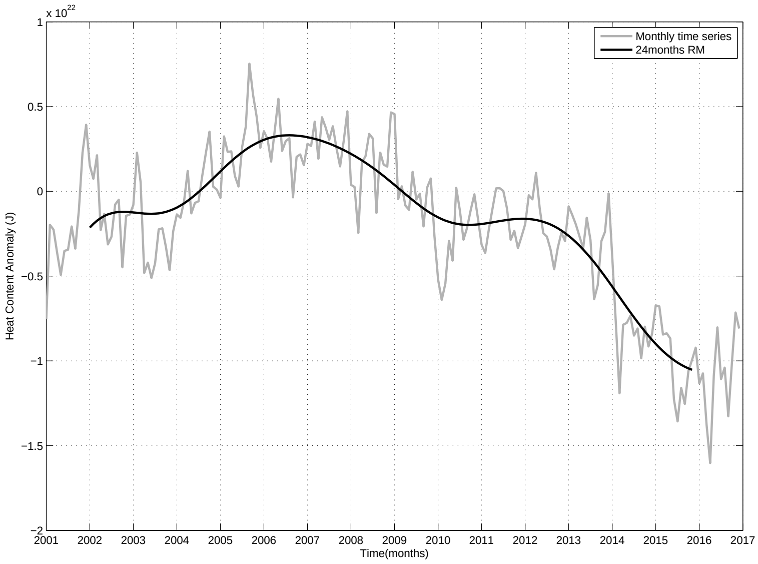

Figure 1: Heat content anomalies in relation to the mean heat content for the period 2002 - 2012 in the upper 1000m of the region 40°N-60°N and 45°W-10°W. Grey line is the monthly time series; black line is the 2-year running mean of the monthly time series. Data source: EN4 database (Good et al. 2013).

Fig. 1.

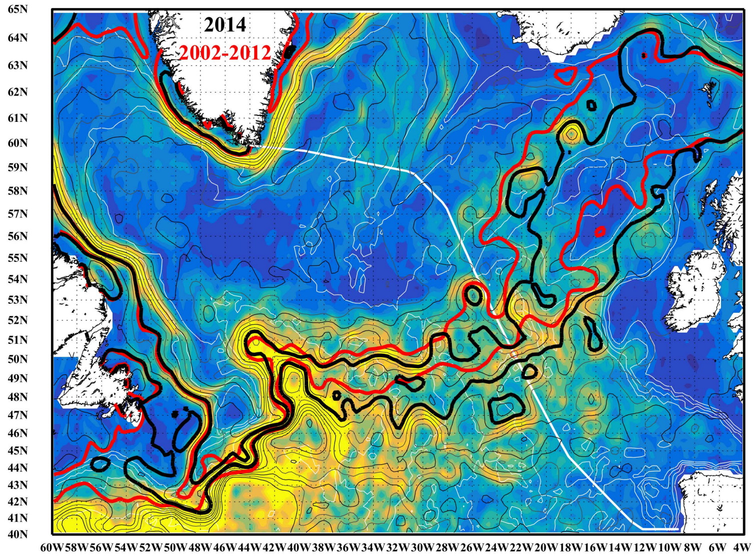

Figure 2: Contours of the Absolute Dynamical Topography averaged over 2014 (in thin lines). Contours are every 0.05m. Thick contours correspond to the levels encompassing the SAF front during OVIDE cruises: bold red lines for the mean 2002 – 2012 and bold black lines for 2014. Note that the temporal 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. 2.