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Climate of the Past Discussions

Interactive comment on "Holocene evolution of the North Atlantic subsurface transport" *by* Janne Repschläger et al.

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Response to the reviewers on behalf of all co-authors

Response to Referee #1

We greatly acknowledge the thoughtful scientific comments and very detailed technical hints for corrections in the text and figures of Referee #1. They will improve the manuscript considerably.

Although in general positive towards our study, Referee #1 asked for a critical reconsideration of three major issues:

1) Referee #1 proposed to include a brief discussion about the role of the strength of Mediterranean outflow water (MOW) on the position of the Azores Front / Azores

Current (AF/AC), as MOW may exert a pivotal influence on the existence of the AC (Volkov et Fu 2010). For example, it should be discussed whether the apparent Mid Holocene northward movement of the AF/AC might be related to a weakening of the MOW is likely or not.

To our opinion, according to modeling studies (e.g. Volkov and Fu, 2010) MOW is indeed closely linked to the strength of the AC, however, little is known about its influence on the AC position. Reconstructions of MOW strength based on contourite grain size data from the Gulf of Cadiz indicate that MOW was sluggish during Early Holocene and strengthened after 8 ka BP. During the last 2 millennia MOW strength decreased again (Rogerson et al., 2012; Toucanne et al., 2007). Thus the timing of the early Holocene MOW strengthening roughly coincides with an increased subsurface warm water transport towards the Azores. On the other hand, the Late Holocene southward movement of the AF/AC, reconstructed from G. ruber w. abundance at 4 ka BP, corresponds with MOW weakening although the timing of the latter at about 2 ka BP, does not exactly match the AF/AC signal. Thus a connection between more intense MOW and increasing subsurface warm water transport in the AC/AF seems likely. However, the coincidence of a Mid-Holocene increase in MOW strength with a more northerly AF/AC position opposes the suggestion of Referee #1 that a sluggish MOW would lead to a northward movement of the AF. Since MOW outflow is mainly driven by the density gradient between the Mediterranean Sea and the Strait of Gibraltar (Ivanovic et al., 2014 and citations therein), the latter is probably governed by the strength of the thermohaline circulation in the North Atlantic as well as by atmospheric circulation changes (Bozec et al., 2011; Voelker et al., 2006). If both are also closely related to the position and strength of the AC/AF this suggests that atmospheric and thermohaline circulation act as a common driver for the Early to Mid Holocene changes in the AF/AC position and MOW strength rather than MOW strength being the main driver in the position of the AC/AF. As suggested by Referee #1 we will include this paragraph discussing the potential role of MOW for the AF/AC position..

2) Referee #1 proposed to include the Labrador Sea temperature and salinity records from P-012 and P-094 (Solignac et al., 2004) in one of our figures. We agree that the reasoning in the manuscript will strongly benefit from including theses records and will do so in a revised version.

3) Referee #1 asked to specify size fractions of G. ruber w. and G. truncatulinoides as well as the coiling direction of G. truncatulinoides of the specimens used for analyses in order to avoid species specific and size related offsets in temperature reconstructions. Furthermore, under specific comments referee #1 asked to improve the methods section by providing more specific details. In order to address all methods related questions, we suggest to rewrite the methods chapter for a revised manuscript version as follows: "For our study we used core GEOFAR KF16 taken at 38°N, south of the Azores Islands at the Mid Atlantic Ridge, from 3060 m water depth. This position in the vicinity of the AF is ideal to trace changes in STG position and associated varying influence of subtropical and temperate waters (Repschläger et al., 2015). The age model for core GEOFAR KF16 is published in Schwab et al. (2012). Results are compared to published data from the subtropical (Bahr et al., 2013; Cléroux et al., 2012) and subpolar North Atlantic (Thornalley et al., 2009) along the warm water route. We combine published δ18O data of planktonic surface and subsurface dwelling foraminifera G. ruber w. (Schwab et al., 2012) and G. truncatulinoides (Repschläger et al., 2015) with new Mg/Ca records from the same species. All measurements were conducted on samples of the size fraction 315-400 μm on monospecific samples of 10-25 specimens of G. ruber w. and 15 specimens of mixed left and right coiling G. truncatulinoides. Stable isotope analyses were carried out at Leibniz Laboratory for Radiometric Dating and Stable Isotope Research at Kiel University. For analyses a Finnigan MAT 523 mass spectrometer coupled with a Kiel I carbon preparation device was used and results were calibrated to the Vienna Pee Dee Belemnite (V-PDB) scale. The 2 σ standard deviation (std) obtained from 10 replicates of downcore samples was +/- 0.11 ‰ for G. ruber w. and +/- 0.12 ‰ for G. truncatulinoides. Mg/Ca analyses followed the cleaning procedure of Martin and Lea (2002) and Repschläger et al. (2015), using reductive

and oxidative cleaning. Measurements were carried out with a simultaneous inductively coupled plasma-optical emission spectrometry (ICP-OES) instrument with radial plasma observation. Potential shell contamination or coatings by authigenic minerals were monitored using additional Fe, Al and Mn measurements. Analytical 2 σ std was +/-0.20 mmol/mol Mg/Ca for G. ruber w. and +/-0.14 mmol/mol Mg/Ca for G. truncatulinoides. To convert Mg/Ca values into water temperature estimates, we used the principle equation format Mg/Ca = b exp (a*T) with species-specific variables a=0.76 and b=0.07 for G. ruber w. and a=0.78 and b=0.04 for G. truncatulinoides (equation for mixed subsurface dwellers) published by Cleroux et al. (2008). The summed analytical and calibration 2 σ std is +/- 1°C for G. ruber w. and +/- 2°C for G. truncatulinoides. The calibrated Mg/Ca temperature estimates for both species in our core top samples match well with modern surface and subsurface (200 m depth) temperatures at the Azores coring site. Seasonal temperature effects on the foraminiferal Mg/Ca signal are assumed to play a subordinate role at our coring site (Cléroux et al., 2008; Repschläger et al., 2015). In addition, we assume that the subsurface temperature signal of G. truncatulinoides is predominantly determined by the conditions at the AF and not by the migration of G. truncatulinoides to shallower, warmer water depths or by thermocline shoaling (see supplementary information and Repschläger et al. (2015)). Changes in salinity are reconstructed following the procedure described in Repschläger et al. (2015). The temperature effect, estimated from the Mg/Ca was removed from the foraminiferal δ18Ocarbonate using the general equation of Shackleton (1974) for both, G. ruber w. and G. truncatulinoides, in order to be consistent with the datasets used for comparison. A correction for VPDB to SMOW was included resulting seawater δ18Ow values discussed in the following. For estimation of δ18Ow uncertainties we followed the approach of Cleroux et al., (2011) and used their equation S8:

σ (δ18Ow-ivc) = ((σ (δ18Oforam))2+(σ (Temp))2*(0.23)2)1/2

leading to calculated 2 σ std of +/- 0.35 ‰ and +/- 0.68 ‰ for G. ruber w and G. truncatulinoides, respectively. Given the relative large error in temperature and δ18Ow re-

constructions, we only used 5-point average time series for interpretation to investigate longer-term trends in the datasets. The δ18Ow records were corrected for ice volume, using the eustatic sea level curve of Austermann et al. (2013) and are expressed as δ18Ow-ivc values throughout the text. Changes in the AF front were reconstructed using the relative abundance of G. ruber w. published by Weinelt et al. (2015). Abundance counts possess a 2 σ std of +/- 2.5 %. As G. ruber w. is most abundant within the STG (Ottens, 1991; Schiebel et al., 2002; Storz et al., 2009), low/high abundances indicate a southward/northward movement of the AF relative to the coring site. Because the position of the AF is mainly related to changes in the westerly wind belt, the abundances of G. ruber w. indicate the relative contribution of subtropical water and can be used as tracer for the position of the northern STG rim and thus of the position of westerlies as discussed in Repschläger et al. (2015) before. "

Considering the concerns of Referee #1 about the used size fractions and coiling varieties of G. truncatulinoides we would like to respond referring to Friedrich et al (2012):

Despite the more recent results presented by Billups et al. (2016), the dataset of Friedrich et al. (2012) shows that G. truncatulinoides left and right coiling have similar Mg/Ca ratios in the size fraction 315-400μm, though only based on one measurement. Therefore we used a limited size fraction window with relative small size-dependent changes.

With respect to coiling varieties the Mg/Ca calibration dataset of Cléroux et al. (2008) shows that the difference in Mg/Ca temperature estimates between the left and right coiling variety of G. truncatulinoides is within the calibration error of +/- 2 °C that is assumed for the mixed calibration used in our work. However, we will include a sentence mentioning that pooling of G. truncatulinoides coiling varieties should be avoided to decrease the uncertainty level in Mg/Ca derived surface ocean temperatures.

Additional to the changes proposed above we will carefully revise the manuscript according to the numerous technical comments that will definitely increase the quality of

the manuscript.

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