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Discussions

Holocene evolution of the North Atlantic subsurface transport

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Abstract. Previous studies suggested that short term freshening events in the subpolar gyre can be counterbalanced by interactions with the subtropical gyre and thus stabilize the Atlantic Meridional Overturning Circulation (AMOC). However, little is known about the intergyre transport pathways. Here, we reconstruct surface and subsurface transport between the
10   subtropical and polar North Atlantic during the last 10000 years, by combining new temperature and salinity reconstructions obtained from surface and subsurface dwelling foraminifera with published data from the tropical and subpolar North Atlantic and published foraminiferal abundance data from the subtropical North Atlantic. These observations imply an overall stable warm surface water transport. Subsurface warm water transport started at about 8 ka with subtropical heat storage, and reached its full strength at about 7 ka, probably associated with the onset of the modern AMOC mode.
15   Comparison of different potential forcing mechanisms suggests a freshwater control on these ocean transport changes.

1 Introduction

The Holocene, though often considered a generally stable warm climate mode, is characterized by a distinct long-term climate trend, and strong oscillations on millennial to annual time scales. The long-term trend is formally divided into the
20   Early Holocene (11.6 to 8.2 ka BP), the Mid Holocene (8.2 to 4.3 ka BP) and the Late Holocene (4.3-0 ka BP) (Walker et al., 2012). This gradual change is caused by variations in the incoming solar radiation due to, changes in Earth's orbit, expressed as insolation at 60°N in June. Northern hemisphere insolation changes are inferred to control strength and position of the global wind systems, and to have caused the early Holocene thermal maximum observed in the high northern latitudes (e.g. Leduc et al., 2010; Moros et al., 2006). This warming induced the final melting of glacially extended ice sheets and released
25   a significant amount of meltwater from the Laurentian ice sheets into the North Atlantic (e.g. Jennings et al., 2015).

Shorter periodic climatic cycles, with average duration of about 1500 years, are observed in many Holocene climate records, and are superimposed on the long-term trend. The causes of these cycles are controversially discussed, with hypotheses ranging from meltwater pulses induced by variations in solar irradiance, to internal ocean-ice-atmosphere feedback mechanisms, or volcanism (e.g. Andrews and Giraudeau, 2003; Bond et al., 2001; Campbell et al., 1998; Schulz et al., 2004;
30   Viau et al., 2006; Wanner, 2008). Due to the wide range of feedback mechanisms, involving northern hemisphere ocean and atmospheric circulation, climate patterns with strong local differences are observed for the Holocene. Therefore,

identification and understanding of the importance of the different driving forces and stabilizing mechanisms for the Holocene climate remains challenging. It is assumed that the stabilization is related to a strong Atlantic Meridional Overturning Circulation (AMOC), driven by deep water formation in the Nordic Seas and the Labrador Sea, and fueled by the northward transport of warm saline waters. In this scenario, the main stabilization occurred via the formation of Labrador

5 Sea Water (LSW), which is inferred to have been established at about 7 ka BP (Hoogakker et al., 2011; Kissel et al., 2013; Solignac et al., 2004b; Thornalley et al., 2013). A stable LSW formation is related to the interaction between warm water transport in the clockwise circulating subtropical gyre (STG) and the subpolar gyre (SPG) circulating counterclockwise in the Irminger Basin and the Labrador Sea (Thornalley et al., 2009). Antiphase heat and salt storage within the SPG during times when STG freshens (Cléroux et al., 2012; Thornalley et al., 2009) and the later advection of the warm saline water into

10 the SPG leads to a strengthening of the deepwater formation by convection within the SPG (e.g. Born and Stocker, 2014). Investigation of the different pathways of the warm water masses from the tropical into the subpolar North Atlantic is limited to a few studies thus far. The transport into the subpolar North Atlantic and the Nordic Seas via surface flow within the NAC, on the other hand, is relatively well known from oceanographic studies (Sarafanov et al., 2012) and paleoceanographic reconstructions (e.g. Andersen et al., 2004; Came et al., 2007; Farmer et al., 2011; Giraudeau et al., 2010; Moros et al., 2004;

15 Staines-Uréas et al., 2013).

The warm water transport into the Labrador Sea, however, is still a matter of investigation. Drifter and modeling studies of the modern ocean indicate a lack of warm surface water transport *vis-a-vis* a major warm water transport into the SPG via a subsurface (>500m) pathway into the Irminger Sea (Brambilla and Talley, 2006; Foukal and Lozier, 2016; Lozier, 2012). In contrast, hydrographic data from ocean cross sections indicate a transport of warm, saline water between 10 and 1000 m

20 water depth into the Irminger Basin and Labrador Sea (Sarafanov et al., 2012; Våge et al., 2011) with a recirculation and mixing zone of NAC waters into the SPG in the North west corner of the SPG (Mertens et al., 2014)

Most paleo reconstructions focus on the surface water structure in the subpolar North Atlantic (Came et al., 2007; Farmer et al., 2011; Staines-Uréas et al., 2013) and neglect the probably significant subsurface component of the transport. The two studies that investigated the interaction between the STG and SPG (Solignac et al., 2004a; Thornalley et al., 2009) focus on

25 surface water pathways mainly, while changes in the tropical origin of the water masses are not considered. Thus a systematic investigation of the subsurface transport from the tropical into the subpolar North Atlantic and its potential impact on the stabilization of the late Holocene AMOC mode is critically missing. Here, the role of surface and subsurface warm water transport from the tropics into the subpolar North Atlantic on the evolution and stabilization of the Holocene climate mode is investigated, and different forcing mechanisms are entertained. This knowledge is pivotal to establish robust

30 scenarios for future AMOC changes under ongoing anthropogenic climate change leading to warming and potential freshening of the subpolar NA.

2 Regional Setting

The warm water circulation in the North Atlantic is governed by the North Atlantic Current (NAC) that transports warm saline water (e.g. Roessler et al., 2015) into the high northern latitudes. On its northward path, several warm water currents branch off the main pathway (Figure 1). The most distinct ones are the Azores Current (AC) and the Irminger Current (IC).

5   The eastward flowing AC leaves the NAC between 30 and 40°N and forms the northern boundary of the STG. The latter rotates clockwise and recirculates warm water between 10 and 40°N. The AC is associated with the Azores Front (AF) that is characterized by strong eddy activity and forms the boundary between cool transitional and warm oligotrophic subtropical waters. The AF is characterized by the depth of the 15° isotherm (Gould, 1985) and is therefore not traceable in SST (Alves et al., 2002) but by distinct shifts in foraminiferal assemblages from subtropical to transitional/subpolar (Ottens and

10 Nederbragt, 1992; Schiebel et al., 2002b) and thus also by abundances of *G. ruber w.* (Repschläger et al., 2015 and citations therein). The strength and position of the westerly wind belt control the position of the AF and AC (Volkov and Fu, 2011) with increasing/decreasing wind strength leading to a southward/northward displacement of the AF, respectively.

South of Iceland at about 50°N, the IC branches off the main northward path of the NAC. It flows in north-westward direction following the bathymetry of the Irminger Basin. South of the Denmark Strait, The IC returns southward following

15 the coast of Greenland into the Labrador Sea (Spall and Pickart, 2003). It thereby feeds warm saline waters into the counterclockwise rotating SPG, and fuels deepwater convection in the Labrador Sea (Born and Stocker, 2014; Sarafanov et al., 2012; Våge et al., 2011).

3 Methods

For our study, we used core GEOFAR KF16 taken at 38°N, south of the Azores Islands at the Mid Atlantic Ridge, from

20 3060 m water depth. This position in the vicinity of the AF is ideal to trace the varying position of the STG and associated varying influence of subtropical and temperate waters (Repschläger et al., 2015). Results are compared to published data from the tropical (Bahr et al., 2013; Cléroux et al., 2012) and subpolar North Atlantic (Thornalley et al., 2009) along the warm water route.

We combine published $\delta^{18}O$ data of planktonic surface and subsurface dwelling foraminifera *G. ruber w.* and *G.*

25 *truncatulinoides* (Repschläger et al., 2015) with new Mg/Ca records from the same species. Mg/Ca analyses followed the same procedure as in (Repschläger et al., 2015), with a 2 σ STD of +/-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 a species-specific calibration of *G. ruber w.*, and an equation for mixed subsurface dwellers for *G. truncatulinoides,* both published by Cléroux et al., (2008). The summed analytical and calibration 2 σ STD is +/- 1 °C for *G. ruber w.* and +/- 2 °C for *G.*

30 *truncatulinoides*. The calibrated Mg/Ca temperatures for both species from our core top match well with modern surface and subsurface (200 m depth) temperatures at the Azores coring site, and seasonal overprints on foraminiferal calcite are

assumed to play a subordinate role at our coring site (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))

5   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 $\delta^{18}O_{carbonate}$ using the general equation of *Shackleton (1974)* for *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. The $\delta^{18}O_w$ records were corrected for ice volume, using the relative sea level composite curve of Waelbroeck (2002). For $\delta^{18}O_w$ uncertainty evaluation we followed the argumentation of Cleroux 2011 and used and

10   used eq. S8 of Cleroux et al., (2011), leading to an calculated 2 σ STD of +/- 0.35 ‰ for *G. ruber w.* and +/- 0.68 ‰ for *G. truncatulinoides,* respectively. Given the relative large error in reconstruction, we only used 5- point average data for interpretation to investigate longer-term trends in the datasets.

Changes in the AF front were reconstructed using the relative abundance of *G. ruber* w. published by (Weinelt et al., 2015) These abundance counts have an 2 σ STD +/- 2.5 %. As *G. ruber* w. is most abundant within the STG (Ottens, 1991;

15   Schiebel et al., 2002a; 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 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 (Repschläger et al., 2015).

4 Results

20   Surface and subsurface $\delta^{18}O$ records (Figure 2a) show a parallel trend over the Holocene, with a 0.5 ‰ decrease from 0.2 ‰ and 1.5 ‰ at 11 ka BP to -0.3 ‰ and 0.9 ‰ at 8 ka BP. After 6 ka BP both records stabilize with minor fluctuations of 0.2‰ around an average of 0.3 ‰ and 1 ‰, respectively. Additionally, both records show a major positive $\delta^{18}O$ excursion of 0.7 ‰ between 7 and 6 ka BP.

The SST record of *G. ruber* w. (Figure 2b) is relatively stable over the entire Holocene, fluctuating between 17.5 and 20 °C.

25   In contrast, subsurface temperatures (T_{sub}) show an increase from low temperatures around 12.5°C at 11 ka BP to about 17° C between 11 and 8 ka BP. Over the last 7 ka BP, T_{sub} fluctuate by 2.5 °C around an average value of 16°C and parallel the surface water record with an average offset of ~ 4°C.

The $\delta^{18}O_{w-ivc}$ records of the surface and subsurface water (Figure 2c) both show strong short-term variability of 0.5 ‰ thus single points cannot be interpreted. The 5 - point average values of both records, however, indicate an evolution. Both

30   records are similar between 11 and 10.5 ka with average values between 0.5 ‰ to 0.3 ‰. Between 10.5 and the

records start to decrease to values between 1.5 ‰ 1.7 ‰ at 6 ka BP. After 6 ka BP surface and subsurface $\delta^{18}O_{w\text{-ivc}}$ records separate, only slightly exceeding the error of calculation.

Low abundances of *G. ruber w.* (7- 15 %) (Figure 2d) between 11 and 9.5 ka BP indicate a southward displacement of the AF and correlate with low T_{sub} and low subsurface $\delta^{18}O_{w\text{-ice}}$. High abundances of *G. ruber w.* (~20 %) between 8 and 4 ka BP

5   indicate a northward movement of the AF, coeval to a warming of the subsurface waters and high $\delta^{18}O_{w\text{-ice}}$ in *G. truncatulinoides*. Between 6 and 7 ka BP a short excursion with a decrease in *G. ruber w.* abundances to as low as 10% coincide with an increase in the $\delta^{18}O$ records and a decrease in T_{sub}. This event is associated is related to a discontinuity in the sediment core.

After 4 ka BP, the abundances of *G. ruber w.* decrease to15%, indicating a southern position of the AF. This decrease does

10   not coincide with any changes surface and subsurface T and in $\delta^{18}O_{w\text{-ivc}}$.

5 Discussion

Based on the records presented here, and following the suggestion of the INTIMATE group (Walker et al., 2012), the Holocene can be divided into four sections.

The Early Holocene (11-8.2 ka BP) is characterized by a thermal difference between surface and subsurface waters. Together

15   with the similarity in the $\delta^{18}O_{w\text{-ivc}}$ records, this points toward a T-driven stratification during a period when the AF was south of its modern position. In the early Mid Holocene (8-6 ka BP) the thermal difference between surface and subsurface waters decreased while the difference in $\delta^{18}O_{w\text{-ivc}}$ remained small. This phase can be interpreted as an intermediate phase with a weak stratification that is accompanied by a northward movement of the AF, reaching its northernmost position. In the late Mid Holocene (6-4 ka BP) the AF remained at the northernmost position, evolving differences between surface and

20   subsurface T and S indicate a stabilization of the thermohaline stratification. The Late Holocene (4-0 ka BP) differs from the previous phase only in the position of the STG. The latter is displaced to a more southern position that is also observed under modern conditions.

5.1 Transport between tropical and subpolar North Atlantic

In order to investigate how changes in the mixed layer at our subtropical coring site can be related to changes in surface and

25   subsurface warm water transport between the tropical and subpolar North Atlantic, we compare our records with records from the tropical (Bahr et al., 2013; Cléroux et al., 2012) and the subpolar NA (Thornalley et al., 2009).

In general, SST estimates from the tropical, subtropical and subpolar sites (Figure 3) fluctuate by 2°C around rather stable mean values of 27°C, 18°C and 10°C, respectively. The $\delta^{18}O_{w\text{-ivc}}$ records are fluctuating by +/- 0.4 ‰ around values of 1.2 ‰, 0.9‰, and 0 ‰. These fluctuations are within the errors of Mg/Ca temperature estimation and seawater $\delta^{18}O$

determinations. Assuming that the surface water properties at the three coring sites are mainly driven by changes in the surface water transport, we conclude that the mean northward surface water transport remained stable over the Holocene.

Thus the variability described above, must originate from changes in the subsurface transport. The subsurface signal from the tropical site is rather constant during the entire Holocene, with average tropical T_{sub} fluctuating by +/- 3°C around a mean

5 of 17.5°C and $\delta^{18}O_{w-ivc}$ varying by 0.5 ‰ around a mean of 1.2 ‰, and with no apparent long-term trends In contrast, distinct temporal differences are observed in the subsurface records at the subtropical and subpolar site (Figure 3b).

From 11 to 8 ka BP, coincident with a southern position of the AF, subtropical subsurface records are very similar to subpolar values with low T_{sub} (12/10°C) and low subsurface $\delta^{18}O_{w-ivc}$ of about 0.5 ‰. The surface water records suggest active northward water transport, similar to the state described at the transition between the Allerød and the Younger Dryas

10 (Repschläger et al., 2015). The low subsurface T and $\delta^{18}O_{w-ice}$ during the Early Holocene can be explained with an intrusion of transitional Eastern North Atlantic Water (ENAW) reaching the Azores coring site (Figure 4a). This intrusion is probably related to the influence of meltwater from the Laurentide ice sheet that is also inferred from a freshening in the subpolar North Atlantic (Came et al., 2007; Thornalley et al., 2009), although the $\delta^{18}O_{w-ivc}$ needs to be confirmed by independent proxies.

15 During the Mid Holocene transitional phase (8-6 ka BP), subtropical and subpolar subsurface records diverge. The subtropical T_{sub} and subsurface $\delta^{18}O_{w-ivc}$ values converge towards those from the tropical record after 8.2 ka BP, while the subpolar T_{sub} record remains in the Early Holocene mode and the $\delta^{18}O_{w-ivc}$ imply further freshening. This state coincides with a northward migration of the AF. Warm subsurface waters reached the Azores coring site, but was not transported further northward yet (Figure 4b).

20 At 7 ka BP subtropical and subpolar subsurface records start to converge toward the tropical record, with the subpolar record lagging behind changes in the subtropical record by at least 1,000 years. This indicates the onset of modern transport of warm subsurface waters from the tropics into the subpolar region (Figure 4c). At the same time, LSW formation started with a temperature decrease in Labrador Sea surface waters (Solignac et al., 2004a) and decreasing warm water transport within the NAC into the Nordic seas (Staines-Uréas et al., 2013). These changes are potentially accompanied by a divergence of the

25 warm water transport into the Irminger Basin and Labrador Sea at subsurface. To investigate this transport route further high- resolution SST and T_{sub} reconstructions from the subpolar gyre would be needed.

In the Late Holocene after 6 ka BP, the tropical, subtropical and subpolar records are showing parallel patterns with millennial-scale fluctuations in S and T that anti-correlate with records from the Labrador Sea as already described by Thornalley et al. (2009) and Cléroux et al. (2012). With this circulation mode, short-term variability including anti-phasing

30 between the SPG and STG temperature and salinity records is observed. Our data thus confirm earlier suggestions of anti-phasing between gyre properties during the Late Holocene (Cléroux et al., 2012; Thornalley et al., 2009) implying that short-term freshening events in the Labrador Sea can be balanced by increased warm and saline water transport between the SPG

and the STG stabilizing the AMOC. However, our data indicate that the major pathway in this stabilization mechanism must be the subsurface warm water route in the North Atlantic.

Surprisingly, no changes in the long-term trend of the Late Holocene are observed after 4 ka BP when changes in the *G. ruber* w. abundance indicate a southward movement of the AF position(Repschläger et al., 2015), that can be associated with

5   a global southward shift of the wind systems (Wanner, 2008).

5.2 Driving factors for subsurface transport changes

In light of observed and anticipated anthropogenic climate change it is important to understand the underlying mechanism of Holocene climate variability. In addition to the forcing by increases in atmospheric CO_2, three driving factors for Holocene climate variability are discussed 1) changes in the atmospheric circulation related to the NH summer insolation (Renssen,

10   2005) 2) changes in meltwater forcing over the North Atlantic region due to melting of continental ice sheets (Mayewski et al., 2004) and 3) changes in solar activity (Bond et al., 2001).In the following we will discuss which of those factors can be identified as main cause of the variability in subsurface transport.

Changes in NH insolation are coupled with changes in the position of the westerly wind belt (Renssen, 2005). Major changes in the atmospheric circulation are probably related to the early Holocene thermal maximum, however the position of the

15   westerlies within this time period remains unclear. During the Late Holocene (since 4.3 ka BP), ITCZ changes (Wanner, 2008) are probably related to the southward movement of the westerly wind belt and southward displacement of the AF. The *G. ruber* w. data indicate a northward movement of the AF between 8 and 9 ka BP and southward movement of the AF and associated strengthening of the westerly wind belt at about 4 ka BP, the latter matching the tropical changes within the limitations of the age models (Repschläger et al., 2015). Despite the coincidence of frontal movements with Holocene

20   changes in the northern hemisphere wind fields, inferred changes in the AF position do not coincide with the onset of the northward subsurface water transport. The onset of the subsurface transport and LSW formation lag behind the northward movement of the AF by about 2 ka and lead the southward movement of the AF at 4 ka BP by 2 ka. Thus, the onset of the subsurface transport seems to be decoupled from changes in the atmospheric circulation.

The onset of the northward subsurface warm water transport at about 7 ka BP agrees with the onset of LSW formation and

25   stabilization of the global sea level at that time (Wanner, 2008), and the end of meltwater flow into the Labrador Sea (Jennings et al., 2015). This coincidence between changes in surface water transport and the end of meltwater input to the North Atlantic region argues for the cessation of meltwater input to the Labrador Sea and North Atlantic as a major driver for the onset of the modern mode of subsurface warm water transport and LSW formation.

In addition to this long-term evolution, short-term variability in the LSW subsurface transport and in the inter-gyre dynamics

30   is observed during the last 7 ka BP. These short-term fluctuations match roughly a 1500 year cycle, possibly implying another driving force such as solar activity or volcanism that generates smaller scale variability, not addressed in this study.

6. Conclusion

In this study we show a stepwise evolution of the mixed layer temperature and salinity at the AF during the Holocene that is closely linked to a northward migration of the AF and related transport of warm water within the NAC system.

The mean surface warm water transport from the tropics into the subpolar North Atlantic remained relatively stable over the last 11 ka BP. In contrast, subsurface transport into the North Atlantic evolved in three phases: an early Holocene meltwater phase (11-8 ka BP) with no subsurface transport, a mid Holocene transitional phase (8-6 ka BP) with subsurface transport that reached the AF but not the subpolar NA and a late Holocene to modern phase (6-0 ka BP) with subsurface transport into the subpolar NA that coincides with the onset of LSW formation.

The subsurface transport changes are mainly driven by the amount of meltwater in the subpolar North Atlantic that are probably more important for the AMOC evolution than changes in the atmospheric circulation. Short-term variability in the subsurface transport over the last 6 ka BP is anti-phased with Labrador Sea records, corroborating previous studies postulating inter gyre dynamics as a potential stabilizing mechanism for the modern LSW formation.

Subsurface transport pathways appear to have an important role in the Mid- to Late Holocene climate stabilization. However, this aspect needs to be investigated further in high latitudes in order to obtain a full understanding of underlying forcing mechanisms.

Data availability

Data is available under https://doi.pangaea.de/10.1594/PANGAEA.868108.

Acknowledgments

References

Alves, M., Gaillard, F., Sparrow, M., Knoll, M., and Giraud, S.: Circulation patterns and transport of the Azores Front-Current system, Deep Sea Research Part II: Topical Studies in Oceanography, 49, 3983-4002, 2002.

Andersen, C., Ko√ß, N., and Moros, M.: A highly unstable Holocene climate in the subpolar North Atlantic: evidence from diatoms, Quaternary Science Reviews, 23, 2155-2166, 2004.

Andrews, J. T. and Giraudeau, J.: Multi-proxy records showing significant Holocene environmental variability: the inner N. Iceland shelf (Húnaflói), Quaternary Science Reviews, 22, 175-193, 2003.

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Bahr, A., Nürnberg, D., Karas, C., and Grützner, J.: Millennial-scale versus long-term dynamics in the surface and subsurface of the western North Atlantic Subtropical Gyre during Marine Isotope Stage 5, Global and Planetary Change, 111, 77-87, 2013.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and
5   Bonani, G.: Persistent Solar Influence on North Atlantic Climate During the Holocene, Science, 294, 2130, 2001.

Born, A. and Stocker, T. F.: Two Stable Equilibria of the Atlantic Subpolar Gyre, Journal of Physical Oceanography, 44, 246-264, 2014.

Brambilla, E. and Talley, L.: Surface drifter exchange between the North Atlantic subtropical and subpolar gyres, J. Geophys. Res., 111, C07026, 2006.

10   Came, R. E., Oppo, D. W., and McManus, J. F.: Amplitude and timing of temperature and salinity variability in the subpolar North Atlantic over the past 10 k.y, Geology, 35, 315-318, 2007.

Campbell, I. D., Campbell, C., Apps, M. J., Rutter, N. W., and Bush, A. B. G.: Late Holocene ~1500 yr climatic periodicities and their implications, Geology, 26, 471-473, 1998.

Cléroux, C., Cortijo, E., Anand, P., Labeyrie, L., Bassinot, F., Caillon, N., and Duplessy, J.-C.: Mg/Ca and Sr/Ca ratios in
15   planktonic foraminifera: Proxies for upper water column temperature reconstruction, Paleoceanography, 23, n/a-n/a, 2008.

Cléroux, C., Debret, M., Cortijo, E., Duplessy, J.-C., Dewilde, F., Reijmer, J., and Massei, N.: High-resolution sea surface reconstructions off Cape Hatteras over the last 10 ka, Paleoceanography, 27, PA1205, 2012.

Farmer, E. J., Chapman, M. R., and Andrews, J. E.: Holocene temperature evolution of the subpolar North Atlantic recorded in the Mg/Ca ratios of surface and thermocline dwelling planktonic foraminifers, Global and Planetary Change, 79, 234-243,
20   2011.

Foukal, N. P. and Lozier, M. S.: No inter-gyre pathway for sea-surface temperature anomalies in the North Atlantic, Nat Commun, 7, 2016.

Giraudeau, J., Grelaud, M., Solignac, S., Andrews, J. T., Moros, M., and Jansen, E.: Millennial-scale variability in Atlantic water advection to the Nordic Seas derived from Holocene coccolith concentration records, Quaternary Science Reviews, 29,
25   1276-1287, 2010.

Gould, W. J.: Physical oceanography of the Azores front, Progress in Oceanography, 14, 167-190, 1985.

Hoogakker, B. A. A., Chapman, M. R., McCave, I. N., Hillaire-Marcel, C., Ellison, C. R. W., Hall, I. R., and Telford, R. J.: Dynamics of North Atlantic Deep Water masses during the Holocene, Paleoceanography, 26, PA4214, 2011.

Jennings, A., Andrews, J., Pearce, C., Wilson, L., and Ólfasdótttir, S.: Detrital carbonate peaks on the Labrador shelf, a 13-7
30   ka template for freshwater forcing from the Hudson Strait outlet of the Laurentide Ice Sheet into the subpolar gyre, Quaternary Science Reviews, 107, 62-80, 2015.

Kissel, C., Van Toer, A., Laj, C., Cortijo, E., and Michel, E.: Variations in the strength of the North Atlantic bottom water during Holocene, Earth and Planetary Science Letters, 369-370, 248-259, 2013.

Leduc, G., Schneider, R., Kim, J. H., and Lohmann, G.: Holocene and Eemian sea surface temperature trends as revealed by
35   alkenone and Mg/Ca paleothermometry, Quaternary Science Reviews, 29, 989-1004, 2010.

Lherminier, P., Mercier, H., Huck, T., Gourcuff, C., Perez, F. F., Morin, P., Sarafanov, A., and Falina, A.: The Atlantic Meridional Overturning Circulation and the subpolar gyre observed at the A25-OVIDE section in June 2002 and 2004, Deep Sea Research Part I: Oceanographic Research Papers, 57, 1374-1391, 2010.

Lozier, M. S.: Overturning in the North Atlantic, Annual Review of Marine Science, 4, 291-315, 2012.

40   Mayewski, P. A., Rohling, E. E., Curt Stager, J., Karlén, W., Maasch, K. A., David Meeker, L., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R., and Steig, E. J.: Holocene climate variability, Quaternary Research, 62, 243-255, 2004.

Mertens, C., Rhein, M., Walter, M., Böning, C. W., Behrens, E., Kieke, D., Steinfeldt, R., and Stöber, U.: Circulation and transports in the Newfoundland Basin, western subpolar North Atlantic, Journal of Geophysical Research: Oceans, 119,
45   7772-7793, 2014.

Moros, M., Andrews, J. T., Eberl, D. D., and Jansen, E.: Holocene history of drift ice in the northern North Atlantic: Evidence for different spatial and temporal modes, Paleoceanography, 21, 10, 2006.

Moros, M., Emeis, K., Risebrobakken, B., Snowball, I., Kuijpers, A., McManus, J., and Jansen, E.: Sea surface temperatures and ice rafting in the Holocene North Atlantic: climate influences on northern Europe and Greenland, Quaternary Science
50   Reviews, 23, 2113-2126, 2004.

Ottens, J. J.: Planktic foraminifera as North Atlantic water mass indicators, Oceanologica Acta, 14, 123-140, 1991.

Ottens, J. J. and Nederbragt, A. J.: Planktic foraminiferal diversity as indicator of ocean environments, Marine Micropaleontology, 19, 13-28, 1992.

Renssen, H.: Simulating the Holocene climate evolution at northern high latitudes using a coupled atmosphere-sea ice-ocean-vegetation model, Clim. Dyn., 24, 23-43, 2005.

Repschläger, J., Weinelt, M., Kinkel, H., Andersen, N., Garbe-Schönberg, D., and Schwab, C.: Response of the subtropical North Atlantic surface hydrography on deglacial and Holocene AMOC changes, Paleoceanography, 30, 2015.

Roessler, A., Rhein, M., Kieke, D., and Mertens, C.: Long-term observations of North Atlantic Current transport at the gateway between western and eastern Atlantic, Journal of Geophysical Research: Oceans, 120, 4003-4027, 2015.

Sarafanov, A., Falina, A., Mercier, H., Sokov, A., Lherminier, P., Gourcuff, C., Gladyshev, S., Gaillard, F., and Daniault, N.: Mean full-depth summer circulation and transports at the northern periphery of the Atlantic Ocean in the 2000s, J. Geophys. Res., 117, C01014, 2012.

Schiebel, R., Schmuker, B., Alves, M., and Hemleben, C.: Tracking the Recent and late Pleistocene Azores front by the distribution of planktic foraminifers, Journal of Marine Systems, 37, 213-227, 2002a.

Schiebel, R., Waniek, J., Zeltner, A., and Alves, M.: Impact of the Azores Front on the distribution of planktic foraminifers, shelled gastropods, and coccolithophorids, Deep Sea Research Part II: Topical Studies in Oceanography, 49, 4035-4050, 2002b.

Schlitzer, R.: Ocean Data View, http://odv.awi.de,, 2012. 2012.

Schott, F. A., Zantopp, R., Stramma, L., Dengler, M., Fischer, J. r., and Wibaux, M.: Circulation and Deep-Water Export at the Western Exit of the Subpolar North Atlantic, Journal of Physical Oceanography, 34, 817-843, 2004.

Schulz, M., Paul, A., and Timmermann, A.: Glacial–interglacial contrast in climate variability at centennial-to-millennial timescales: observations and conceptual model, Quaternary Science Reviews, 23, 2219-2230, 2004.

Shackleton, N. J.: Attainment of isotopic equilibrium ocean water and the benthonic foraminifera genus Uvigerina: Isotopic changes in the ocean during the last glacial, Cent. Natl.Rech. Sci. Colloq. Int., 219, 203–209, 1974.

Solignac, S., de Vernal, A., and Hillaire-Marcel, C.: Holocene sea-surface conditions in the North Atlantic: contrasted trends and regimes in the western and eastern sectors (Labrador Sea vs. Iceland Basin), Quaternary Science Reviews, 23, 319-334, 2004a.

Solignac, S., de Vernal, A., and Hillaire-Marcel, C.: Holocene sea-surface conditions in the North Atlantic‚Äîcontrasted trends and regimes in the western and eastern sectors (Labrador Sea vs. Iceland Basin), Quaternary Science Reviews, 23, 319-334, 2004b.

Spall, M. and Pickart, A.: Wind-driven recirculations and exchange in the Labrador and Irminger Seas, Journal of Physical Oceanography, 33, 2003.

Staines-Uréas, F., Kuijpers, A., and Korte, C.: Evolution of subpolar North Atlantic surface circulation since the early Holocene inferred from planktic foraminifera faunal and stable isotope records, Quaternary Science Reviews, 76, 66-81, 2013.

Storz, D., Schulz, H., Waniek, J. J., Schulz-Bull, D. E., and Kuƒçera, M.: Seasonal and interannual variability of the planktic foraminiferal flux in the vicinity of the Azores Current, Deep Sea Research Part I: Oceanographic Research Papers, 56, 107-124, 2009.

Thornalley, D. J. R., Blaschek, M., Davies, F. J., Praetorius, S., Oppo, D. W., McManus, J. F., Hall, I. R., Kleiven, H., Renssen, H., and McCave, I. N.: Long-term variations in Iceland-Scotland overflow strength during the Holocene, Clim. Past, 9, 2073-2084, 2013.

Thornalley, D. J. R., Elderfield, H., and McCave, I. N.: Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic, Nature, 457, 711-714, 2009.

Våge, K., Pickart, R. S., Sarafanov, A., Knutsen, ò., Mercier, H., Lherminier, P., van Aken, H. M., Meincke, J., Quadfasel, D., and Bacon, S.: The Irminger Gyre: Circulation, convection, and interannual variability, Deep Sea Research Part I: Oceanographic Research Papers, 58, 590-614, 2011.

Viau, A. E., Gajewski, K., Sawada, M. C., and Fines, P.: Millennial-scale temperature variations in North America during the Holocene, Journal of Geophysical Research: Atmospheres, 111, D09102, 2006.

Volkov, D. L. and Fu, L.-L.: Interannual variability of the Azores Current strength and eddy energy in relation to atmospheric forcing, J. Geophys. Res., 116, C11011, 2011.

Waelbroeck, C.: Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records, Quat. Sci. Rev., 21, 295-305, 2002.

Walker, M. J. C., Berkelhammer, M., Björck, S., Cwynar, L. C., Fisher, D. A., Long, A. J., Lowe, J. J., Newnham, R. M., Rasmussen, S. O., and Weiss, H.: Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy), Journal of Quaternary Science, 27, 649-659, 2012.

Wanner, H.: Mid- to late Holocene climate change: An overview, Quat. Sci. Rev., 27, 1791-1828, 2008.

Weinelt, M., Schwab, C., Kneisel, J., Hinz, M., and Climate and societal change in the western Mediterranean area around 4.2 ka BP. In: 2200 BC – Ein Klimasturz als Ursache für den Zerfall der Alten Welt? 2200 BC – A climatic breakdown as a cause for the collapse of the old world? 7. Mitteldeutscher Archäologentag vom 17. bis 19. Oktober 2013 in Halle (Saale). 7th Archaeological Conference of Central Germany October 23–26, 2014 in Halle (Saale). Meller, H., Arz, H. W., Jung, R., and Risch, R. (Eds.), Tagungen des Landesmuseums für Vorgeschichte Halle 12 Halle [Saale] 2015.
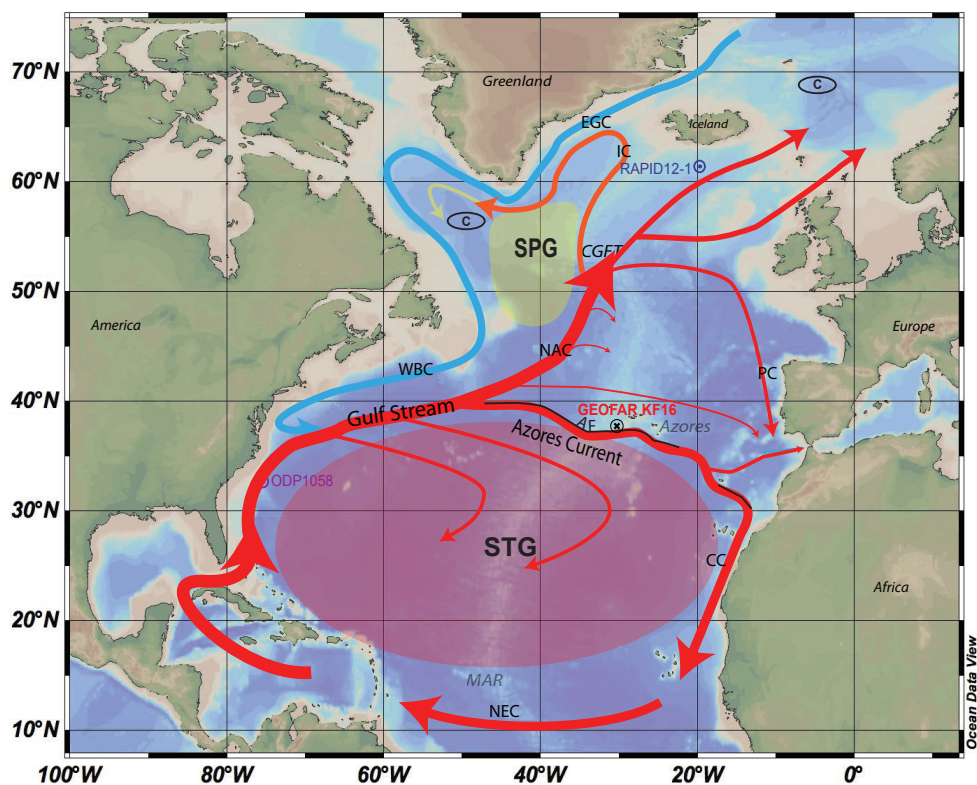
Figures

Figure 1: Modern surface water hydrography of the North Atlantic currents are modified from (Schott et al., 2004) and (Lherminier et al., 2010), basic maps stems from ocean data view (Schlitzer, 2012) warm surface currents are shown by red arrows, black line indicates the position of the Azores fronts (Abbreviations AC Azores Current, AF Azores Front, FC Florida Current, IC Irminger Current, NAC North Atlantic Current, NEC North Equatorial Current, STG Subtropical Gyre, PC Portugal Current, TW Transitional Water, WBC Western Boundary Current), ©. Indicates the position of deepwater convection sites, the Mid Atlantic Ridge is marked with MAR.
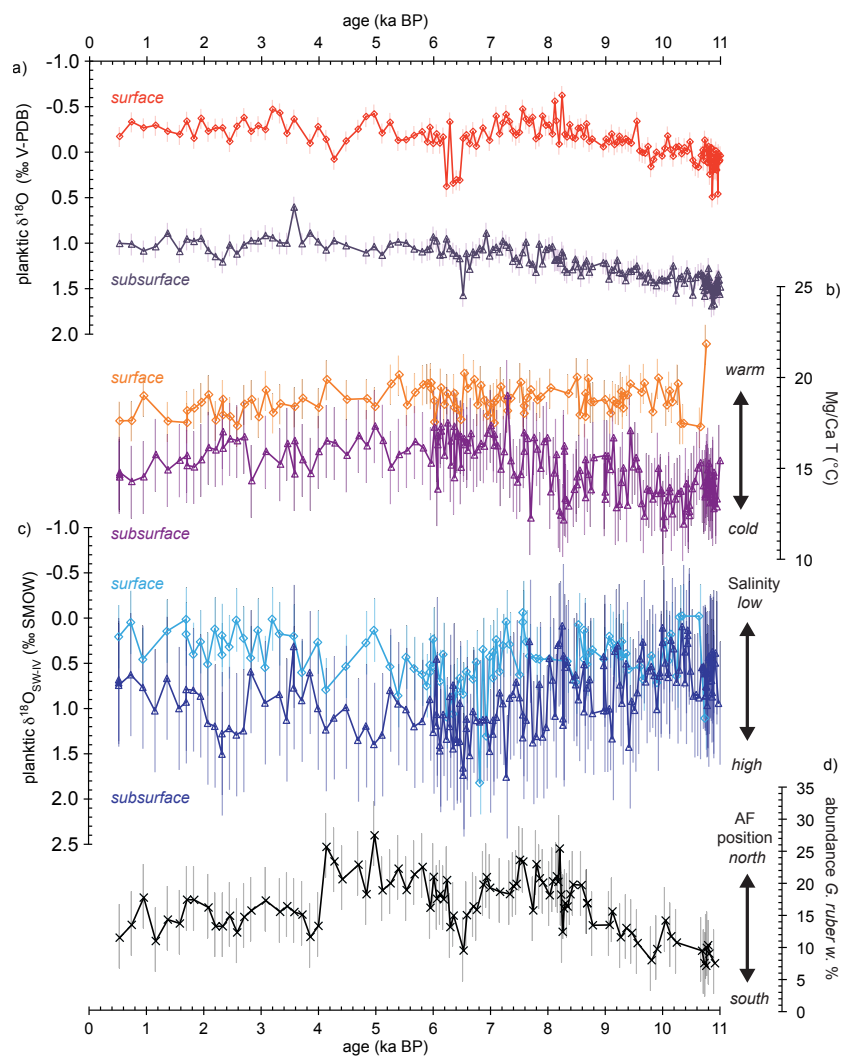
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Figure 2: Results obtained from cores GEOFAR KF16 a) δ¹⁸O records from surface (*G. ruber* w.) (red, diamonds) and subsurface (*G. truncatulinoides*) (dark blue, triangles) dwelling planktonic foraminifera (Repschläger et al., 2015) b) Mg/Ca SST records from surface (*G. ruber* w.) (orange, diamonds) and subsurface (*G. truncatulinoides*) (violet, triangles) c) δ¹⁸O$_{w-ivc}$ records from surface 5 (*G. ruber* w.) (light blue, diamonds) and subsurface (*G. truncatulinoides*) dwelling planktonic foraminifera (blue, triangles), Comparison between d) *G. ruber* w. abundance as indicator for the AF position (black crosses), grey bars indicate the 2σ STD for all records
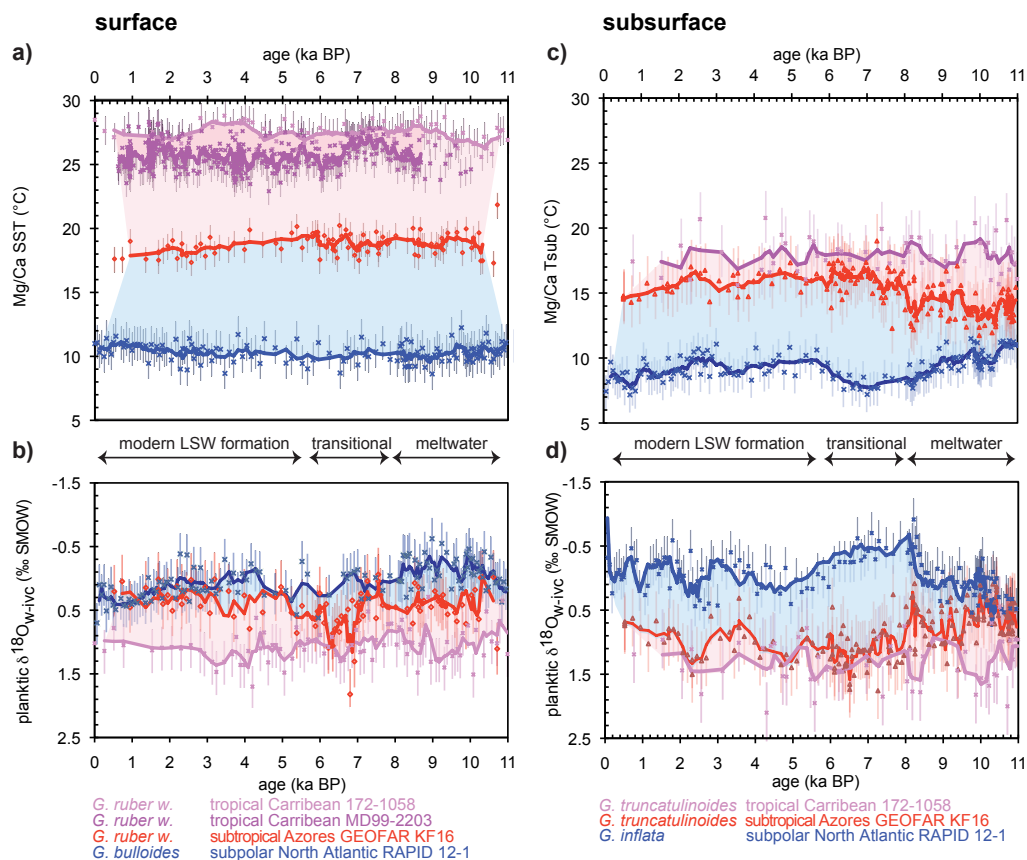
Figure 3: Surface and subsurface temperature and salinity reconstructions from tropical to subpolar North Atlantic. Left panel: comparison between a) surface temperatures and b) δ18O$_{w\text{-}ivc}$ records from the tropical (pink) (Bahr et al., 2013), subtropical (red), and subpolar (blue) (Thornalley et al., 2009) North Atlantic indicates only minor variability. Right panel: comparison between c) subsurface temperatures and d) δ18O$_{w\text{-}ivc}$ records from the tropical (pink) (Bahr et al., 2013), subtropical (red), and subpolar (blue) (Thornalley et al., 2009) North Atlantic indicate a three step evolution of subsurface water transport over the Holocene. During a Mid Holocene transitional phase (6-8 ka BP) subsurface waters, influenced by cold meltwater influx, were replaced by a warmer, more saline subsurface waters with an increasing northward transport of this water mass. Parallel subpolar subsurface waters experienced a freshening and slight cooling. The late Holocene stabilization phase can be associated with the establishment of LSW formation.

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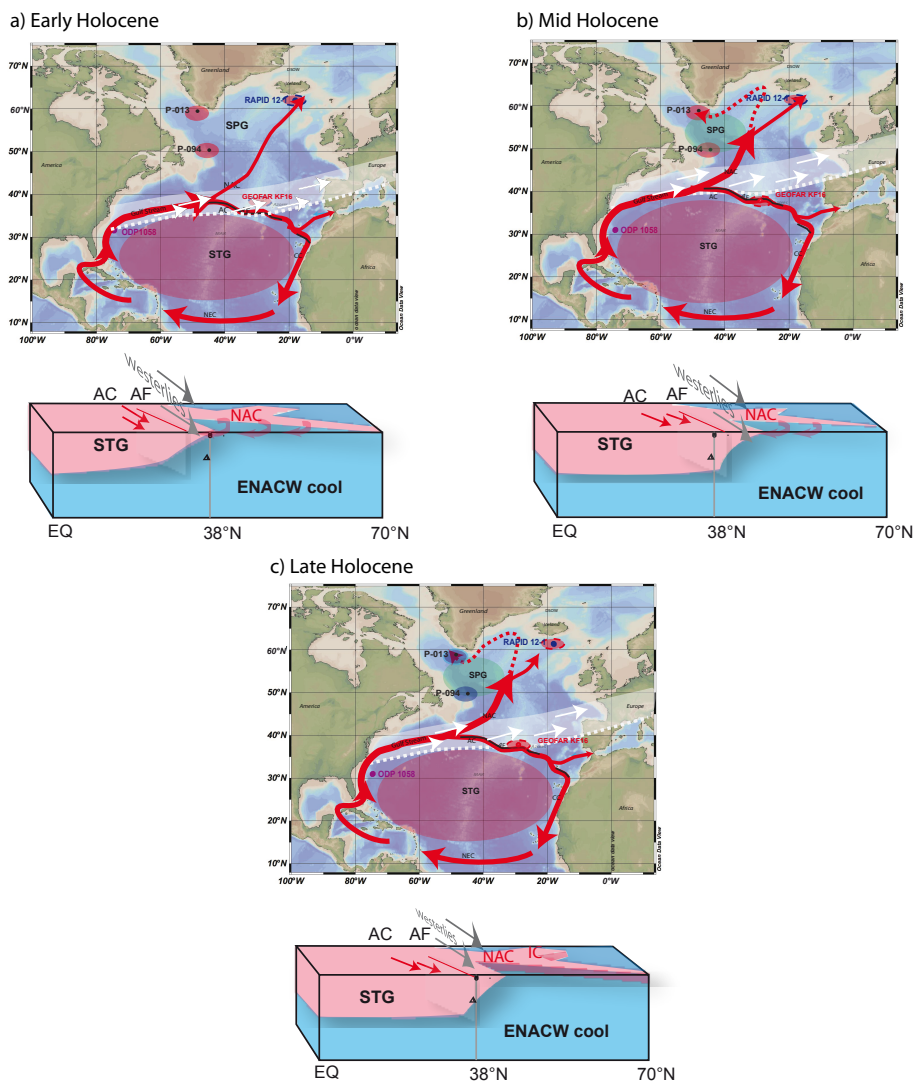Open Access

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Figure 4: Conceptual model showing the three different states of subsurface transport a) early Holocene meltwater phase b) mid Holocene transitional phase c) late Holocene modern phase