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Climate of the Past Discussions

Interactive comment on "Tracing winter temperatures over the last two millennia using a NE Atlantic coastal record" *by* Irina Polovodova Asteman et al.

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Author's response to reviewer 2

We sincerely thank anonymous reviewer 2 for insightful comments and valuable suggestions on how to improve the manuscript. Below we respond to each of the comments. Also the corrected figures and manuscript with markups are attached as a single PDF file.

Major comment 1: Relevance: The authors need to explain better why the study is important. It is mentioned in the introduction that only few high-resolution records of

late Holocene conditions exist from the eastern North Atlantic region. But records also exist from other regions, both Iceland and the western North Atlantic and the Labrador Sea region. Why is the Eastern North Atlantic region important? Please add a short explanation, what is special/different about this region compared to other areas. How can this study improve our general understanding of the late Holocene climate of the North Atlantic and which mechanisms control climate and ocean variability?

Response: We are aware of the existing records from other regions, such as Iceland, the W North Atlantic and the Labrador Sea (among many others Jiang et al., 2005; Andresen et al, 2012; Seidenkrantz et al., 2012; Perner et al., 2011, 2013, Sicre et al., 2008, 2014 etc). However, in this paper we merely wanted to stay focused on available fjord records from the NE Atlantic, which all share high temporal resolution (i.e. annual to subdecadal) and similar fjordic hydrography allowing calm sedimentation and continuous sediment accumulation with minor dilution by glaciomarine and/or terrigenous component. One of the reasons for a specific focus on the NE Atlantic is due to a geographical location of the majority of the NH temperate silled fjords, which are simply less frequent on the western side of the Atlantic. In addition, we believe that since the North Atlantic Current (NAC), and it's northward extension in a form of the Norwegian Atlantic Current, is one of the branches carrying a major part of the volume flux (and hence heat and salt) into the Nordic Seas (Hansen and Østerhus, 2000) and its ameliorating effect on NW European climate, more high-resolving records from sites influenced by the NAC and having long-term instrumental observations are needed. This is especially important in view that future predictions warn about NAC weakening (through AMOC) due to greenhouse forcing and, also, given the AMOC close connection to other mechanisms and phenomena controlling climate and ocean variability not only locally (for NW Europe) but also regionally and through teleconnections (e.g. NAO, AMO, ENSO).

We added the following section into the introduction following the reviewer's suggestion: "The North Atlantic region plays in this respect a paramount role for climate variability and global carbon budget by modulating the Atlantic Meridional Overturning Circulation (AMOC) (e.g. Eiríksson et al., 2006; Lund et al., 2006; Park and Latif, 2008; Trouet et al., 2009). The upper northern limb of the AMOC, the North Atlantic Current, delivers heat, salt and nutrients from tropics to the mid- and high latitudes and carries a major part of the volume flux into the Nordic Seas (Hansen and Østerhus, 2000). The AMOC is thought to be linked to the sea surface temperature variability of the Atlantic multidecadal oscillation (AMO; Enfield et al., 2001) and is connected to decadal variability of the North Atlantic Oscillation (NAO), where the NAO index is defined as the normalized sea level pressure difference between the Icelandic Low and the Azores High (Hurrel et al., 1995). The AMOC also contributes to a multidecadal modulation of El Niño-Southern Oscillation (ENSO) (Ortega et al., 2012 and references therein). Finally, variability of ocean temperature in high latitude North Atlantic and Nordic Seas are reflected in NW European climate and in winter Arctic sea ice extent (Årthun et al., 2017). Model projections predict AMOC slowdown in response to future warming and enhanced Arctic freshwater fluxes (e.g. Schmittner et al., 2005; Ortega et al., 2012) with potential detrimental impacts on the climate, the ecosystems and the economy of many European countries (e.g. Kuhlbrodt et al., 2009; Jackson et al., 2015). Hence, high-resolution paleoceanographic records, which preferably overlap with instrumental observations and historical data, are needed from the eastern North Atlantic region in order to document climate variability related to physical properties of the North Atlantic Current and AMOC strength."

Major comment 2: Bottom Water Temperatures: Page 3, line 28-31. It is stated that the water exchange only occurs during winter. Does any change in salinity or temperature conditions of the bottom waters occur during spring/summer? Explain more clearly whether the Bottom Water Temperatures actually represent winter conditions (mention this also in the abstract). As this is a central part of the work, it needs to be explained very clearly. Seasons used in the bottom-water temperature reconstruction (p9): Traditionally the winter season is described through the months DJF, but here the period JFM is used. Why? Is there a local environmental reason for this, purely due to

available data, or. . .Similarly an explanation should be given for the use of May-August as the summer period, but this is normally JJA. It is not directly stated in paragraph 4.3 that these periods correspond to “winter” (JFM) and “summer (MJJA) but in the following discussion (paragraph 5) winter temperatures are mentioned, so I assume that this is the case? However, it needs to be stated clearly and explained properly.

Response: We tried to be more specific and to clarify the “winter temperature signal” by modifying the corresponding Study area section accordingly: ” The deep water temperatures vary between the years depending on the temperature of the inflowing water mass but remain stable seasonally (Fig. 2D). The deep-water salinities seasonally do not vary much from the average value of 34.5 (Fig. 2B). The stratification of the water column is strengthened during the summer by the development of a strong thermocline, which impedes deep-water exchange. The deep-water exchange of the fjord basin water takes place once a year during winter, mostly between January and March, based on long-term instrumental observations performed in the fjord (Arneborg et al., 2004). Due to a presence of a sill isolating the fjord deep-water mass from the adjacent seas and the large basin volume, the winter temperature and salinity of the inflowing North Sea/Skagerrak water, are “annually preserved” in the fjord basin until the next deep-water turnover, which does not occur until the winter of the year to come (Arneborg et al., 2004). This results in a bottom water environment characterised by the winter temperatures. The benthic foraminifers reproduce and grow in the fjord during the spring and summer (Gustafsson and Nordberg 2001), thus incorporating this annually preserved winter temperature signal of the ambient deep-water into their shells. This results in a stable oxygen isotope signal mainly reflecting winter temperatures of the North Sea surface water and the Skagerrak intermediate water.”

As regarding the choice of JFM for winter months instead of the most commonly used DJF, this is due the deep-water turnover timing (Jan-March) described above. For example this can be seen clearly in Fig. 2 (C-E), where the bottom water exchange occurred in March 1993 (green rectangle). In addition, March is a month included in calculation of the winter NAO index (Hurrell, 1995), which has a documented effect on the deep-water exchange in the fjord (Björk and Nordberg, 2003). In contrast, it is very unlikely for bottom water renewal to occur in December, based on instrumental time series available for the fjord deep basin.

Similarly, May-August, are the months associated with foraminiferal growth in the fjord (Gustafsson & Nordberg, 2001), and hence we use those months when plotting instrumental observations for "summer season", instead of commonly used JJA. We added this information in section 4.3.

Major comment 3: General interpretation and potential link to the NAO: 3a) The section on the influence of the North Atlantic Oscillation (NAO) on the Gullmar Fjord (p 11, lines 1.6) should be moved to the introduction, with reference also to modern data from NE Europe/NE Atlantic. No reference to NAO during past climate periods should be mentioned as fact before this is discussed in the following paragraphs.

3b) The potential role of the NAO is discussed for the MCA and LIA. But what about the RWP and the DACP? Several studies have indicated that climate during these periods may also be linked to the NAO, and the manuscript would benefit form a more in-depth discussion – and reference to a wider range of previously published studies. It is also noteworthy that the authors only refer to work that shows comparable conditions as seen in Gullmar Fjord, omitting any other studies. The authors should also look towards studies on the Late Holocene from further afield, e.g. Portugal, East Greenland, the Labrador Sea.

Response: 3a) This has been done. We added the general info regarding the NAO into the introduction (see response to major comment 1) and also inserted the following text into the Study area section: "The deep-water exchange in the fjord is driven by wind forcing, and largely depends on wind direction and wind strength (Björk and Nordberg, 2003). The latter two properties, in turn, are governed by the NAO, which is the dominant mode of climate variability in the region during the winter. In Gullmar

fjord, the higher frequency and duration of NE winds, common during the negative NAO index periods, result in Ekman transport of surface water from the coast and facilitate coastal upwelling, which causes the deep-water exchange (Björk and Nordberg, 2003). In contrast, a positive NAO index causes stronger westerly winds, which prevent the deep-water renewals to occur. From the late 1970s the NAO has been in its prolonged positive phase and is believed to trigger severe seasonal hypoxia in the deep fjord basin (Nordberg et al., 2000; Björk and Nordberg, 2003; Filipsson and Nordberg, 2004).

3b) We added the potential role of the NAO for the RWP and DACP in the discussion: For RWP: "Other studies report an increased contribution of the Atlantic water to the East Greenland shelf, a reduced sea ice concentration and an increased export of fresh water from the Arctic with the East Greenland Current during the RWP, which are thought to be linked to a shift from negative to positive NAO after $\sim$500 BCE/0 CE and changes in the AMO regime (e.g. Perner et al., 2015 and references therein; Kolling et al., 2017)".

For DACP we also added references to a negative NAO mode as suggested by e.g. Orme et al, 2015 and Helama et al 2017.

Major comment 4: Hypoxia: 4a) On P. 7, line 5 and again Page 10, line 17-18 it is mentioned that C. laevigata has become a rare species in the Gullmar Fjord since 1990. One page 7 no explanation is given, page 10 the phenomenon is explained through hypoxia. However on page 15 a discussion is raised, whether it is due to hyposix and if yes, why. The discussion is certainly relevant but the fact that first a statement is made and later a discussion is raised, makes it confusing and somewhat messy. I would suggest just to refer to "see†discussion" instead of jumping the gun on p7 and 10. AlsoÂÍ the discussion on p 15 does not really fit well to the remaining text, and a solution may be to move this hypoxia discussion to its own, separate paragraph.

4b)With respect to this discussion, the authors basically explain the hypoxia as due to climate change. However, what about the increased nutrient supply seen due to more intensified farming seen in the general region, may this also play a role? Please discuss.

Response: 4a) We referred to discussion on p.7 and 10 regarding mentioning hypoxia and absence of C. laevigata, following reviewer's suggestion. We also added a separated subsection "Environmental conditions explaining absence or rare occurrence of C. lavigata in the record" to separate the discussion about hypoxia.

4b)We added the following sentence into the discussion: "To a large extent, the oxygen status of fjords and estuaries on the Swedish west coast, is controlled by climate (e.g. Nordberg et al., 2000; Filipsson and Nordberg 2004a, b), but the late Holocene changes in land use and organic enrichment in the fjord are also suggested to play a role (Filipsson and Nordberg, 2010)."

Major comment 5: Conclusions: The paragraph should be expanded with a synopsis on the discussion on the processes driving the climate change.

Response: We included the following sentences into the section: "Those warming (cooling) intervals during the last 2500 years were likely caused by the strengthening (weakening) of the AMOC linked to changes in atmospheric and oceanic forcing, such as the NAO, the AMO and, also perhaps, the ENSO, as suggested by other studies. In addition, changes in solar activity, volcanic forcing and, more recently, the anthropogenic greenhouse gas emissions and aerosols have also been important drivers of the observed climate variability during the late Holocene."

Minor comments: "Foraminiferal species: add author name to the species name the first time a species is mentioned: i.e., Cassidulina laevigata d'Orbigny, 1826; Adercotryma glomerata (Brady, 1878); Hyalinea balthica (Schröter in Gmelin, 1791)." - This has been corrected and the author's names have been added.

"P5, line 14; reservoir correction: How many bivalve shells and from how many sites

in the Gullmar Fjord is this reservoir correction based on?" – The shells were taken at four sites in a fjord deep basin (>100 m) and in total 14 samples were analysed for 14C reservoir effect. Four replicates were taken from each of 3 stations, while 1 station had only 2 replicates. The average reservoir age based on those 14 analysed samples is 497$\pm$30yr (Nordberg & Possnert, unpubl. data).

"P.9, line 24: add reference for timing of the foraminiferal growth season." – The reference has been added.

"P10, line 22-25: add references for the mentioned climatic intervals." – All references are present in the text above, just before the climate intervals are mentioned, however we also added some new references as suggested by reviewer 1.

"Page 15: Could the stronger recent warming of the Marlangen Fjord region be due to a more direct link to the northward flow of Atlantic water compared to Gullmar Fjord, which is not in direct contact with the core of the Atlantic water?" – It is true and we added this argument into discussion.

Figures and figure captions: "All terms and abbreviations should be explained."– This has been corrected.

"Fig 1: explain abbreviations for current names" – This has been done.

"Fig 1a: land masses are shown in a very pale gray – it would be easier to see, if landmasses were shown in a slightly darker colour." – The figure was changed accordingly.

"Fig. 2: BWT needs to be explained wither in the figures or the figure captions, as it should be possible to understand the figures without reading the main text." – This has been done.

"Fig 3A: I cannot distinguish between the upper and lower symbol; please make them more different." – The symbols have been changed.

"Fig. 5: explain BWT, RWP, DA, LIA etc in the figure caption. Mark the present BWT range on the figure.” – This has been done.

“Fig. 6: explain the pink and blue intervals.” – Has been done, as well.

“Fig. 7: Here “bottom water temperature” is written in full (not giving the abbreviation) – be consistent.” – This has been corrected.

“Some additional comments are provided as comments in pdf file of the manuscript (only relevant pages).” – Those changes were applied to the text accordingly.

Please also note the supplement to this comment:
https://www.clim-past-discuss.net/cp-2017-160/cp-2017-160-AC2-supplement.pdf

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Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2017-160, 2018.

Figure 1

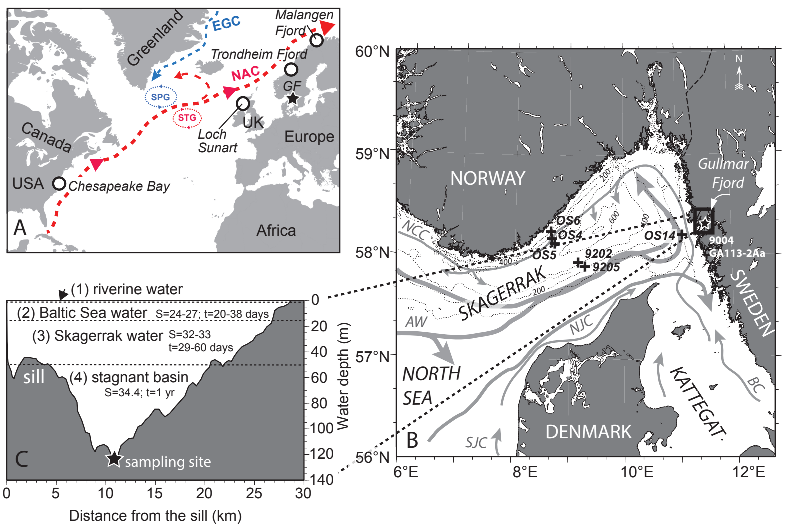

Fig. 1.

Figure 2

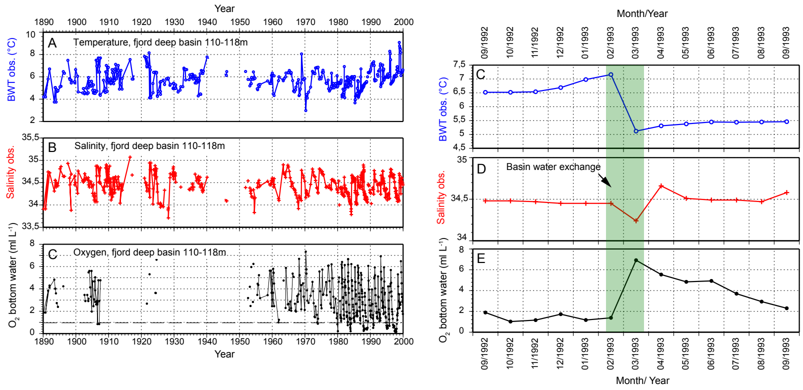

Fig. 2.

Figure 3

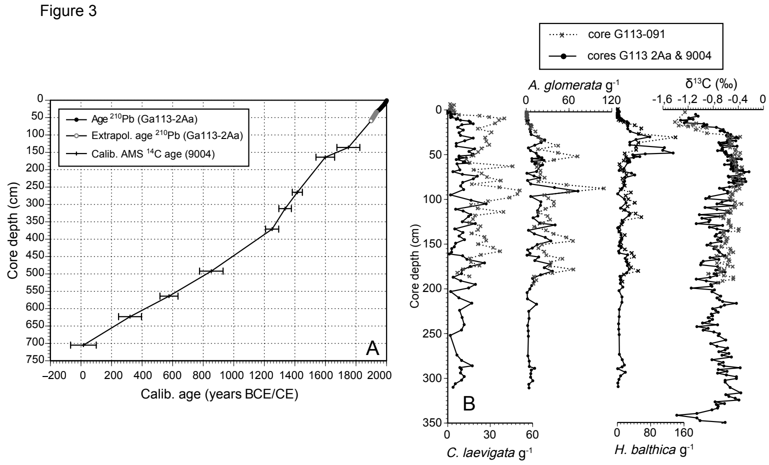

Fig. 3.

Figure 4

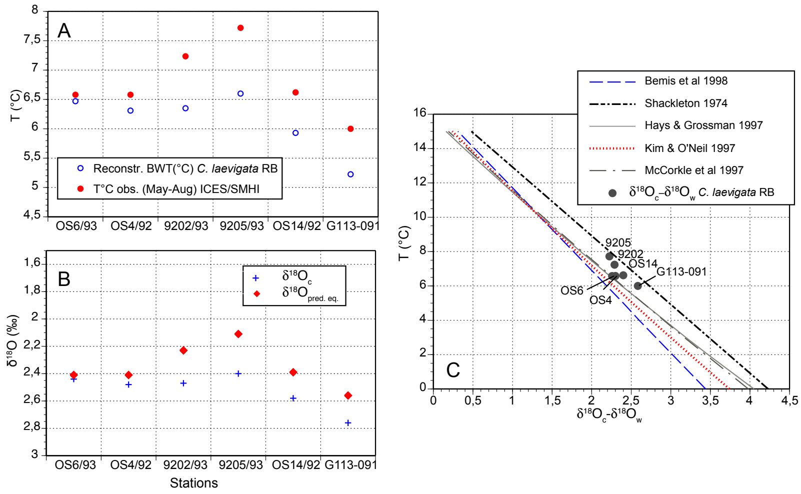

Fig. 4.

Figure 5

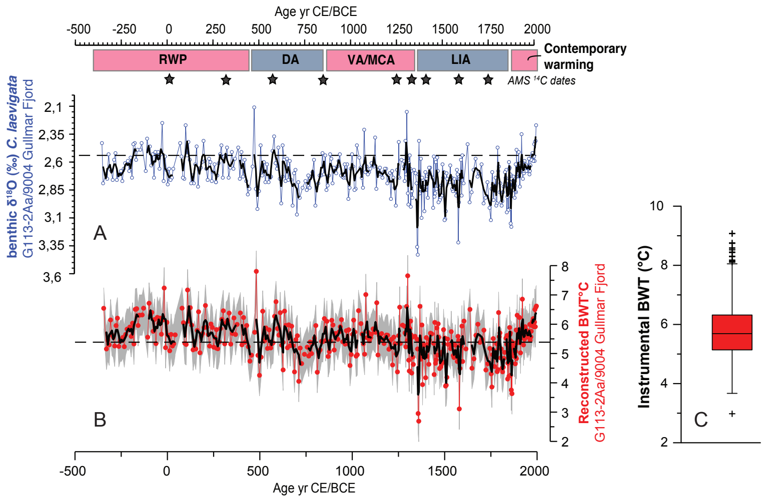

Fig. 5.

Figure 6

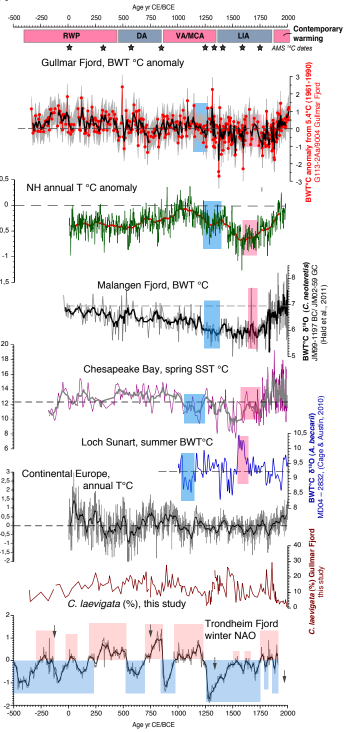

Fig. 6.

Figure 7

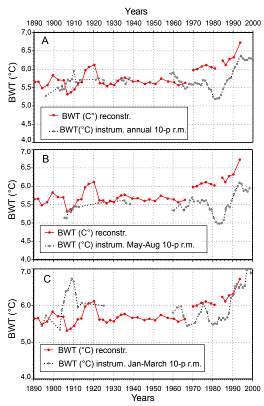

Fig. 7.

Figure 8

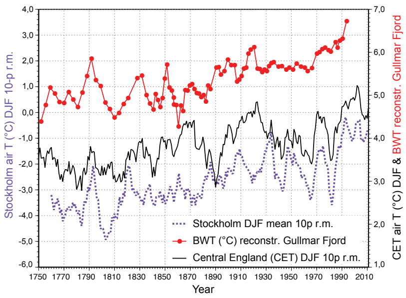

Fig. 8.

Supplementary Fig. 1

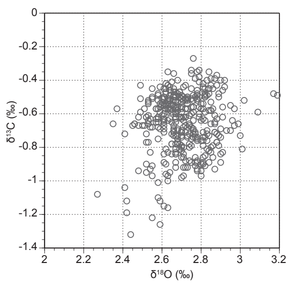

Fig. 9.