Response to Reviewer #2

General comments: *The paper deals with the Atlantic Multidecadal Oscillation (AMO) found in the instrumental record (since AD 1850). The authors claim that they found that this decadal oscillation pattern is indeed the dominant SST pattern for the entire Holocene. The authors also address two climate events: the cold 8.2 ka event and the Medieval Warm Period (c. AD 800–1300) in relation to the AMO. Although this paper addresses an interesting aspect to describe the Holocene SST variability, I feel that their argument is not fully supported by the current Holocene proxy data. I have difficulties with the interpretation of the pattern, cooling in the North Atlantic is not related to AMO or NAO, it is related to the response mainly to the insolation. NAO may explain some heterogeneities. My specific comments that the authors should consider for their paper are listed below.*

Response: See our point-to-point response to your specific comments, as all of your general comments are addressed in it.

Reviewer's comment 1. Compilation of the Holocene SST data:
To investigate the Holocene SST variability and its similarity with the AMO in the Atlantic Ocean, the authors used mostly the GHOST data (Kim, J.-H., Schneider R.R., (2004), GHOST global database for alkenone-derived Holocene sea-surface temperature records. Available from: http://www.pangaea.de/Projects/GHOST) but added a few additional Mg/Ca and δ18O records to their Holocene dataset. The statistics and interpretations by the authors are therefore based on this mixed proxy dataset. In my view, this approach strongly biased the results and thus influenced their interpretation. Recently, Leduc et al. extended the GHOST dataset and compiled a new dataset for the Mg/Ca (the paper is accepted for the publication in Quaternary Science Reviews). They confirmed the SST distribution pattern previously described based on alkenone data. However, comparison of Holocene SST records derived from two different methods reveals contrasting – sometimes divergent – SST evolution, particularly at low latitudes where SST records are abundant enough to infer systematic discrepancies at a regional scale. This suggests that a strong contrast in the ecological responses of coccolithophores and planktonic foraminifera to winter and summer oceanographic conditions can be the ultimate reason for seasonal differences in the origin of the temperature signal provided by these organisms. In summary, it is not appropriate to use a mixed dataset derived from different proxies.

Response: Firstly, we used a mixed proxy dataset in this study because multiple proxies have frequently been used to understand past climate changes (e.g. Mann, 2002; National Research Council, 2006; Moberg et al., 2005; Kaufman et al., 2009; McGregor et al., 2010). "Multiproxy" methods can exploit the complementary strengths of each of these proxies, thereby yielding more reliable reconstructions of the large-scale climate changes during the past (Mann, 2002). Secondly, we examined the robustness of our results using the subset of 19 alkenone based and 5 non-alkenone based SST records. The EOF01 of the alkenone based, the non-alkenone based, and the entire 24 SST records remain the same (for details, please see page 2473, last paragraph and Table 1). Therefore, the use of multiple proxies does not change any of our conclusions. This also suggests that our results and interpretation are not biased as indicated by the reviewer. For comparison, the results based on merely the alkenone based SST records are shown in the supplement. [We do not have access to Leduc et al. paper, as it is not yet published.]

Reviewer's comment 2. First EOF: long-term trend vs centennial-millennial cycles
2a) *The most dominant SST pattern (EOF1) in Fig. 3a,b is a trend, which has been interpreted as a response to insolation changes in previous studies as well as in the paper presented here. However, it is not entirely clear how this insolation-driven trend is related to the AMO pattern. Are they the same thing? The trend can be considered more reasonably insolation-driven glacial-interglacial cycles while the AMO pattern might be associated with shorter (centennial to millennial) cycles at the best, like shown in Fig. 4. The authors should clarify whether they are referring both trend and cycles in relation to the AMO. If yes, firstly, it should be explained how both insolation and AMO are connected to the SST trend.* **2b)** *Secondly, it should be explained how significant the residual of PC1 showing millennial cycles is. Most proxy records presented in this study can be used to study the Holocene SST trend with confidence. However, considering the time resolution of proxy records and the amplitude of SST changes during the Holocene, it is uncertain how credible the residual of PC1 is for the investigation of centennial to millennial cycles.* **2c)** *For example, the analytical uncertainty of alkenone records can be about 0.5°C and the calibration uncertainty can be +/- 1.5°C.*

Response to comment 2a: The EOF method is used to decompose the SST variations from different locations (or grid points) into spatial variations (modes) and temporal variations (von Storch and Zwiers 1999). To understand the results of our study, we need to keep in mind the difference between the spatial modes and the temporal variations. The first spatial mode (EOF01) of the modern observed SST showed a basin-wide spatial structure in the North Atlantic (see Fig.3a, and Fig. S1), denoted as the AMO mode (or AMO pattern). The principal component (temporal variations, termed as PC01) associated with EOF01 contains a significant multidecadal cycle, which can be considered as the AMO index.

The first spatial mode (EOF01) of the Holocene SST shows a dominant and coherent SST variation in the extra-tropical North Atlantic. This spatial mode is similar to the first spatial mode of the modern observed SST (Fig.3a), suggesting that the Holocene and the observed SST share similar spatial variations. The temporal variations (PC01) of the first spatial mode of the Holocene and the observed SST differ. As an analog, the EOF01 of the Holocene SST is called the AMO-like pattern, while the associated temporal variations (PC01) can be considered as the index of this AMO-like pattern. The temporal variations of PC01 of the Holocene SST are clearly related to solar insolation (Fig. 3b). Superimposed on the insolation-driven trend in PC01 are centennial variations, which presumably are related to the THC (Fig.4). In summary, the long-term trend and the centennial variations of PC01 of the Holocene SST are both related to the AMO-like pattern (Fig. 3a). In other words, our results suggest that the SST variations in the North Atlantic contain an AMO-like pattern. The temporal SST variations associated with this AMO-like pattern varied on different temporal timescales and is (presumably) controlled by different physical processes. We suggest the long-term variations associated with the AMO-like pattern during the Holocene are controlled by solar insolation, while the centennial variations are related to THC. Some modeling studies have argued that multidecadal variations of this pattern during the instrumental period are also related to

THC, though historical oceanic observations are not sufficient to fully support such a relationship.

Response to comment 2b: The MTM spectrum suggests that the centennial cycles of PC01 are significant at the 95% confidence level. Similar centennial cycles were also identified by Rimbu et al. (2004). Because the centennial SST variations are closely related to THC and their spatial variations are also supported by proxy data for the 8.2kaBP cold event and the medieval warm period (Fig.5), the centennial variations of the residual of PC01, though small in magnitude, are very likely real signals.

Response to comment 2c: We thank the reviewer for bringing to our attention the possible uncertainties of SST reconstructions based on alkenone records. For a single SST record, those uncertainties are large. If multiple SST records are analyzed, those uncertainties are very likely averaged out. In our study, the synthesis of 24 SST records should reduce the analytical uncertainty of the alkenone records from 0.5°C to $^{0.5}\!\big/_{\sqrt{24}} = 0.1\,^{\circ}\mathrm{C}$, and the calibration uncertainty from to +/- 1.5°C to $^{1.5}\!\big/_{\sqrt{24}} = 0.3\,^{\circ}\mathrm{C}$ (Dowdy et al. 2004).

Reviewer's comment 3: AMO-SST vs. NAO-SST pattern:
3a) *This paper describes the monotone SST pattern for the entire Atlantic Ocean, which resembles the AMO SST pattern (see Fig. 3a). However, if we consider only alkenone records (see also the comments above), which is the most dominant records considered in this paper, the SST pattern is indeed heterogeneous, showing a contrasting pattern between the North Atlantic and tropical western Atlantic as well as between eastern Mediterranean/Northern Red Sea and western Mediterranean/eastern North Atlantic. Such patterns do not appear in any seasonal AMO-SST patterns.* **3b)** *The authors claim that the Holocene AMO-SST pattern can be explained by the THC changes. If it is the case, the Holocene SST pattern in the South Atlantic should show an anti-phase compared to that of the North Atlantic. At least, the existing data do not fully support this interpretation. The core showing a warming in the Southeast Atlantic is not necessarily representative of the whole South Atlantic. This record can be also explained as a local signal according to the original paper (Kim et al., 2003) considering the local oceanic frontal system in the eastern boundary system in the Southeast Atlantic. It is also worth to note that the authors describe a whole basin wide homogeneous SST pattern in the Atlantic Ocean in relation to the AMO (see Fig. 3a) but the THC mechanism predicts an anti-phase SST pattern between the North and South Atlantic.* **3c)** *The authors also argued that the basin-wide homogeneous SST pattern in the North Atlantic induced dipolar SLP pattern in the Atlantic region and thus an anti-phase SST pattern between the eastern Mediterranean and the North Red Sea and the rest Atlantic. However, AMO related SLP pattern does not produce such an anti-phase SST relationship. That is why the NAO has been introduced to explain this SST pattern in the previous studies. It should be also noted that the NAO-related SST pattern is not considered as the dominant Holocene SST pattern in the previous studies. It is rather considered as a secondary order pattern superimposed on the insolation induced SST pattern.*

Response to comments 3a: The AMO is usually defined by SST in the North Atlantic Ocean, though several previous studies argued that an AMO signal can also be found in the South Atlantic Ocean. Due to very few proxy records available in the South Atlantic, the focus of this study is the Holocene SST variations in North Atlantic Ocean. We have stressed this point everywhere except the last paragraph of the paper. Additionally, we stated that there is a basin-wide SST pattern in the *North Atlantic*, not that 'there is a monotone SST pattern for the *entire Atlantic Ocean'*. To clarify the confusion, we will reiterate this point when revising the manuscript.

The reviewer argued that Holocene SST variations in the north Atlantic is opposite to SST in the southwest tropical North Atlantic (our site 14) as well as the eastern Mediterranean and Red Sea. Because this out-of-phase relationship is not shown in the observed AMO-pattern, they argue that the Holocene SST pattern is not AMO-like. However, we believe the Holocene SST pattern is indeed AMO-like for the following reasons:

1) The AMO mode as revealed by EOF01 of the instrumental data showed coherent SST variations in the North Atlantic, weak SST variations in the tropical Atlantic and opposite but weak SST variations in the South Atlantic (Fig.3a). The weak SST eigenvector of EOF01 in the tropical and south Atlantic suggest that the temporal variations of SST in those regions are not always follow the temporal variations of PC01. In other words, in certain periods, the SST in those regions varied simultaneously with the SST in the extra-tropical North Atlantic. In other periods, the SST in those regions varied oppositely to the SST in the extra-tropical North Atlantic. As a result, the boundary between opposite (or between positive and negative) SST variations is shifting north or south on different period. If we considered only the alkenone records, the EOF01 showed coherent SST variations in the extra-tropical North Atlantic, but opposite variations in the tropical (south of 10^{o}N) Atlantic and the eastern Mediterranean and Red Sea. Because we did not find any opposite variations in the extra-subtropical North Atlantic (see our sites 1-13), the EOF01 of the Holocene SST is still AMO-like pattern except the boundary between opposite SST variations during the Holocene was shift to around 10^{o}N. This was also supported by the modeling study of Lorenz et al. (2006). Their modeling study suggested that, when forced by orbital insolation changes during the Holocene, the model could simulate a basin-wide cooling in the North Atlantic, but a warming south of 10^{o}N (see their Fig.4b).

2) We analyzed simulations made by two fully coupled atmosphere-ocean models. Correlations between the modeled AMO index (averaged SST over 0-60N, 7.5-75W) and the modeled surface temperature showed a reverse relationship between the extra-tropical North Atlantic and the southwest tropical Atlantic (where site 14 is located) and the eastern Mediterranean and Red Sea (see the Figure.R1 below). These results suggest the AMO pattern can indeed demonstrate opposite SST variations in the extra-tropical North Atlantic and the west tropical Atlantic, as well as the eastern Mediterranean and Red Sea. Those model results also suggest that the AMO-like pattern can show such an out-of-phase relationship during the Holocene.

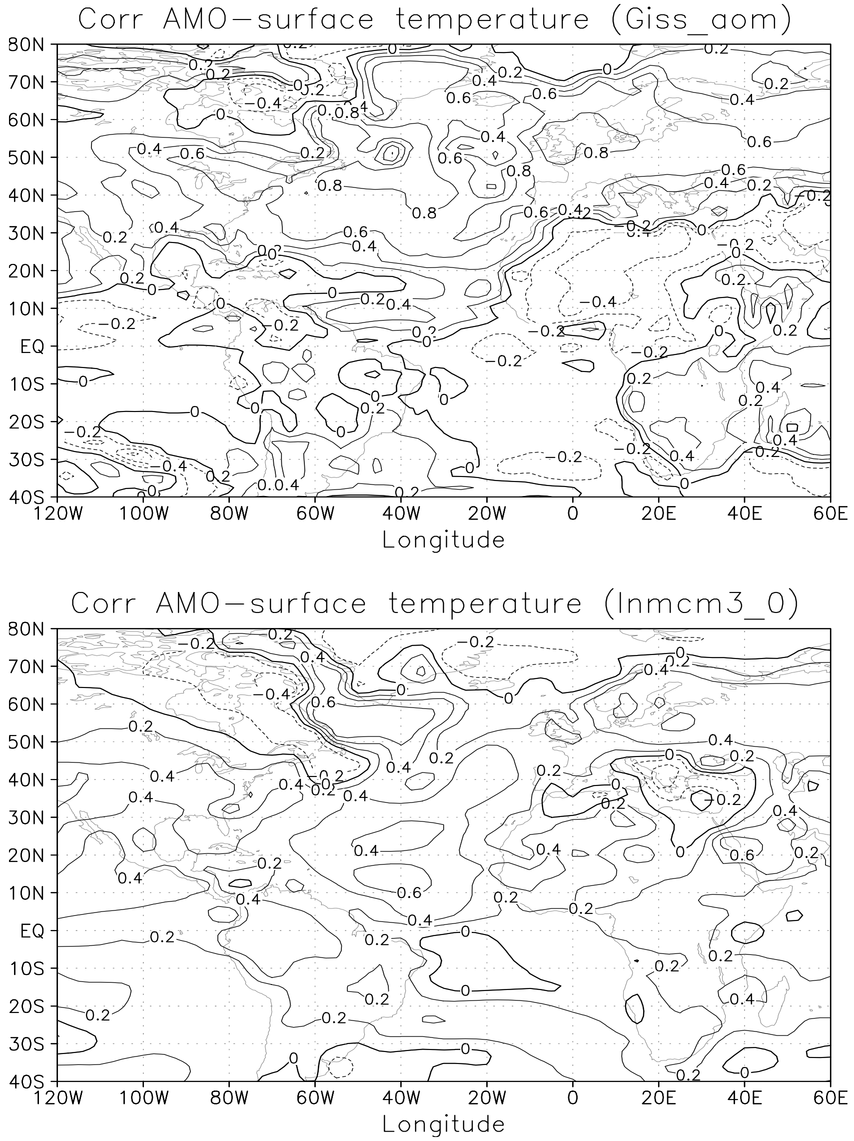

Figure R1. Correlation between annual AMO index (averaged SST over 0-60N, 7.5-75W) and the annual surface temperature (TS) simulated by GISS-AOM (251 years) and INMCM3.0 model (330 years). Both models are fully coupled atmosphere-ocean models. Before calculating the correlation, the data were detrended and smoothed with 19 years running filter.

3) Though the SST variations in the eastern Mediterranean and Red Sea are related to SST variations in the North Atlantic, they are also influenced by other factors (e.g. ENSO and North Pacific, Felis et al., 2000). It is interesting to note that the proxy records in the Red Sea were used to reconstruct ENSO and PDO variations in the Pacific Ocean (McGregor et al., 2010). The net effect of North Atlantic influences and all other factors are responsible for the SST variations in the eastern Mediterranean and Red Sea. In other words, teleconnections between SST in the North Atlantic and the eastern Mediterranean and Red Sea may be reinforced (or weakened) by the impacts of other

factors. In fact, many of the well-known teleconnections are unstable because those teleconnections come and go on different periods (e.g. Kumar et al., 1999; Lu and Greatbatch, 2002; Hilmer and Jung 2000). Therefore, it is reasonable that the teleconnection between North Atlantic and the eastern Mediterranean and Red Sea during the Holocene is different from the modern times.

4) The AMO is typically defined by SST in the North Atlantic Ocean. If a basin-wide SST pattern (e.g. the EOF01, and the 8.2ka event and MWP) occurs in the North Atlantic Ocean, it can be interpreted as an AMO-like pattern. Our interpretation of AMO-like SST pattern in North Atlantic is similar to the interpretation of El Nino/La Nina SST variations in the Pacific Ocean. During the El Nino/La Nina cycle, the SST in the eastern tropical Pacific is usually (but not always) out-of-phase with the SST in the western tropical Pacific Ocean. However, an El Nino/La Nina event is defined merely by the SST in the eastern tropical Pacific Ocean. If the eastern tropical Pacific (e.g. the Nino 3 region) is warm (cold), we say there is an El Nino (La Nina) event no matter whether the western tropical Pacific is cold, warm or in neutral conditions.

Response to comments 3b: The AMO is usually defined by SST in the North Atlantic Ocean. We also focused on Holocene SST variations in the North Atlantic Ocean because there are very few SST records available in the South Atlantic. Additionally, we interpret the basin-wide homogeneous SST pattern in the *North Atlantic Ocean*, not '*a whole basin wide homogeneous SST in the Atlantic Ocean*', in relating to AMO. We also suggest the long-term variations (PC01) associated with the AMO-like pattern (EOF01) during the Holocene are controlled by solar insolation, while the centennial variations are related to THC. The THC can cause a dipolar pattern between the North Atlantic and the mid- and high-latitude South Atlantic Ocean. This was also supported by the AMO variations during the instrumental periods. Our Fig.3a, Fig. S1 and the Fig.1 of the reviewer #1 all suggested that, compared to North Atlantic, the opposite SST variations are mainly appeared on high latitude South Atlantic. Due to the paucity of SST records available from the South Atlantic, the first EOF of the Holocene SST could not resolve the dipole pattern between the North and South Atlantic. We pointed out this on page 2482. We also said that more SST records in the mid- and high- latitude South Atlantic are need to prove or disprove these seasaw SST variations during the Holocene. Despite the paucity of SST records from the South Atlantic, we believe it is still reasonable to call the EOF01 of Holocene SST AMO-like because most of the previous studies defined the AMO pattern in the North Atlantic.

Response to comments 3c:

The reviewer argued that the NAO could explain the out-of-phase relationship between SST in North Atlantic and the eastern Mediterranean and Red Sea. This statement is incorrect for summer and annual NAO and is only partly true for the winter season. The winter NAO can explain the anti-phase SST pattern between the east Mediterranean and Rea Sea and the *eastern* North Atlantic, but it cannot explain the basin-wide SST variations in the extra-tropical North Atlantic. The summer and annual

NAO cannot produce the anti-phase SST pattern between the east Mediterranean and Rea Sea and the rest Atlantic (see our Fig6a and the following Figure.R2). It is worth noting that, in high latitudes, the variations of alkenone are related to warm season temperature (Vaillencourt et al., 2009). In other regions, the seasonality of the Holocene SST cannot be resolved by the alkenone and Mg/Ca SST reconstructions. The proxy SST records used in this study are commonly interpreted as the annual temperature (Marchal et al., 2002). Therefore, we cannot use the winter NAO pattern to explain the annual SST variations during the Holocene.

Our study as well as modeling studies by others showed that the AMO can induce a dipolar SLP (NAO) pattern in the Atlantic region. Because the NAO leads to an anti-phase relationship between the temperature in the Middle East and the Atlantic, it is thus reasonable to argue that the AMO-related dipolar SLP pattern could induce an anti-phase SST pattern between the eastern Mediterranean and Red Sea during the Holocene. Our reasoning is that the AMO induces a dipolar SLP (NAO) pattern and the NAO then induces the reversed sign SST variations in the eastern Mediterranean and Red Sea. In other words, the NAO atmospheric pattern did play some roles on the Holocene SST variations in the eastern Medeterranean and Red Sea, but the NAO is caused by oceanic (AMO) SST variations. This interpretation reconciles the AMO-like pattern in this study and the NAO-like SST pattern as suggested in previous studies.

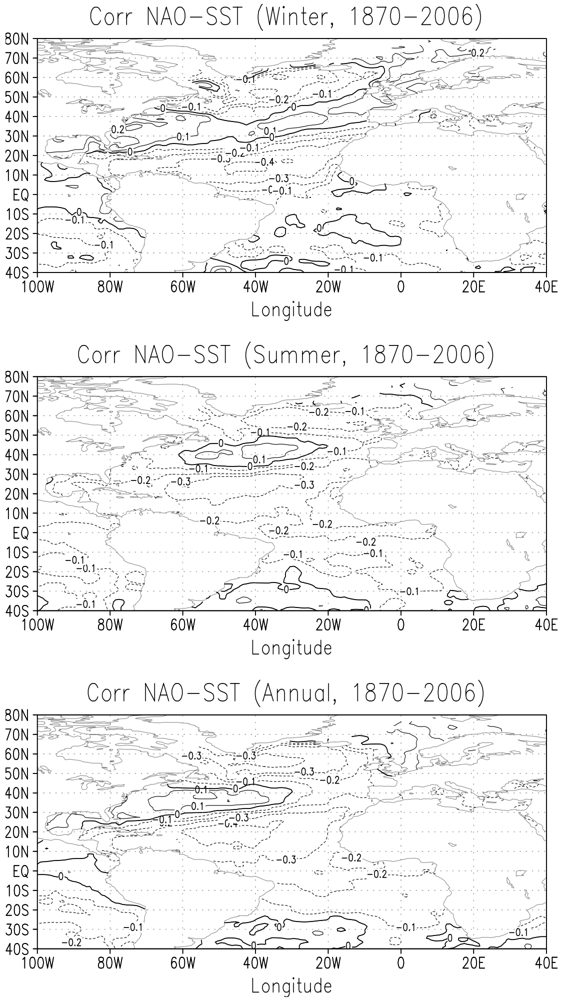

Figure R2. Correlation between NAO index and the SST on winter (upper panel), summer (middle panel) and annual (lower panel) during 1870-2006. The NAO index was from http://www.cru.uea.ac.uk/cru/data/nao/nao.dat, and the SST was from HadISST1.

In summary, we feel it is more appropriate to interpret the Holocene SST in the North Atlantic as an AMO-like pattern, rather than NAO-pattern for the following reasons. Detail of those discussions can be found at our section 4.

1) The AMO is a basin-wide mode of *ocean* variability occurring in the North Atlantic Ocean which has its principal expression in the SST field. Usually the AMO index (or temporal variations of AMO) is defined as the average of the detrended SST over 0-60N, and 7.5-75W. Recent studies also use the first principal component (PC01) of the detrended SST in the North Atlantic Ocean as the AMO index. The NAO is a dominant pattern of *atmospheric circulation* variability. It refers to the seasaw variations in atmospheric mass with centers of action near Iceland and over the subtropical Atlantic from the Azores across the Iberian Peninsula. Most commonly the NAO index is based on the sea level pressure (SLP) difference between the Subtropical (Azores) high and the Subpolar (Island) low. The Climate Prediction Center at NOAA also uses the PC01 of the monthly 500hPa height to define the NAO index. Therefore, AMO is a *SST*

pattern, while NAO is fundamentally an *atmospheric* pattern. The two phenomena should be related to each other. To some extent, they may be manifestations of the same basic climatic system phenomenon, just manifested somewhat differently for the atmosphere and the ocean. We point this out on page 2479, lines 26-29. Because we are analyzing the SST variations during the Holocene, it is better to interpret the SST pattern as oceanic (AMO) pattern.

2) AMO is associated with basin-wide SST anomalies in the North Atlantic, while NAO is associated with tripolar SST anomalies in the North Atlantic. We find that the spatial variations of Holocene SST over the extra-tropical North Atlantic are dominated by basin-wide, not tripolar variations. Our interpretation is also supported by the modeling study of Kim et al. (2004, see their Fig. 6), though they interpret their results as NAO-like pattern. For detail, see page 2479, 2nd paragraph, of our CPD paper.
3) The SST anomalies associated with NAO are dominated by interannual variations (Fig.6 and S1), while the SST anomalies associated with AMO are dominated by decadal and longer scales variations (Fig.3a and Fig.S1). The proxy SST records cannot resolve SST variations on interannual time scales.
4) Both basin-wide and tripolar SST patterns in the North Atlantic are associated with a similar bi-polar atmospheric structure, the NAO atmospheric pattern. In other words, one NAO atmospheric pattern may be associated with different SST patterns. Our interpretation is again supported by the modeling study of Rimbu et al. (2004, see their Fig.9). Rimbu et al. interpret the Holocene SST as NAO-like, but their Fig.9 did suggest that similar NAO pattern is associated with different SST patterns. For detail, see page 2480 of our CPD paper.

Reviewer's comment 4: 8.2 ka event and MWP:

It is obvious from Figure 5 that most records are coming from the Northern Hemisphere and only a few records from the Southern Hemisphere. The provided Southern Hemisphere records do not provide strong supporting evidence of the homogeneous SST pattern, especially for the MWP. Therefore, their interpretation related to 8.2 ka event and MWP are still speculative. Definitely, more records are needed from the Southern Hemisphere to confirm or disprove their claim. Most interestingly, the SST pattern for 8.2 ka event and MWP in Fig. 5 is not the same as that in Fig 3 (EOF01). Therefore, it is not clear whether the physical mechanisms behind them should be the same at all.

Response: We agree that there are very few paleo temperature records available from the South Hemisphere. Because AMO is usually defined by SST in the North Atlantic Ocean, the lack of proxy records in the south Atlantic did not per se affect our interpretation of an AMO-like pattern in the North Atlantic. Our results clearly showed that there is a basin-wide cooling (warming) during the 8.2ka event (MWP) in the North Atlantic, suggesting an AMO-like cold (warm) phase in the North Atlantic during both periods. Though AMO is the dominant signal in the North Atlantic; it is presumably not the dominant signal in the eastern Mediterranean and Red Sea. Other factors (local or remote) may also influence the temperatures in this region. Fig.5 just suggests that other factors such as those of ENSO and PDO (Felis et al., 2000) override the impact of AMO during both periods.

Fig.5 showed the observed temperature anomalies (in C) on ocean and land during the AMO warm and cold phases, while Fig.3a showed the spatial mode EOF01 of observed SST in the ocean (the eigenvector, which is unit-less because the observed SST is detrended and normalized before EOF analysis). However, the spatial distributions of the temperature variations are very similar because both figures described the AMO pattern from different perspectives.

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