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REPLY

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Key Point:

- Reply to Rashid et al. [2016] about the winter SSTs in the North Atlantic and northern Indian Ocean

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Reply to comment by Rashid et al. on "Asynchronous variation in the East Asian winter monsoon during the Holocene"

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Abstract Rashid et al. (2016) questioned the use of the Mg-/Ca-based sea surface temperature (SST) data from the subpolar North Atlantic Ocean as well as the alkenone-based SST data from the western tropical Indian Ocean we used to reflect the winter SSTs or regional changes in the Holocene SSTs. We first would like to reemphasize that the main message we wanted to convey in our article is that the East Asian winter monsoon (EAWM) strength decreased and then increased again during the Holocene but with a substantial lag in southern China as compared to northern China. We, of course, wanted to back up our model results with published SST data that may have detected such an asynchronous variation in the EAWM. For convenience, we used a series of proxy records extracted from the extended Global database for alkenone-derived HOlocene Sea-surface Temperature (GHOST) database that were initially intended to provide a template of Holocene SST trends for model/data comparison purpose (http://doi.pangaea.de/10.1594/PANGAEA.737370). Rashid et al. (2016) questioned our model/data comparison exercise, arguing that the data we present in Zhang et al. (2015a) cannot be used to track leads and lags in winter SSTs in the North Atlantic and northern Indian Ocean. Below we address point by point the issues raised by Rashid et al. (2016) and thank the authors for giving us the opportunity to sharpen our model/data comparison analysis.

1. SST of the Subpolar North Atlantic Ocean

The first point raised by *Rashid et al*. [2016] concerns a series of proxy SST data from the northwestern Atlantic Ocean core OCE326-26GGC that was used to indicate middle latitude North Atlantic boreal winter SST variations during the Holocene, especially for the rising trend in SSTs between 4.5 ka and 2 ka [*Zhang et al*., 2015a, Figure 11b3], which is just the curve of the Mg-/Ca-based SST from the planktonic foraminifera *Globigerina bulloides* from the Laurentian Fan core OCE326-26GGC [*Keigwin et al*., 2005, Figure 5b]. This curve is referred to as Figure 1b2 in *Rashid et al*. [2016]. After having carefully checked the data and curves in our paper [*Zhang et al*., 2015a], we realized that the citation of *Sachs* [2007] for the Mg-/Ca-derived SST from the core OCE326-26GGC is a misuse of *Keigwin et al.* [2005], and we thank *Rashid et al.* [2016] for reporting us this mistake.

Then, *Rashid et al*. [2016] question our interpretation of the Laurentian Fan core OCE326-26GGC SST results in terms of seasonality and depth habitat. We acknowledge that seasonality and depth habitat in this region and elsewhere is a long-standing debate so that different interpretations and opinions may vary among different authors [see, e.g., *Hillaire-Marcel and de Vernal*, 2008]. As mentioned by *Rashid et al.* [2016], *G. bulloides* seasonality may vary upon latitudes and cite, in particular, the study by *Tolderlund and Bé* [1971]. This paper reports seasonal fluxes of *G. bulloides* being maximum during summer at two stations located at ~56° and 53°N, and during winter at three stations located at ~44°, 35°, and 32°N in the northwestern Atlantic [see *Tolderlund and Bé*, 1971, Figure 5]. Core OCE326-26GGC being located at 43°N, the study by *Tolderlund and Bé* [1971], tends to confirm our interpretation of OCE326-26GGC core in terms of winter SST.

Rashid et al. [2016] then turn to core MD99-2251, that was recovered further to the north and hence may be located in a region where *G. bulloides* is more sensitive to summer temperatures [*Tolderlund and Bé*, 1971]. We, however, did not discuss this record in length since, as we quoted, "The core however was collected from an area at the boundary of negative anomalies identified in the KCM simulated SST EOF1 component (Figure 11a)" [*Zhang et al*., 2015a]. However, *Rashid et al*. [2016] finish their comment on core MD99-2251 by comparing its Mg/Ca signal to the one published in *Berner et al*. [2008] that represent August SSTs and point out that the data "do not show any rising trend in SSTs at 4.5 ka either" [*Rashid et al*., 2016].

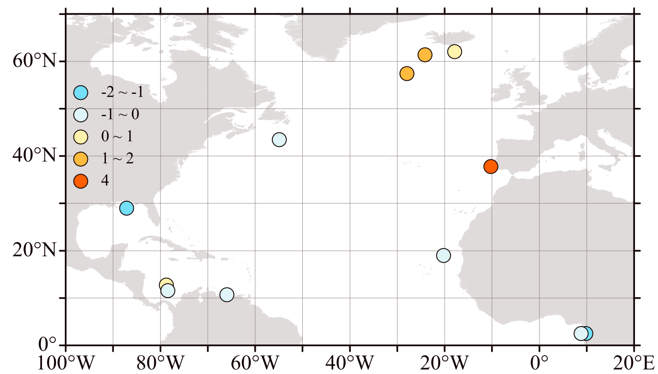

Figure 1. Mg-/Ca-based SST linear trends (°C/9.5 ka) during the Holocene (9.5–0 ka BP) over the North Atlantic. Summary of Mg/Ca records are described in Table 1.

Although *Rashid et al.* [2016] do not develop further this remark, we find it encouraging that August SST does not resemble to the MD99-2251 Mg/Ca signal that we initially suggested as being reflective of winter temperature.

In addition, we would like to perform further comparisons between model results and proxy records to confirm our results as model-data comparisons can reduce the seasonal bias in proxy records [*Schneider et al.*, 2010; *Lohmann et al.*, 2013]. Mg/Ca records generally reveal warming trends in the subtropical and subpolar North Atlantic (north of 30°N) except the eastern part of the subtropical North Atlantic during the Holocene (Figure 1, Table 1), which fit well with modeled winter and spring SSTs (Figures 2a and 2b) but differ somewhat from summer SSTs [*Zhang et al.*, 2015b] as estimated in the Kiel Climate Model (KCM) Holocene transient simulation (HT) simulation [*Jin et al.*, 2014]. The warming trends in the subtropical and subpolar North Atlantic (north of 30°N) can be attributed to the increasing winter insolation (Figure 3) [*Liu et al.*, 2003; *Came et al.*, 2007; *Leduc et al.*, 2010]. North Atlantic SSTs tend to extend their memories from winter to spring as shown in Figure 2c showing high correlations between winter and spring SSTs on interannual to interdecadal timescales even when the linear trends (insolation forcing) were removed (Figure 2d), generating similar modes in the changing trends of winter and spring SSTs during the Holocene in terms of spatial pattern and amplitudes (Figures 2a and 2b) in spite of significantly different changing trends in winter and spring insolation (Figure 3). The lagged response of spring SSTs to winter insolation has also been suggested by other studies [e.g., *Laepple and Lohmann*, 2009; *Timmermann et al.*, 2014]. These suggest that variability in spring SSTs in the North Atlantic during the Holocene probably resulted from winter SSTs. Winter SSTs in the North Atlantic store their signals not only in winter water but also in spring water. Therefore, Mg/Ca records in the subtropical and subpolar North Atlantic can reflect winter SSTs even if there were no evidence for a calcifying population of planktonic foraminifera being present in winter as planktonic foraminifera records (both *N. pachyderma* (s) and *G. bulloides*) in this area can record spring ocean conditions [*Jonkers et al.*, 2013; *Rashid et al.*, 2016] that receives signal from winter SSTs.

2. Western Indian Ocean SST

Rashid et al. [2016] then turn to the reliability of our interpretation of the alkenone-derived SST record from core MD77-194. They start by arguing that long-distance transport of alkenones may obscure the SST signal from the region. This process is of course probably at least partly at play at this site, and we further note that such process may even alter foraminifera at other locations [*van Sebille et al.*, 2015], in the same manner than

Table 1. Summary of Mg/Ca Records Used in the Study

ID	Core name	Latitude (°N)	Longitude (°E)	Linear trend (°C/9.5 ka)	Reference
1	RAPID-12-1 K	62.09	−17.82	0.7	*Thornalley et al.* [2009]
2	ODP984	61.425317	−24.08242	1.4	*Came et al.* [2007]
3	MD99-2251	57.447833	−27.90783	1.2	*Farmer et al.* [2011]
4	OCE326-GGC26	43.483	−54.867	−0.9	*Keigwin et al.* [2005]
5	MD02-2575	29.0017	−87.1188	−2.0	*Nürnberg et al.* [2008]
6	ODP999	12.75	−78.733	0.9	*Schmidt et al.* [2004]
7	VM28-122	11.567	−78.417	0	*Schmidt et al.* [2004]
8	PL07-39PC	10.7	−65.942	−0.2	*Lea et al.* [2003]
9	MD03-2707	2.502	9.395	−1.7	*Weldeab et al.* [2007a]
10	GeoB4905-4	2.5	9.39	−0.8	*Weldeab et al.* [2007b]
11	BOFS31_1K	18.9979	−20.1621	−0.4	*Elderfield and Ganssen* [2000]
12	MD99-2334	37.801167	−10.17133	4.0	*Skinner and Elderfield* [2005]

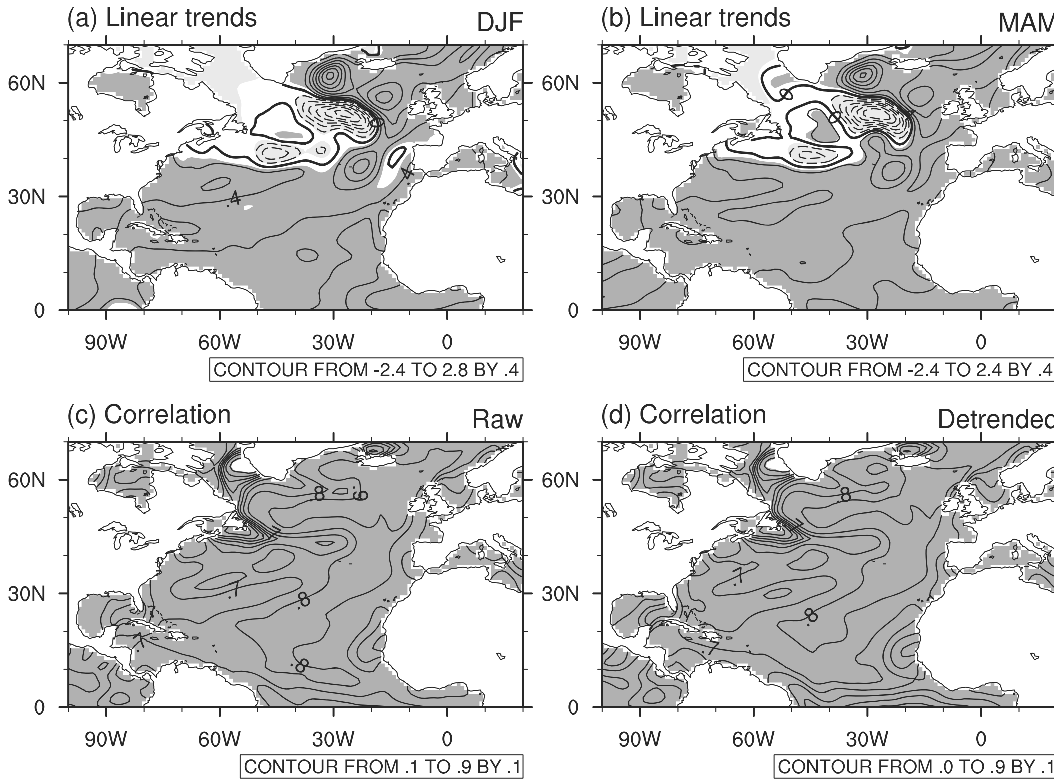

Figure 2. Changing trends (°C/9.5 ka) in (a) winter and (b) spring North Atlantic SSTs during the Holocene as estimated in the KCM HT simulation. Point-to-point correlations between December–February (DJF) and March–May (MAM) SSTs on interannual to interdecadal timescales (c) without and (d) with the removal of linear trends (insolation forcing). Dark (light) shading indicates areas where trends (correlations) are positively (negatively) significant at the 99% confidence level.

for virtually every single proxy record from the marine realm. This process cannot be avoided, though, but other records suggest that the alkenone-based winter SST trends we present in *Zhang et al.* [2015a] are not an artifact (see detailed discussion below).

Rashid et al. [2016] further provided four evidences arguing against our reported winter SST record ((a) The core MD77-194 does not contain sediments younger than 2.71 ka. (b) Fluctuation of 0.3 °C SST between 4.5 ka and 2 ka is negligible in estimating the SSTs from alkenone concentration from core MD77-194. (c) Modern analog technique-derived (MAT-derived) SST estimates from the same core (i.e., MD77-194) do not show the "apparent cooling of 0.2°C," rather it shows the warming trend which is bigger than 0.2°C. (d) There is no abrupt increase in SSTs in the eastern (it is not the western) tropical Indian Ocean) to conclude that the alkenone-derived SSTs from core MD77-194 is "not a reliable in-situ temperature" and "generally assumed to be an annual average SST proxy." In addition, *Rashid et al.* [2016] compared recent Mg/Ca-SST data from a nearby core SK237-GC04 [*Saraswat et al.*, 2013] with the alkenone-derived SSTs from core MD77-194 [*Rashid et al.*, 2016, Figure 2].

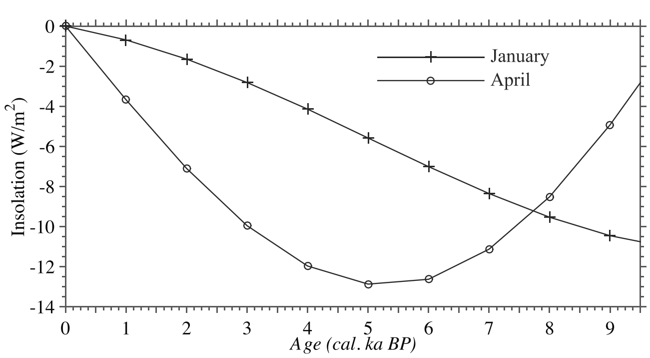

Figure 3. Changes in January (plus line) and April (circle line) insolation at 45°N during the Holocene [*Berger and Loutre*, 1991].

On point (a), to reflect the evolution of SSTs during the Holocene over the low-latitude Indian Ocean, we used SSTs over the western tropical Indian Ocean from core MD77-194 [*Sonzogni et al.*, 1998] as it was used to compute long-term Holocene SST trends in *Leduc et al.* [2010]. As no radiocarbon data

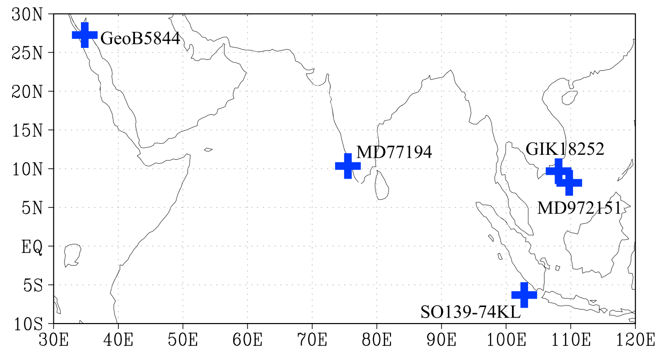

Figure 4. Locations of alkenone records (GeoB5844 [*Arz et al.*, 2003], MD77194 [*Sonzogni et al.*, 1998], GIK18252 [*Kienast et al.*, 2001], MD972151 [*Zhao et al.*, 2006], and SO139-74KL [*Lückge et al.*, 2009]) over the tropical Indian Ocean and surrounding oceans given below in Figure 5.

were available for that core, MD77-194 age model was considered as constant through the Holocene, with core top assigned to a "zero age" [*Leduc et al.*, 2010]. Although probably appropriate to estimate the long-term Holocene SST trend, we agree with *Rashid et al.* [2016] that other cores with better age control are warranted. In the north-eastern Indian Ocean, an extended bibliographic survey made us aware of two other alkenone-based SST records with a much better age control than for core MD77-194 [*Doose-Rolinski et al.*, 2001; *Huguet et al.*, 2006].

On points (a), (b), and (d), many other studies do share a common SST increase during the mid-Holocene, although not "abrupt," ranges from ~0.5°C to 1.5°C starting at around 6 ka seen in four different cores (Figure 4) over the tropical Indian Ocean and surrounding ocean [*Arz et al.*, 2003; *Kienast et al.*, 2001; *Zhao et al.*, 2006; *Lückge et al.*, 2009], i.e., in synchrony with other climatic records other than MD77-194 (Figure 5) that trend back toward values suggestive of a reinforced EAWM in southern Asia.

On point (c), along with the remark that the Mg-/Ca-derived SSTs from core SK237-GC04 [*Saraswat et al.*, 2013] does not share the above mentioned trends, we emphasize that (1) the MAT records are more and more questioned in the paleocommunity since, in the MARGO effort, it has been identified to be responsible for a much stronger level of spatial heterogeneity in the tropics than has been simulated by coupled model runs (see, e.g., discussion in *Kageyama et al.* [2013] and *Lea et al.* [2014]), and (2) by mixing the alkenone-derived and Mg/Ca-derived SST, *Rashid et al.* [2016] seem to ignore the increasing number of tropical to subtropical SST records suggesting that mixing SST proxies may lead to misinterpret SST signals because they do not record SST over the same seasons [*Koutavas and Sachs*, 2008; *Leduc et al.*, 2010; *Schneider et al.*, 2010; *Lohmann et al.*, 2013; *Wang et al.*, 2013; *Hessler et al.*, 2014; *Timmermann et al.*, 2014; *Leduc et al.*, 2014]. Among above mentioned articles, those that deal with SST estimates from the northern tropics all interpret alkenone-derived SSTs as being reflective of winter-skewed SST records. Such a winter-skewed interpretation of alkenone-based SST records is also in agreement with the seasonality of coccolithophorids fluxes that peak in winter [*Chen et al.*, 2007]. At low latitudes, where light is always available and the upper ocean largely stratified,

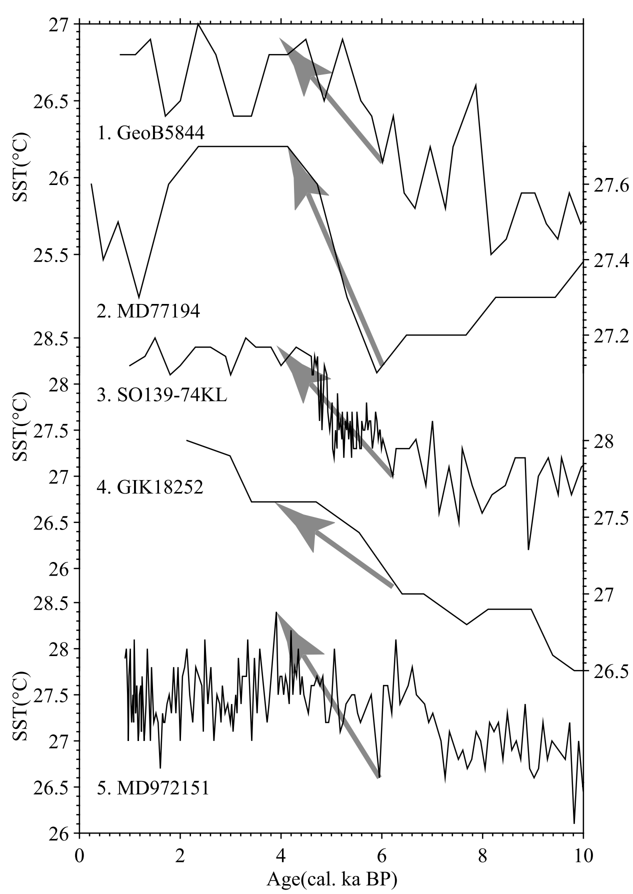

Figure 5. Evolution of SSTs in the tropical Indian Ocean and surrounding oceans. Locations of proxy records are given above in Figure 4.

the first-order limiting factor for growth of primary producers such as coccolithophorids is nutrient availability, which increases in winter when upper ocean mixing occurs [*Behrenfeld et al.*, 2006].

3. Conclusion

The divergences in the use of the SSTs records from the subpolar North Atlantic and tropical Indian Ocean during the Holocene between *Zhang et al.* [2015a] and *Rashid et al.* [2016] mirror enormous controversy interpreting paleo-SST records [e.g., *Mann et al.*, 2009; *Leduc et al.*, 2010; *Schneider et al.*, 2010; *Lohmann et al.*, 2013; *Liu et al.*, 2014]. Further studies, e.g., modern process analysis, model-data comparisons, are needed to address this controversy.

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