Response Letter of

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Title: Drastic shrinking of the Hadley circulation during the mid-Cretaceous Supergreenhouse
By H. Hasegawa, R. Tada, X. Jiang, Y. Suganuma, S. Imsamut, C. Punya, N. Ichinnorov, Y. Khand

Dear Dr. Thorsten Kiefer and Dr. Simon Jung

Thank you for editing our manuscript. We very much appreciate careful and critical reviews of our manuscript. The comments and suggestions by three referees and editor, Dr. Simon Jung, are very helpful and highly appreciated. We tried our best to answer questions and criticisms pointed by referees, and follow many of suggestions to revise our manuscript. We apologize for the delay in revising our manuscript.

Below, we listed individual points raised by referees and editor and described our responses point-by-point. The comments and suggestions are underlined, and our responses are given subsequently. Sentences newly added or revised in our revised manuscript are shown in red color.

We hope that all of the problems pointed out by referees and editor are solved and our revised manuscript is improved sufficiently.

Sincerely yours,

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Response to the Editor Dr. Jung's comments

Your manuscript has now been seen by three referees. The overall thrust of those reviews is rather positive. There are, however, a few concerns that I would like you to consider in a revised version of your manuscript. During the revision process all issues raised by the referees should be addressed. This should be a straightforward process. Particular attention is required to the comments made with regard to chapter 3.5 by Ramstein and Wagreich. Both (as am still I) are unconvinced by your argument. This section requires either a substantial rewrite or you may consider taking it out. A second point of interest is a better discussion of the paleolatitude shifts in the light of the (rather large) error bars inherent to the methodology. The constructive reviews provided by the three referees should allow for a streamlined revision.

(1) Chapter 3.5 are unconvinced argument and/so requires either a substantial rewrite or taking it out.

As was pointed out by two referees (Ramstein, Wagreich) and editor, chapter 3.5 are unconvincing argument and require substantial revision. We agreed that the previous version of chapter 3.5 include unconvincing argument, particularly regarded to the causal linkage of the changes in deep ocean circulation and changes in Hadley circulation width. Although referees and editor recommended either a substantial rewrite or the consideration of taking out this entire chapter, we thought that it is important to point out the temporal synchronicity of the changes in deep-ocean circulation and changes in the width of Hadley circulation in this paper. Thus, we largely revised several sentences, and notified the importance of the coincidence of switches of both oceanic and atmospheric circulation system between the mid- and late Cretaceous time. In addition, we demonstrated the several scenarios of the possible causal linkage of changes in ocean and atmospheric circulation system. This argument is described from Page 14, Line 29 to Page 15, Line 17 in the revised manuscript, "The approximately synchronous occurrences of the changes in the deep-ocean circulation and the width of the Hadley circulation during the mid- to late Cretaceous indicate a possible linkage in the ocean and atmosphere circulation system during the Cretaceous "greenhouse" period (**Fig. 4**). Although the causal relationship between the changes of Hadley circulation width and deep ocean circulation during the Cretaceous is currently unclear, we infer following possible scenarios. Poleward shifts of the subtropical high-pressure belt during the late Cretaceous could have resulted in the formation of more saline surface water in higher latitude that possibly promoted the onset of deep-ocean circulation in higher latitude ocean. On the other hand, during the mid-Cretaceous, equatorward shift of the subtropical high-pressure belt and increased humidity in the mid-latitude extratropics could have resulted in the formation of saline water in lower latitude and development of less saline water in higher latitude so that the deep water formations in higher latitude oceans were suppressed (weaker deep-ocean circulation). Alternatively, enhanced ocean vertical mixing (upwelling) by wind-driven turbulent in mid- to high latitude oceans, due to the enhanced extratropical cyclone activity in in the mid-Cretaceous (**Fig. 4D**), could have resulted in weaker (more local and chaotic) deep water formations in higher latitude oceans (resemble to the "eddy-filled ocean"; Hay, 2008). The other alternative scenario is both the changes of ocean and atmospheric circulation systems were triggered by the changes of meridional temperature gradients and atmospheric CO_2 level.

Conclusively, although further work is needed to address their possible causal linkage, it is noteworthy that there is temporal synchronicity in the switches of the ocean and atmospheric circulation system during the mid- to late Cretaceous (**Fig. 4**).". In addition, because we would like to notify the temporal synchronicity of switches of both oceanic and atmospheric circulation system, we also revised the title of this chapter as "Synchronous changes in ocean and atmospheric circulation system", instead of the previous title (Relationship with variations of ocean circulation during the Cretaceous).

In addition, as is pointed out by a referee (Wagreich), there exist other models on the Cretaceous oceanic circulation (e.g. Hay, 2011). Thus, we also slightly revised the several sentences (introductory part of the chapter 3.5) from Page 12, Line 31 to Page 13, Line 6 in revised manuscript as follows "It is well-established that the wind-driven circulation drove the surface currents in the ocean gyres, whereas the deep ocean circulation ventilated the interior with cold and relatively saline water from the poles (thermohaline circulation). Increasing evidence also suggested that wind-driven turbulent mixing is also an important factor for ocean circulation (e.g., Kuhlbrodt et al., 2007; Toggweiler and Russell, 2008). Thus, changes in the width of the Hadley circulation system during the Cretaceous could have been related with the changes of the ocean circulation system such as latitudinal shifts of the subtropical gyre circulation and/or possible development of the "eddy-filled ocean" as is proposed by Hay (2008, 2011).".

Furthermore, as is pointed out by a referee (Ramstein), even the sentences about the reconstruction of ocean circulation change based on the Nd isotope data in the previous manuscript were not appropriate due to the lack of the controversial argument by MacLeod et al. (2008). Thus, to appropriately describe the argument of the reconstruction of ocean circulation change based on the Nd isotope data, we added arguments of MacLeod et al. (2008) and recent papers of MacLeod et al. (2011) and Robinson and Vance (2012), and revised the several sentences. Furthermore, we also revised the **Fig. 4E** with the adding of the new data-sets presented by Robinson and Vance (2012). As is described in the revised manuscript, we stand on the Robinson and Vance (2012)'s interpretation such that the Nd-isotope data from Demerara Rise (MacLeod et al., 2008) did not significantly demonstrate the changes of deep-water masses in the abyssal North Atlantic during the Late Cretaceous. In addition, as is described in the revised manuscript, although some controversy exists in interpretation of Cretaceous ocean circulation change by Nd isotopic datasets, the new evidences (e.g., Robinson and Vance, 2012; shown in revised **Fig.4E**) also suggests nearly synchronized changes of ocean water mass have occurred in North to South Atlantic oceans during the mid- to late Cretaceous. Therefore, we thought that reconstruction of Cretaceous ocean circulation change based on the Nd isotope data (mainly by Robinson et al., 2010; Robinson and Vance, 2012) is appropriate.

Revised sentences are from Page 13, Line 15 to Page 14, Line 21 in revised manuscript as follows, "Using the Nd isotope composition of fish debris, recent studies demonstrated the variations of intermediate- to deep-water ε_{Nd} values in the South Atlantic and South Indian oceans (Robinson et al., 2010), equatorial Atlantic ocean (MacLeod et al., 2008, 2011), and North Atlantic ocean (MacLeod et al., 2008; Robinson and Vance, 2012) through the mid- to late Cretaceous. The results of Nd-isotopic variations in those oceans revealed that the constantly higher ε_{Nd} values (-8 to -4) in high-latitude oceans (South and Noth Atlantic and South Indian oceans) during the mid-Cretaceous, whereas the ε_{Nd} values in high-latitude oceans became gradually lower (-12 to -8) during the late Cretaceous (with the exception of a higher ε_{Nd} value of Site 1276 sample in the Maastrichtian) (Robinson et al., 2010; Robinson and Vance, 2012; **Fig. 4E**). The relatively low ε_{Nd} values (-12 to -8) of South and North Atlantic and South Indian oceans during the late Cretaceous are very similar to those values (< -8) of the Late Paleocene–Early Eocene at South Atlantic sites (e.g., Thomas et al., 2003). Thus, the broad synchronicity of the shift to lower ε_{Nd} values (< -8) are interpreted as the onset and/or intensification of deep-ocean circulation in southern higher latitude ocean during the late Cretaceous (between Coniacian–Santonian and Campanian) (Robinson et al., 2010; Robinson and Vance, 2012; **Fig. 4E**). On the other hand, constantly higher ε_{Nd} values (-8 to -4) during the mid-Cretaceous are interpreted as "sluggish" ocean circulation, which may have allowed dissolution of volcanic dust to make a greater contribution to deep-water Nd-isotope values via seawater particle exchange (Robinson et al., 2010; Robinson and Vance, 2012).

Although the mid- and late Cretaceous Nd-isotope data from Demerara Rise (equatorial Atlantic) shows dominance of extremely low values (typically -16 to -11; MacLeod et al., 2008, 2011), this data stand in marked difference to the ε_{Nd} values from South and North Atlantic and South Indian ocean data (MacLeod et al., 2008; Robinson et al., 2010; Robinson and Vance, 2012). This observation supports the suggestion that the dominance of intermediate water (so-called "Demerara Bottom Water: DBW") at water depths of <1 km, in a manner analogous to Mediterranean outflow water (MacLeod et al., 2008, 2011; Robinson and Vance, 2012). Thus, as suggested by Robinson and Vance (2012), the Nd-isotope data from Demerara Rise did not significantly demonstrate the changes of deep-water masses in the abyssal equatorial Atlantic during the Late Cretaceous.

Therefore, although some controversy exists in interpretation of the Cretaceous ocean circulation change by Nd isotopic datasets, the increasing evidences suggests nearly synchronized changes of ocean circulation have occurred in North to South Atlantic oceans during the mid- to late Cretaceous (**Fig. 4E**). Specifically, the deep-ocean circulation in North and South Atlantic and South Indian oceans was "sluggish" during the mid-Cretaceous, whereas the deep-ocean circulation was intensified in high-latitude oceans (especially in southern high-latitude ocean) during the late Cretaceous (Robinson et al., 2010; MacLeod et al., 2011; Robinson and Vance, 2012), consistent with reconstructions by ocean circulation models (Poulsen et al., 2001; Otto-Bliesner et al., 2002).".

(2) Better discussion of the paleolatitude shifts in the light of the (rather large) error bars inherent to the methodology.

As was pointed out by referees (Ramstein, Wagreich) and editor, better discussion of the paleolatitudes shifts in the light of the rather large error bars is required. Thus, we revised the several sentences to demonstrate much clearer explanation of the significance of the latitudinal shifts of eolian sandstone distributions and paleo-wind directions. The revised and added sentences are as follows. First, we added sentences in Page 4, Line 10–13 in revised manuscript as follow, "Latitudinal differences of the studied basins are large (**Table 1**), and no substantial changes in their relative positions have occurred during the Cretaceous (e.g., Li, 1994; Meng and Zhang, 1999). Thus, changes in the latitudinal distribution of the eolian sandstone deposits exhibit the absolute latitudinal shifts of desert climatic zone.". Then, we added and revised several sentences in Page 4, Line 24–31 in revised manuscript as follow, "Paleolatitude of the studied basins are the critical basis for the present study which demonstrate that the location of the subtropical high-pressure belt changed significantly during the Cretaceous. The reconstructed paleolatitudes of the studied basins have errors of less than ±5˚ (between ±1.1˚ and ±4.2˚), which stem from the paleomagnetic data (**Table 1**). Although the reconstructed paleolatitudes of the basins have relatively large error bars, both eolian sandstone distribution and paleo-wind direction data suggest that marked latitudinal shifts of the subtropical high-pressure belt have occurred during the Cretaceous (**Figs.1B, 2**), as described below.". In addition, we revised several sentences in Page 5, Line 19–27 in revised manuscript as follow, "Although the reconstructed magnitude of the latitudinal shifts have relatively large error bars, which stem from uncertainty in the paleomagnetic data, it is noteworthy that the southern margin of the desert zone was located in the Tarim basin (N36.3˚ ± 3.3˚) during the early Cretaceous, whereas its northern margin was shifted to Sichuan basin (N27.5˚ ± 2.0˚) during the mid-Cretaceous. Thus, there was not only no overlap in the distributions of desert zone between the early and mid-Cretaceous time, but also a marked latitudinal gap (8.8˚ ± 5.3˚) between its southern and northern margins had existed between the early and mid-Cretaceous (**Figs. 1B, 2**). Therefore, the large-scale latitudinal shifts of the climate zones (ca. 13.8˚–15.4˚ in mean values) have occurred in Asia during the Cretaceous.".