Response to the Dr. Ramstein's comments

General comment: This paper deals with an important and unsolved question: the cause of a flatter meridional gradient of temperature from Equator to Pole during Mid-Cretaceous. Indeed, there are now some evidences of diagenesis in O18 of carbonate that could provide wrong temperature reconstructions, these new informations are given by the O18 of apatite (PO4) which may be more reliable to reconstruct temperature (Puceat, 2007). Nevertheless, the distribution of meridional temperature is still a challenge during very warm climates (LPTM, early Eocene and Mid-Cretaceous). The authors suggest here, that desert could be an appropriate "proxy" to understand Hadley cell variation, tropical dynamics and energy distribution. The major input of the paper is therefore to reconstruct from deserts, location and divergence axis, the descending branch of the Hadley cell and to correlate the width of the Hadley cell (mainly in Northern Hemisphere which is better constrained) to different CO2 levels during mid-Cretaceous. More precisely this width decreases from early to mid-Cretaceous and increases again from mid to late Cretaceous (around 10°). This is an interesting contribution to our understanding of atmospheric dynamics during the Cretaceous. Nevertheless, I have some questions and comments, I'll like the authors answer before publication. I give below a detailed review on these points.

1. Introduction In the introduction, the authors give a good summary of Cretaceous climate and suggest that this study could bring new constraint on subtropical high pressure belt and divergence axis.

2. Cretaceous eolian sandstones in Asia I'm not an expert on these measurements, but this is indeed crucial for the paper. The latitudinal shift for the deserts poleward for late and early Cretaceous and the shrinking equatorward for mid Cretaceous have to be robust. Despite large error bars, it seems to be reliable. Nevertheless, this section is not clear and not very easy to read. Especially, the methodology allowing inferring this shift in sandstone distribution should be more clearly addressed.

As was pointed out by referee, the methodology inferring the shift in sandstone distribution should be more clearly addressed, and 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.”.

3. Results For Section 3.1 (Latitudinal shift of the subtropical high pressure belt) and 3.2 (Changes in the width of the Hadley circulation), the link between the sandstone distributions in the different basins and the width of Hadley cell is well described.

In the section 3.3 (Possible cause of changes in the width of the Hadley circulation), the authors describe the possible causes of the Hadley cell shrinking. The modelling part of the discussion could be enhanced: 1- A previous study in a glacial climate of such a possibility was first published in 1998 by Ramstein et al. This was done in another context (LGM) using an AGCM model but it did show the possibility of changes in the width of the Hadley cell related to changes in Equator to Pole temperature gradient. This study may be cited because, in contrast with Poulsen simulations which are, more appropriate Cretaceous simulations (Poulsen, 2003), Ramstein et al. (1998) show changes in the Hadley cell width. 2- Concerning the Mid-Cretaceous, the authors should care on the fact that Poulsen (2003) uses an AOGCM and Fluteau et al. (2007) prescribed the SST. This is indeed a major difference and should be discussed.

According to the referee’s comments, we enhanced the modeling part of the discussion in the section 3.3 (and also partly in section 3.4). First, we added the sentence of climatic simulation results of the changes of Hadley circulation width in the increasing atmospheric CO_2 level and global warming scenario from Page 9, Line 12–17 in revised manuscript as follows “In addition, the widening of the Hadley circulation in response to increased concentrations of greenhouse gases are also supported by climatic simulation results (e.g., Kushner et al., 2001; Lu et al., 2007; Previdi and Liepert, 2007; Johanson and Fu, 2009; Lu et al., 2009; Schneider et al., 2009). Climatic simulation results of the Lu et al. (2009) further suggested that the widening of the

Hadley circulation can be attributed entirely to the radiative forcing, in particular those related to greenhouse gases and stratospheric ozone depletion.".

Then, we added the sentences of the climatic simulation results of the changes of Hadley circulation width in glacial–interglacial oscillations with citation of Ramstein et al. (1998) from Page 9, Line 29 to Page 10, Line 3 in revised manuscript as follows "Changes in width of the Hadley circulation during the glacial–interglacial oscillations are also demonstrated by the paleoclimatic simulation results (e.g., Ramstein et al., 1998; Otto-Bliesner and Clement, 2004; Williams and Bryan, 2006; Dinezio et al., 2011). The results of atmospheric general circulation model (AGCM; Ramstein et al., 1998) and coupled atmosphere-ocean general circulation models (AOGCM; Otto-Bliesner and Clement, 2004; Williams and Bryan, 2006; DiNezio et al., 2011) demonstrated that the changes in the width of the Hadley circulation are related with the changes of equator-to-pole temperature gradients.".

In addition, according to the referee's comments, we revised several sentences of mid-Cretaceous climatic simulation results to emphasize the significant difference between AGCM model of Fluteau et al. (2007) and AOGCM model of Poulsen et al. (2003) from Page 10, Line 20–24 in revised manuscript as follows "Poulsen et al. (2003) conducted a coupled atmosphere-ocean general circulation model (AOGCM) experiment for the mid-Cretaceous with different paleogeographic conditions (presence or absence of an Atlantic gateway between the South America and Africa), in order to examine the impact of the formation of an Atlantic gateway to the oceanic circulation and global climate changes.", and from Page 11, Line 3–9 in revised manuscript as follows "Fluteau et al. (2007) conducted an atmospheric general circulation model (AGCM) experiment with boundary conditions of reduced meridional surface temperature gradient with mid-Cretaceous paleogeography and four-times higher atmospheric CO_2 level. Although Fluteau et al. (2007) using AGCM models and they prescribed the meridional temperature gradient, significantly different from the AOGCM model (e.g., Poulsen et al., 2003), their model results demonstrated the reduction of the Hadley circulation intensity with equatorward shrinking of the cell (Figure 12 of Fluteau et al., 2007)".

Furthermore, we also added some sentences of the climatic simulation results of enhancement of the extratropical storm track intensity and increased humidity in the mid-latitude in warmer climate state to use an supporting evidence of our hypothesis of the intensified mid-latitude extratropical cyclone activity in the mid-Cretaceous "supergreenhouse" period from Page 12, Line 6–11 in revised manuscript as follows, "In addition, enhancement of the extratropical storm track intensity and increased humidity in the mid-latitude in warmer climatic state are also supported by recent climatic simulation studies (e.g., Schneider et al., 2009; Lu et al., 2010; O'Gorman, 2010; Riviere, 2011), although their model did not produce the shrinking of the Hadley circulation so that we cannot directly infer the Cretaceous "greenhouse" climate system by their results.".

Whereas section 3.4 (Drastic shrinking of the Hadley circulation and intensified Midlatitude humidity), is fine for me. I'm not at all convinced by section 3.5 (Relationship with variations of ocean circulation during the Cretaceous). The relationship between changes in deep water circulation and width of the Hadley cell is not really convincing as far as simulations available do not show such a correlation. Moreover, as honestly, shown by the authors, this hypothesis is not supported by Nd data (MacLeod, 2008) and therefore I'll remove this section and replace it by a shorter discussion.

As was pointed out by referee, we agreed that the previous version of chapter 3.5 include unconvincing argument, particularly regarded to the causal linkage of changes in deep ocean circulation and changes in Hadley circulation width. In addition, referee pointed that even the sentences of 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).

Firstly, although referee 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 these sentences, and notified the importance of the coincidence of switch 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, 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).".

Concerning section 3.6 (Hypothesis: non-linear response of the width of the Hadley circulation), the authors should discuss seriously the possibility of such phenomenon during LPTM and Early Eocene in data and models. Indeed, the CO2 threshold may be dependent on paleogeography and therefore, the same pCO2 will not lead to the same Hadley cell behaviour, nevertheless this point should be discussed more deeply. Last but not least point concerns the need for non linear response to explain the data which is not clearly demonstrated.

As is pointed out by referee, the possibility of the non-linear response of the Hadley circulation and presence of CO_2 threshold should be explored in more detail in other extremely warm climate periods, such as PETM and early Eocene, as is also described in our previous manuscript (Lines 7 to 10 of Page 134). We agreed that the presence of CO_2 threshold can be verified by the occurrence of similar Hadley cell behavior in the period characterized by similar atmospheric CO_2 level with different paleogeography, such period as PETM and Early Eocene.

However, we thought that verification of this hypothesis by other geologic period should be the next target of our research (e.g., examination of the latitudinal changes of desert distribution and paleo-wind directions during the Paleocene to Eocene period). In addition, we thought that discussion of the possible changes of the Hadley circulation width based on some published data-sets and models are also should be demonstrated in our future paper. Nevertheless, we partly agreed to the referee's suggestion such that it is important to indicate at least some evidences of the possible occurrence of similar phenomenon during the Early Eocene periods.

Thus, we revised several sentences to indicate our future research direction of the verification of the presence of CO_2 threshold in changes of Hadley circulation width. In addition, we added several sentences to demonstrate some existing evidences of the increased humidity in inland mid-latitude that also indicate the possible presence of CO_2 threshold and occurrence of similar phenomenon during the Early Eocene period. Revised sentences are described from Page 16, Line 6–23 in the revised manuscript as follow "The possible presence of such a threshold in atmospheric CO_2 level can be explored in other extremely warm climate periods, such as the Paleocene/Eocene Thermal Maximum (PETM) and Early Eocene Climatic Optimum (EECO) (e.g., Zachos et al., 2008).

As Beerling and Royer (2011) recently presented, the Eocene period is also characterized by extremely warm climate with atmospheric CO_2 level reached more than ca. 1000 ppm. Although we leave the detail investigation of the Eocene paleoclimatic records to future studies, available geological evidence suggests that the similar phenomenom of the increased humidity in the inland mid-latitude have also occurred in the early–middle Eocene period (e.g., widespread deposition of organic-rich lacustrine sediments such as Green River oil-shale and Messel oil-shale; e.g., Smith et al., 2010; Lenz et al., 2010). Clementz and Sewall (2011) also provided the evidence of enhanced hydrological cycles during the Eocene period. Conclusively, our results, in conjunction with recent observations, suggest the existence of a threshold in atmospheric CO_2 level and/or global temperature, beyond which the Hadley circulation shrinks drastically. The possibility of such a drastic switch in atmospheric circulation system with increasing atmospheric CO_2 level should be explored in more detail in other extremely warm climate periods (e.g., PETM and EECO) to better understand and prepare for the future climatic changes.".