Clim. Past Discuss., 7, 119–151, 2011
www.clim-past-discuss.net/7/119/2011/
doi:10.5194/cpd-7-119-2011

Climate
of the Past
Discussions

Drastic shrinking of the Hadley circulation during the mid-Cretaceous supergreenhouse

H. Hasegawa[1,*], **R. Tada**[1], **X. Jiang**[2], **Y. Suganuma**[1,3], **S. Imsamut**[4], **P. Charusiri**[5], **N. Ichinnorov**[6], **and Y. Khand**[6]

[1]Department of Earth and Planetary Science, the University of Tokyo, Tokyo, Japan
[2]Chengdu Institute of Geology and Mineral Resources, Chengdu, China
[3]National Institute of Polar Research, Tokyo, Japan
[4]Department of Mineral Resources, Bureau of Geological Survey, Bangkok, Thailand
[5]Department of Geology, Chulalongkorn University, Bangkok, Thailand
[6]Paleontological Center, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia
[*]now at: Department of Natural History Science, Hokkaido University,
Sapporo 060-0810, Japan

Received: 14 September 2010 – Accepted: 7 December 2010 – Published: 13 January 2011

Correspondence to: H. Hasegawa (hito_hase@mail.sci.hokudai.ac.jp)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Understanding the behaviour of the global climate system during extremely warm periods is one of the major themes of paleoclimatology. Proxy data demonstrate that the equator-to-pole temperature gradient was much lower during the mid-Cretaceous "supergreenhouse" period than at present, implying larger meridional heat transport by atmospheric and/or oceanic circulation. However, reconstructions of atmospheric circulation during the Cretaceous have been hampered by a lack of appropriate data sets based on reliable proxies. Desert distribution directly reflects the position of the subtropical high-pressure belt, and the prevailing surface-wind pattern preserved in desert deposits reveals the exact position of its divergence axis, which marks the poleward margin of the Hadley circulation. We reconstructed temporal changes in the latitude of the subtropical high-pressure belt and its divergence axis during the Cretaceous based on spatio-temporal changes in the latitudinal distribution of deserts and prevailing surface-wind patterns in the Asian interior. We found a poleward shift in the subtropical high-pressure belt during the early and late Cretaceous, suggesting a poleward expansion of the Hadley circulation. In contrast, an equatorward shift of the belt was found during the mid-Cretaceous "supergreenhouse" period, suggesting drastic shrinking of the Hadley circulation. These 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.

1 Introduction

Paleoclimatic reconstructions of extremely warm periods are important in understanding the dynamics of Earth's climate system under an exceptionally warm "supergreenhouse" mode (Huber and Sloan, 2001; Huber et al., 2002; Wilson et al., 2002; Jenkyns et al., 2004; Forster et al., 2007; Borneman et al., 2008). Proxy records demonstrated that the mid-Cretaceous "supergreenhouse" period is characterized by higher atmospheric CO_2 levels (Royer et al., 2001; Wallmann, 2001; Berner, 2006; Fletcher et al., 2008; Breecker et al., 2010), long-lasting extreme warmth of deep-ocean and polar surface temperatures (~15–20 °C; Huber et al., 2002; Jenkyns et al., 2004) than modern values ($\lesssim$4 °C), substantially warmer tropical sea surface temperatures (SSTs) (~33°C and 35–36 °C at the peak; Wilson et al., 2002; Forster et al., 2007; Borneman et al., 2008) than modern values (~27–29°C), and/so reduced equator-to-pole temperature gradients compared to the present-day gradients. Although some of the recent studies cast doubt on the validity of the lower meridional temperature gradients (Bice et al., 2006; Pucéat et al., 2007; Zhou et al., 2008), the paleobotanical and paleontological evidences of the extremely warm polar climate (Herman and Spicer, 1996; Skeleton et al., 2003; Jenkyns et al., 2004; Spicer et al., 2008) support the lower meridional temperature gradients during the mid-Cretaceous compared to the present-day gradients.

To explain such a reduced gradient under elevated $p\mathrm{CO}_2$, climate modelers have invoked viable but difficult-to-test hypotheses of either major changes in the latitudinal distribution of the radiation budget (Sloan and Pollard, 1998; Kump and Pollard, 2008; Abbot et al., 2009) or increased poleward heat transport (Schmidt and Mysak, 1996; Huber and Sloan, 2001; Korty et al., 2008). Despite the efforts of these intensive studies, the mechanisms and causes of reduced meridional temperature gradients remain a point of controversy. Atmospheric and/or oceanic circulation systems undoubtedly played a significant role in poleward heat transport during the past. However, reconstructions of these circulation systems and evaluations of their role in maintaining reduced temperature gradients have been hampered by a lack of appropriate data sets based on reliable proxies.

Deserts are the direct products of meridional atmospheric circulation. Modern deserts are generally developed under the subtropical high-pressure belt as a result of downwelling of the Hadley circulation. Hence, the equatorward and poleward parts of desert areas are dominated by trade winds and westerlies, respectively (Bigarella, 1972; Livingstone and Warren, 1996). Eolian dunes in desert areas migrate leeward of the wind, thereby recording the direction of the prevailing surface-wind pattern (dominantly winter wind flow) in the form of large-scale cross-sets. Therefore, the distribution of desert deposits and prevailing surface-wind patterns recorded in such deposits provide direct information on the past position of the subtropical high-pressure belt and its divergence axis.

In this paper, we reconstructed temporal changes in the latitude of the subtropical high-pressure belt and its divergence axis during the Cretaceous, based on a reconstruction of spatio-temporal changes in the latitudinal distribution of desert deposits and the prevailing surface-wind patterns recorded in the Asian interior, which marks the subsidence of the Hadley circulation during the past. We then reconstructed the temporal changes in the width of the Hadley circulation throughout the Cretaceous, and discussed their possible causes. We also discussed the possible role of the meridional atmospheric circulation system on the poleward heat transport in such an extremely warm climatic mode.

2 Cretaceous eolian sandstones in Asia

Cretaceous eolian sandstones are widely distributed in low- to mid-latitude areas of Asia (Jiang and Li, 1996; Jiang et al., 2001, 2004; Hasegawa et al., 2009, 2010). The Asian Continent was the largest continental mass during the Cretaceous, with relatively low topographic relief (maximum ca. 2000 m in height; Scotese, 2001; Sewall et al., 2007). Given that uplift of the Himalaya and Tibetan Plateau only commenced after 40 Ma, a zonal climate would have been prevailed in Asia during the Cretaceous, with less intense monsoonal system compared with the present-day and Neogene climates (Sun and Wang, 2005; Fluteau et al., 2007; Guo et al., 2008; Hasegawa et al., 2010).

Configuration of the paleo-Asian continent and their paleogeography during the Cretaceous has been reconstructed based on the paleomagnetic studies (modified after Plate-Tracker program of PALEOMAP project; Eldridge et al., 2000; Fig. 1a). Based on the reconstructed paleogeographic map of the Asian interior, the studied basins (Gobi

Basin in Southern Mongolia, Ordos, Tarim, Subei, Jianguan, Sichuan, Simao Basins in China, and Khorat Basin in Northern Thailand) are arranged from north to south, forming a latitudinal transect of low- to mid-latitude in paleo-Asian continent (Cheng et al., 1988; Zhuang, 1988; Li, 1990; Otofuji et al., 1990; Enkin et al., 1991; Zheng et al., 1991; Chen et al., 1992, 1993; Huang and Opdyke, 1993; Gilder et al., 1999; Hankard et al., 2005; Charusiri et al., 2006; Zhu et al., 2006; Fig. 1a and Table 1; Supplement).

Figure 1b shows temporal changes in the latitudinal distribution of climate-sensitive sediments and paleo-wind direction data in the Asian interior during the Cretaceous. Numerical ages for most of the basins were obtained based on magnetostratigraphic and biostratigraphic data (Li, 1982; Jerzykiewicz and Russell, 1991; Jiang and Li, 1996; Hao et al., 2000; Khand et al., 2000; Meesok, 2000; Jiang et al., 2001, 2004; Chen et al., 2006; Sha, 2007; Supplement Table S1), including the results of our magnetostratigraphic studies (Imsamut, 1996; Pan et al., 2004; Hasegawa et al., 2010; Supplement; Figs. S1 and S2). Paleo-wind direction data were determined from the dip directions of eolian dune sediments, corrected for post-Cretaceous rotation of the crust based on paleomagnetic data (Jiang et al., 2001, 2004; Hasegawa et al., 2009, 2010). The reconstructed paleolatitudes and rotation angles of the studied basins have errors of less than ±5° and ±10°, respectively, which are errors for the paleomagnetic data (Cheng et al., 1988; Zhuang, 1988; Li, 1990; Otofuji et al., 1990; Enkin et al., 1991; Zheng et al., 1991; Chen et al., 1992; Huang and Opdyke, 1993; Gilder et al., 1999; Hankard et al., 2005; Charusiri et al., 2006; Zhu et al., 2006; Table 1).

3 Results and discussions

3.1 Latitudinal shift of the subtropical high pressure belt

The latitudinal distribution of eolian sandstone deposits varied markedly throughout the Cretaceous (Figs. 1 and 2). Namely, (1) eolian sandstone deposits were distributed in mid-latitude areas of Ordos and Tarim basins in Northern China (between 32.6° N and

41.0° N: 36.8° N ± 4.2°) during the early Cretaceous (Berriasian–Barremian), (2) distribution of eolian sandstone deposits shifted southward to Sichuan and Simao Basins in Southern China and the Khorat Basin in Northern Thailand (between 16.3° N and 29.6° N: 23.0° N ± 6.6°) during the mid-Cretaceous (Aptian–Turonian), and (3) its distribution shifted northward again to Gobi Basin in Southern Mongolia and the Ordos and Subei basins in Northern China (between 30.8° N and 46.1° N: 38.4° N ± 7.6°) during the late Cretaceous (Coniacian–Maastrichtian) (Table 1). In addition, a humid climate zone prevailed in mid-latitude areas to the north of the desert zone during the mid-Cretaceous, as is indicated by the occurrence of perennial lacustrine deposits and coal-bearing deposits in the Gobi Basin of Southern Mongolia and the Ordos Basin of Northern China (Jerzykiewicz and Russell, 1991; Jiang and Li, 1996; Figs. 1 and 2). Thus, it is suggested that large-scale latitudinal shifts in climate zones have occurred in Asia during the Cretaceous. The magnitude of the latitudinal shifts of desert zone, estimated based on paleomagnetic data, are 13.8° ± 10.9° between the early and the mid-Cretaceous and 15.4° ± 14.2° between the mid- and the late Cretaceous, respectively, where errors are stemmed from paleomagnetic data. Although reconstructed paleolatitudes of the studied basins have errors of approximately ±5°, latitudinal difference of each basins are large (by more than 5°) and no substantial changes in their relative positions (e.g., between Ordos and Sichuan Basins) have occurred during the Cretaceous (sensu, Li, 1994; Meng and Zhang, 1999). In addition, it is noteworthy that southern margin of the desert zone was located in the Ordos basin (between 32.6° N and 41.0° N: 36.8° N ± 4.2°) during the early Cretaceous, whereas northern margin of the desert zone was shifted to Sichuan Basin (between 25.5° N and 29.6° N: 27.5° N ± 2.0°) during the mid-Cretaceous. Therefore, significant latitudinal shifts of the desert zone (by more than 9.3° ± 6.2° difference in latitude between its southern and northern margins) have occurred between the early and the mid-Cretaceous (Fig. 2).

Paleo-wind direction data provide significant information on the zonal boundary between the westerlies and trade winds during the Cretaceous. In general, south- to southwestward paleo-wind directions are interpreted to be caused by the northeasterly trade winds, while north to northeastward directions are caused by westerlies in desert areas of the Northern Hemisphere (Bigarella, 1972; Livingstone and Warren, 1996). In addition, southeasterly winds occur in areas close to the zonal boundary between the westerlies and trade winds (i.e., divergent axis of the subtropical high-pressure belt).

The spatial distribution of the reconstructed paleo-wind directions in Asia (Figs. 1 and 2) revealed that (1) zonal boundary between the westerlies and trade winds situated in the Ordos Basin (between 32.6° N and 41.0° N) during the early Cretaceous with gradual southwards shifting, (2) westerlies prevailed in the Sichuan Basin (between 25.5° N and 29.6° N), while trade winds prevailed in the Simao Basin (between 21.8° N and 27.6° N) and Korat Basin (between 16.3° N and 21.6° N) during the mid-Cretaceous, and (3) westerlies prevailed in the Gobi Basin (between 44.0° N and 46.1° N), and zonal boundary between the westerlies and trade winds situated in the Subei Basin (between 30.8° N and 37.0° N) during the late Cretaceous (Figs. 1, 2 and Table 1). Based on these data, the divergence axis of the subtropical high-pressure belt was located between 32.6° N and 41.0° N (36.8° N ± 4.2°) during the early Cretaceous, between 21.8° N and 29.6° N (25.7° N ± 3.9°) during the mid-Cretaceous, and between 30.8° N and 37.0° N (33.9° N ± 3.1°) during the late Cretaceous, respectively (Fig. 2). Thus, the magnitude of the latitudinal shifts of the divergence axis of the subtropical high-pressure belt are 11.1° ± 8.1° between the early and the mid-Cretaceous, and 8.2° ± 7.0° between the mid- and the late Cretaceous, respectively. Therefore, although the errors of the reconstructed latitudinal shifts are relatively large, the latitudinal shifts of the divergence axis of the subtropical high-pressure belt of ca. 8.2°–11.1° observed in Asia between the early and the mid-Cretaceous, and between the mid- and the late Cretaceous are clearly above the error, and consequently should be real.

3.2 Changes in the width of the Hadley circulation

The global distribution of climate-sensitive sediments (e.g., coals, laterite, bauxite, evaporite and eolian sandstone deposits) also demonstrates the development of arid zones in relatively low-latitude areas and the predominance of a broad humid zone in mid-latitude areas both in Asia and North America during the mid-Cretaceous, whereas the development of a broad arid zone in low- to mid-latitude areas only becomes apparent during the late Cretaceous (Fig. 3). For example, mid-latitude areas of North America during the mid-Cretaceous is characterized by fluvio-lacustrine deposits which contain abundant spherosiderites (Ludvigson et al., 1998), suggesting dominance of wetland soils and sediments under humid climate (e.g., British Columbia (8); Northern Alberta (9); Southern Alberta (10); Ontario Basin (11); Western Iowa Basin (12); New Mexico Basin (14); localities in Fig. 3 and Table S2). In contrast, mid-latitude areas of North America during the late Cretaceous are characterized by abundant occurrence of red-bed with calcretes, which suggest dominance of relatively arid climate (e.g., Southern Alberta (30); Western Montana Basin (31); New Mexico Basin (35); Western Texas Basin (36)). Although the paleoclimate records of the Southern Hemisphere are relatively sparse throughout the Cretaceous, the mid-latitudes of the Southern Hemisphere appear to be characterized by a relatively humid climate during the mid-Cretaceous, whereas the development of an arid desert climate during the late Cretaceous, which is consistent with the trend recorded in the Northern Hemisphere (Fig. 3). Importantly, no mid-Cretaceous eolian sandstone deposits have been reported from low- to mid-latitude Southern Hemisphere. In contrast, upper Cretaceous eolian sandstone deposits exist in the Salta Basin, Argentina (37: Lecho Formation; Marquillas et al., 2005), the Bauru Basin, Brazil (38: Caiuá Group; Fernandes et al., 2007), the Parana Basin, Brazil (39: Marilia Formation; Goldberg and Garcia, 2000), and the Southern Congo Basin, Angola (42: Nsele Group; Giresse, 2005), and lower Cretaceous eolian sandstone deposits exist in the Panama Basin, Brazil (Botucatu Formation; Scherer and Goldberg, 2007), the Neuquen Basin, Argentina (Agrio Formation; Veiga et al., 2002), and the Huab Basin, Namibia (Etjo Formation; Mountney et al., 1999).

In addition to the distribution of eolian sandstone deposits, the distribution of evaporite deposits can be used to characterize the descending limbs of the Hadley cells. At present, the descending limbs of the Hadley cells are located between 10° and 40° of northern and southern latitudes where evaporation exceeds precipitation, whereas the low-latitude coal, laterite and bauxite deposits represent everwet climates associated the Inter-Tropical Convergence Zone (ITCZ) (sensu, Ziegler et al., 2003). Figure 3 shows the distribution of evaporite deposits prevailed in the subtropical arid region (between ca. 10° and 40° in the northern and southern latitudes during the late Cretaceous, and between ca. 15° and 30° during the mid-Cretaceous; shown as yellow color zone in Fig. 3), which coincide with the desert distribution. On the other hand, the distributions of coal, laterite and bauxite deposits are distributed near the equator (within ca. 10° in the northern and southern latitudes during the late Cretaceous, and ca. 15° during the mid-Cretaceous; shown as pink color zone in Fig. 3), which is interpreted as representing the everwet climates under the ITCZ (Fig. 3). Furthermore, the location of the ITCZ, indicated by the distribution of everwet climate sediments, seems to have remained stationary near the equator during the mid- and late Cretaceous (Fig. 3). Therefore, latitudinal shifts in the subtropical high-pressure belt recorded in Asia during the Cretaceous were at least a Northern Hemisphere phenomenon, and were possibly global in extent (Figs. 2 and 3), although additional Southern Hemisphere data are required to verify whether the latitudinal shifts of the subtropical high-pressure belts were symmetric with respect to the equator or not.

Our results indicate that the paleolatitude of the Northern Hemisphere subtropical high-pressure belt was located between ca. 31° N and 41° N during the early and late Cretaceous, whereas it was shifted southward and located between ca. 22° N and 30° N during the mid-Cretaceous (Fig. 2). Given that the subtropical high-pressure belt develops on the poleward margin of the Hadley circulation, and that the ITCZ remained stationary over the equator during the Cretaceous (Fig. 3), the latitudinal shifts in the subtropical high-pressure belt during the Cretaceous appear to be related to changes in the width of the Hadley circulation. In other words, the Hadley circulation expanded poleward during the early and late Cretaceous, and shrunk equatorward during the mid-Cretaceous, at least in the Northern Hemisphere (Figs. 3 and 4a).

3.3 Possible cause of changes in the width of the Hadley circulation

The latitudinal shifts in the subtropical high-pressure belt described above coincided with changes in the global climate modes during the Cretaceous, as indicated by changes in global SSTs (Clarke and Jenkyns, 1999; Pucéat et al., 2003; Fig. 4a, b). Specifically, the equatorward shrinking of the Hadley circulation occurred during the extremely warm mid-Cretaceous "supergreenhouse" period, which is generally attributed to elevated levels of atmospheric CO_2 (e.g., Royer et al., 2001; Wallmann, 2001; Berner, 2006; Fletcher et al., 2008; Breecker et al., 2010; Fig. 4c). Although the reconstruction of the variations in the atmospheric CO_2 through the Cretaceous are still limited, available data of the proxy-based estimates (Royer et al., 2001; Fletcher et al., 2008; Breecker et al., 2010) are generally in good agreement with the carbon cycle model estimates (Wallmann, 2001; Berner, 2006, GEOCARBSULF). These limited data-sets of the atmospheric CO_2 estimates suggest slightly higher $p\text{CO}_2$ value (ca. 1000–1500 ppm) during the extremely warm mid-Cretaceous "supergreenhouse" period, compared to the slightly lower value (ca. 500–1000 ppm) during the late Cretaceous period. Therefore, changes in the width of the Hadley circulation appear to have been closely linked to changes in global climate modes induced by increasing levels of atmospheric CO_2 (Figs. 4 and 5).

Recent observational studies have reported that present-day Hadley circulation is expanding poleward in response to increasing atmospheric $p\text{CO}_2$ and consequent global warming (Hu and Fu, 2007; Seidel et al., 2008; Johanson and Fu, 2009; Lu et al., 2009). Such a relationship between the width of the Hadley circulation and global temperature and/or atmospheric CO_2 levels has also been reported for glacial – interglacial transitions (Nicholson and Flohn, 1980; Toggweiler et al., 2006; Williams and Bryan, 2006; Toggweiler and Russell, 2008), although some studies cast doubt on such a symmetrical shift of the width of the Hadley circulation in both hemisphere (e.g., Anderson et al., 2009). For example, some studies suggest the southward shifts of both the ITCZ and westries belt during the deglaciation period (Lamy et al., 2007; Tierney and

Russell, 2007; Anderson et al., 2009). However, several evidences support the latitudinal shifts of the wind belt tend to be symmetric with respect to the equator between the glacial and interglacial, even though ITCZ may have shifted asymmetrically (Mayewski et al., 2004; Toggweiler and Russell, 2008; Robinson and Sigman, 2008; Tierney et al., 2008; Bard and Rickaby, 2009). Furthermore, recent studies reported the possible poleward shifts of the subtropical high-pressure belt during the warmer climatic periods such as early Pleistocene (Sniderman et al., 2009) and early Pliocene (Brierley et al., 2009). Therefore, the occurrence of the subtropical high-pressure belt in relatively high latitudes during the early and late Cretaceous can be explained by poleward expansion of the Hadley circulation in association with increased atmospheric $p\mathrm{CO}_2$ and consequent global warming (Figs. 4 and 5). In contrast, the Hadley circulation showed a drastic equatorward shrinking beyond the present position during the mid-Cretaceous "supergreenhouse" period – the opposite trend to that expected with increasing global temperatures and atmospheric $p\mathrm{CO}_2$. These observations suggest that (1) the Hadley circulation gradually expands poleward in response to increasing global temperatures and/or atmospheric CO_2 levels, and (2) when global temperatures and/or atmospheric CO_2 levels exceed a certain threshold, the Hadley circulation experiences a marked equatorward retreat (Fig. 5).

Alternatively, the changes in the width of the Hadley circulation as well as latitudinal shifts in the subtropical high-pressure belt can be caused by the long-term changes in the land-sea distributions through the Cretaceous (e.g., opening of an Atlantic gateway: rifting of the South America and Africa). Poulsen et al. (2003) conducted a coupled ocean-atmosphere general circulation model experiment for the mid-Cretaceous by 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. The results demonstrate that the formation of an Atlantic gateway could cause the increase in heat transport into North Atlantic from Pacific Ocean, and the freshening of the North and Northern South Atlantic upper oceans (Poulsen et al., 2003). However, these results did not cause any equatorward shift of the subtropical high-pressure belt. In addition, the onset timing of the opening of the equatorial Atlantic gateway (deep water connection) is between Albian and Cenomanian (Wagner and Pletsch, 1999), significantly younger than the initial timing of the equatorward shift of the subtropical high-pressure belt that took place between Barremian and Aptian.

On the other hand, the proposed equatorward shrinking of the Hadley circulation during the mid-Cretaceous is consistent with the results of a recent climate-modeling study obtained by Fluteau et al. (2007). Fluteau et al. (2007) conducted an atmospheric general circulation model experiment with boundary conditions of reduced meridional surface temperature gradient with mid-Cretaceous paleogeography and four-time higher $p\mathrm{CO}_2$. The modeling results demonstrated that the lower meridional temperature gradient under the mid-Cretaceous condition resulted in reduction of the Hadley circulation intensity with equatorward shrinking of the cell (Fig. 12 of Fluteau et al., 2007), which is consistent with our results.

3.4 Drastic shrinking of the Hadley circulation and intensified mid-latitude humidity

We also note that terrestrial sedimentary records in Asia revealed increased humidity in mid-latitude areas during the mid-Cretaceous, as is indicated by the occurrence of perennial lacustrine deposits and coal-bearing deposits in the Gobi Basin of Southern Mongolia and the Ordos Basin of Northern China (Jerzykiewicz and Russell, 1991; Jiang and Li, 1996; Figs. 1 and 2). The global distribution of climate-sensitive sediments also suggests the predominance of a broad humid zone in mid-latitude areas of both in North America and Southern Hemisphere during the mid-Cretaceous as is described earlier (Fig. 3). This finding is supported by increased precipitation rates estimated for North American mid-latitude (Ludvigson et al., 1998; Ufnar et al., 2004). Based on the oxygen isotope composition of spherosiderites, millimeter-scale spherulitic siderite (FeCO_3) formed in wetland soils and sediments (Ludvigson et al., 1998), Ufnar et al. (2004) reconstructed the latitudinal variations in the δ^{18}O values of groundwater and precipitation, thereby revealing increased humidity in mid-latitude areas of North America during the mid-Cretaceous (Fig. 3). They further suggested that intensified hydrological activity and enhanced latent heat transport possibly contributed to the reduced meridional thermal gradients in North America during this period (Ufnar et al., 2004). Furthermore, temporal changes in storm wave intensity, estimated from the wavelengths of hummocky cross-stratification in the mid- to high latitudinal areas of the Northern Hemisphere, indicate a maximum in the storm wave intensity during the mid-Cretaceous (Ito et al., 2001; Fig. 4d). Therefore, our results, together with additional geological data, suggest that intensification of mid-latitude extratropical cyclone activity and an intensified hydrological cycle possibly replaced the role of poleward heat transport by the Hadley circulation during the mid-Cretaceous "supergreenhouse" period (Figs. 4 and 5). This hypothesis is also supported by the results of recent studies, which report that ongoing global warming has led to a substantial increase in the intensity of tropical cyclones and hurricanes, which also increase poleward heat transport (Emanuel, 2005; Elsner et al., 2008; Korty et al., 2008).

3.5 Relationship with variations of ocean circulation during the Cretaceous

Because it is well-established that the surface winds drive the surface currents of the ocean to form gyres, changes in the width of the Hadley circulation during the Cretaceous could have been accompanied by the changes of the Cretaceous ocean circulation system such as latitudinal shifts of the subtropical gyre circulation and/or changes in the formation site of the deep ocean circulation. Although some of numerical climate model studies proposed possible changes in the ocean circulation system through the Cretaceous such as formation of the warm saline deep water either in the low latitude (Brass et al., 1982) or in the high latitude (Brady et al., 1998; Haupt and Seidov, 2001; Poulsen et al., 2001; Otto-Bliesner et al., 2002), reconstruction of the paleocirculation system during the Cretaceous had been hampered by a lack of appropriate data sets based on reliable proxies. Aside from numerical climate model studies, recent studies tried to reconstruct the changes of the paleocirculation system during the Cretaceous based on the Nd isotopes (e.g., Frank et al., 2005; Pucéat et al., 2005; Soudry et al., 2006; MacLeod et al., 2008; Robinson et al., 2010).

In the present configuration of continents and oceans, there are distinct differences in the Nd-isotopic compositions of deep waters in the Pacific, Indian, and Atlantic Oceans, and seawater Nd isotopic ratios are used as a good tracer of the past ocean circulation system (e.g., Thomas, 2004). Using the Nd isotope composition of fish debris, Robinson et al. (2010) demonstrated the variations of intermediate- to deep-water Nd-isotopic values in the South Atlantic and proto-Indian oceans through the mid- to late Cretaceous, with compilation of those values in the North Atlantic and Equatorial Pacific (Frank et al., 2005; MacLeod et al., 2008) (Fig. 4e). The results of Nd-isotopic variations in several oceans revealed that the predominance of relatively radiogenic Nd-isotope values (−8 to −5) in high-latitude oceans during the mid-Cretaceous (Albian–Santonian), whereas the development of more nonradiogenic values (−8 to −11) in such high-latitude oceans only becomes apparent during the late Cretaceous (Campanina–Maastrichtian) (sensu, Robinson et al., 2010; Fig. 4e). Robinson et al. (2010) concluded that the deep-water circulation in the North and South Atlantic and the proto-Indian oceans was sluggish during the mid-Cretaceous, whereas the deep-water formation was initiated in such high-latitude oceans during the late Cretaceous, consistent with reconstructions by ocean circulation models (Poulsen et al., 2001; Otto-Bliesner et al., 2002). In addition to these Nd-isotope data, planktonic–benthic oxygen isotope gradients in the Southern Hemisphere records (Clark and Jenkyns, 1999; Huber et al., 2002) also show that larger planktonic–benthic oxygen isotope gradients during the Cenomanian–Santonian at high southern latitudes suggesting stratified water columns, whereas smaller planktonic–benthic gradients during the Campanian–Maastrichtian suggest onset of significant high-latitude deep-water formation (Huber et al., 2002; Robinson et al., 2010).

The approximately synchronous occurrences of the changes in the deep-water circulation and the width of the Hadley circulation during the mid- to late Cretaceous indicate a possible linkage between the ocean and atmosphere circulations during the

Cretaceous "greenhouse" period. Specifically, the onset of the deep-water formation in the high-latitude oceans is consistent with the poleward shift of the subtropical high-pressure belt and formation of more saline waters in higher latitude oceans during the late Cretaceous. On the other hand, the formation site of the saline waters should have been switched to the lower latitudes in response to the equatorward shift of the subtropical high-pressure belt during the mid-Cretaceous. However, Nd-isotopic data from the Demerara Rise in the Equatorial Atlantic (MacLeod et al., 2008) appears to show no substantial change in between Cenomanian–Turonian and Campanian–Maastrichtian with the exception of the excursion during OAE2 interval, which does not support the linkage between ocean and atmosphere circulations during the mid-Cretaceous. Nevertheless, the mid-Cretaceous Nd-isotopic data from the equatorial oceans are very limited (e.g., only Valanginian and Campanian–Maastrichtian data are presented in the Equatorial Pacific; Fig. 4e) so that further work is needed to elucidate the possible relationships between the changes in the ocean circulation and the changes in the width of the Hadley circulation during the Cretaceous.

3.6 Hypothesis: non-linear response of the width of the Hadley circulation

The long-term relationships among the width of the Hadley circulation, global temperatures, and atmospheric CO_2 levels during the Cretaceous reported in this study suggest a non-linear response of global atmospheric circulation to atmospheric CO_2 increase and/or global warming (Figs. 4 and 5). Specifically, (1) Hadley circulation gradually expands poleward with the progressive increase in atmospheric CO_2 and consequent climatic warming from a modern "icehouse" condition ($p\mathrm{CO}_2 \cong 180$–375 ppm; Luthi et al., 2008) to late Cretaceous "greenhouse" condition ($p\mathrm{CO}_2 \cong 500$–1000 ppm), and (2) when atmospheric CO_2 exceeds a threshold level and reaches mid-Cretaceous "supergreenhouse" level ($p\mathrm{CO}_2 \cong 1000$–$1500$ ppm), Hadley circulation drastically shrink equatorwards and was possibly replaced by enhanced extratropical cyclone activity in the middle latitude (Figs. 4c and 5; atmospheric $p\mathrm{CO}_2$ values from Berner, 2006, GEOCARBSULF, and proxy-based estimates compiled by Breecker et al., 2010). If atmospheric CO_2 is the forcing of this drastic switch in atmospheric circulation system, our results suggest the existence of a probable threshold at pCO_2 of approximately 1000 ppm, beyond which the Hadley circulation would shrink drastically (Fig. 5), although the predicting threshold value is based on the limited data-sets (Fig. 4c) and/so further study of the Cretaceous pCO_2 reconstruction is required. This predicting threshold value will possibly reach in the near future if we continue to emit CO_2 (e.g., IPCC, 2007: AR4 scenario A2). The possibility of presence of such a threshold should be explored in more detail in other extremely warm climate periods, such as Paleocene/Eocene Thermal Maximum and early Eocene, to better understand and prepare for the future climatic changes.

4 Conclusions

Spatio-temporal changes in the latitudinal distribution of deserts and prevailing surface-wind patterns in the Asian interior have been examined to reconstruct the temporal changes in the latitude of the subtropical high-pressure belt and its divergence axis during the Cretaceous. We found a poleward shift in the subtropical high-pressure belt to the latitudes between ca. 31° N and 41° N during the early and late Cretaceous (36.8° N ± 4.2° and 33.9° N ± 3.1°, respectively). In contrast, an equatorward shift of the belt to the latitudes between ca. 22° N and 30° N (25.7° N ± 3.9°) was found during the mid-Cretaceous. The magnitude of the latitudinal shifts are 11.1° ± 8.1° between the early and the mid-Cretaceous, and 8.2° ± 7.0° between the mid- and the late Cretaceous, respectively.

The latitudinal shifts in the subtropical high-pressure belt appear to be related to changes in the width of the Hadley circulation, which could be linked to the changes in global temperatures and/or atmospheric CO_2 levels during the Cretaceous. These results, in conjunction with observations of modern climate, suggest that (1) the Hadley circulation gradually expands poleward in response to increasing global temperatures and/or atmospheric CO_2 levels, and (2) when global temperatures and/or atmospheric

CO_2 levels exceed a certain threshold, the Hadley circulation drastically shrink equatorwards.

The long-term relationships among the width of the Hadley circulation, global temperatures, and atmospheric CO_2 levels during the Cretaceous suggest 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 pCO_2 should be explored in more detail to better understand and prepare for the future climatic changes.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/119/2011/cpd-7-119-2011-supplement.pdf.

Acknowledgements. We thank T. Moore and E. Tajika for fruitful discussions and critical reading of the manuscript. We also thank A. Abe-Ouchi, Y. Yokoyama, N. Suzuki, K. Sawada, T. Hasegawa, Y. Iba, K. Moriya, J. Kuroda, K. Nagashima, Y. Sekine, and participants of IGCP507 for their valuable comments. Thanks also go to L. Jacobs for providing information of the African Cretaceous records. This study was supported by a Grant-in-Aid for Japan Society for the Promotion of Science Fellows (No. 18-05250) provided to H. Hasegawa, the 21 century COE Program at the Dept. of Earth and Planetary Science of the Univ. of Tokyo, a Grant-in-Aid for Scientific Research (S) (No. 18101001) provided to R. Tada, and a grant from the National Natural Science Foundation of China (No. 40372064) provided to X. Jiang.

References

Abbot, D. S., Huber, M., Bousquet, G., and Walker, C. C.: High-CO_2 cloud radiative forcing feedback over both land and ocean in a global climate model, Geophys. Res. Lett., 36, L05702, doi:10.1029/2008GL036703, 2009.

Anderson, R. F., Ali, S., Bradtmiller, L. I., Nielsen, S. H. H., Fleisher, M. Q., Anderson, B. E., and Burckle, L. H.: Wind-driven upwelling in the southern ocean and degracial rise in atmospheric CO_2, Science, 323, 1443–1448, 2009.

Bard, E. and Rickaby, R. E. M.: Migration of the subtropical front as a modulator of glacial climate, Nature, 460, 380–384, 2009.

Berner, R. A.: GEOCARBSULF: a combined model for Phanerozoic atmospheric O_2 and CO_2, Geochim. Cosmochim. Ac., 70, 5653–5664, 2006.

Bice, K. L., Birgel, D., Meyers, P. A., Dahl, K. A., Hinrichs, K. U., and Norris, R. D.: A multiple proxy and model study of Cretaceous upper ocean temperatures and atmospheric CO_2 concentrations, Paleoceanography, 21, PA2002, doi:10.1029/2005PA001203, 2006.

Bigarella, J. J.: Eolian environments: Their characteristics, recognition, and importance, in: Recognition of Ancient Sedimentary Environment, Spec. Pub. SEPM Talsa, 16, 12–62, 1972.

Borneman, A., Norris, R. D., Friedrich, O., Beckmann, B., Schouten, S., Damste, J. S. S., Vogel, J., Hofmann, P., and Wagner, T.: Isotopic evidence for glaciation during the Cretaceous supergreenhouse, Science, 319, 189–192, 2008.

Brady, E. C., DeConto, R. M., and Thompson, S. L.: Deep water formation and poleward ocean heat transport in the warm climate extreme of the Cretaceous (80 Ma), Geophys. Res. Lett., 25, 4205–4208, 1998.

Brass, G. W., Southam, J. R., and Peterson, W. H.: Warm saline bottom water in the ancient ocean, Nature, 296, 620–623, 1982.

Breecker, D. O., Sharp, Z. D., and McFadden, L. D.: Atmospheric CO_2 concentrations during ancient greenhouse climates were similar to those predicted for AD 2100, Proc. Natl. Acad. Sci., 107, 576–580, 2010.

Brierley, C. M., Fedorov, A. V., Liu, Z., Herbert, T. D., Lawrence, K. T., and LaRiviere, J. P.: Greatly expanded tropical warm pool and weakened Hadley circulation in the early Pliocene, Science, 323, 1714–1718, 2009

Charusiri, P., Imsamut, S., Zhuang, Z. H., Ampaiwan, T., and Xu, X. X.: Paleomagnetism of the earliest Cretaceous to early late Cretaceous sandstones, Khorat Group, Northeast Thailand: implications for tectonic plate movement of the Indochina block, Gondwana Res., 9, 310–325, 2006.

Chen, P. J., Li, J. J., Matsukawa, M., Zhang, H. C., Wang, Q. F., and Lockley, M. G.: Geological ages of dinosaur-track-bearing formations in China, Cretaceous Res., 27, 22–32, 2006.

Chen, Y., Cogne, J. P., and Courtillot, V.: New Cretaceous paleomagnetic poles from the Tarim Basin, Northwestern China, Earth Planet Sc. Lett., 114, 17–38, 1992.

Chen, Y., Courtillot, V., Cogne, J. P., Besse, J., Yang, Z. Y., and Enkin, R.: The Configuration of

Asia prior to the collision of India–Cretaceous paleomagnetic constraints, J. Geophys. Res., 98, 21927–21941, 1993.

Cheng, G., Bai, Y., and Sun, Y.: Paleomagnetic study on the tectonic evolution of the Ordos Block, North China, Seismol. Geol., 10, 81–87, 1988.

Chumakov, N. M., Zharkov, M. A., Herman, A. B., Doludenko, M. P., Kalandadze, N. N., Lebedev, E. L., Ponomarenko, A. G., and Rautian, A. S.: Climate zones in the middle of the Cretaceous Period, Stratigr. Geol. Correl., 3, 3–14, 1995.

Clarke, L. J. and Jenkyns, H. C.: New oxygen isotope evidence for long-term Cretaceous climatic change in the Southern Hemisphere, Geology, 27, 699–702, 1999.

Eldridge, J. D., Walsh, D., and Scotese, C. R.: Plate Tracker for Windows/NT, Version 2.0. Paleomap Project, Arlington, Texas, 2000.

Elsner, J. B., Kossin, J. P., and Jagger, T. H.: The increasing intensity of the strongest tropical cyclones, Nature, 455, 92–95, 2008.

Emanuel, K. A.: Increasing destructiveness of tropical cyclones over the past 30 years, Nature, 436, 686–688, 2005.

Enkin, R. J., Courtillot, V., Xing, L., Zhang, Z., and Zhang, J.: The stationary Cretaceous paleomagnetic pole of Sichuan (South China Block), Tectonics, 10, 547–559, 1991.

Fernandes, L. A., de Castro, A. B., and Basilici, G.: Seismites in continental sand sea deposits of the Late Cretaceous Caiuá Desert, Bauru Basin, Brazil, Sediment. Geol., 199, 51–64, 2007.

Fletcher, B. J., Brentnall, S. J., Anderson, C. W., Berner, R. A., and Beerling, D. J.: Atmospheric carbon dioxide linked with Mesozoic and early Cenozoic climate change, Nat. Geosci., 1, 43–48, 2008.

Fluteau, F., Ramstein, G., Besse, J., Guiraud, R., and Masse, J. P.: Impacts of paleogeography and sea level changes on mid-Cretaceous climate, Palaeogeogr. Palaeocl., 247, 357–381, 2007.

Forster, A., Schouten, S., Moriya, K., Wilson, P. A., and Damste, J. S. S.: Tropical warming and intermittent cooling during the Cenomanian/Turonian oceanic anoxic event 2: sea surface temperature records from the equatorial Atlantic, Paleoceanography, 22, PA1219, doi:10.1029/2006PA001349, 2007.

Frank, T. D., Thomas, D. J., Leckie, R. M., Arthur, M. A., Bown, P. R., Jones, K., and Lees, J. A.: The Maastrichtian record from Shatsky Rise (Northwest Pacific): a tropical perspective on global ecological and oceanographic changes, Paleoceanography, 20, PA1008, doi:10.1029/2004PA001052, 2005.

Freeman, K. H. and Hayes, J. M.: Fractionation of carbon isotopes by phytoplankton and estimates of ancient CO_2 levels, Global Biogeochem. Cy., 6, 185–198, 1992.

Gilder, S. A., Leloup, P. H., Courtillot, V., Chen, Y., Coe, R. S., Zhao, X., Xiao, W., Halim, N., Cogne, J. P., and Zhu, R.: Tectonic evolution of the Tancheng-Lujiang (Tan-Lu) fault via Middle Triassic to Early Cretaceous Paleomagnetic data, J. Geophys. Res., 104, 15365–15390, 1999.

Giresse, P.: Mesozoic–Cenozoic history of the Congo Basin, J. Afr. Earth Sci., 43, 301–315, 2005.

Goldberg, K. and Garcia, A. J. V.: Palaeobiogeography of the Bauru Group, a dinosaur-bearing Cretaceous unit, Northeastern Parana Basin, Brazil, Cretaceous Res., 21, 241–254, 2000.

Gradstein, F., Ogg, J., and Smith, A.: A Geological Time Scale 2004, Cambridge Univ. Press, Cambridge, UK, 589 pp., 2004.

Guo, Z. T., Sun, B., Zhang, Z. S., Peng, S. Z., Xiao, G. Q., Ge, J. Y., Hao, Q. Z., Qiao, Y. S., Liang, M. Y., Liu, J. F., Yin, Q. Z., and Wei, J. J.: A major reorganization of Asian climate by the early Miocene, Clim. Past, 4, 153–174, doi:10.5194/cp-4-153-2008, 2008.

Hankard, F., Cogne, J. P., and Kravchinsky, V.: A new Late Cretaceous paleomagnetic pole for the west of Amuria block (Khurmen Uul, Mongolia), Earth Planet Sc. Lett., 236, 359–373, 2005.

Hao, Y., Su, D., Yu, J., Li, Y., Zhang, Q., and Liu, X.: Cretaceous System of China, Geological Publishing House, Beijing, 301 pp., 2000 (in Chinese).

Hasegawa, H., Tada, R., Ichinnorov, N., and Minjin, C.: Lithostratigraphy and depositional environments of the Upper Cretaceous Djadokhta Formation, Ulan Nuur basin, Southern Mongolia, and its paleoclimatic implication, J. Asian Earth Sci., 35, 13–26, 2009.

Hasegawa, H., Imsamut, S., Charusiri, P., Tada, R., Horiuchi, Y., and Hisada K.: "Thailand was a desert" during the mid-Cretaceous: equatorward shift of the subtropical high-pressure belt indicated by eolian deposits (Phu Thok formation) in the Khorat Basin, Northeastern Thailand, Island Arc, 19, 605–621, 2010.

Haupt, B. J. and Seidov, D.: Warm deep-water ocean conveyor during Cretaceous time, Geology, 29, 295– 298, 2001.

Herman, A. B. and Spicer, R. A.: Palaeobotanical evidence for a warm Cretaceous Arctic Ocean, Nature, 380, 330–333, 1996.

Hu, Y. and Fu, Q.: Observed poleward expansion of the Hadley circulation since 1979, Atmos.

Chem. Phys., 7, 5229–5236, doi:10.5194/acp-7-5229-2007, 2007.

Huang, K. and Opdyke, N. D.: Paleomagnetic results from Cretaceous and Jurassic rocks of South and Southwest Yunnan: evidence for large clockwise rotations in the Indochina and Shan Thai Malay terrenes, Earth Planet Sc. Lett., 117, 507–524, 1993.

Huber, B. T., Norris, R. D., and MacLeod, K. G.: Deep-sea paleotemperature record of extreme warmth during the Cretaceous, Geology, 30, 123–126, 2002.

Huber, M., and Sloan, L. C.: Heat transport, deep waters, and thermal gradients: coupled simulation of an Eocene greenhouse climate, Geophys. Res. Lett., 28, 3481–3484, 2001.

Imsamut, S.: Magnetostratigraphy of the Phu Thok Formation at Phu Thok and Phu Wua areas, Changwat Nong Khai, M.Sc. Thesis, Chulalongkorn University, Bangkok, 1996.

Ito, M., Ishigaki, A., Nishikawa, T., and Saito, T.: Temporal variation in the wavelength of hummocky cross-stratification: implications for storm intensity through Mesozoic and Cenozoic, Geology, 29, 87–89, 2001.

Jenkyns, H. C., Forster, A., Schouten, S., and Sinninghe Damste, J. S.: High temperatures in the late Cretaceous Arctic Ocean, Nature, 432, 888–892, 2004.

Jerzykiewicz, T. and Russell, D. A.: Late Mesozoic stratigraphy and vertebrates of the Gobi Basin, Cretaceous Res., 12, 345–377, 1991.

Jiang, X. S. and Li, Y. W.: Spatio-temporal distribution of the Cretaceous deserts in Central and Eastern China and its climatic significance, Sediment. Facies Palaeogeogr., 16, 42–51, 1996, (in Chinese).

Jiang, X. S., Pan, Z. X., and Fu, Q. P.: Primary study on pattern of general circulation of atmosphere before uplift of the Tibetan Plateau in Eastern Asia, Sci. China Ser. D, 44, 680–688, 2001.

Jiang, X. S., Pan, Z. X., Xie, Y., and Li, M. H.: Cretaceous desert cycles, wind direction and hydrologic cycle variations in Ordos Basin: evidence for Cretaceous climatic unequability, Sci. China Ser. D, 47, 727–738, 2004

Johanson, C. M. and Fu, Q.: Hadley cell widening: model simulations versus observations, J. Climate, 22, 2713–2725, 2009.

Khand, Y., Badamgarav, D., Ariunchimeg, Y., and Barsbold, R.: Cretaceous System in Mongolia and its depositional environments, in: Cretaceous Environments of Asia, edited by: Okada, H. and Mateer, N. J., Elsevier Science B. V., 49–79, Amsterdam, 2000.

Korty, R. L., Emanuel, K. A., and Scott, J. R.: Tropical cyclone-induced upper-ocean mixing and climate: application to equable climates, J. Climate, 21, 638–654, 2008.

Kump, L. R. and Pollard, D.: Amplification of Cretaceous warmth by biological cloud feedbacks, Science, 320, 195–195, 2008.

Lamy, F., Kaiser, J., Arz, H. W., Hebbeln, D., Ninnemann, U., Timm, O., Timmermann, A., and Toggweiler, J. R.: Modulation of the bipolar seesaw in the Southeast Pacific during termination 1, Earth Planet Sc. Lett., 259, 400–413, 2007.

Li, Y.: Late Jurassic–Paleogene Ostracods in Sichuan Basin, and their significance of stratigraphy, in: Continental Mesozoic Stratigraphy and Paleontology of Stratigraphy and Paleontology in Sichuan Basin of China (Part II), People's Publishing House of Sichuan, 274–345, Chengdu, 1982.

Li, Y. P.: An apparent polar wander path from the Tarim Block, China, Tectonophysics, 181, 31–41, 1990.

Li, Z. X.: Collision between the North and South China blocks: a crustal-detachment model for suturing in the region east of the Tanlu fault, Geology, 22, 739–742, 1994.

Livingstone, I. and Warren, A.: Aeolian Geomorphology, Longman, Singapore, 211 pp., 1996.

Ludvigson, G. A., Gonzalez, L. A., Metzger, R. A., Witzke, B. J., Brenner, R. L., Murillo, A. P., and White, T. S.: Meteoric sphaerosiderite lines and their use for paleohydrology and paleoclimatology, Geology, 26, 1039–1042, 1998.

Lu, J., Deser, C., and Reichler, T.: Cause of the widening of the tropical belt since 1958, Geophys. Res. Lett., 36, L03803, doi:10.1029/2008GL036076, 2009.

Luthi, D., Floch, M. L., Bereiter, B., Blunier, T., Barnola, J. M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. F.: High-resolution carbon dioxide concentration record 650 000–800 000 years before present, Nature, 453, 379–382, 2008.

Marquilliams, R. A., Papa, C., and Sabino, I. F.: Sedimentary aspects and paleoenvironmental evolution of a rift basin: Salta Group (Cretaceous–Paleogene), Northwestern Argentina, Int. J. Earth Sci., 94, 94–113, 2005.

MacLeod, K. G., Martin, E. E., and Blair, S. W.: Nd isotopic excursion across Cretaceous ocean anoxic event 2 (Cenomanian-Turonian) in the tropical North Atlantic, Geology, 36, 811–814, 2008.

Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlen, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. P., and Steig, E. J.: Holocene climate variavility, Quaternary Res., 62, 243–255, 2004.

Meesook, A.: Cretaceous environments of Northeastern Thailand, in: Cretaceous Environments of Asia, edited by: Okada, H. and Mateer, N. J., Elsevier Science B. V., Amsterdam, 207–224, 2000.

Meng, Q. R. and Zhang, G. W.: Timing of collision of the North and South China blocks: controversy and reconciliation, Geology, 27, 123–126, 1999.

Mountney, N., Howell, J., Flint, S., and Jerram, D.: Relating eolian bounding-surface geometries to the bed forms that generated them: Etjo Formation, Cretaceous, Namibia, Geology, 27, 159–162, 1999.

Nicholson, S. E. and Flohn, H.: African environmental and climatic changes and the general atmospheric circulation in late Pleistocene and Holocene, Climatic Change, 2, 313–348, 1980.

Otofuji, Y., Inoue, Y., Funahara, S., Murata, F., and Zheng, X.: Paleomagnetic study of Eastern Tibet – deformation of the Three Rivers region, Geophys. J. Int., 103, 85–94, 1990.

Otto-Bliesner, B. L., Brady, E. C., and Shields, C.: Late Cretaceous ocean: coupled simulations with the National Center for Atmospheric Research Climate System Model, J. Geophys. Res., 107, D2, 4019, doi:10.1029/2001JD000821, 2002.

Pan, Z., Jiang, X. S., Zhuang, Z., and Fu, Q.: Magnetic study of the Cretaceous desert sediments in the Sichuan Basin and its significance, Journal of Graduate School, China University of Geoscience, 13, 30–35, 2004.

Poulsen, C. J., Barron, E. J., Arthur, M. A., and Peterson, W. H.: Response of the mid-Cretaceous global oceanic circulation to tectonic and CO_2 forcings, Paleoceanography, 16, 576–592, 2001.

Poulsen, C. J., Gendaszek, A. S., and Jacob, R. L.: Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum?, Geology, 31, 115–118, 2003.

Pucéat, E., Lecuyer, C., Sheppard, S. M. F., Dromart, G., Reboulet, S., and Grandjean, P.: Thermal evolution of Cretaceous Tethyan marine waters inferred from oxygen isotope composition of fish tooth enamels, Paleoceanography, 18(1029), doi:10.1029/2002PA000823, 2003.

Pucéat, E., Lécuyer, C., and Reisberg, L.: Neodymium isotope evolution of NW Tethyan upper ocean waters throughout the Cretaceous, Earth Planet Sc. Lett., 236, 705–720, 2005.

Pucéat, E., Lecuyer, C., Donnadieu, Y., Naveau, P., Cappetta, H., Ramstein, G., Huber, B. T., and Kriwet, J.: Fish tooth δ^{18}O revising Late Cretaceous meridional upper ocean water temperature gradients, Geology, 35, 107–110, 2007.

Racey, A., Love, M., Canham, A. C., Goodall, J. G. S., Polachan, S., and Jones, P. D.: Stratigraphy and reservoir potential of the Mesozoic Khorat Group, NE Thailand, J. Petrol. Geol., 19, 5–40, 1996.

Robinson, S. A., Murphy, D. P., Vance, D., and Thomas, D. J.: Formation of "Southern Component Water" in the Late Cretaceous: evidence from Nd-isotopes, Geology, 38, 871–874, 2010.

Robinson, R. S. and Sigman, D. M.: Nitrogen isotopic evidence for a poleward decrease in surface nitrate within the ice age Antarctic, Quaternary Sci. Rev., 27, 1076–1090, 2008.

Royer, D. L., Berner, R. A., and Beerling, D. J.: Phanerozoic atmospheric CO_2 change: evaluating geochemical and paleobiological approaches, Earth-Sci. Rev., 54, 349–392, 2001.

Scherer, C. M. C. and Goldberg, K.: Palaeowind patterns during the latest Jurassic-earliest Cretaceous in Gondwana: Evidence from aeolian cross-strata of the Botucatu Formation, Brazil, Palaeogeogr. Palaeocl., 250, 89–100, 2007.

Schmidt, G. A. and Mysak, L. A.: Can increased poleward oceanic heat flux explain the warm Cretaceous climate?, Paleoceanography, 11, 579–593, 1996.

Scotese, C. R.: Atlas of Earth History, vol. 1, Paleogeography, 1. PALEOMAP Project, Arlington, TX, 52 pp., 2001.

Seidel, D. J., Fu, Q., Randel, W. J., and Reichler, T. J.: Widening of the tropical belt in a changing climate, Nat. Geosci., 1, 21–24, 2008.

Sewall, J. O., van de Wal, R. S. W., van der Zwan, K., van Oosterhout, C., Dijkstra, H. A., and Scotese, C. R.: Climate model boundary conditions for four Cretaceous time slices, Clim. Past, 3, 647–657, doi:10.5194/cp-3-647-2007, 2007.

Sha, J. G.: Cretaceous stratigraphy of Northeast China: non-marine and marine correlation, Cretaceous Res., 28, 146–170, 2007.

Skelton, P. W., Spicer, R. A., Kelley, S. P., and Gilmour, I.: The Cretaceous World, 249–258, Cambridge University Press, Cambridge, 2003.

Sloan, L. C. and Pollard, D.: Polar stratospheric clouds: a high latitude warming mechanism in an ancient greenhouse world, Geophys. Res. Lett., 25, 3517–3520, 1998.

Sniderman, J. M. K., Porch, N., and Kershaw, A. P.: Quantitative reconstruction of Early Pleistocene climate in Southeastern Australia and implications for atmospheric circulation, Quaternary Sci., Rev., 28, 3185–3196, 2009.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L.: Climate Change 2007: The Physical Science Basis – Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge Univ. Press, Cambridge, 2007.

Soudry, D., Glenn, C. R., Nathan, Y., Segal, I., and Von der Haar, D.: Evolution of Tethyan phosphogenesis along the northern edges of the Arabian-African shield during the Cretaceous-Eocene as deduced from temporal variations of Ca and Nd isotopes and rates of P accumulation, Earth-Sci. Rev., 78, 27–57, 2006.

Spicer, R. A., Ahlberg, A., Herman, A. B., Hofmann, C. C., Raikevich, M., Valdes, P. J., and Markwick, P. J.: The Late Cretaceous continental interior of Siberia: a challenge for climate models, Earth Planet Sc. Lett., 267, 228–235, 2008.

Sun, X. J. and Wang, P. X.: How old is the Asian monsoon system? – Palaeobotanical records from China, Palaeogeogr. Palaeocl., 222, 181–222, 2005.

Thomas, D. J.: Evidence for deep-water production in the North Pacific Ocean during the early Cenozoic warm interval, Nature, 430, 65–68, 2004.

Tierney, J. E. and Russell, J. M.: Abrupt climate change in southeast tropical Africa influenced by Indian monsoon variability and ITCZ migration, Geophys. Res. Lett., 34, L15709, doi:10.1029/2007GL029508, 2007.

Tierney, J. E., Russell, J. M., Huang, Y., Sinninghe Damste, J. S., Hopmans, E. C., and Cohen, A. S.: Northern Hemisphere controls on Tropical Southeast African climate during the past 60 000 years, Science, 252–255, 2008.

Toggweiler, J. R. and Russell, J.: Ocean circulation in a warming climate, Nature, 451, 286–288, 2008.

Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages, Paleoceanography, 21, PA2005, doi:10.1029/2005PA001154, 2006.

Ufnar, D. F., Gonzalez, L. A., Ludvigson, G. A., Brenner, R. L., and Witzke, B. J.: Evidence for increased latent heat transport during the Cretaceous (Albian) greenhouse warming, Geology, 32, 1049–1052, 2004.

Veiga, G. D., Spalletti, L. A., and Flint, S.: Aeolian/fluvial interactions and high-resolution sequence stratigraphy of a non-marine lowstand wedge: the Avile' Member of the Agrio Formation (Lower Cretaceous), Central Neuquen Basin, Argentina, Sedimentology, 49, 1001–1019, 2002..

Wagner, T. and Pletsch, T.: Tectono-sedimentary controls on Cretaceous black shale deposition along the opening of the Equatorial Atlantic Gateway (ODP Leg 159), in: The Oil and

Gas Habitats of the South Atlantic, edited by: Cameron, N. R., et al., Geological Society of London, Special Publication, London, 153, 241–265, 1999.

Wallmann, K.: Controls on the Cretaceous and Cenozoic evolution of seawater composition, atmospheric CO_2 and climate, Geochim. Cosmochim. Ac., 65, 3005–3025, 2001.

Williams, G. P. and Bryan, K.: Ice age winds: an aquaplanet model, J. Climate, 19, 1706–1715, 2006.

Wilson P. A., Norris, R. D., and Cooper, M. J.: Testing the Cretaceous greenhouse hypothesis using glassy foraminiferal calcite from the core of the Turonian tropics on Demerara Rise, Geology, 30, 607–610, 2002.

Yang, Z. and Basse, J.: Paleomagnetic study of Permian and Mesozoic sedimentary rocks from Northern Thailand supports the exteuction model for Indochina, Earth Planet Sc. Lett., 117, 525–552, 1993.

Zheng, Z., Kono, M., Tsunakawa, H., Kimura, G., Wei, Q., Zhu, X. Y., and Hao, T.: The apparent polar wander path for the North China Block since the Jurassic, Geophys. J. Int., 104, 29–40, 1991.

Zhou, J., Poulsen, C. J., Pollard, D., and White, T. S.: Simulation of modern and middle Cretaceous marine d^{18}O with an ocean-atmosphere general circulation model, Paleoceanography, 23, PA3223, doi:10.1029/2008PA001596, 2008.

Zhu, Z., Morinaga, H., Gui, R., Xu, S., and Liu, Y.: Paleomagnetic constraints on the extent of the stable body of the South China Block since the Cretaceous: new data from the Yunma Basin, China, Earth Planet Sc. Lett., 248, 533–544, 2006.

Zhuang, Z.: The Cretaceous-Tertiary Paleomagnetic study from Ya'an to Tianquan section, Sichuan Basin, Phys. Chem. Explos., 12, 224–228, 1988.

Ziegler, A. M., Eshel, G., Rees, P. M., Rothfus, T. A., Rowley, D. B., and Sunderlin, D.: Tracing the tropics across land and sea: Permian to present, Lethaia, 36, 227–254, 2003.

Table 1. Paleoposition of the Cretaceous eolian sandstones in Asia. Paleolatitudes and rotations of the basins are based on paleomagnetic data (modified from, Cheng et al., 1988; Zhuang, 1988; Li, 1990; Otofuji et al., 1990; Enkin et al., 1991; Zheng et al., 1991; Chen et al., 1992; Huang and Opdyke, 1993; Hankard et al., 2005; Charusiri et al., 2006; Zhu et al., 2006).

Basin	Paleolatitude	Rotation	References
Gobi Basin	44.0–46.1° N	5.2–15.3°	Hankard et al. (2005)
Ordos Basin	32.6–41.0° N	7.2–12.1°	Zheng et al. (1991) Cheng et al. (1988)
Tarim Basin	33.0–39.5° N	15.7–21.5°	Li (1990) Chen et al. (1992)
Subei Basin	30.8–37.0° N	1.3–16.7°	Gilder et al. (1999) Zhu et al. (2006)
Sichuan Basin	25.5–29.6° N	10.5–15.6°	Enkin et al. (1991) Zhuang et al. (1988)
Simao Basin	21.8–27.6° N	36.3–48.6°	Huang and Opdyke (1993) Otofuji et al. (1990)
Khorat Basin	16.3–21.6° N	20.0–25.0°	Charusiri et al. (2005)

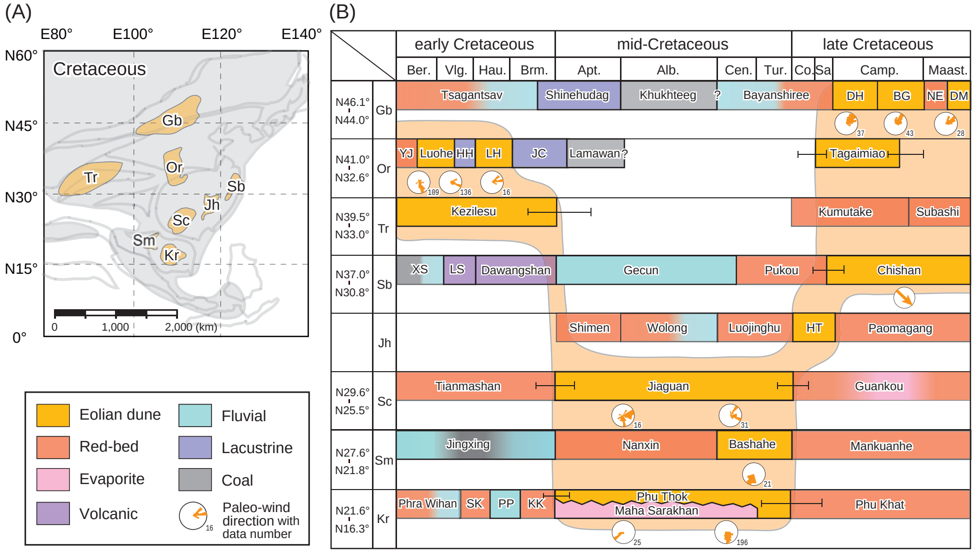


Fig. 1. (A) Paleogeographic map of the Asian continent during the Cretaceous, showing the locations of sedimentary basins cited in this study (modified after Eldridge et al., 2000; Table 1). Abbreviated basin names are as follows: Gb = Gobi; Or = Ordos; Tr = Tarim; Sb = Subei; Jh = Jianghan; Sc = Sichuan; Sm = Simao; Kr = Khorat. **(B)** Stratigraphic chart of climate-sensitive sediments and rose diagrams of paleo-wind directions recorded in eolian dune deposits. The vertical axis is arranged (from north to south) based on the paleolatitudes of the studied basins, forming a latitudinal cross-section of mid- and low-latitude records. The horizontal axis represents depositional ages of the formations, estimated based on biostratigraphic and magnetostratigraphic data (see Supplementary Material). Estimation errors are indicated as error bars. Abbreviated formation names are as follows: DH = Djadokhta; BG = Barungoyot; NE = Nemegt; DM = Dzunmod; YJ = Yijun; HH = Huanhe-Huachi; LH = Luohangdong; JC = Jingchuang; XS = Xihengshan; LS = Longwangshan; HT = Honghuatao; SK = Sao Khua; PP = Phu Phan.

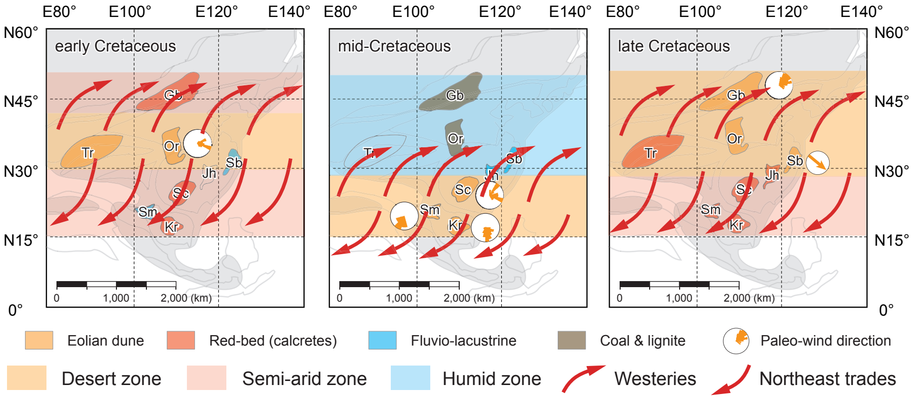


Fig. 2. Spatio-temporal changes in the distribution of climate-sensitive sediments and paleo-wind directions in the Asian interior during the early, mid-, and late Cretaceous. The distribution of the reconstructed subtropical arid zone (yellow-colored desert zone and red-colored semi-arid zone) shows marked changes in latitude through the Cretaceous. The paleo-wind directions, plotted on rose diagrams, also indicate drastic shifts in the boundary position of the westerlies and northeast trade winds in the Asia. Based on the paleo-wind direction data, together with the latitudinal distribution of deserts in the Asian interior, the divergence axis of the subtropical high-pressure belt is estimated to have been situated between 30° N and 40° N during the early and late Cretaceous, and between 20° N and 30° N during the mid-Cretaceous. The original data regarding depositional ages, paleolatitudes, and paleo-wind directions in each basin are shown in Fig. 1 and Table 1.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◀
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

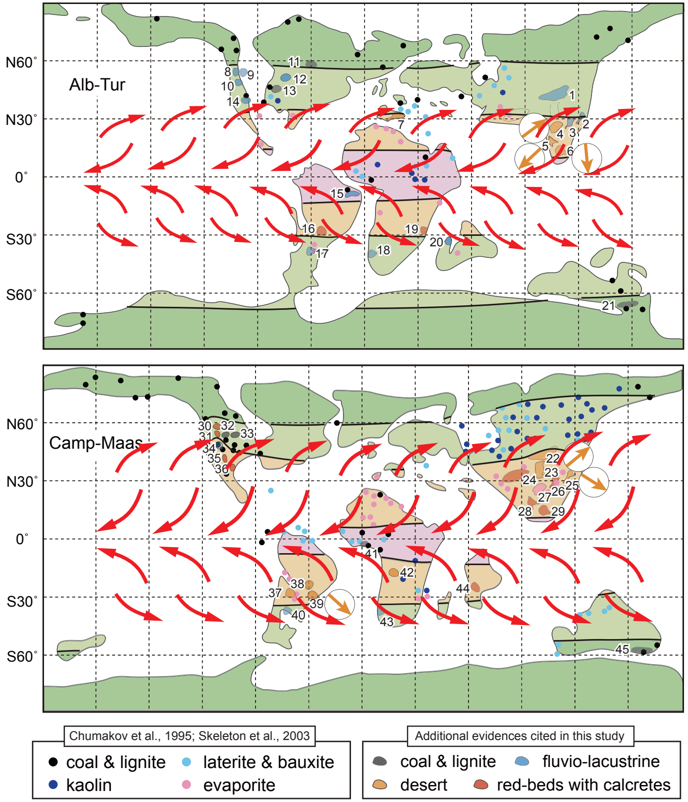
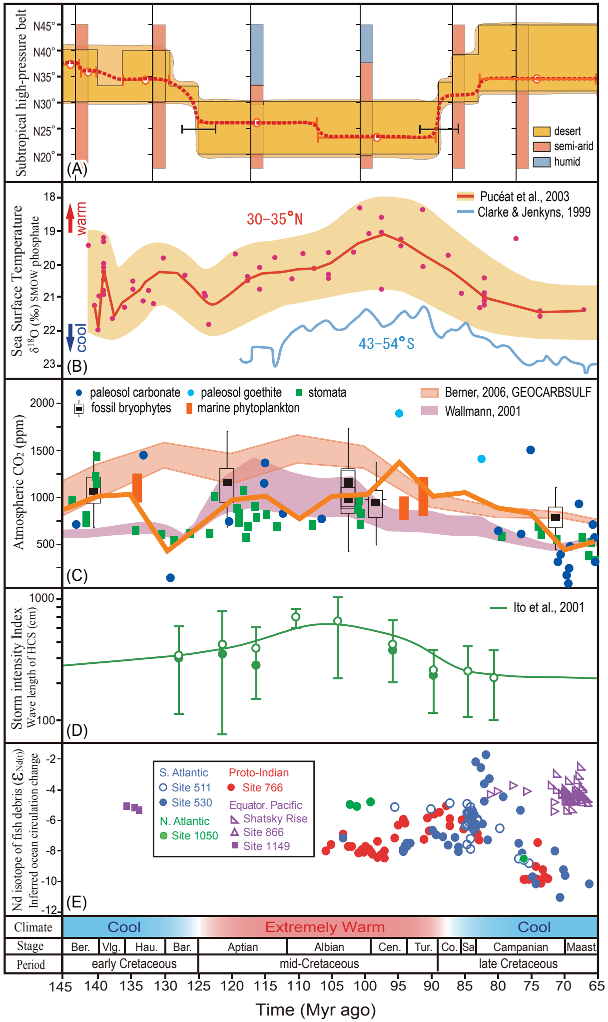


Fig. 3. Global distribution of climate-sensitive sediments (e.g., coals, laterite, and desert deposits) and the inferred latitudinal distribution of paleoclimatic zones during the mid-Cretaceous (Albian–Turonian) and late Cretaceous (Campanian–Maastrichtian) (modified after, Chumakov et al., 1995; Skeleton et al., 2003; and additional evidences cited in this study (localities listed by number in Supplement Table S2)). Pink, yellow, light green and dark green zones represent the distribution of tropical humid, subtropical arid, mid-latitude warm humid, and high-latitude temperate zones, respectively.



Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Fig. 4. (A) Reconstructed latitudinal distribution of the subtropical high-pressure belt in Asia (this study). Gray areas represent the latitudinal distribution of desert deposits (sense, Fig. 1), and the black-dotted line shows the inferred divergence axis of the subtropical high-pressure belt. Estimation errors of the depositional ages of the formations are indicated as error bars. **(B)** Sea surface temperature at 30–35° N estimated from the oxygen isotope record of fish-tooth phosphates (Pucéat et al., 2003) and at 43–54° N estimated from the oxygen isotope record of bulk shallow-marine carbonates (Clarke and Jenkyns, 1999). **(C)** Atmospheric CO_2 levels are based on estimates derived from proxy records (modified after, compilation of Breecker et al. (2010); and additional evidences: fossil bryophytes (Fletcher et al., 2008); and marine phytoplankton (Freeman and Hayes, 1992; Royer et al., 2001)) and carbon cycle model estimates (Wallmann, 2001; Berner, 2006; GEOCARBSULF). 5 million year means of the proxy-based estimates are shown by the orange line. These limited data-sets of the atmospheric CO_2 estimates suggest slightly higher $p\mathrm{CO}_2$ value (ca. 1000–1500 ppm) during the extremely warm mid-Cretaceous "supergreenhouse" period, compared to the slightly lower value (ca. 500–1000 ppm) during the late Cretaceous period. **(D)** Variations in storm intensity estimated based on the wavelength of hummocky cross-stratification (HCS) (Ito et al., 2001). Vertical bars indicate ranges in wavelength, and open and filled circles represent the mid-point wavelength and average wavelength, respectively. The solid line represents a two-point moving average of mid-point values (Ito et al., 2001). **(E)** Variations in Nd-isotope data from the Cretaceous intermediate- to deep-water masses (modified after, Robinson et al., 2010). North Atlantic (green closed circle) and Equatorial Pacific of the ODP Site 866 (purple triangle) data are from MacLeod et al. (2008). Equatorial Pacific of the Shatsky Rise data (purple delta) is from Frank et al. (2005). South Atlantic (blue open and closed circles), Proto-Indian (red closed circle), and Equatorial Pacific of the ODP Site 1149 (purple square) data are from Robinson et al. (2010). The Nd-isotopic variations in several oceans demonstrated that the predominance of relatively radiogenic Nd-isotope values (−8 to −5) in high-latitude oceans in the mid-Cretaceous (Albian–Santonian), whereas the development of more nonradiogenic values (−8 to −11) in such high-latitude oceans only becomes apparent during the late Cretaceous (Campanina–Maastrichtian) (sensu, Robinson et al., 2010).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◀
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

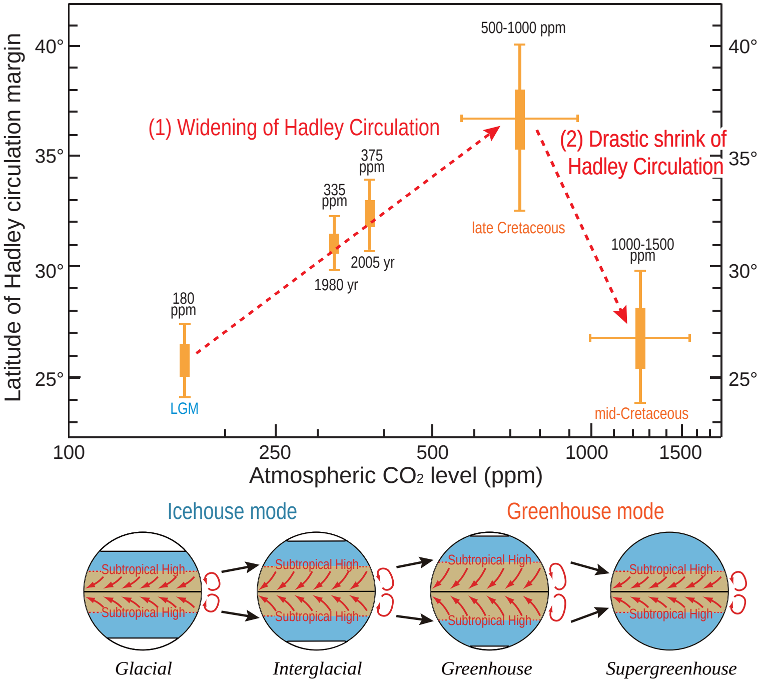


Fig. 5. Conceptual scheme of the latitudinal change in the subtropical high-pressure belt versus atmospheric CO_2 levels. Also shown is inferred evolutionary trend of the atmospheric circulation pattern (variations in the width of the Hadley circulation) in response to climatic warming (from icehouse mode to greenhouse mode). Values of atmospheric pCO_2 during the middle and late Cretaceous are based on the carbon cycle model estimates (Berner, 2006, GEOCARBSULF) and proxy-based estimates (compiled by Breecker et al., 2010) (Fig. 4c). Latitudes of the subtropical high-pressure belt at the present-day and Last Glacial Maximum are based on recent observational studies (Hu and Fu, 2007; Seidel et al., 2008) and geological data (Nicholson and Flohn, 1980; Toggweiler and Russell, 2008). Vertical bars indicate ranges in the latitude of the subtropical high-pressure belt. Arrows in the lower figures represent trade winds.