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Climate of the Past

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

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Abstract. Understanding the behavior 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 datasets 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 (Aptian–Turonian: 125–89 Ma) is characterized by higher atmospheric CO_2 levels (Royer et al., 2001; Wallmann, 2001; Berner, 2006; Fletcher et al., 2008; Breecker et al., 2010; Hong and Lee, 2012), long-lasting extreme warmth of deep-ocean and polar surface temperatures ($\sim$15–20 °C; Huber et al., 2002; Jenkyns et al., 2004; Friedrich et al., 2012) compared to modern values ($\lesssim$4 °C), substantially warmer tropical sea surface temperatures (SSTs) ($\sim$33 °C and 35–36 °C at the maximum; Wilson et al., 2002; Forster et al., 2007; Borneman et al., 2008) than modern values ($\sim$27–29 °C), and 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 evidence of the extremely warm polar climate (Herman and Spicer, 1996; Skelton et al., 2003; Jenkyns et al., 2004; Spicer et al., 2008) supports the lower meridional temperature gradients during the mid-Cretaceous.

To explain such a reduced gradient under elevated atmospheric CO_2 levels, 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 in 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 datasets 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; Gasse and Roberts, 2004). 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 reconstruct 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 reconstruct the temporal changes in the width of the Hadley circulation throughout the Cretaceous, and discuss their possible causes. We also discuss 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 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 its paleogeography during the Cretaceous has been reconstructed based on paleomagnetic studies (modified after the Plate-Tracker program of the 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 the 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). Latitudinal differences of the studied basins are large, and no substantial changes in their relative positions have occurred during the Cretaceous (e.g. Li, 1994; Meng and Zhang, 1999).

Figure 1b shows temporal changes in the latitudinal distribution of climate-indicative 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 of the studied basins, which stem from the paleomagnetic data, have errors of less than ±5° (between ±1.1° and ±4.2°; Table 1). Although the error bars are relatively large, both eolian sandstone distribution and paleo-wind direction data suggest that significant latitudinal shifts of the subtropical high-pressure belt have occurred during the Cretaceous (Figs. 1b and 2), as described below.

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 the Ordos and Tarim basins in northern China (between 32.6° N and 41.0° N : 36.8° N ± 4.2° N) during the early Cretaceous

Table 1. Paleoposition of the Cretaceous eolian sandstones in Asia. Paleolatitudes and rotations of the basins are based on paleomagnetic data.

Basin	Paleolatitude	Rotation	References
Gobi basin	44.0° N–46.1° N (45.1° N ± 1.1° N)	5.2°–15.3° (10.3° ± 5.1°)	Hankard et al. (2005)
Ordos basin	32.6° N–41.0° N (36.8° N ± 4.2° N)	7.2°–12.1° (9.7° ± 2.5°)	Zheng et al. (1991) Cheng et al. (1988)
Tarim basin	33.0° N–39.5° N (36.3° N ± 3.3° N)	15.7°–21.5° (18.6° ± 2.9°)	Li (1990) Chen et al. (1992)
Subei basin	30.8° N–37.0° N (33.9° N ± 3.1° N)	1.3°–16.7° (9.0° ± 7.7°)	Gilder et al. (1999) Zhu et al. (2006)
Sichuan basin	25.5° N–29.6° N (27.5° N ± 2.0° N)	10.5°–15.6° (13.1° ± 2.6°)	Enkin et al. (1991) Zhuang et al. (1988)
Simao basin	21.8° N–27.6° N (24.7° N ± 2.9° N)	36.3°–48.6° (42.5° ± 6.2°)	Huang and Opdyke (1993) Otofuji et al. (1990)
Khorat basin	16.3° N–21.6° N (19.0° N ± 2.7° N)	20.0°–25.0° (22.5° ± 2.5°)	Charusiri et al. (2005)

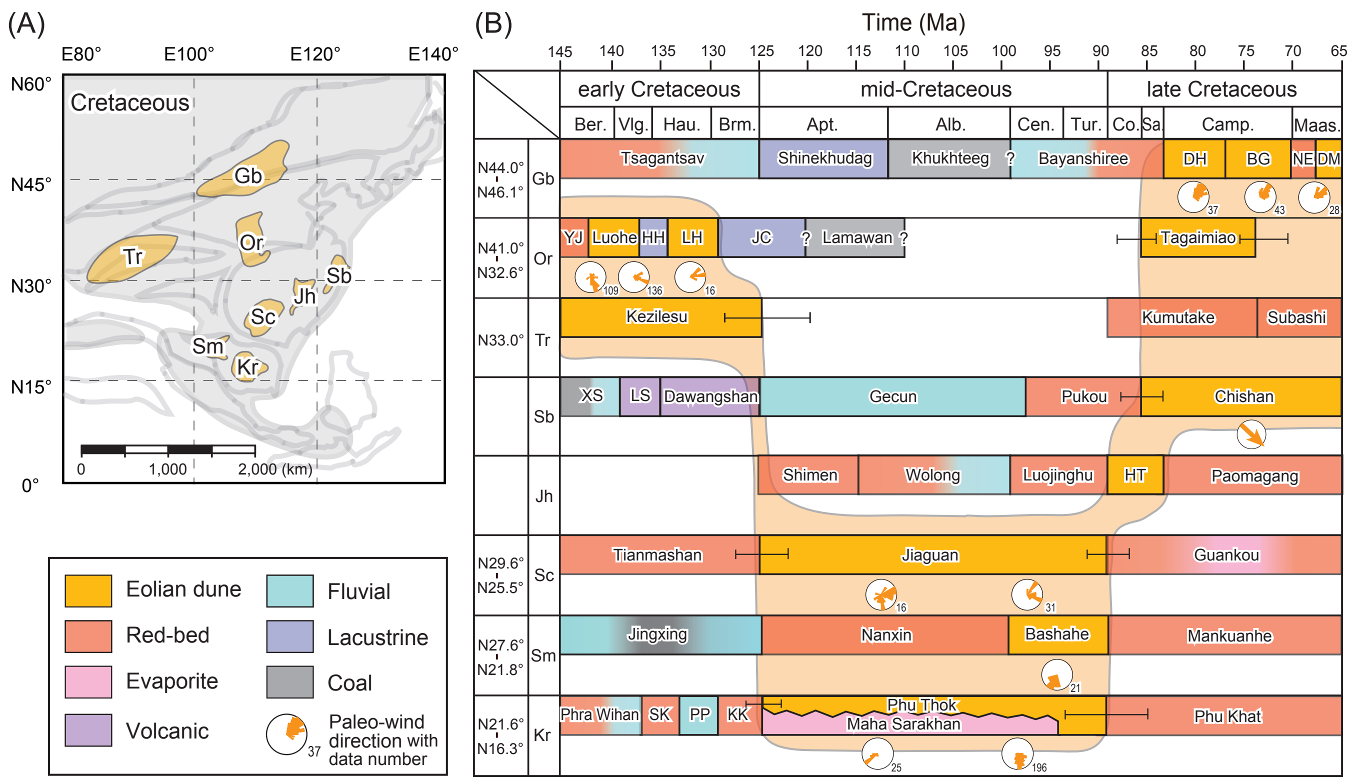

Fig. 1. (A) Paleogeographic map of the Asian continent during the Cretaceous, showing the locations of sedimentary basins cited in this study (modified after Eldridge et al., 2000; Table 1). Abbreviated basin names are as follows: Gb = Gobi; Or = Ordos; Tr = Tarim; Sb = Subei; Jh = Jianghan; Sc = Sichuan; Sm = Simao; Kr = Khorat. **(B)** Stratigraphic chart of climate-indicative 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 Supplement). Estimation errors are indicated as error bars. Abbreviated stage names are as follows: Ber = Berriasian; Vlg = Valanginian; Hau = Hauterivian; Brm = Barremian; Apt = Aptian; Alb = Albian; Cen = Cenomanian; Tur = Turonian; Co = Coniacian; Sa = Santonian; Camp = Campanian; Maas = Maastrichtian. 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.

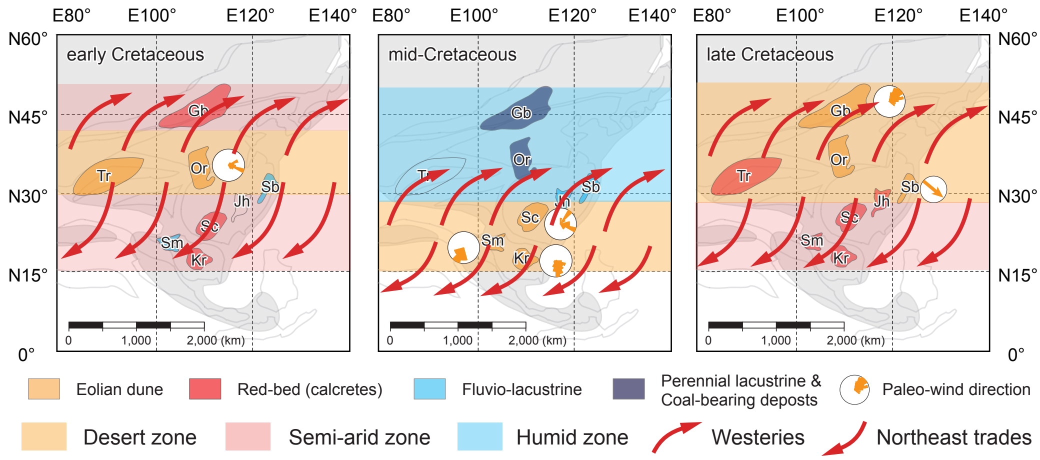

Fig. 2. Spatio-temporal changes in the distribution of climate-indicative sediments and paleo-wind directions in the Asian interior during the early, mid-, and late Cretaceous. The distribution of the reconstructed subtropical arid zone (yellow-colored desert zone and red-colored semi-arid zone) shows 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 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.

(Berriasian–Barremian), (2) distribution of eolian sandstone deposits shifted southward to the 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° N) during the mid-Cretaceous (Aptian–Turonian), and (3) its distribution shifted northward again to the 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° N) 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. 1b 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 the desert zone are 13.8° ± 10.8° between the early and the mid-Cretaceous, and 15.4° ± 14.2° between the mid- and the late Cretaceous, respectively. Despite relatively large error bars, it is noteworthy that the southern margin of the desert zone was located in the Tarim basin (36.3° N ± 3.3° N) during the early Cretaceous, whereas its northern margin was shifted to Sichuan basin (27.5° N ± 2.0° N) during the mid-Cretaceous. Thus, there was not only no overlap in the distribution of the 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 and 2). Therefore, evidence for large-scale latitudinal shifts of the climate zones (ca. 13.8°–15.4° in mean values) in Asia during the Cretaceous are significant.

In addition to the latitudinal distribution of eolian sandstone deposits, paleo-wind direction data further 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) the zonal boundary between the westerlies and trade winds was situated in the Ordos Basin (between 32.6° N and 41.0° N) during the early Cretaceous with gradual southward shifting; (2) westerlies prevailed in the Sichuan Basin (between 25.5° N and 29.6° N), while the trade winds prevailed in the Simao Basin (between 21.8° N and 27.6° N) during the mid-Cretaceous; and (3) westerlies prevailed in the Gobi Basin (between 44.0° N and 46.1° N), and the zonal boundary between the westerlies and trade winds were situated in the Subei Basin (between 30.8° N and 37.0° N) during the late Cretaceous (Figs. 1 and 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° N) during the early Cretaceous, between 21.8° N and 29.6° N

(25.7° N ± 3.9° N) during the mid-Cretaceous, and between 30.8° N and 37.0° N (33.9° N ± 3.1° N) 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, the latitudinal shifts of the divergence axis of the subtropical high-pressure belt (ca. 8.2°–11.1° in mean values) 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 significant.

3.2 Changes in the width of the Hadley circulation

The global distribution of climate-indicative sediments (e.g. coals, laterite, bauxite, kaolin, 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 are characterized by fluvio-lacustrine deposits that contain abundant spherosiderites (Ludvigson et al., 1998; Ufnar et al., 2004) 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, that suggest dominance of relatively arid climate (e.g. Southern Alberta (30); Western Montana Basin (31); New Mexico Basin (35); Western Texas Basin (36)). An eolian sandstone record of mid-Cretaceous age has been reported from the Iberia basin, southern Spain (7: Escucha and Ultrillas Formations; Rodriguez-Lopez et al., 2008), although their paleo-wind direction data show largely variable directions. Given that the paleolatitude of the Iberia basin was approximately at 25° N–30° N (Stampfli and Borel, 2002), it was probably situated at the northern limit of the subtropical arid belt during the mid-Cretaceous, similar to the Sichuan basin of southern China (Fig. 3).

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 and an arid desert climate during the late Cretaceous. This is consistent with the trend recorded in the Northern Hemisphere. Importantly, no mid-Cretaceous eolian sandstone deposits have been reported from low- to mid-latitudes in the Southern Hemisphere (Fig. 3). In contrast,

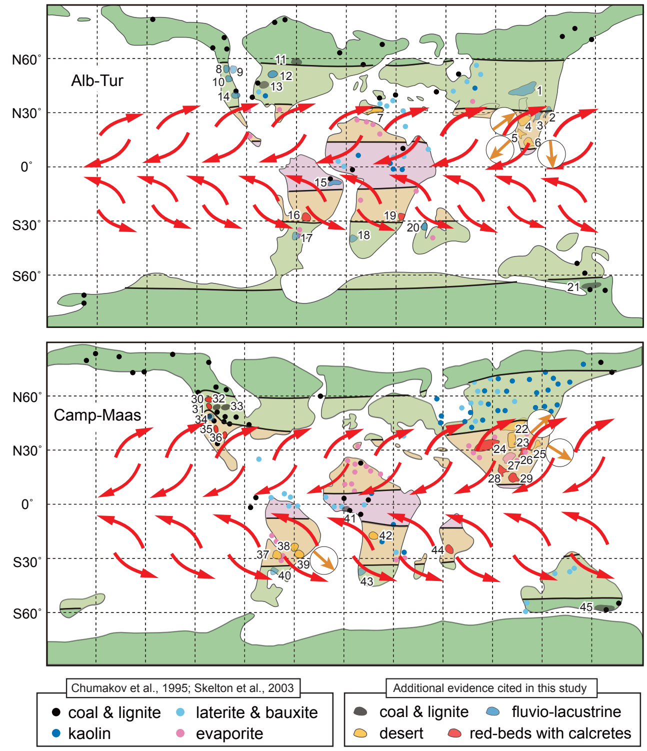

Fig. 3. Global distribution of climate-indicative sediments (e.g. coals, laterite, and desert deposits) and the inferred latitudinal distribution of paleoclimatic zones during the mid-Cretaceous (Albian–Turonian) and late Cretaceous (Campanian–Maastrichtian) (modified after, Chumakov et al., 1995; Skelton 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.

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 (Ziegler et al., 2003). 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 ever-wet climates associated with the Inter-Tropical Convergence

Zone (ITCZ) (Ziegler et al., 2003). Figure 3 shows the distribution of evaporite deposits which prevailed in the subtropical arid zone (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), which coincided 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), which is interpreted as representing the ever-wet climates under the ITCZ (Fig. 3). Furthermore, the location of the ITCZ, indicated by the distribution of ever-wet 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.

Conclusively, our results indicate that the paleolatitude of the Northern Hemisphere subtropical high-pressure belt was located between ca. 33° N and 41° N during the early Cretaceous and between ca. 31° N and 37° N during the late Cretaceous, whereas it shifted southward and was 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. Specifically, 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 and 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; Hong and Lee, 2012) are generally in good agreement with carbon cycle model estimates (Wallmann, 2001; Berner, 2006, GEOCARBSULF). These limited datasets of atmospheric CO_2 estimates suggest slightly higher atmospheric CO_2 value (ca. 1000–1500 ppm) during the extremely warm mid-Cretaceous "supergreenhouse" period, compared to the slightly lower values (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 the increasing atmospheric CO_2 level and consequent global warming (Hu and Fu, 2007; Lu et al., 2007, 2009; Seidel et al., 2008; Johanson and Fu, 2009). In addition, the widening of the Hadley circulation in response to increased concentrations of greenhouse gases is also supported by climate simulation results (e.g. Kushner et al., 2001; Lu et al., 2007, 2009; Previdi and Liepert, 2007; Johanson and Fu, 2009; Schneider et al., 2009). Climate simulation results of Lu et al. (2009) further suggest that the widening of the Hadley circulation can be attributed entirely to radiative forcing, in particular those related to greenhouse gases and stratospheric ozone depletion. Such a relationship between the width of the Hadley circulation and global temperature and/or atmospheric CO_2 levels has also been reported from paleoclimatic records of glacial–interglacial transitions (Nicholson and Flohn, 1980; Andreasen and Ravelo, 1997; Chylek et al., 2001; Gasse and Roberts, 2004; Toggweiler et al., 2006; Toggweiler and Russell, 2008), although some studies cast doubt on such a symmetrical shift of the width of the Hadley circulation in both hemispheres (e.g. Anderson et al., 2009). For example, some studies suggest a southward shift of both the ITCZ and westerlies belt during the deglaciation period (Lamy et al., 2007; Tierney and Russell, 2007; Anderson et al., 2009). However, there is evidence that the latitudinal shifts of the wind belt tend to be symmetric with respect to the Equator between glacial and interglacial periods, even though the 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). Changes in the width of the Hadley circulation during the glacial–interglacial oscillations are also demonstrated by 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 an 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 changes in the width of the Hadley circulation are related to changes of equator-to-pole temperature gradients. Furthermore, recent studies reported the possible poleward shifts of the subtropical high-pressure belt during past warmer climatic periods such as the early Pleistocene

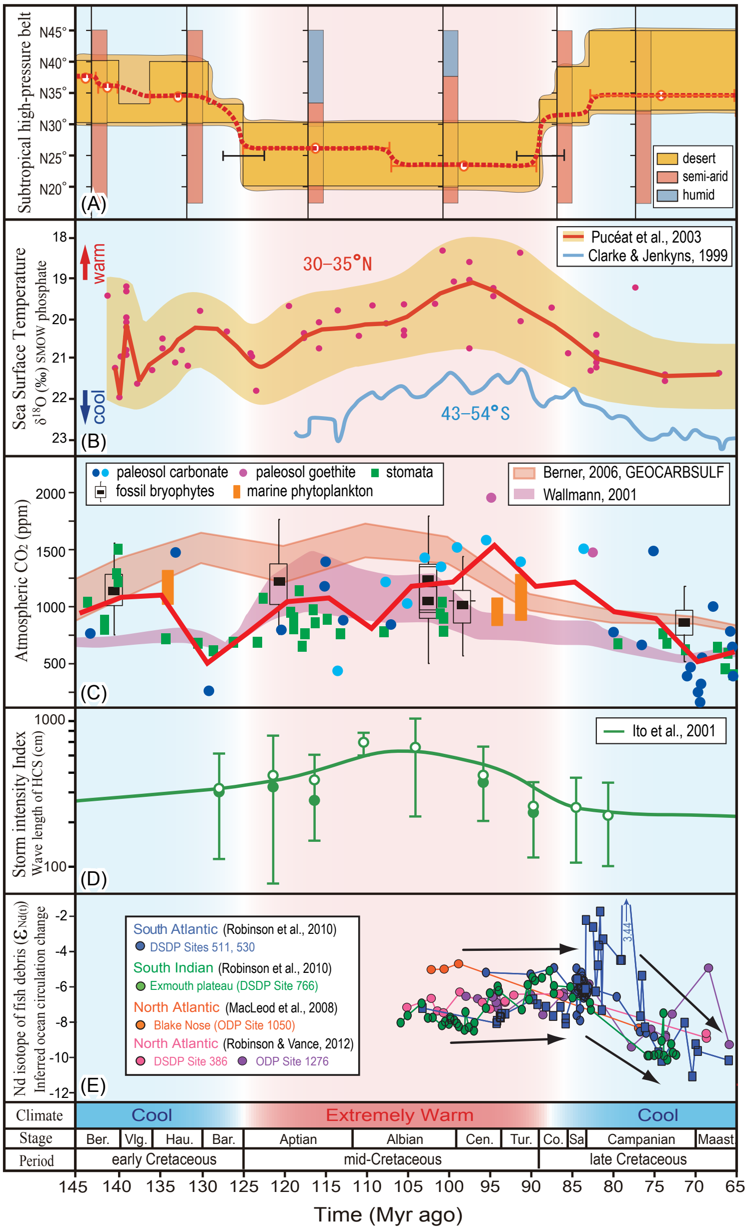

Fig. 4. **(A)** Reconstructed latitudinal distribution of the subtropical high-pressure belt in Asia (this study). Orange areas represent the latitudinal distribution of desert deposits (sense, Fig. 1), and the red dotted line shows the inferred divergence axis of the subtropical high-pressure belt. 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 paleosol carbonate (blue), paleosol goethite (purple), and stomata (green) by Breecker et al. (2010); and additional evidence: fossil bryophytes (black; Fletcher et al., 2008), marine phytoplankton (orange; Freeman and Hayes, 1992; Royer et al., 2001), and paleosol carbonate (light blue; Hong and Lee, 2012)) and carbon cycle model estimates (Wallmann, 2001; Berner, 2006, GEOCARBSULF). Five million year means of the proxy-based estimates are shown by the red line. These limited datasets of the atmospheric CO_2 estimates suggest slightly higher atmospheric 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; MacLeod et al., 2011; Robinson and Vance, 2012). North Atlantic ODP Site 1050 data (orange circle) are from MacLeod et al. (2008). North Atlantic data from DSDP Site 386 (pink circle) and ODP Site 1276 (purple circle) are from Robinson and Vance, 2012. South Atlantic (blue circle and square) and southern Indian data (red closed circle) are from Robinson et al. (2010). The Nd-isotopic variations in several oceans demonstrated consistently higher Nd-isotope values (−8 to −4) during the mid-Cretaceous (Albian to Coniasian–Santonian), whereas the values became gradually lower (−12 to −8) during the late Cretaceous (Campanian–Maastrichtian), suggesting an intensification of deep ocean circulation in high-latitude oceans (especially at southern high-latitudes) during the late Cretaceous (Robinson et al., 2010; MacLeod et al., 2011; Robinson and Vance, 2012). **(F)** Inferred climate mode of the early, mid- and late Cretaceous. The mid-Cretaceous is characterized by an extremely warm "supergreenhouse" mode, while the early and late Cretaceous are characterized by a relatively cooler, but still moderately warm "greenhouse" mode.

(Sniderman et al., 2009) and the early Pliocene (Brierley et al., 2009).

Therefore, the occurrence of the subtropical high-pressure belt at relatively high latitudes during the early and late Cretaceous can be explained by poleward expansion of the Hadley circulation in association with an increased atmospheric CO_2 level 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 CO_2 level. 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 could be caused by the long-term changes in the land–sea distributions during the Cretaceous (e.g. opening of an Atlantic gateway: rifting of South America and Africa). Poulsen et al. (2003) conducted a coupled atmosphere-ocean general circulation model (AOGCM) experiment for the mid-Cretaceous with different paleogeographic conditions (with and without an Atlantic gateway between South America and Africa), in order to examine the impact of the formation of an Atlantic gateway on oceanic circulation and global climate. The results demonstrate that the formation of an Atlantic gateway could cause the increase in heat transport into the North Atlantic from the 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 of the opening of the equatorial Atlantic gateway (deep water connection) occurred between the Albian and the Cenomanian (Wagner and Pletsch, 1999), significantly later than the initial equatorward shift of the subtropical high-pressure belt that took place between the Barremian and the 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 (AGCM) experiment with boundary conditions of a reduced meridional surface temperature gradient with mid-Cretaceous paleogeography and an atmospheric CO_2 level four times as high as present-day. Although Fluteau et al. (2007) use an AGCM model and prescribed the meridional temperature gradient, which is significantly different from some AOGCM simulations (e.g. Poulsen et al., 2003), their model results demonstrated the 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.

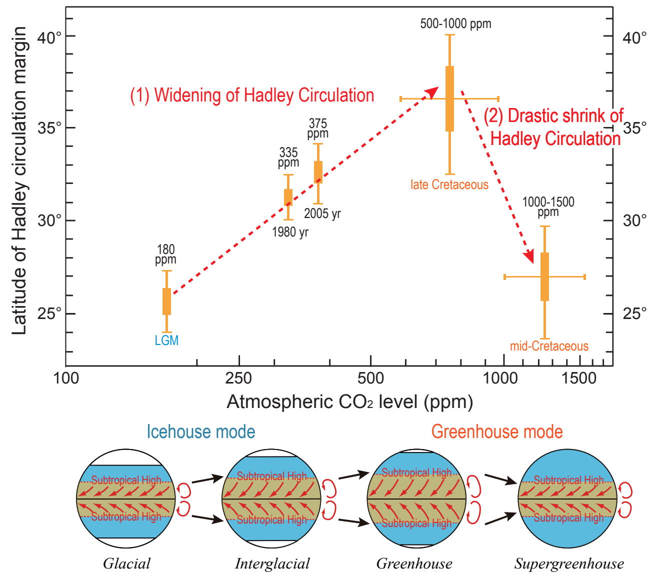

Fig. 5. Conceptual scheme of the latitudinal change in the subtropical high-pressure belt versus atmospheric CO_2 levels. Also shown is the inferred evolutionary trend of the atmospheric circulation pattern (variations in the width of the Hadley circulation) in response to climatic warming (from icehouse mode to greenhouse mode). Values of atmospheric CO_2 during the middle and late Cretaceous are based on 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.

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-indicative sediments also suggests the predominance of a broad humid zone in mid-latitude areas of both North America and the Southern Hemisphere during the mid-Cretaceous as was described earlier (Fig. 3). This finding is supported by increased precipitation rates estimated for North American mid-latitudes (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 $\delta^{18}O$

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. Furthermore, temporal changes in storm intensity, estimated from the wavelengths of hummocky cross-stratification in the mid- to high-latitudinal areas of the Northern Hemisphere, indicate a maximum in storm 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). In addition, enhancement of the extratropical storm track intensity and increased humidity at mid-latitudes in warmer climatic states are also supported by recent climatic simulation studies (e.g. Schneider et al., 2009; Lu, 2010; O'Gorman, 2010; Riviere, 2011), although none of these model simulations did produce the shrinkage of the Hadley circulation.

Research results of the high resolution proxy data and paleoclimatic simulations of the Upper Cretaceous deposits of the equatorial Atlantic off coastal Africa (Hofmann et al., 2003; Beckmann et al., 2005; Flögel and Wagner, 2006) and coastal South America (Flögel et al., 2008) also suggest an enhanced hydrological cycle in the tropics during the climatically warm interval of the Coniacian–Santonian Ocean Anoxic Event 3 (OAE-3). Firstly, Hoffman et al. (2003) presented the orbital-scale variations of the organic carbon burials and river discharges from the African continents. They suggested that ocean anoxia and organic carbon burials were triggered by the increased humidity and enhanced river discharge, which could be caused by the latitudinal shifts of the ITCZ. Then, paleoclimatic simulation results (Flögel and Wagner, 2006) further suggested that the enhanced hydrological cycles in the African tropics during the climatically warm intervals were ultimately triggered by increased humidity in the mid-latitude extratropics, instead of the latitudinal movement of ITCZ. Thus, although the results of Flögel and Wagner (2006) are not the direct evidence of the changes of Hadley circulation width, and their time-scales of climate changes are different from our results, the enhanced hydrological cycle in both the tropics and the mid-latitude extratropics during the climatically warm interval of Coniacian–Santonian OAE-3 are indicated, which are trend consistent with our results.

3.5 Covarying trends in oceanic and atmospheric circulation systems

It is well-established that generally 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) (e.g. Rahmstorf, 2002). Increasing evidence suggests 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 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). However, reconstruction of the ocean circulation system during the Cretaceous had been hampered by a lack of appropriate datasets based on reliable proxies. Recent intensive studies tried to reconstruct the changes in the ocean circulation system during the Cretaceous based on Nd isotopes (e.g. Pucéat et al., 2005; Soudry et al., 2006; MacLeod et al., 2008, 2011; Robinson et al., 2010; Robinson and Vance, 2012).

In the present configuration of continents and oceans, there are distinct differences in the Nd isotopic values of deep waters in the Pacific, Indian, and Atlantic Oceans. Thus, seawater ε_{Nd} values (the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio) are used as a good tracer of the past ocean circulation system (Frank, 2002; Thomas et al., 2003; Thomas, 2004; Roberts et al., 2010). 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 consistently 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 at ODP Site 1276 in the Maastrichtian) (Robinson et al., 2010; Robinson and Vance, 2012; Fig. 4e). The relatively low ε_{Nd} values (-12 to -8) of the South and North Atlantic and southern 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) is interpreted as the onset and/or intensification of deep-ocean circulation in the 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, consistently 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) show dominance of extremely low values (typically −16 to −11; MacLeod et al., 2008, 2011), these data stand in marked difference to the ε_{Nd} values from the South and North Atlantic and southern Indian Oceans (MacLeod et al., 2008; Robinson et al., 2010; Robinson and Vance, 2012). This observation supports the suggestion of a dominance of intermediate water (so-called "Demerara Bottom Water") 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 mid- and late Cretaceous.

Therefore, although some controversy exists in interpretation of the Cretaceous ocean circulation change by Nd isotopic datasets, the increasing evidence suggests that nearly synchronous changes of ocean circulation have occurred in the North and South Atlantic during the mid- to late Cretaceous (Fig. 4e). Specifically, the deep-ocean circulation in the North and South Atlantic and southern Indian Oceans was "sluggish" during the mid-Cretaceous, whereas the deep-ocean circulation was intensified in high-latitude oceans (especially in the southern high-latitude ocean) during the late Cretaceous (Robinson et al., 2010; MacLeod et al., 2011; Robinson and Vance, 2012), consistent with simulation results 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 larger planktonic–benthic oxygen isotope gradients during the Cenomanian–Santonian at southern high latitudes, suggesting stratified water columns, whereas smaller planktonic–benthic gradients during the Campanian–Maastrichtian suggest an onset of significant high-latitude deep-water due to the initiation of the global cooling at that time (Huber et al., 2002; Robinson et al., 2010; MacLeod et al., 2011; Robinson and Vance, 2012).

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 systems during the Cretaceous "greenhouse" period (Fig. 4). Although the causal relationship between the covariations of Hadley circulation width and deep ocean circulation during the Cretaceous is currently unclear, we speculate about the following potential linkages. Poleward shifts of the subtropical high-pressure belt during the late Cretaceous could have resulted in the formation of more saline surface water at higher latitudes that possibly promoted the onset of deep-ocean circulation in higher latitude oceans. 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 at lower latitudes and development of less saline water at higher latitudes 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 turbulence 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 deep water formation in higher latitude oceans (e.g. sparsely distributed mesoscale eddies; similar to the "eddy-filled ocean"; Figs. 10 and 11 of Hay, 2008). An alternative scenario is that both the variations in ocean and atmospheric circulation systems were triggered by the changes of meridional temperature gradients and atmospheric CO_2 level. In conclusion, although further work is needed to address their possible causal linkage, it is noteworthy that there is a temporal synchronicity in the switches of the oceanic and atmospheric circulation systems during the mid- to late Cretaceous (Fig. 4).

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 expanded poleward with the progressive increase in atmospheric CO_2 and consequent climatic warming from modern "icehouse" conditions (atmospheric $CO_2 \cong 180$–375 ppm; Luthi et al., 2008) to late Cretaceous "greenhouse" conditions (atmospheric $CO_2 \cong 500$–1000 ppm), and (2) when atmospheric CO_2 exceeded a threshold level and reached a mid-Cretaceous "supergreenhouse" level (atmospheric $CO_2 \cong 1000$–1500 ppm), Hadley circulation drastically shrank equatorwards and was possibly replaced by enhanced extratropical cyclone activity at middle latitudes (Figs. 4c and 5; atmospheric CO_2 values from Berner, 2006, GEOCARBSULF, and proxy-based estimates compiled by Breecker et al., 2010). If atmospheric CO_2 is the forcing mechanism of this drastic switch in atmospheric circulation system, our results suggest the existence of a probable threshold at atmospheric CO_2 level of approximately 1000 ppm, beyond which the Hadley circulation would shrink drastically (Fig. 5), although the predicted threshold value is based on the limited datasets and further reconstructions of Cretaceous atmospheric CO_2 levels are required. This predicted threshold value may be reached in the near future if we continue to emit CO_2 at the current rate (e.g. IPCC, 2007: AR4 scenario A2). The possible presence of such a threshold of atmospheric CO_2 level on the Hadley circulation changes 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 levels reaching more than ca. 1000 ppm. Although we leave the detailed investigation of Eocene paleoclimate to future studies, available geological evidence suggests that a similar phenomenon 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 evidence for an enhanced hydrological cycle during the Eocene period. In conclusion, 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 the 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 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 at the latitudes 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 latitudes between ca. 33° N and 41° N during the early Cretaceous and between ca. 31° N and 37° N during the late Cretaceous (36.8° N $\pm$ 4.2° N and 33.9° N $\pm$ 3.1° N, respectively). In contrast, an equatorward shift of the belt to the latitudes between ca. 22° N and 30° N (25.7° N $\pm$ 3.9° N) was found during the mid-Cretaceous. The magnitude of the latitudinal shifts are $11.1° \pm 8.1°$ between the early and the mid-Cretaceous, and $8.2° \pm 7.0°$ 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 shrinks equatorwards.

The long-term relationships among the width of the Hadley circulation, global temperatures, and atmospheric CO_2 levels during the Cretaceous suggest the existence of a threshold in atmospheric CO_2 level (approximately 1000 ppm) and/or global temperature, beyond which the Hadley circulation shrinks drastically. The possibility of such a drastic switch in the atmospheric circulation system with increasing atmospheric CO_2 should be explored in more detail to better understand and prepare for future climatic changes.

Supplementary material related to this article is available online at: http://www.clim-past.net/8/1323/2012/cp-8-1323-2012-supplement.pdf.

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