Front. Earth Sci. 2017, 11(4): 740–750
DOI 10.1007/s11707-017-0661-0

RESEARCH ARTICLE

# Major transgression during Late Cretaceous constrained by basin sediments in northern Africa: implication for global rise in sea level

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**Abstract** The global rise in sea level during the Late Cretaceous has been an issue under discussion by the international geological community. Despite the significance, its impact on the deposition of continental basins is not well known. This paper presents the systematic review on stratigraphy and sedimentary facies compiled from 22 continental basins in northern Africa. The results indicate that the region was dominated by sediments of continental facies during Early Cretaceous, which were replaced by deposits of marine facies in Late Cretaceous. The spatio-temporal distribution of sedimentary facies suggests marine facies deposition reached as far south as Taoudeni-Iullemmeden-Chad-Al Kufra-Upper Egypt basins during Turonian to Campanian. These results indicate that northern Africa underwent significant transgression during Late Cretaceous reaching its peak during Turonian to Coniacian. This significant transgression has been attributed to the global high sea-level during this time. Previous studies show that global rise in sea level in Late Cretaceous may have been driven by an increase in the volume of ocean water (attributed to high $CO_2$ concentration and subsequently warm climate) and a decrease in the volume of the ocean basin (attributed to rapid production of oceanic crust and seamounts). Tectonic mechanism of rapid production of oceanic crust and seamounts could play a fundamental role in driving the global rise in sea level and subsequent transgression in northern Africa during Late Cretaceous.

Received December 24, 2016; accepted April 19, 2017

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**Keywords** global sea-level changes, Late Cretaceous, transgression, sedimentary facies, northern Africa

## 1 Introduction

Sea levels have fluctuated frequently throughout Earth's history, resulting in consequent transgression/regression cycles. Within these eustatic events, the Late Cretaceous transgression is thought to represent the highest sea-level in geologic past (Haq et al, 1987; Miller et al., 2004, 2005; Miller and Pekar, 2005; Guiraud et al., 2005; Fluteau et al., 2007; Müller et al, 2008), which was under a 'Greenhouse Climate' (Larson and Erba, 1999; Wilson et al., 2002; Jenkyns et al, 2004; Miller and Pekar, 2005; Hay and Floegel, 2012; Wendler and Wendler, 2016) with more frequent and rapid sea-level fluctuations (Hancock and Kauffman, 1979; Haq et al., 1987; Larson, 1991a; Kauffman and Caldwell, 1993; Bosellini et al., 1999a; Jarvis et al., 2002; Haq and Al-Qahtani, 2005; Miller et al., 2005; Wang and Hu, 2005; Haq, 2014). This high sea-level event was proposed to take place during ca. 95–80 Ma (Haq et al, 1987; Miller et al., 2004; Guiraud et al., 2005; Miller and Pekar, 2005; Fluteau et al., 2007; Müller et al., 2008), which would exert a broad impact on climate and deposition in addition to bearing important implications for global tectonics (Bosellini et al., 1999b; Adatte et al., 2002; Bachmann and Hirsch, 2006; Fluteau et al., 2007; Kidder and Worsley, 2010).

Previous studies on the Late Cretaceous high sea-level event were mostly based on paleoclimatic changes constrained by carbonate and foraminifera carbon and oxygen isotopes, concentrations of atmospheric carbon dioxide and oxygen, sea surface temperatures, and other methods (Hancock and Kauffman, 1979; Kauffman and Caldwell, 1993; Bosellini et al., 1999a; Jarvis et al., 2002; Wang and Hu, 2005), with some studies directly showing the sea-level changes through reconstruction of sea-level curves (Haq et al., 1987; Haq and Al-Qahtani, 2005; Miller et al., 2005; Müller et al, 2008; Haq, 2014). The impact of the high sea-level event on deposition in continental basins has rarely been addressed. Basin sediments are effective in recording paleoclimate, paleoenvironment, and sea-level history (Gale et al., 2002; Haq and Al-Qahtani, 2005; Wang et al., 2013; Haq, 2014; Giorgioni et al., 2015; Wendler and Wendler, 2016). Such work has been conducted in New Jersey margin and succeeds in back-stripping the sea-level history (Watts and Thorne, 1984; Kominz et al., 1998, 2008; Miller et al., 1998, 2008; Miller and Pekar, 2005). Northern Africa, which formed part of the stable northern margins of Gondwanaland during Cretaceous (Goncuoglu and Kozlu, 2000; Badalini et al., 2002; Veevers, 2004) and should be very sensitive to the Late Cretaceous high sea-level event, has been rarely addressed (except for a primary study by Guiraud et al., 2005).

This paper presents our systematic review on Cretaceous stratigraphy compiled from 22 continental basins in northern Africa (Fig. 1). We established 12 time segments (12 ages in Cretaceous period) of distribution of sedimentary facies to reveal the spatio-temporal variations of deposition in this region. Dominance of marine facies deposition has been used as an indicator of transgression and the high sea-level event.

## 2 Geological setting

After formation of the Gondwanaland during the Pan-Africa tectonism (Veevers, 2004; Viola et al., 2008; Santosh et al., 2009), northern Africa formed part of the stable north margins of the Gondwanaland until its collision with the Laurentia during Carboniferous-Permian. This collision caused widespread uplift, denudation and sedimentary hiatus or foreland deposition in northern Africa (Badalini et al., 2002; Guiraud et al., 2005). After the Triassic opening of the North Atlantic Ocean (Mosar et al., 2002; Stoker et al., 2005), northern Africa returned into a passive continental margin setting and sustained tectonic stabilization during the breakup of the Gondwanaland since Jurassic (Badalini et al., 2002; Veevers, 2004), although subordinate extension may exert impact within

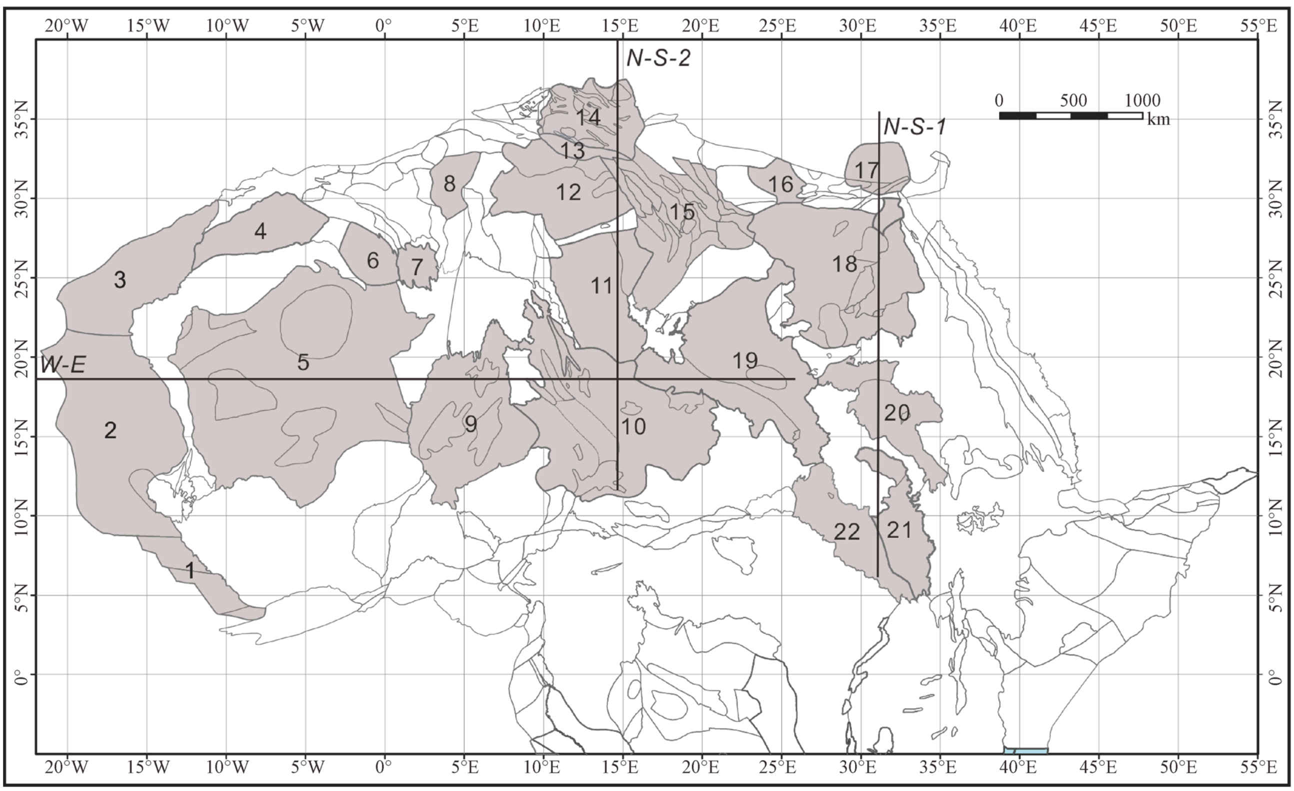


**Fig. 1** The locations of basins in northern Africa cited in the study; gray shaded regions indicate the basins with available stratigraphic data. The dark straight lines show the three stratigraphic sections described in this study. 1. Sierra Leone-Liberia Basin; 2. Senegal MSGBC (abbreviation of Mauritania-Senegal-Gambia-Guinea-Bissau-Cape Verde) Basin; 3. Aaiun-Tarfaya Basin; 4. Tindouf Basin; 5. Taoudeni Basin; 6. Reggane Basin; 7. Anhet Basin; 8. Oued Mya Basin; 9. Iullemmeden Basin; 10. Chad Basin; 11. Murzuq Basin; 12. Ghadames Basin; 13. Djefara Basin; 14. Pelagian Basin; 15. Sirte Basin; 16. Marmarica Basin; 17. Nile Delta Basin; 18. Upper Egypt Basin; 19. Al Kufra Basin; 20. Khartoum Basin; 21. Melut Basin; 22. Muglad Basin.

the breakup episode (Meert, 2003; Guiraud et al., 2005). During Cenozoic, the Atlas orogeny caused significant deformation and erosion in northernmost Africa (Barbero et al., 2007; Haji et al., 2014).

In particular, the Cretaceous northern Africa was in a tectonic-stable setting and located in the northern margins of the Gondwanaland facing the Tethys Ocean (Goncuoglu and Kozlu, 2000; Badalini et al., 2002), providing an ideal place that was sensitive to the sea-level fluctuations at this time. Thick continental and marine facies sediments that were deposited in the continental basins of this region (Adatte et al., 2002; Guiraud et al., 2005) open a window to reveal the impact of the Late Cretaceous high sea-level event.

## 3 Methods

Twenty-two basin-stratigraphic datasets were obtained from the IHS energy database. These datasets cover most basins in northern Africa (Fig. 1), allowing the deposition and sedimentary facies to be constrained in a spatial resolution of basin-scale. The stratigraphic datasets were compiled at different time segments allowing for the sedimentary facies of the region to be established in a temporal resolution of age-scale.

In this study, stratigraphic datasets from 15 representative basins were selected to construct three sections, one orientating W-E and the other two orientating N-S (Fig. 1). The W-E-direct stratigraphic section covers five basins, including Senegal MSGBC, Taoudeni, Iullemmeden, Chad and Al Kufra Basins from west to east (Fig. 1). The N-S-direct section N-S-1 crosses Nile Delta, Upper Egypt, Khartoum, Melut and Muglad Basins, while the other N-S-direct section N-S-2 covers Pelagian, Sirte, Ghadames, Murzuq and Chad Basins from north to south (Fig. 1). These stratigraphic sections cover most areas of northern Africa, allowing the variation of deposition to be well constrained. Twelve time segments (12 Cretaceous ages) of sedimentary facie distribution were established. The dominated sedimentary facies were selected to represent facies for each age. For simplification, sedimentary facies in this study were divided into three types, including fluvo-alluvial, lacustrine, and marine.

## 4 Cretaceous stratigraphy in northern Africa

The Cretaceous stratigraphy in northern Africa is presented in this study through the description of the three aforementioned representative sections. These sections cover most basins in northern Africa and thus provide insights into the main characteristics of the sedimentary variations in the region.

In the W-E section, sediments in the Dakar-Banjul region of the Senegal MSGBC Basin were dominated by limestone and dolomite while sandstone-siltstone-mudstone packages with limestone were dominant in the Orango-Conakry region during Berriasian to Aptian (Fig. 2). From Albian to Maastrichtian, mudstone-siltstone-mudstone packages prevailed in the basin with occasional limestone, marl, and volcanic rocks (Fig. 2). The Taoudeni Basin did not witness significant variation in sediments during Cretaceous and was dominated by sandstone and mudstone (Fig. 2). Systematic variation in sediments occurred in the Iullemmeden and Chad Basins, with the emergence of limestone since Turonian (Fig. 2), along with the prevalence of sandstone and subordinate mudstone and siltstone. The Iullemmeden Basin provides an extreme example for such change, with limestone dominating the basin from Turonian to Campanian (Fig. 2). Sediments in Al Kufra Basin were dominated by sandstone and subordinate marl during Early Cretaceous, with Late Cretaceous sediments absent (Fig. 2). The presence of preserved Late Cretaceous sediments to the south and north of the basin (Fig. 3) implies that Late Cretaceous sediments were deposited in the Al Kufra Basin, with subsequent erosions speculated in later tectonic events.

In the N-S-1 section, the lowermost Cretaceous sediments in the Nile Delta Basin have not yet been penetrated or proven by boreholes. The fact that a hiatus occurred in the surrounding regions during the latest Jurassic to earliest Cretaceous (Sestini, 1984, 1989; Keeley, 1994) implies that deposition of the lowermost Cretaceous sediments in the basin is unlikely. The remainder of the Cretaceous succession was composed of sandstone-mudstone-limestone-dolomite packages in the Nile Delta Basin (Fig. 3). The other basins in this section were affected by multiple episodes of extension spanning from Jurassic to early Cenozoic (Bosworth, 1992; Guiraud and Maurin, 1992), documented by episodic hiatus, unconformity, conglomerate, and volcanic rocks during Cretaceous (Fig. 3). Taking these as an exception, deposition was typically dominated by sandstone-mudstone packages with prevailing siltstone during Cenomanian to Campanian in the Upper Egypt Basin, minor siltstone in the Muglad Basin, and subordinate limestone during Maastrichtian in the Upper Egypt and Khartoum Basins (Fig. 3).

In the N-S-2 section, sediments in Pelagian Basin were dominated by limestone and subordinate mudstone throughout Cretaceous (Fig. 4). In the Sirte and Ghadames Basins, sandstone-mudstone packages with occasional limestone prevailed during Early Cretaceous; while sediments shifted into mudstone-limestone-dominated sequences with subordinate evaporite, marl, and dolomite in Late Cretaceous (Fig. 4). Such a shift of an upward-finer sequence was also observed in Chad Basin, with limestone emerging in Late Cretaceous compared to sandstone-mudstone packages with occasional siltstone during Early

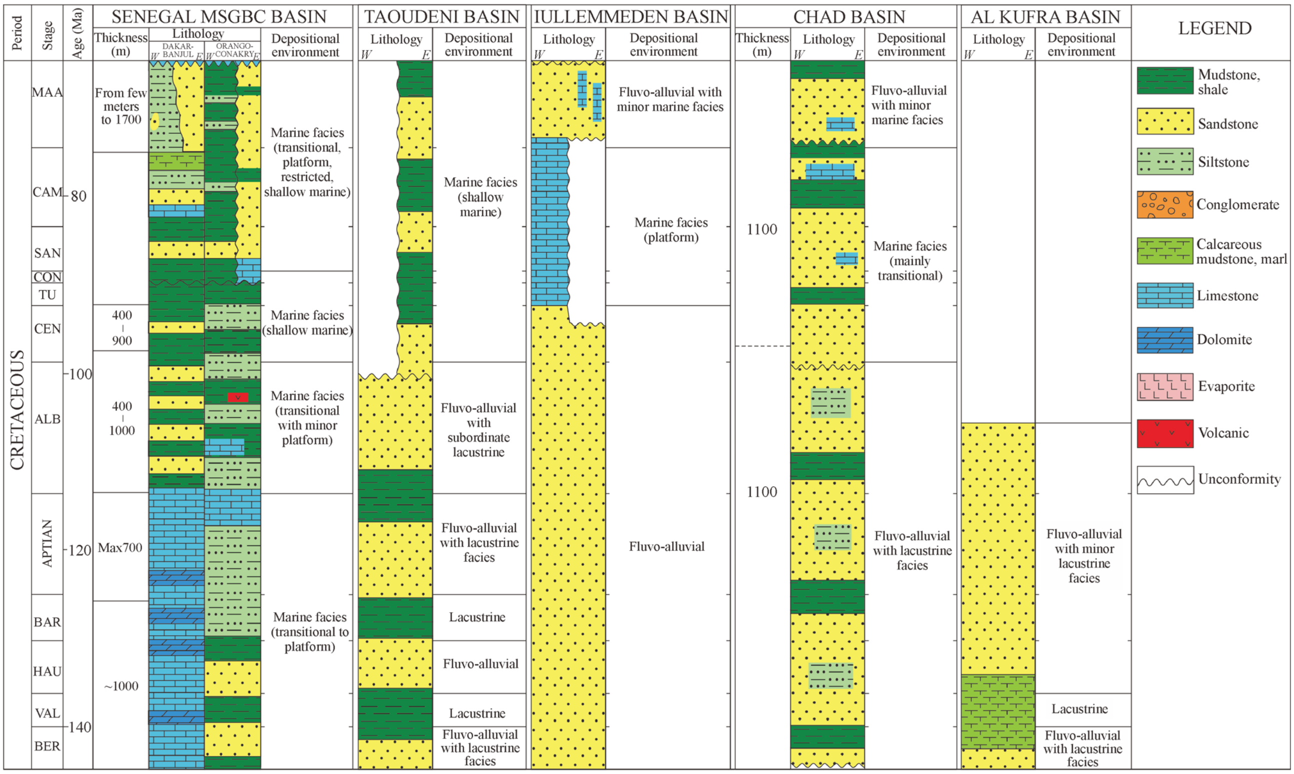


**Fig. 2** The W-E-direct stratigraphic section W-E in northern Africa, including the stratigraphic data from Senegal MSGBC, Taoudeni, Iullemmeden, Chad, and Al Kufra Basins from west to east. Stratigraphic data were obtained from the IHS energy database. Location of the section is shown in Fig. 1.

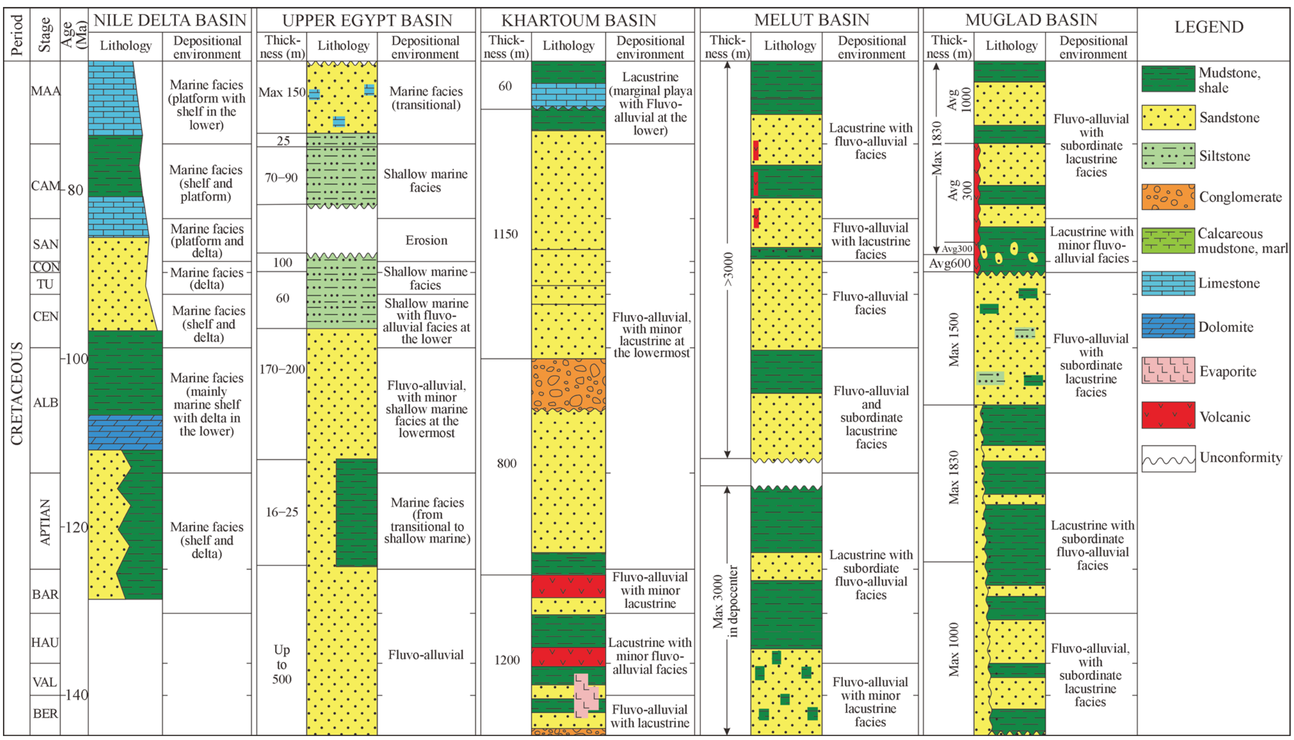


**Fig. 3** The N-S-direct stratigraphic section N-S-1 in northern Africa, including the stratigraphic data from Nile Delta, Upper Egypt, Khartoum, Melut and Muglad Basins from north to south. Stratigraphic data were obtained from the IHS energy database. Location of the section is shown in Fig. 1.

Cretaceous (Fig. 4). The Early Cretaceous strata in the Murzuq Basin were dominated by sandstone with occasional conglomerate; while the Late Cretaceous sequences were absent (Fig. 4). Again, considering the fact that the Late Cretaceous sediments were preserved to the south and north of the basin (Fig. 4), it can be assumed that sediments were deposited in the basin during Late Cretaceous, and then eroded by later tectonic events.

## 5 Interpretation and spatio-temporal distribution of the Cretaceous sedimentary facies in northern Africa

The stratigraphy described above provides direct constraint for determining the sedimentary facies of these basins in a temporal age-scale. The chief facies type of each age has been selected to represent the sedimentary facies of a specific basin. Given these basins cover most regions of northern Africa, the distribution of sedimentary facies has been established in a temporal age-scale and spatial basin-scale through this process.

In the W-E section, sediments in the Senegal MSGBC Basin suggest that deposition of marine facies was dominant during Cretaceous, including transitional to platform during Berriasian to Aptian, transitional with subordinate platform facies during Albian, shallow marine facies from Cenomanian to Coniacian, and transitional to shallow marine facies from Santonian to Maastrichtian (Fig. 2). The Taoudeni Basin was dominated by sandstone-mudstone packages during Cretaceous. The regional sediment variation leads to an interpretation that sedimentary facies changed from fluvo-alluvial- and lacustrine-dominated facies during Berriasian to Albian to shallow marine facies from Cenomanian to Maastrichtian (Fig. 2). The Iullemmeden and Chad Basins underwent a similar continental-marine-continental facies variation during Cretaceous, with the timing of shift from continental to marine facies changing from Cenomanian in the Chad Basin to Turonian in the Iullemmeden Basin (Fig. 2). The sediments in the Al Kufra Basin during Berriasian to Albian have been interpreted as fluvo-alluvial facies with subordinate lacustrine facies, with later Cretaceous sediments absent in the basin (Fig. 2).

In the N-S-1 section, the sandstone-mudstone-limestone/dolomite packages in the Nile Delta Basin have been interpreted to represent marine facies deposition, including shelf, delta, and platform settings (Fig. 3). The sediments deposited in the Upper Egypt Basin suggest fluvo-alluvial-dominated deposition in Early Cretaceous, with deposition dominated by transitional to shallow marine facies in Aptian, and marine facies dominant in Late Cretaceous with a short-lived local uplift resulting in a hiatus during Santonian (Fig. 3). The other three basins in this section were dominated by alternating fluvo-alluvial and lacustrine facies deposition during Cretaceous (Fig. 3).

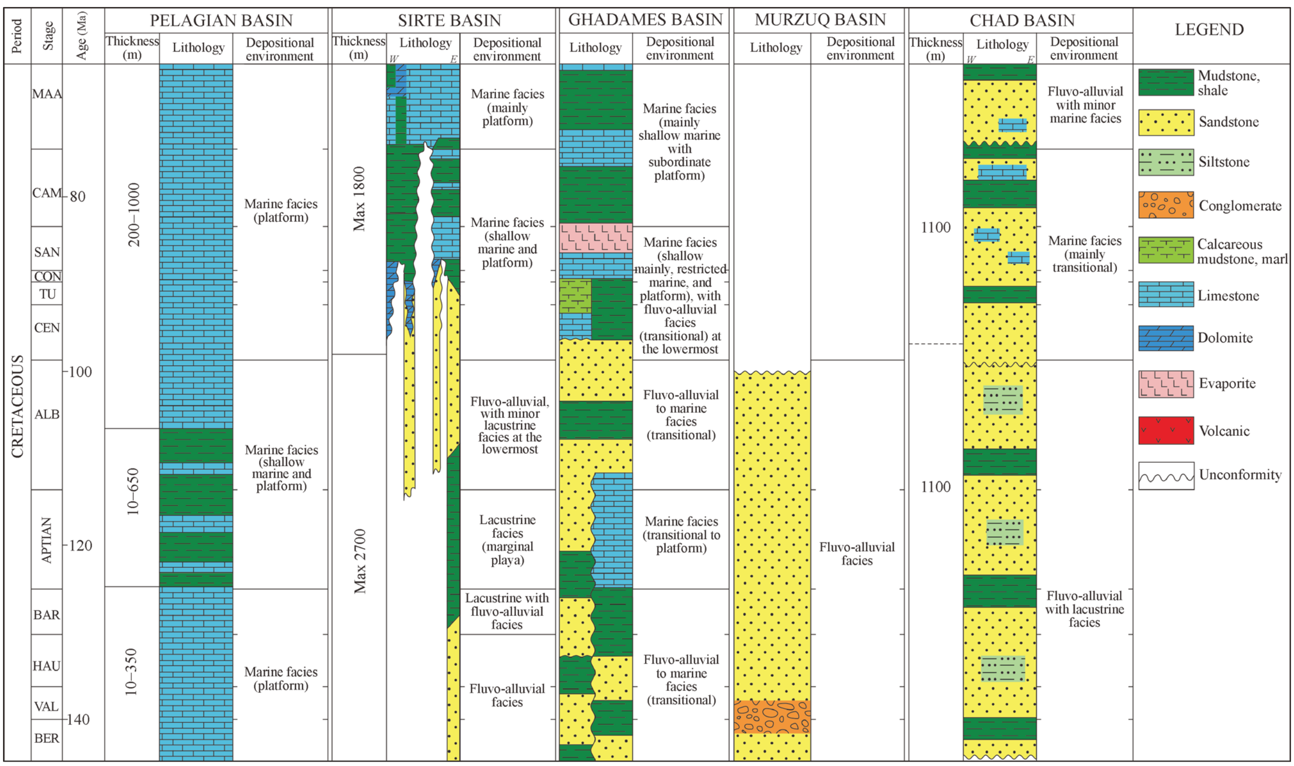


**Fig. 4** The N-S-direct stratigraphic section N-S-2 in northern Africa, including the stratigraphic data from Pelagian, Sirte, Ghadames, Murzuq and Chad Basins from north to south. Stratigraphic data were obtained from the IHS energy database. Location of the section is shown in Fig. 1.

In the N-S-2 section, a systematic shift from continental to marine facies occurred in Sirte, Ghadames, Chad, and possibly Murzuq Basins at the Early/Late Cretaceous boundary (approximately during Cenomanian) (Fig. 4). Notably, the aforementioned deposition in Chad Basin returned to fluvo-alluvial facies during Maastrichtian (Fig. 4). The Pelagian Basin was however dominated by marine facies deposition during Cretaceous.

The stratigraphy, lithology, and sedimentary facies interpretations of these specific basins provide constraint for determining spatio-temporal distributions of sedimentary facies in northern Africa during Cretaceous. These distributions were constructed for 12 ages in this study (Figs. 5–7).

The results indicate that northern Africa was covered by continental sediments of fluvo-alluvial and lacustrine facies during Early Cretaceous (from Barriasian to Albian), with subordinate marine facies deposition distributed along the western and northern margins (Figs. 5, 6(a) and 6(b)). Deposition of marine facies was limited in the Senegal MSGBC and Aaiun Tarfaya Basin west to the Taoudeni Basin in the western margin (Fig. 5). In the northern margin, sediments of marine facies distributed north to the Tindouf-Ghadames-Sirte-Upper Egypt Basins during Early Cretaceous (Figs. 5, 6(a) and 6(b)). A minor transgression occurred during Aptian, with deposition of marine facies reaching the Upper Egypt Basin (Fig. 6(a)), followed by a slight regression in Albian with marine facie sediments retreating from the basin (Fig. 6(b)).

In contrast to the prevalence of continental deposition during Early Cretaceous, northern Africa was dominated by deposition of marine facies during Late Cretaceous (Figs. 6(c), 6(d), and 7). During Cenomanian, a significant transgression occurred, resulting in the marine facies sediments reaching the Taoudeni-Chad-Al Kufra-Upper Egypt Basins (Fig. 6(c)). Transgression continued during Turonian, with the Iullemmeden Basin covered by deposition of marine facies (Fig. 6(d)). Marine facies deposition maintained in a broad region reaching as far south as the Taoudeni-Iullemmeden-Chad-Al Kufra-Upper Egypt Basins until Campanian (except for a local hiatus in Upper Egypt Basin during Santonian) (Figs. 7(a)–7(c)), before a significant regression during Maastrichtian when marine sediments retreated from the Iullemmeden-Chad-Al Kufra Basins (Fig. 7(d)).

## 6 Discussion

### 6.1 Transgression in northern Africa during Turonian to Campanian consistent with the synchronous highest global sea-level

The results in this study indicate several transgression and

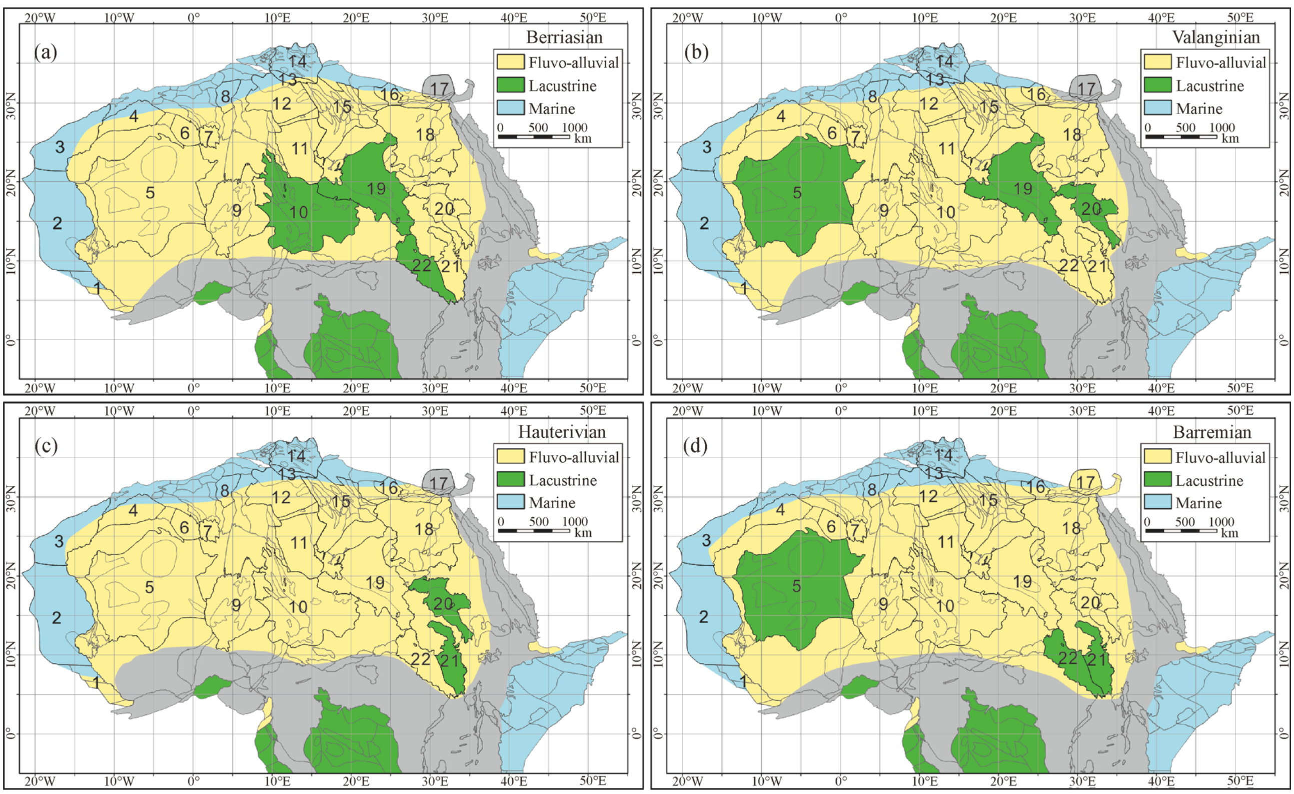


**Fig. 5** Sedimentary facies distributions in northern Africa from Berriasian to Barremian, including time segments of (a) Berriasian, (b) Valanginian, (c) Hauterivian, and (d) Barremian. Sedimentary facies have been simplified into three types, including fluvo-alluvial, lacustrine, and marine facies. Number labels represent the same basins as in Fig. 1.

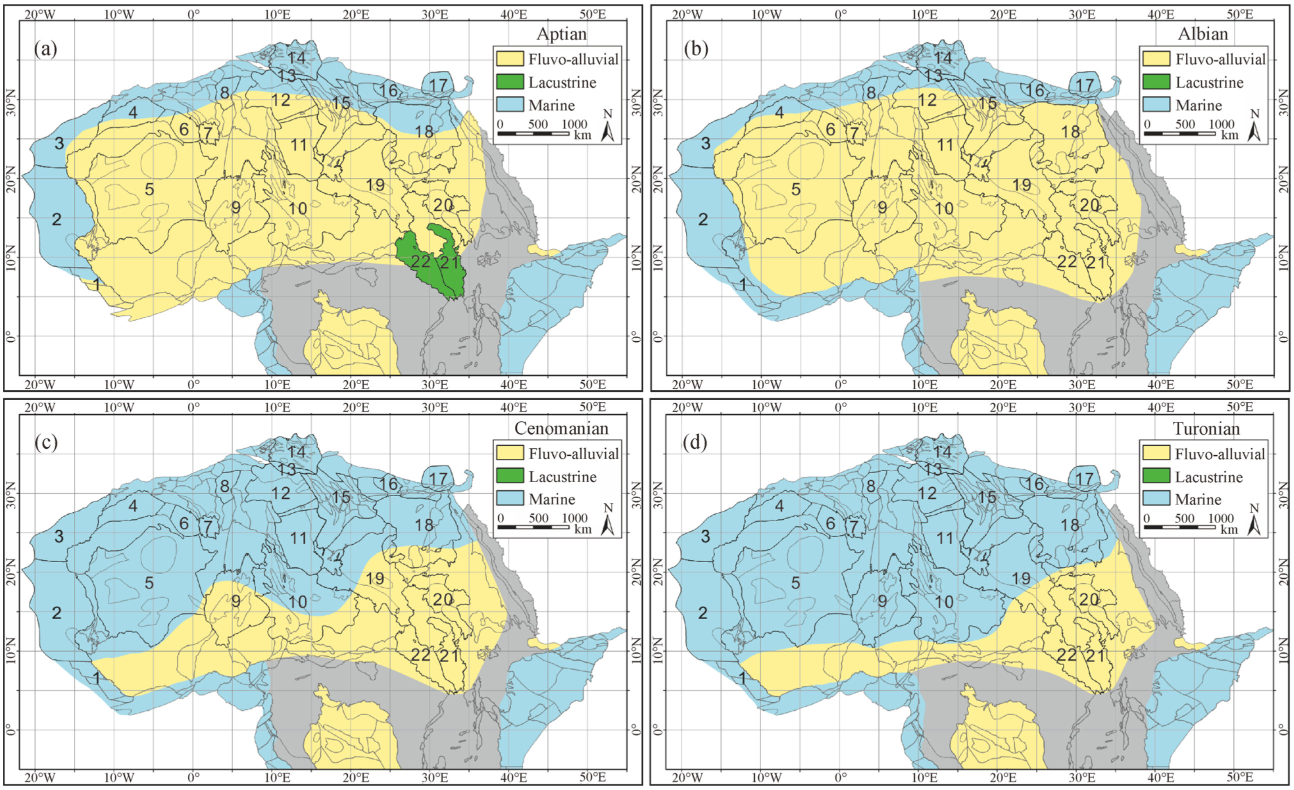


**Fig. 6** Sedimentary facies distributions in northern Africa from Aptian to Turonian, including time segments of (a) Aptian, (b) Albian, (c) Cenomanian, and (d) Turonian. Sedimentary facies have been simplified into three types, including fluvo-alluvial, lacustrine, and marine facies. Number labels represent the same basins as in Fig. 1.

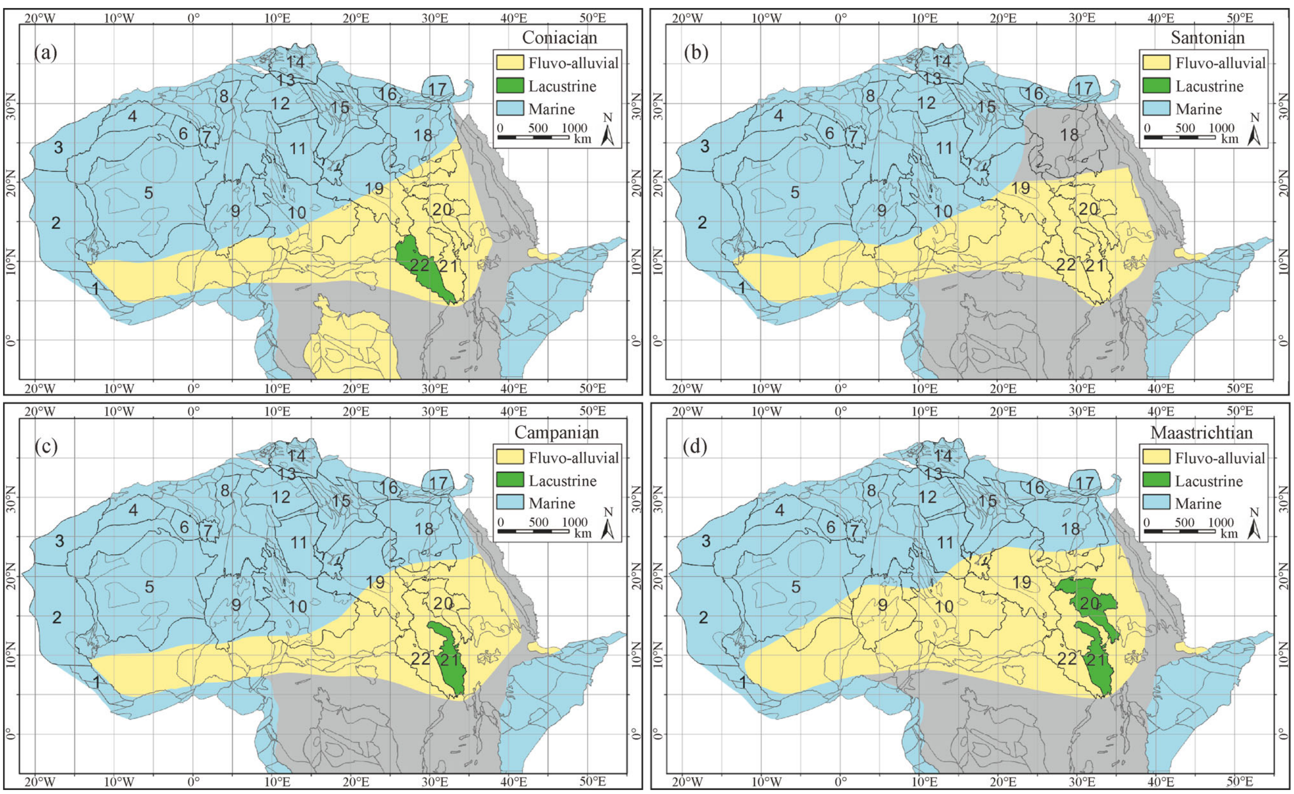


**Fig. 7** Sedimentary facies distributions in northern Africa from Coniacian to Maastrichtian, including time segments of (a) Coniacian, (b) Santonian, (c) Campanian, and (d) Maastrichtian. Sedimentary facies have been simplified into three types, including fluvo-alluvial, lacustrine, and marine facies. Number labels represent the same basins as in Fig. 1.

regression events in northern Africa during Cretaceous. Within these, the most notable transgression happened at the Early/Late Cretaceous boundary (Fig. 8), evidenced by significant expansion of marine facies sediments (Figs. 5–7). The largest transgression took place during Turonian to Coniacian, with the marine facies deposition reaching the Taoudeni-Iullemmeden-Chad-Al Kufra-Upper Egypt Basins in northern Africa (Fig. 6 and Fig. 7).

The largest transgression in northern Africa could be related to tectonic extension of the basins (Guiraud et al., 2005). However, the fact that this event was synchronous with the Late Cretaceous global high sea-level (Fig. 8) implies the transgression event is more likely attributed to the global high sea-level during this time (Miller and Pekar, 2005; Kominz et al., 2008; Miller et al., 2008; Haq, 2014). Previous sea-level curves suggest that the highest levels occurred during ca. 95–80 Ma (Haq et al., 1987; Kominz et al., 1998; Miller and Pekar, 2005; Kominz et al., 2008; Miller et al., 2008; Haq, 2014), consistent with the time interval of the largest transgression in northern Africa observed in this study. Based on comprehensive reconstruction of bathymetry and distribution of ocean basins, Müller et al. (2008) estimated that the sea-level was 170 m higher during this time, high enough to create the widespread marine facies sediments in the basins in northern Africa.

### 6.2 Likely driving mechanism for the highest global sea-level in Late Cretaceous

Global sea-level is dominated by two major factors: the volume of ocean water and the volume of the ocean basin (Müller et al., 2008). With these factors, the volume of ocean water is primarily determined by climate (Wagreich et al., 2014), while the volume of the ocean basin relies on oceanic crustal and seamount production (Gurnis, 1990; Husson and Conrad, 2006; Moucha et al., 2008; Müller et al., 2008).

High $CO_2$ concentration and the subsequent extreme greenhouse climate during Late Cretaceous would exert a direct effect on increasing the volume of ocean water (DeConto and Pollard, 2003; Robson et al., 2014; Sames et al., 2016). Benthic foraminifera $\delta^{18}O$ and $\delta^{13}C$ data indicate high sea surface temperature, corresponding to an extremely warm climate since the Cenomanian/Turonian boundary (Huber et al., 1995, 2002; Stoll and Schrag, 2000; Price and Hart, 2002; Friedrich et al., 2008, 2012; Wang et al., 2014). These data are consistent with the carbon isotope results obtained from chalk successions in England, France, and Tunisia by Jarvis et al. (2002, 2006). Such high temperatures should be related to a synchronously high concentration of greenhouse gas $CO_2$, proven to be a primary driver for the Phanerozoic greenhouse climate (Royer et al., 2004; Wang et al., 2014). Berner and Kothavala (2001) and Bice and Norris (2002) demonstrated that the $CO_2$ concentration during Late Cretaceous was 4–10 times higher than the present (pre-industrial) value, providing a direct correlation between greenhouse climate and the subsequently high global sea-level during Late Cretaceous (Berner, 1992; Wignall, 2001; Bodin et al., 2015). Given the extreme Late Cretaceous warming climate, both continental and polar ice sheets melted and flowed into the ocean (DeConto and Pollard, 2003; Miller and Pekar, 2005; Miller et al., 2005; Robson et al., 2014; Sames et al., 2016) thus increasing ocean water volume (Stoll and Schrag, 1996). In addition,

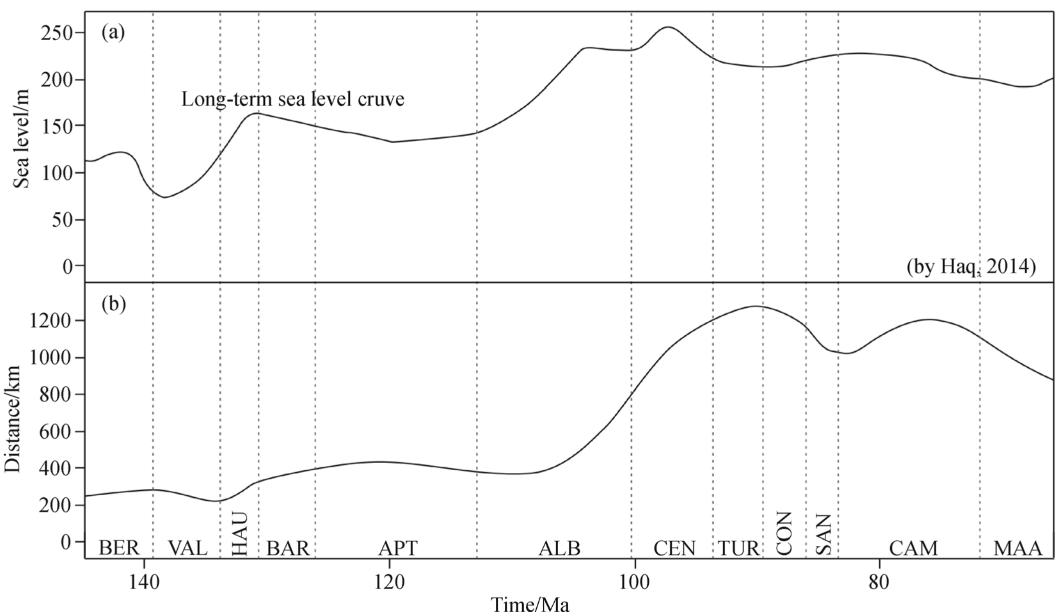


**Fig. 8** The relative sea-level changes obtained in this study compared with eustatic curve (Haq, 2014). Average distance between continental coast line and tip of marine facies deposition was used to represent the relative sea-level curve.

thermal expansion of seawater was also a potential factor for the increase (Cazenave and Llovel, 2010).

Rapid production of oceanic crust and seamounts during Late Cretaceous would efficiently decrease the volume of the ocean basin (Kerr, 1998; Larson and Erba, 1999; Bodin et al., 2015). Previous studies indicated that the oceanic crustal production rate reached $57\times10^6$ $km^3/Ma$ (Jones, 2001) at the Cenomanian/Turonian boundary (Larson, 1991b; Kerr, 1998; Larson and Erba, 1999), ca. 1.8 times more than at present (Larson, 1991a). During this time, the South Atlantic Ocean opened rapidly (Torsvik et al., 2009). In addition, the seamount/plateau caused by oceanic Large Igneous Provinces (LIPs) was widespread during Late Cretaceous (Jones, 2001; Bryan and Ferrari, 2013) thus decreasing the volume of the ocean basin. Ontong Java and Kerguelen LIPs provide two extreme examples for this scenario. The Ontong Java LIPs in the Pacific Ocean covered an area of ca. $4.88\times10^6$ $km^2$ (almost three times greater than Alaska), while the Kerguelen LIPs in the Indian Ocean covered an area of ca. $2.30\times10^6$ $km^2$ (Coffin and Eldholm, 1994).

In addition, the outgassing process during the rapid oceanic crust and seamount production in Late Cretaceous would release more greenhouse gas into the atmosphere resulting in an extremely warm climate and high global sea-level (Jones, 2001; Wignall, 2001; Tejada et al., 2009; Bryan and Ferrari, 2013). Therefore, we cautiously attribute the large transgression and global high sea-level during Late Cretaceous (with peak during Turonian to Coniacian) to rapid production of oceanic crust and seamounts of a tectonic mechanism.

## 7 Conclusions

In this study, stratigraphic data of 22 continental basins in northern Africa were analyzed to construct the spatio-temporal distribution of sedimentary facies during the Cretaceous. The results suggest that marine facies deposition reached as far south as the Taoudeni-Iullemmeden-Chad-Al Kufra-Upper Egypt Basins, implying a significant transgression in Late Cretaceous, with peak transgression during Turonian to Coniacian. The transgression was synchronous with the global rise in sea-level during this time, suggesting a direct attribution of the transgression to the high sea-level event.

**Acknowledgements** We are grateful for discussions with Prof. Bingsong Yu, Renchen Xin, Ancheng Xiao and Dong Jia, and comments from two anonymous reviewers. This work was funded by the National Natural Science Foundation of China (Grant Nos. 41330207, 41472181, 41102128, and 41072154), the National Science and Technology Major Project (No. 2011ZX05028-003), the MOST of China (No. 2016YFC0600402), the National Program on Global Change and Air-Sea Interaction, SOA (No. GASI-GEOGE-01), and the Fundamental Research Funds for the Central Universities (Nos. 2017FZA3008, and 2017XZZX007-01).

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