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Toward understanding Cretaceous climate—An updated review

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Abstract New data and ideas are changing our view of conditions during the Cretaceous. Paleotopography of the continents was lower than originally thought, eliminating the 'cold continental interior paradox' of fossils of plants that could not tolerate freezing occurring in regions indicated by climate models to be well below freezing in winter. The controversy over the height of Cretaceous sea levels has been resolved by knowledge of the effects of passage of the subducted slab of the Farallon Plate beneath the North American crust. The cause of shorter term sea level changes of the order of 30 to 50 meters is not because of growth and decay of ice sheets, but more likely the filling and release of water from groundwater reservoirs and lakes although there may have been some ice in the Early and latest Cretaceous. Carbon dioxide was not the only significant greenhouse gas; methane contributed significantly to the warmer climate. Suggestions of very warm tropical ocean temperatures (> 40°C) have implications for the nature of plant life on land limited by Rubisco activase. The land surfaces were much wetter than has been thought, with meandering rivers and many oxbow lakes providing habitat for large dinosaurs. A major rethinking of the nature of conditions on a warmer Earth is underway, and a new suite of paleoclimate simulations for the Cretaceous is needed.

Keywords Cretaceous, Paleogeography, Paleotopography, Sea level, Greenhouse, Paleohydrology, Paleoclimate

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1. Introduction

The past few years have seen major advances in our knowledge of the Cretaceous Earth, offering new insights and solutions to several vexing problems concerning the nature of conditions on a warm Earth. Among the problems that have concerned geologists have been: (1) the 'cold continental interior paradox'-mismatch between evidence from fossil floras in northeastern Siberia, which indicate that temperatures never went below freezing, and climate models that show that area to be well below freezing in winter; (2) the height of sea level in the Cretaceous, variously estimated to be from +230 m to as low as +50 m depending on stratigraphic evidence from different areas; (3) the cause of sea level changes, recently attributed to glaciation during some of the warmest times of the Mesozoic; (4) uncertainties concerning the bathymetry of the sea floor and topography of the continents; (5) conflicting evidence for land and ocean temperatures from different proxies; (6) uncertainty concerning greenhouse gas content of the atmosphere; and (7) the extent and cause of oceanic anoxic events (OAEs).

2. Reconstructing the shape of the Cretaceous Earth

Evaluation of conditions on or near the surface of any planet requires knowledge of the shape and distribution of land and sea. The theory of plate tectonics provides such a basis, but has continued to evolve since its introduction in the 1960s. Most paleogeographic reconstructions for the Cretaceous have not taken into account the refinements introduced over

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the past two decades. Numerical climate models use these reconstructions as an initial input (e.g. Markwick and Valdes, 2004; Sellwood and Valdes, 2006; Donnadieu et al., 2006; Sewall et al., 2007; Flögel et al., 2008).

First, consider the bathymetry of the ocean basins. At present they have an area of about 360 × 10^6 km^2. The oldest bits of ocean floor are about 180 my old. The area of ocean floor younger than Cretaceous is about 229 × 10^6 km^2; that younger than Jurassic is about 288 × 10^6 km^2. The area of the Earth is about 510 × 10^6 km^2 so that about 56% of Earth's surface is younger than Jurassic and 45% is younger than Cretaceous. This means that large areas of the Earth's surface have been subducted and are gone, and, it was thought, unknowable. However, a number of recent papers have explored crustal production, sea floor spreading, subduction and other aspects of plate tectonic configurations, providing new information and analysis (Cogné and Humler, 2004; Coltice et al., 2012; Müller et al., 2008a, 2008b; Torsvik et al., 2008).

In particular, the group working on ocean-floor history at the University of Sydney in Australia, have produced an analysis of older plate tectonic history that makes it possible to make reasonable reconstructions of the age of the ocean floor further back in time and to explore their implications. Müller et al. (2008a) have reconstructed the pattern of subducted crust back to 140 Ma, providing a valuable information base for reconstructing topography along subduction zones. At present the eastern margin of the Pacific is the site of subduction of warm young ocean crust and the adjacent margins of North and South America are uplifted as mountain ranges. However, if the crust being subducted is older than about 50 my it has cooled sufficiently that the continental margin is not significantly elevated and with more ancient ocean crust may even by pulled downward. The Müller et al. (2008a) reconstructions of Pacific Ocean crust indicate that old ocean crust was being subducted along all of the margins of North and Central America and northern and central South America. This implies that the uplifted western margins of the Americas shown on Cretaceous paleogeographic maps have been incorrect.

These new insights into paleobathymetry can improve our developing understanding of the nature and extent of 'Oceanic Anoxic Events' (Erba, 2004; Trabucho-Alexandre et al., 2010; Jenkyns, 2010) and the transition from an ocean with low oxygen levels to the oxygen-rich ocean in which red sediments accumulated (Wang et al., 2005, 2011; Hu et al., 2005).

There is also new information concerning the topography of the continents themselves. First, it is useful to review how the topography of the continents in the past has been reconstructed. Topographic highland areas are sites of erosion, so their reconstruction is made by determining the volume of sediment eroded from them and replacing it onto the source areas (Hay et al., 1989a, 1989b, 1990; Shaw and Hay, 1989; Wold et al., 1993). This can work well for detrital sediment as long as the continent itself is not deformed and the stratigraphic section eroded did not contain carbonates. There is a problem if limestones or dolomites made up a significant part of the lost stratigraphic section, because upon weathering these are carried in solution to the sea and can be precipitated (usually by plants or animals) anywhere in the world but mostly in the tropics, often far from their original source. Thus a reconstruction based only on the detrital sediments that accumulated peripherally to the uplifted area is a minimal model. There is also a problem that sediments are often recycled, so that the age of the deposits surrounding an uplift may be younger than the time of their erosion.

The elevations shown on the maps in the atlases of Ronov et al. (1984, 1989) are 'relative elevations'-low or high, based on the nature and amount of material eroded from them. Although not specifically stated I suspect that most of the continental elevations shown on the global paleogeographic maps produced by other authors (Ron Blakey, at: https://www2.nau.edu/rcb7/globaltext2.html; Chris Scotese, at: http://www.scotese.com/) are ultimately derived from the Ronov et al. (1984, 1989) maps, or were produced using a similar technique.

The continental elevation problem becomes apparent when considering average elevations. The average elevation of the continents today is about 830 m. That includes ice-covered Antarctica, with an average elevation of about 2500 m. Harrison et al. (1983) analyzed data for the modern continents and discussed their hypsography. Asia with the Tibetan Plateau is also anomalous. The average elevation of some modern continents are North America (w/o Greenland) 499 m; South America, 523 m; Africa, 623 m; Europe, 202 m; Australia, 243 m. Average elevation of the land areas on maps used for climate modeling are not included in most papers, but Donnadieu et al. (2006) cited the average elevations of land on their maps by age: Aptian, 665 m; Cenomanian, 515 m; Maastrichtian, 525 m. Preliminary calculation of the hypsometry and average elevations of the paleogeographic maps used for climate modeling by Flögel (2001) and Floegel et al. (2005) yields similar values. These numbers are very similar to modern continents without ice or lacking anomalous elevated areas. However, if Cretaceous sea levels were 100 to 200 m meters higher, as discussed below, the average continental elevations used in Cretaceous climate models are much too high and the topography should be revised as shown in Figure 1a and b.

Surface temperatures are elevation dependent; the average 'lapse rate' (decline of temperature with altitude) for the modern Earth is commonly cited as 6°C/km and this is used in most climate models. However, the modern lapse rate varies from 6.5 to 4.5°C/km depending on the region, with the lower rates at higher latitudes (Mokhov and Akperov, 2006).

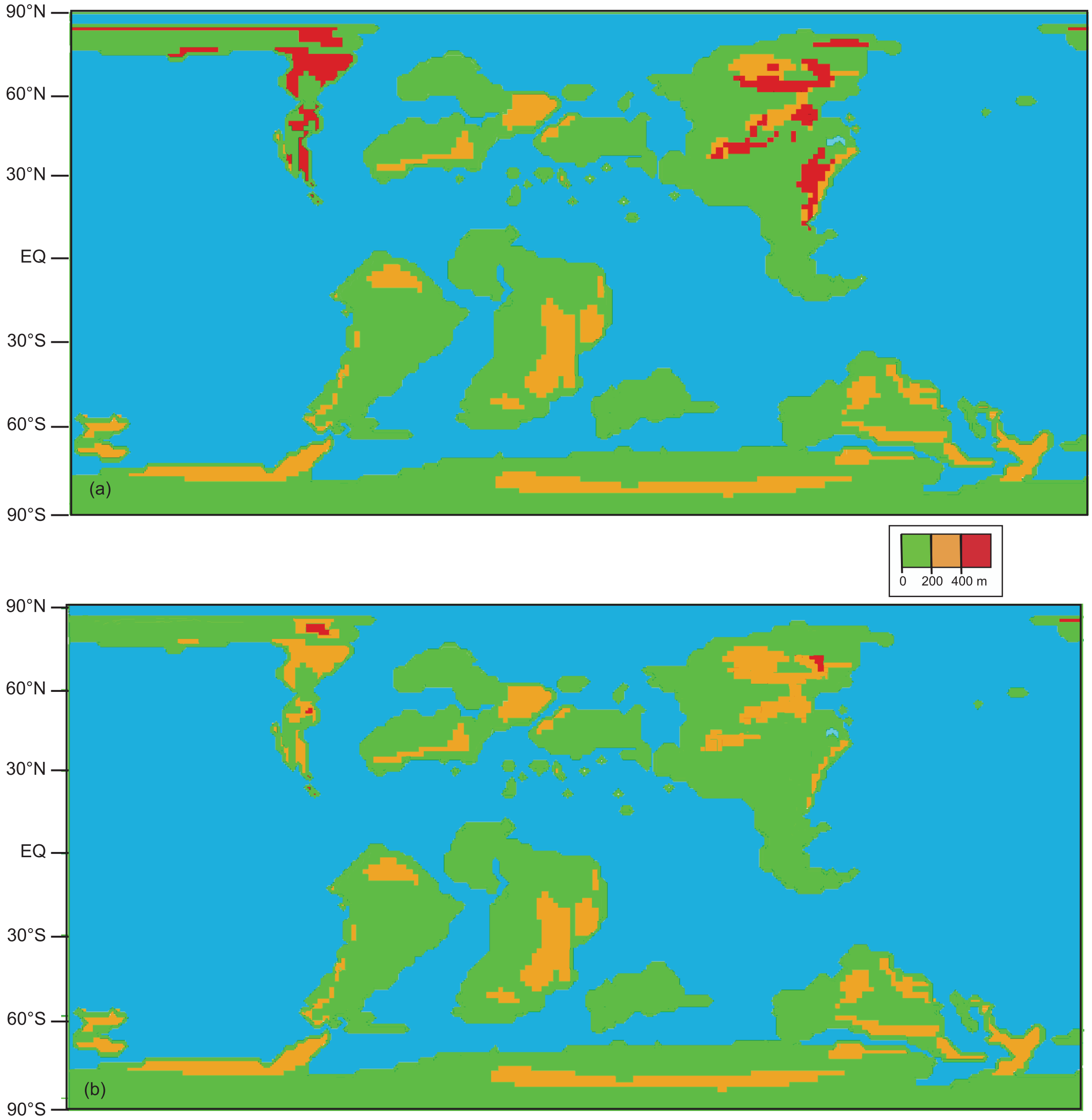

Figure 1 (a) Paleotopographic map for the early Turonian prepared by Alexander Balukhovsky and Areg Migdisov for numerical climate models described in Flögel (2001) and Balukhovsky et al. (2004). (b) A revised preliminary paleogeographic map for the early Turonian taking into account the recent work of Müller et al. (2008a, 2008b), Song et al. (2014, 2015) and others.

Deformation of the continental blocks through plate tectonic processes has been a matter of guesswork until recently. The timing and degree of uplift of western North America has been a matter of controversy (Molnar and England, 1990) particularly because of the implications of topographic relief for climate.

Major advances have been made through deep seismic studies, particularly of North America and eastern Asia. The origin of the Cretaceous Western Interior Seaway had long been a mystery. The Cretaceous marine sediments currently have a mean elevation of the order of 2 km above sea level, yet in much of Cretaceous time the seaway extended across the entire continent, from the Gulf of Mexico to the Arctic Ocean. It has long been known that the present uplift is due to the continent overriding the eastern flank of the East Pacific Rise, but that area is actually quite complicated. A tiny fragment of the once large Farallon Plate still forms part of the ocean floor off mid-California, but deep seismic studies have revealed the subducted slab of the Farallon Plate beneath North America. The subducted slab is relatively cold and dense and has drawn down the surface of the continent as it passed beneath it (Liu et al., 2008; Liu et al., 2011), creating the depression occupied by the Western Interior seaway. The subducted Farallon slab is also responsible for the controversy over Cretaceous sea levels, discussed below.

In eastern Asia, analysis of unconformities, radiometric ages and deep seismic imaging were combined with reexamination of the nature of seamount chains in the western Pacific to produce a new history of topographic relief for that area (Song et al., 2014, 2015). They identified an episode of very rapid spreading rates (80–100 cm/yr) in the western Pacific during the interval 87–89 Ma (late Turonian-Coniacian). This caused deformation and uplifts in eastern Asia documented both by formation of unconformities in the sedimentary sequence and by radiometric ages of volcanic materials. As discussed below, this solves the problem of the 'cold continental interior paradox.'

3. The cold continental interior paradox

The cold continental interior paradox derives from a mismatch between the temperatures indicated by rich paleofloral assemblages from the Albian-Cenomanian Krivorechenskaya Formation along and near the banks of the Grebenka River, a tributary of the Amur River, in northeastern Siberia and the temperatures indicated by numerical climate simulations (Figure 2). The paleolatitude was about 72°N. The paleoflora is dominated by angiosperms, with lesser numbers of conifers, ferns and other plant groups (Spicer et al., 2002). The numerical age of the paleofloral assemblages is about 96.5 Ma, based on ^{40}Ar/^{39}Ar analyses of associated volcaniclastics. On the basis of paleosols, the deposits are interpreted as representing a floodplain experiencing episodic aggradation. Multivariate analysis of the leaf physiognomies for the whole flora suggests that the plants experienced a mean annual temperature of 13.0±1.8ºC and a cold month mean temperature of 5.5±3.3ºC.

Numerical climate simulations for this time interval (e.g. Flögel, 2001; Sellwood and Valdes, 2006) show winter temperatures well below freezing in the Grebenka region. Robert DeConto (personal communication, 2015) suggested that the problem is the elevation assigned to the area. Sewall et al. (2007) show the critical area to be between 1000 and 1800 m above sea level. Assuming a lapse rate (decline of temperature with elevation) of 6°C/km, reducing the elevation to near sea level would likely eliminate the below freezing winter temperatures. Assuming everything else in the models to be correct, the adjusted temperatures for this area would be 6 to 10°C warmer than shown in the simulations. This would also explain why the deposits were interpreted as representing floodplain deposition, an environment which would have been unlikely in an elevated region being eroded.

The Grebenka area is included in the Chukotka region discussed by Song et al. (2015). The time of maximum compression and uplift there would be 88–89 Ma, 8.5 to 7.5 million years younger than the age of the Grebenka paleofloras. Thus the apparent contradiction between the temperatures indicated by the paleofloras and climate model simulations appears to be a function of using an incorrect paleotopography as an initial condition for the models.

4. The sea level problem

The Cretaceous was a time when large areas of the continental blocks were flooded. However, the extent, timing and cause of the overall flooding and the shorter term transgression and regression events has been a matter of controversy. The factors determining the position of sea level at any given place at any one time are: (1) the volume of water in the ocean, (2) the motions of the solid Earth's surface, (3) changes in the volume of the ocean basins, (4) the amount of water stored on land as ice or groundwater, (5) the temperature and salinity of ocean water, (6) the gravitational attraction of ice sheets, (7) the speed of rotation of the Earth, (8) the regional evaporation/precipitation balance, and (9) the location of atmospheric high and low pressure systems. Of these, (6)–(9) are relatively small and irrelevant in consideration of sea-level changes during the Cretaceous.

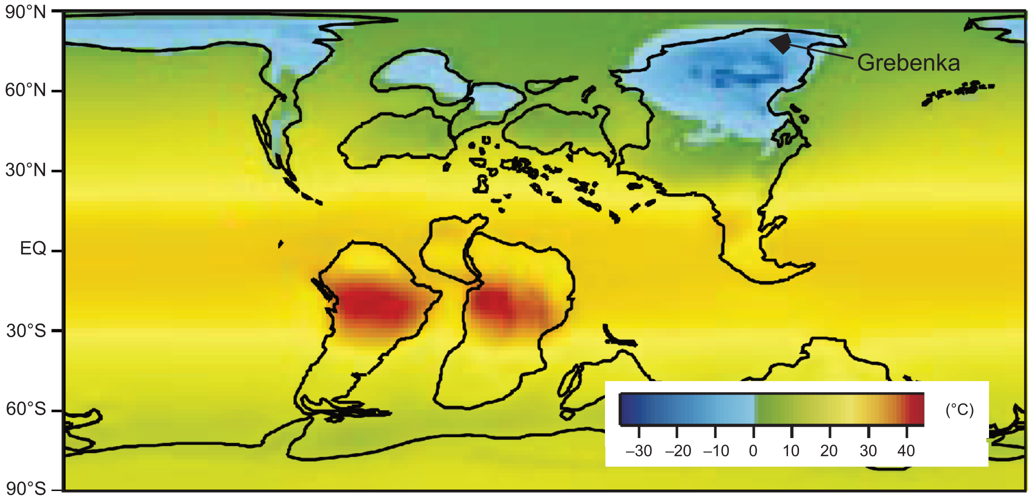

Figure 2 Climate simulation for January, early Turonian After Flögel (2001).

The question of whether the amount of water on the surface of the Earth has remained more or less constant or has changed with time due to additions or losses to or from space or mantle remains unanswered (Harrison, 1999; Kasting, 2003). There is a general pattern of two global ('eustatic') sea-level cycles during the Phanerozoic, the first occurred in the late Precambrian and Paleozoic as the supercontinent of Rodinia broke up, the fragments first drifted apart and during the Paleozoic came together to form Pangaea. The second sea-level cycle is ongoing, starting with the breakup of Pangaea early in the Mesozoic and continuing into the Cenozoic to form the seven continents we recognize today. This latter cycle had its maximum sea levels, lower than those of the Paleozoic, during the Cretaceous (Hallam, 1984; Ronov, 1994). The suspicion is that the two cycles differ because water is gradually being lost to the mantle through subduction (Hay et al., 1988; von Huene and Scholl, 1991).

The original method of determining the global elevation of sea-level (eustatic sea-level) relied on the extent of marine deposits on the continental blocks. The early estimates were based on the assumption that the hypsography of the continents was the same during the Cretaceous as it is today. One of the first attempts to track sea level through the Cretaceous was that of Watts and Steckler (1979), based on shorelines in sediments on the middle of the east coast of North America. It was soon realized that the elevations of past sea levels depended on the hypsography of the continents which are different (Harrison et al., 1981) and might change with time (Harrison et al., 1983; Harrison, 1999) although the complexities of mantle dynamics were unknown at the time.

One of the most important goals was to locate a stable reference point for the highest sea level stand of the Cretaceous. The site chosen was on the eastern side of the North America's Western Interior Seaway, where it laps onto the Canadian Shield in Minnesota (Sahagian, 1987; Sahagian and Holland, 1991; McDonough and Cross, 1991), shown by the '+' sign in Figure 3.

Changes in the volume of the ocean basins depend on their overall size, a function of the changing areas of continental and oceanic crust, the age-area distribution of ocean crust and the length of the mid-ocean ridge. Since the preserved ocean floor older than Cretaceous is less than 20% and that older than Cenozoic is only 36% of the present ocean floor area, only fragments of the Cretaceous ocean floor are preserved. The works of Müller et al. (2008a, 2008b) have been invaluable in helping to resolve the problems of area/age distribution of Mesozoic ocean crust, changing length of the mid-ocean ridge system and estimating the changes in volume of the ocean basins during the Cretaceous. A global sea-level curve based on their calculations is shown in Figure 3.

Another method of determining the global elevation of sea-level relies on the extent of marine deposits on the continental blocks. Ronov (1994) discovered that the extents of Phanerozoic flooding on the northern (Laurasian) and southern (Gondwanan) continents is quite different, for reasons still not understood but probably related to differing hypsographies. His estimate for the Cretaceous highstand was +400 m.

The early estimates for sea level by Watts and Steckler (1979), indicated a maximum of about +80 m in the Early Cretaceous. A decade later, Haq et al. (1987), using global data for onlap and offlap from seismic stratigraphic studies, published a curve indicating a maximum in the Cenomanian-Turonian of about +240 m. In 1991 two studies (McDonough and Cross, 1991; Sahagian and Holland, 1991) used the onlap from the Western Interior Seaway on to the edge of the North American craton, the Canadian Shield, to establish a maximum Cretaceous highstand of about +276 m near the

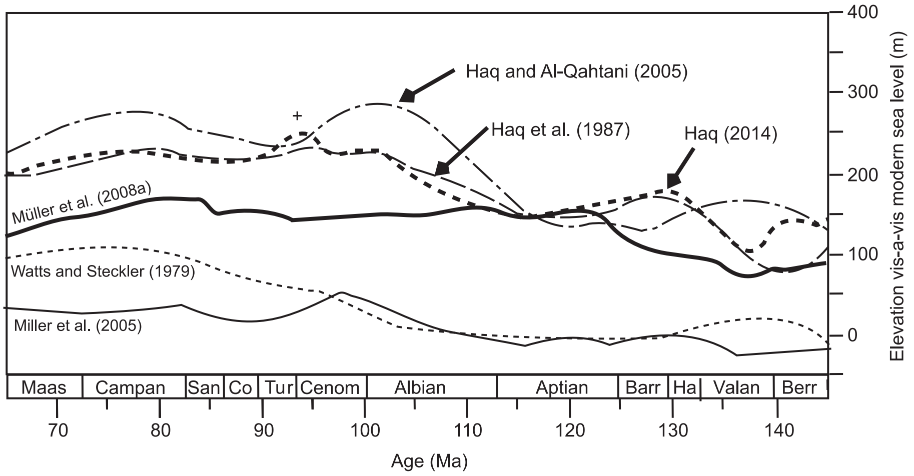

Figure 3 Estimates of the elevation of global ('eustatic') sea level above present sea level. The '+' is the present elevation (265–286 m; avg.276 m) of the late Cenomanian shoreline (~93 Ma) on the eastern side of the Western Interior Seaway on the margin of the craton (Canadian Shield) in Minnesota, defined by McDonough and Cross (1991) and used by Sahagian and Holland (1991), Sahagian et al. (1996) and others as a calibration reference for the highest stand of Cretaceous sea levels.

Cenomanian-Turonian boundary (93.9 Ma). This estimate has not been re-evaluated in the light of possible effects of the passage of the Farallon slab beneath North America.

Miller et al. (1998) published their major revision of the Cretaceous sea level curve, based on the results of onshore and offshore scientific ocean drilling forming what has become known as the 'New Jersey Transect'. Using the technique of backstripping the sediments with appropriate isostatic adjustments, they concluded that the Cretaceous sea level maximum was about +80 m and occurred in the Turonian. In 2005 Miller et al. revised the curve (as shown in Figure 3) with a maximum of about +50 m in the late Cenomanian.

The extension of plate tectonic history back to the Early Cretaceous by Müller et al. (2008a, 2008b) and consideration of the effect of the movement of the Farallon slab beneath North America (Liu et al., 2008; Liu et al., 2011) indicate that the low sea level estimates based on the New Jersey Transect are anomalies resulting from vertical motions of the continental crust in that region.

A second question concerns the magnitude of sea-level change associated with transgressions and regressions during the Cretaceous. The timing and estimates of the magnitude of these events was first documented in detail by Vail et al. (1977) as they introduced 'seismic stratigraphy' into geology. The original estimates (such as a sea-level change of 600 m in the Oligocene) were just guesses and it was Haq et al. (1987) who put realistic numbers on the transgressions and regressions. Their estimate for the Cretaceous sea-level highstand was 260 m at 91.5 Ma and most of their transgression-regression events (indicated by onlap-offlap) were of the order of 20–40 m, with one major exception-a sea level fall of about 100 m at 90 Ma.

In 2005 Bilal Haq and Abdul Motaleb Al-Qahtani published their classic paper on the record of Phanerozoic sea level changes on the Arabian Platform, thoroughly documenting the evidence for the magnitudes of the rises and falls associated with transgressions and regressions (Haq and Al-Qahtani, 2005). Their general curve for sea level, based on the Arabian Platform, which places the Cretaceous maximum near the Albian-Cenomanian boundary, is shown in Figure 3.

In 2014 Haq published his already classic review paper on Cretaceous sea level changes. He found that many of the supposedly global changes could only be found in a single or two closely related areas and came to the conclusion that the absolute eustatic (global) sea level curve that had been sought was a chimera as far as amplitudes were concerned. The sea level records in different areas were different both with respect to the overall rise and fall of sea level and the timing and magnitude of transgressions and regressions. These differences were a result of mobility of the continental crust that had not been anticipated in studies made during the 20th century. He uses the term 'eurybatic' (which he had introduced at the Cretaceous Symposium in Ankara, Turkey, in 2013) for local or relative sea-level changes. The new curve which places the Cretaceous maximum straddling the Cenomanian-Turonian boundary at a height approximating the Minnesota reference level, is also shown in Figure 3. Using seismic stratigraphy to estimate the timing and magnitude of episodes of onlap and offlap, he produced a new short-term (± 1000000 yr) sea level fluctuation diagram, reproduced in simplified form in Figure 4. The magnitudes of short term sea level change range from

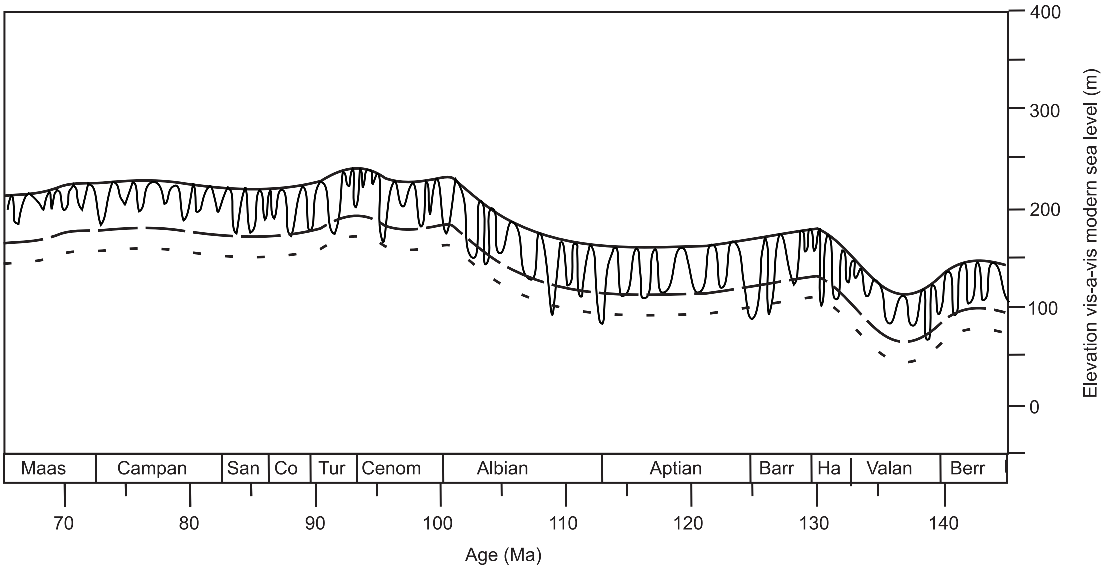

Figure 4 Transgressive-regressive sea level cycles and the quasi-eustatic sea level curve of Haq (2014) shown as solid lines. There are 59 cycles within the 80 Myr duration of the Cretaceous, yielding an average periodicity of 1.356 my. Dashed line is 30 m lower than the solid line, the difference that could easily accommodated by filling groundwater reservoirs and lakes; the dotted line is 50 m lower, probably the maximum difference that could be accommodated by filling groundwater reservoirs and lakes as suggested by Hay and Leslie (1990) and Wendler and Wendler (2016).

< 20 m to > 70 m. There are 59 cycles within the 80 Myr length of the Cretaceous, yielding an average periodicity of 1.356 my. This is not very far from the Earth's 1.2-million-year orbital eccentricity supercycle (Laskar et al., 2011). Recognition of shorter term Milankovitch cycles in Cretaceous sediments, first proposed by Gilbert (1895) is an ongoing pursuit (Herbert, 1992; Gale et al., 2002; Charbonnier et al., 2016) and may yield new insights into the behavior of the Cretaceous oceans.

5. The cause of the sea level changes

The cause of the sea level changes responsible for the transgressions and regressions that as the basis for seismic stratigraphy was initially unknown. Quaternary glacial-interglacial sea level changes are of the order of 130 m. However, the changes in sea level associated with these events in the Cretaceous were estimated to be of the order of 20 to 40 m, with possible rare exceptions of up to 100 m.

The presence of glendonites (Kemper and Schmitz, 1981), along with (presumably ice-rafted) dropstones and possible tillites (Frakes and Francis, 1988) suggested the presence of polar ice, at least in the Early Cretaceous.

In the 1980's it was generally accepted that the sole cause of global transgressions and regressions on time scales of 10s to 100s of thousands of years was the growth and decay of ice sheets on land. However, Hay and Leslie (1990) suggested that storage and release of groundwater in response to climatic change might account for the sea level changes of the magnitudes that occurred during warm 'Greenhouse Earth' times. The idea was pursued by Jacobs and Sahagian (1993) who proposed that changes in storage of water in lakes and as ground water could explain sea level fluctuations in the Triassic.

In 1996 Stoll and Schrag proposed that the sudden periodic increases in strontium contents of some Early Cretaceous (Berriasian-Valanginian) deep sea carbonates might reflect exposure of the continental shelves (Stoll and Schrag, 1996). They proposed that the sea level fluctuations occurred over a time span of about 7 Myr and were of the order of ±50 m and were on time scales of 200000 to 500000 years. Oxygen isotope data were cited as supporting this idea. Quaternary deep sea carbonate sediments, composed mostly of the remains of mixed-layer and thermocline dwelling calcareous nannoplankton and planktonic foraminifera, are enriched in ^{18}O because of both fractionation during evaporation of water from the ocean surface and precipitation from vapor as well as by the temperature effect of colder waters. They proposed that there had been periodic development of glacial ice on Antarctica to account for the sea level changes. Hay (2008) suggested that the site of such ice might have been on the uplifted margins of Antarctica, southern Africa, India and Australia as these blocks were rifting from the original Gondwanan continent during Early Cretaceous times.

Miller et al. (1999) extended the idea of a glacial cause of short term eustatic changes to the Early Maastrichtian. The problem with this idea was that the paleogeographic maps did not show enough high-latitude highlands to accommodate the amounts of ice required. Miller et al. (2003) extended the idea of glacio-eustacy to account for virtually all of the shorter-term sea level changes throughout the 'Greenhouse World' of the Cretaceous citing oxygen isotope fluctuations as proof of the hypothesis. They assumed that the times of enriched δ^{18}O corresponded with sea-level minima. In their proposal of periodic glacio-eustacy throughout the Cretaceous they included the apparently very warm time of the Cenomanian and Turonian. The former had been identified by Kidder and Worsley (2010, 2012) as a 'hothouse episode' associated with OAE 2 and Bice et al. (2003) had reported isotopic evidence for temperatures of 30–32°C at 60°S during the Turonian.

For all of the episodes of glacio-eustacy proposed by Miller et al. (1999), the problem was in finding high-latitude land areas with elevations high enough to accommodate the amounts of ice required during times of undisputed global warmth. The present Antarctic ice sheet contains 26.5 km^3 of water, enough to raise sea level by about 58 m. The amounts of ice required to cause Cretaceous sea level fluctuations of 20 to 40 m on time scales of the order of 100000 to 1 million years would require growth and decay of an ice sheet half to 2/3 as large as that of the Antarctic today.

Resolution of the problem was achieved by Wendler and Wendler (2016) who found that the δ^{18}O isotopic signal attributed to glacio-eustatic sea-level lowstands by Miller et al. (2003) could also be interpreted as an aquifer-eustatic signal, but in this case to sea-level highstands. They cited the record found in carbonate rocks in Jordan where the isotopic signal could be directly correlated with seismic-stratigraphic onlap-offlap data. Further discussion of Cretaceous aquifer-eustasy is presented in Wagreich et al (2016), Sames et al. (2016) and Wendler et al. (2016).

6. The greenhouse gas problem

A major uncertainty in the numerical climate modeling is the atmospheric greenhouse gas concentration. The only greenhouse gases considered in most paleoclimate models for the Mesozoic have been CO_2 and water vapor H_2O. Water vapor content is determined in the simulations from the water surface areas (oceans and lakes) and transpiration from plants, following algorithms dependent on temperature.

Elevated levels of atmospheric carbon dioxide have long been considered critical to explaining Cretaceous warmth (Barron et al., 1995). However, the levels of CO_2 required to bring polar temperature well above freezing during the polar night in numerical climate models are at or above the levels for that gas estimated by proxies and geochemical model calculations (Berner and Kothavala, 2001; Wallmann, 2001; Hansen and Wallmann, 2003). Further, there are significant differences between atmospheric CO_2 estimates made using different geochemical and paleobiologic proxies. They range from 4000–5500 ppm for the Late Cretaceous (Retallack, 2001) to from ~661 to ~565 ppm for the early and late Santonian (Wan et al., 2011), both based on stomata of fossil *Ginkgo.* It remains uncertain which all these methods provide the best estimates (Royer et al., 2001; Sellwood and Valdes, 2006; Wang et al., 2014), but Ginkgo leaves have great potential (Chen et al., 2001; Wang et al., 2014; Barclay and Wing, 2016).

Most numerical climate simulations for the Cretaceous (Barron and Washington, 1984; Barron et al., 1995; Sellwood and Valdes, 2006) have used '4 × present day' atmospheric CO_2 concentrations (whereby 'present day' was taken to be 340 ppm; $4\times340=1360$ ppm). Other experiments have used different values: DeConto et al. (1999) used 1230 ppm and 2500 ppm; DeConto et al. (2000a, 2000b) used 1680 ppm; Donnadieu et al. (2006) used 1120 ppm. Bice and Norris (2002) argued that CO_2 concentrations of 4500 ppm or more might be required to simulate tropical and temperate sea surface temperatures as high as the 30°C indicated by proxy data.

Other possible natural greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O) are not considered in the modelling exercises, but DeConto et al. (2012) has used the term 'CO_2 equivalent' to include the effects of these other gases.

Methane is likely to have been present in the Cretaceous atmosphere in concentrations sufficient to act as a significant greenhouse gas. Its greenhouse gas potential is 23 times that of CO_2, but its atmospheric lifetime at present is only about 12 years. Methane venting from C_{org}-rich deposits on the sea floor has been proposed to explain the 'tepee buttes' of the Western Interior Seaway of North America (Kauffman et al., 1996). Some of this methane would likely have escaped into the atmosphere. However, methane produced by sauropod dinosaurs could have been much more important. The idea was discussed informally in the 1990's and has been considered more seriously in recent years (Wilkinson et al., 2012; van Loon, 2012). Wilkinson et al. (2012) calculate a contribution of > 500 Tg (1 Tg $=10^9$ kg) CH_4 from sauropods alone, more than double the estimated ±200 Tg added annually to the atmosphere from natural sources in pre-industrial times. If there were extensive swamps in the Cretaceous, as suggested below, the flux of methane would have been even much larger.

Unfortunately, there is no proxy for atmospheric methane concentrations; we can only make educated guesses. Because methane is a much more efficient greenhouse gas than CO_2 even though its concentrations are unknown, using 'CO_2 equivalent' greenhouse gas levels well above those indicated by proxies specifically for CO_2 is an appropriate solution for running numerical climate simulations.

7. The hydrological problem

The other significant greenhouse gas is water vapor. Its concentration in the atmosphere depends on evaporation from water surfaces, transpiration by plants and evaporation from soils. Areally, the water surfaces are overwhelmingly dominated by the ocean; today lakes, swamps, river surfaces are much smaller and their areas in the Cretaceous are essentially unknown. Climate models generally assume that rainfall onto land flows directly toward the ocean; only very large lakes might be included. For numerical models of the Cretaceous the land surface is usually considered covered by more or less complex plant communities or deserts. Water vapor enters the atmosphere through transpiration which varies according to the nature of the plant community and directly from moist soil. More lush vegetation on land would decrease the temperature contrasts between the shore and the continental interior. As will be discussed below, the water vapor greenhouse effect has probably been the weakest part of Cretaceous numerical climate simulations.

The ocean is the major source of vapor that rains out periodically over land while evaporation over land goes on continuously. The evaporation rate is dependent on temperature, doubling with every 10°C increase and evaporation is continuous. Some of the water that falls as precipitation onto the land surface is absorbed into the soil and from there can be taken up by plants which then return it to the atmosphere through transpiration. In numerical climate models the excess precipitation returns to the sea as runoff by the shortest possible route. Because evaporation/transpiration is continuous but precipitation is time-limited, it follows that, unless water is stored on land in lakes and wetland swamps the evaporation rate over land will dominate and conditions will become drier. Most numerical climate models do not include possible lakes and swamps. It follows that for the warm Cretaceous the model climate simulations generally indicate that the land areas outside the arid belts should have been drier than they are today.

The maps of Chumakov (Chumakov, 1995; also reproduced in Hay and Floegel, 2012) suggest that the Equatorial-Tropical arid belts associated with the descending limbs of the Hadley cells were extensive in the Early Cretaceous, becoming more restricted in the warmer Late Cretaceous. Also the maps for the Berriasian and Aptian do not show an equatorial humid belt. The equatorial humid belt is a reflection of the Intertropical Convergence, which must have been present. Its apparent absence is a problem at needs to be solved. The maps show proxy evidence for lush vegetation in the Northern and Southern hemisphere temperate and mid-latitude humid belts and both are well developed on the maps for the Late Cretaceous. If the Early Cretaceous was cooler and the Late Cretaceous warmer, the latter should have been drier. This is another apparent Cretaceous climate paradox that needs investigation.

8. Climate models and the cold continental interior paradox

The number of attempts at numerical modeling of Cretaceous climates has been limited, primarily because of the unsatisfactory but seemingly consistent result of the problem of the 'cold continental interior paradox' discussed above.

DeConto et al. (1999) found a partial solution to the paradox in eliminating C_4 plants, which were not present in the Cretaceous, from the vegetation component of NCARs CCM1 model. C_4 plants conserve water and do not transpire as freely as C_3 plants and thereby reduce downwind humidity and increase the lapse rate with elevation. DeConto (personal communication, 2013) suggested that the elevation of eastern Asia might be the real problem.

As discussed above, Song et al.'s revision of Cretaceous sea floor spreading in the Pacific and its effect on the topography of eastern Asia has effectively solved the apparent paradox (Song et al., 2015). The elevation of the critical areas of eastern Asia responsible for the cold temperatures produced by numerical climate simulations postdates the Grebenka paleoflora.

9. The temperature problem

Paleobotanical evidence clearly indicates that during much of the Cretaceous northern polar temperatures on lands surrounding the Arctic Ocean were above freezing during the polar night (Herman and Spicer, 1996, 1997, 2010; Spicer and Herman, 2001, 2010; Herman et al., 2009). Evidence for very warm Arctic Ocean waters (15 to 20°C) has been presented by Jenkyns et al. (2004). Proxy data indicating ocean temperatures of 30°C at 60°S latitude (Bice et al., 2003) supports the idea of warm poles during much of the Cretaceous. Price (1999) discussed the climatological implications of polar ice during the Mesozoic-these would include sea-level falls and large strong meridional temperature gradients. Chin et al. (2008) described the nature of a warm polar sea ecosystem. One obvious problem remains to be solved: since water is an excellent radiator of heat, is it possible for a smaller fresher Arctic Ocean to remain ice-free through the polar night? This may depend on whether the salinity was above or below 24.7‰ (Fisher et al., 1994). At lower salinities the water becomes less dense as it cools toward the freezing point and will float making it easier to freeze. At higher salinities the water simply becomes denser as it approaches the freezing point and sinks. The modern Arctic Ocean has regions with salinities both above (central Arctic) and below (Siberian shelves) 24.7‰. Today the low-salinity Siberian shelf regions, particularly that off the Lena River act as 'ice factories' supplying most of the Arctic Ocean ice.The temperature-salinity balance between the Arctic Ocean and the lower latitude Tethys-Atlantic-Gulf of Mexico complex is important in understanding the nature of frontal systems and water masses in the meridional transcontinental seaways (Fisher and Hay, 1999; Mutterlose et al., 2003; Floegel et al., 2005).

Sea ice formation in seas with a salinity higher than 24.7‰ takes place through another mechanism. At normal ocean salinities of about 35‰ sea ice formation requires freshening of a small volume of water. This occurs through snowfall onto the water, freshening a tiny volume which can then freeze. Once initiated by this mechanism, the tiny bits of sea ice can grow by incorporating and freezing the surrounding sea water while expelling salt. This is the way in which sea ice forms over the Southern Ocean today.

The evidence from well-preserved planktonic foraminifera and other proxies for very warm (34°C) ocean temperatures in the tropics (Norris et al., 2002; Bice and Norris, 2002; Schouten et al., 2003) was cited as requiring atmospheric CO_2 concentration of at least 4500 ppm. Wilson et al. (2002) indicated ocean mixed layer temperatures might be as high as 36°C and Bice et al. (2006) presented proxy evidence for temperatures up to 42°C.

If tropical sea-surface temperatures were so warm, the effects should also be seen on land. RUBISCO activase, the enzyme controlling photosynthesis becomes increasingly ineffective at temperatures above about 28°C (Salvucci and Crafts-Brandner, 2004; Ellis, 2010). The very warm tropical sea-surface temperatures would almost surely be exceeded by temperatures on land and there should be sedimentological evidence for the expected lack of land plants in those latitudes.

10. Atmospheric and oceanic circulation

New data and interpretations have changed some of our ideas about circulation of the atmosphere and ocean. First, the idea of seasonal shifts of the atmospheric circulation from three to two cells, proposed by Hay (2008) is wrong (Figure 10 in that paper was also mislabeled-January should read July and July should read January). The two cell hypothesis violates the forces induced by the Coriolis parameter. The shift must be from three cells in the northern hemisphere winter to four cells in the northern hemisphere summer. The more variable winds would reinforce the idea of an ocean filled with mesoscale eddies.

The Hadley circulation would remain the most stable part of the atmospheric system, but Hasegawa et al. (2012) have shown that shifts of the latitude of the descending limb of the

Hadley cells, producing dry desert conditions on the Earth's surface, are not gradual but occur as jumps from a higher to a lower latitude.

Support for mesoscale eddies dominating the ocean circulation, proposed by Hay (2008) has come from analysis of the distribution of organic carbon in the intensively drilled Cenomanian-Turonian Eagle Ford Shale of Texas (Waite et al., 2013). Observations of the modern ocean circulation by NASA spacecraft show that there are certain mesoscale eddies which are stable throughout the year, with cyclonic circulation inducing upwelling and high productivity in the surface waters. Analogous circulation seems to have occurred along the northern margin of the Gulf of Mexico during the mid-Cretaceous.

Hay (2009) has presented a thorough discussion of ideas concerning Cretaceous ocean circulation and the results of attempts to model the Cretaceous ocean. The major differences in ideas concerning deepwater formation were outlined in a classic paper by Stommel (1961) describing the two possible stable modes of circulation—dominated by either cold polar waters or by warm saline waters. Stommel (1962) described the vexing enigma of deep water formation. It takes place at very small sites which cannot be effectively described in even the most elaborate numerical models available today. Hay (1993) discussed the role of the polar regions in deep water formation and gave examples of the 'small site' problem. Oxygen is much more soluble in cold waters and anoxic conditions are more likely to develop if ocean basins are filled with warm saline waters (Brass et al., 1982). Modeling of intermediate and deeper water formation during the Late Cretaceous have been discussed by Otto-Bliesner et al. (2002). The use of isotopes to evaluate interior water formation has been documented by Li and Keller (1999). A better understanding of the transition of the well oxygenated ocean of the later Cretaceous should develop as more is known about the changing ocean passageways between basins become better known.

Better understanding of the nature of deeper water formation and organic carbon deposition during OAE's of the early and mid-Cretaceous and the transition of the well oxygenated ocean of the later Cretaceous should develop as the changing ocean passageways between basins become better known.

11. Basic rethinking of land surface conditions during the Cretaceous

Impetus for completely rethinking the nature of the land surfaces in the Cretaceous came from an unexpected source. Brian J Ford is a cell biologist who became interested in dinosaurs and their tracks.

At the beginning of the last century it was thought that large dinosaurs may have lived in swamps or shallow lakes. Some paleontologists even questioned whether they ever walked on land (Bird, 1944). During much of the last century dinosaurs were envisioned as having lived mostly on land, retreating to wetlands only to rest (Coombs, 1975; Farlow et al., 1995). However, that idea was rejected from the 1970s in favor of them being strictly land animals, although the fossils are found mostly in floodplain or lacustrine deposits even in desert regions (Jerzykiewicz, 1998; van Itterbeeck et al., 2005; Sweetman and Insole, 2010). The current idea is that large dinosaurs were animals that lived on relatively dry areas similar to modern steppes or savannas, where the largest animals live today. These analogies are made for the Upper Jurassic Morrison Formation of the western United States (Dodson et al., 1980). The climatic conditions under which the deposits of the Morrison Formation formed were described as semi-arid, although there may have been a few areas with permanent water (Demko and Parrish, 1998). We should remember that dinosaur fossils are almost always found in floodplain deposits and dinosaur tracks in sediments that were originally mud.

One of the problems with the savanna-steppe habitat is that the former biome today is characterized by C_3, the latter by C_4 grasses. C_3 grasses did not evolve until the end of the Cretaceous and C_4 grasslands did not appear before the Miocene (Jacobs et al., 1999; Beerling and Osborne, 2006)

Ford was concerned that although most dinosaurs had large heavy tails, dinosaur tracks almost never show tail drag marks (Lockley and Hunt, 1999; Lockley and Meyer, 2000; Pérez-Lorente, 2015). This indicates that the tail must normally have been held above the ground surface (Ford, 2012a). Holding the tail erect would require an enormous amount of metabolic energy by muscle cells and Ford claimed that this was an unreasonable expenditure that did not fit with evolutionary theory. It seemed to him that large dinosaurs had evolved subject to the constraints of an aquatic habitat. Furthermore, the purpose of the large tail was unclear. It had been suggested that it was to counterbalance the long neck, but Ford noted that the modern giraffe, similar in morphology to a herbivorous dinosaur, has evolved a long neck and a small tail. Instead, Ford proposed that the normal dinosaur habitat was in water and the tail was used, like that of modern crocodiles and alligators, for swimming. He also argued that thermal buffering from immersion in water would resolve the controversy over dinosaurs as possibly homeothermic creatures (Ford, 2014). Buoyancy would further explain why trackways in alluvial substrates were always shallow. Figure 5 is adapted from the final figure in his second publication (Ford, 2012b). It shows a number of different types of dinosaur with different body sizes and neck and tail lengths, but all with similar leg lengths, suggesting that they lived in water bodies with a depth of ±5 m. This is typical of modern floodplain and oxbow lakes.

Although many vertebrate paleontologists working on dinosaurs reject Ford's ideas out of hand, they make good sense

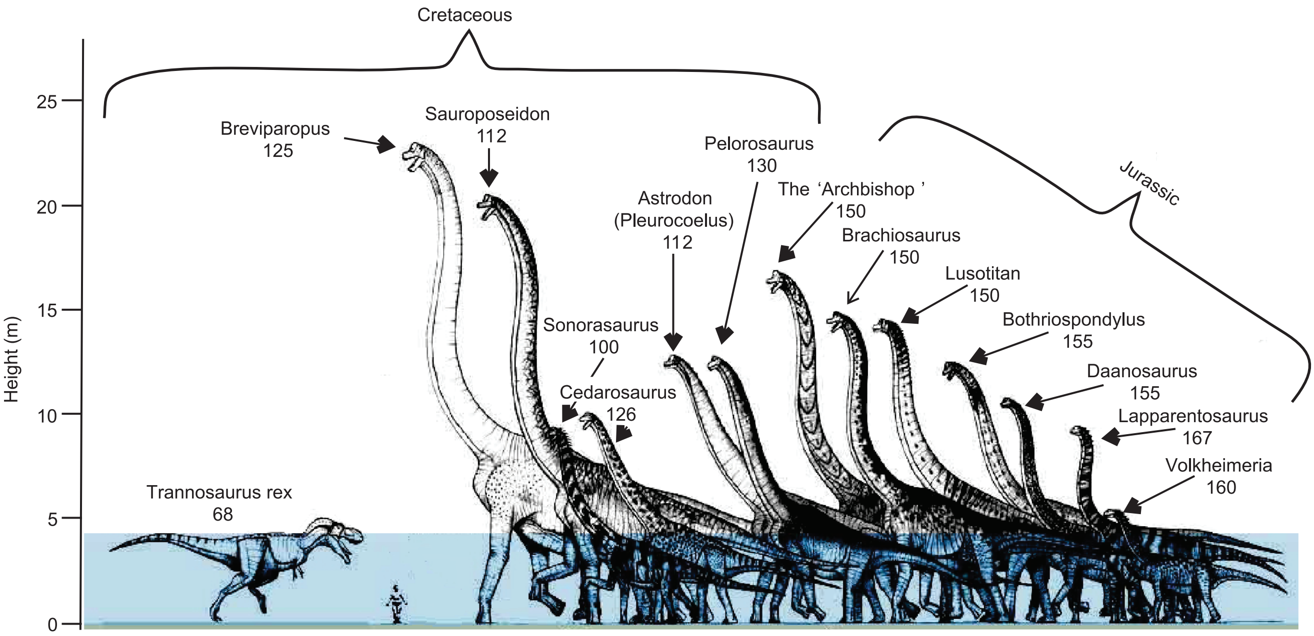

Figure 5 A comparison of brachiosaurid sauropod dinosaurs, after a figure in Ford (2012b). (The original 'Dinosaur Parade' was prepared by Nima Sassani and is at http://paleoking.blogspot.com/2009/11/brachiosaurs-parade-90-million-years-of.html). Numbers are approximate ages. Most of these are known from incomplete skeletons that nevertheless allow reconstructions. *Volkheimeria* is Callovian-Oxfordian, from Patagonia. *Lapparentosaurus* is Mid-Jurassic from Madagascar. *Daanosaurus* is Late Jurassic, from Sichuan, China. *Bothriospondylus* is from the Kimmeridgian of southern England. *Lusotitan* is from the Tithonian of Portugal. Brachiosaurus is from the mid- to late Jurassic Formation of Colorado, U.S. The 'Archbishop' is a mid-Jurassic dinosaur from Tanzania, still awaiting formal description. *Pelorosaurus* is known from the Early Cretaceous of England and Portugal. Astrodon (also known as *Pleurocoelus*) is Aptian-Albian, from the Arundel Formation, eastern U.S. *Cedarosaurus* is from Barremian strata in Utah, U.S. *Sonorasaurus* is Albian to Cenomanian, from Arizona, U.S. *Sauropposeidon* is known from Aptian-Albian strata in Texas, Oklahoma, and Wyoming, U.S. *Brevparopus* is known only from tracks in Cretaceous strata in the Atlas Mountains, Morocco, but from the tracks it must be the largest of the brachiosaurids.

to many geologists. General aspects of the biology of the great sauropod dinosaurs have been reviewed by Sander et al. (2011). Much of the biology fits well with Ford's 'aquatic dinosaur' hypothesis. Xing et al. (2013) found that dinosaurs appear to have been using rivers as roadways to get from one place to another. This then raises the question about how widespread the appropriate environmental conditions might have been. How widespread were water surfaces such as rivers, lakes and wetlands in the Cretaceous? How extensive would they have been as habitats?

First, the new continental reconstructions taking into account the work of Müller et al. (2008a, 2008b) and Song et al. (2014, 2015) are much lower than those currently used in paleoclimate modeling. After the breaking apart of Pangaea it took some time, about 150 Myr, before the continental fragments started colliding and producing high mountains again. Having more extensive lowland areas means that the nature of rivers would have been different from what has been commonly assumed. Instead of being relatively straight, most Cretaceous river courses would have been meandering, greatly increasing the river water surface area. Secondly, meandering rivers frequently change course, leaving behind cutoffs as 'oxbow lakes'. As such cutoffs are filled in with sediment from floods of the parent river, they form swamps, bogs, or other wetlands. The vegetation of these areas would provide a much richer food source for ruminant dinosaurs than the steppe-savanna analogs current in the literature. Much more of the surface of the Cretaceous 'land' was thus covered by water than has been prescribed in numerical paleoclimate simulations. The more extensive water surfaces provided a source for vapor and would thereby have enhanced precipitation over land. The Cretaceous was much wetter than we have thought.

The wetter climate means that the temperature differences between the seashore and continental interiors would have been less. Overall there would have been a more 'equable' climate, not only in terms of latitude but in terms of distance from the oceans. This is another condition counteracting the 'cold continental interiors' that were so puzzling.

We now need a new suite of paleoclimate simulations for the Cretaceous, taking the revised continental elevations and these new hydrographic boundary conditions into account. New models should also give not only long term temperature averages, but the extremes that might be expected. From these we will learn whether we are finally beginning to understand the paleoclimates of the warm Cretaceous Earth.

12. Conclusions

We have had 50 years of serious progress in understanding the climatology of the warm Cretaceous Earth. We have learned much but have not yet arrived at a satisfactory state of understanding. The greatest errors have been in reconstructions of the topography of the landmasses and the nature of the hydrologic systems.

New suites of numerical climate simulations incorporating initial boundary conditions reflecting what we now know can make predictions to be tested by better and more extensive proxy evidence. We are finally on the verge of understanding what conditions on a 'warm Earth' were like.

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