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Cretaceous (Wealden) climates: a modelling perspective

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Abstract

This paper describes the results from a new palaeoclimate modelling exercise for the Early Cretaceous (Barremian) focussed on the Weald (SE England), using a Limited Area Numerical Climate Model (LAM). The palaeoclimate model uses appropriate Barremian boundary conditions and simulates a climate with seasonal surface temperatures akin to those occurring in parts of the modern southern Mediterranean. Cold month mean temperatures are simulated as 4–8 °C, whilst warm month mean temperatures may reach 36–40 °C. Precipitation rates are high during all seasons with little evidence for prolonged drought. The average precipitation rate simulated for any one month is 4–8 mm/day, whilst during parts of the winter (December, January and February) precipitation rates may exceed 16 mm/day. No present-day analogue is available for the climatological pattern predicted for the Barremian.

This result differs from other palaeoclimate interpretations for the Weald based on proxy climate data. These data have been interpreted as showing the existence of a seasonal precipitation pattern with a pronounced dry season. The data/model inconsistency can be resolved by careful examination of the model-predicted moisture budget as a whole. We argue that many of the palaeoclimate moisture proxies record the net hydrological cycle (i.e., precipitation minus evaporation). Although the climate model simulates precipitation year round, the surface temperatures result in very high evaporation rates. Therefore, moisture availability during the Barremian in the soil and for plants during the summer months (June, July and August) is severely restricted even though precipitation levels are substantial.

These results demonstrate the importance of considering the moisture balance as a whole rather than focussing on only precipitation when drawing palaeoenvironmental inferences from proxy data. The work underlines the benefits of using numerical climate models in conjunction with proxy data in understanding past climates and environments.

Keywords: Limited Area Model; Cretaceous; Weald; Palaeoenvironment; Palaeoclimate

1. Introduction

The sedimentary character (e.g., Allen, 1975, 1981, 1989; Sladen, 1983; Taylor, 1996), types of fossil flora and fauna (e.g., Sladen and Batten, 1984; Jarzembowski, 1995; Radley, 1995; Watson and Alvin, 1996), palaeoenvironment (e.g., Batten, 1998; Radley et al., 1998) and palaeoclimate (Allen, 1975, 1981; Allen et al., 1998) of the Early Cretaceous Wealden Beds of southern England has been intensively studied by Earth scientists. The Wealden climate has been summarised by Allen et al. (1998) as hot to very warm (ca. 25 °C) alternating with cooler periods (ca. 10 °C) and seasonal in nature. Rainfall is estimated to have been high during time periods represented by the Ashdown Group and Lower and Upper Tunbridge Wells formations (max. ca. 1250–1500 mm a^{-1}), alternating with remissions (ca. 1000 mm a^{-1}) and droughts during time periods represented by the Wadhurst, Grinstead and Weald Clay formations, the last of these possibly culminating in hot Barremian droughts (Allen et al., 1998). Rainstorms

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leading to flash floods and lightening-generated wildfires were frequent, with predominant winds reconstructed as being NNW and SSE.

Numerical climate modelling using General Circulation Models (GCMs) has been carried out for the Cretaceous using a number of different models. Notable examples include Barron and Washington (1982, 1984, 1985), Barron (1993, 1994), Barron et al. (1994), Price et al. (1995), and Valdes et al. (1996). However, to date, no palaeoclimate modelling study has been published for a time interval that falls within the Wealden Early Cretaceous itself. Furthermore, past Cretaceous modelling studies have been on a global scale using a resolution that is too coarse (several hundred km) to adequately resolve the Wealden region, making effective data/model comparisons impossible. In the past, the mismatch in spatial resolution between model and data has necessitated the construction of spatially extensive proxy data sets for specific time slices that cover at least continent-sized areas (Isarin and Renssen, 1999). Such data sets are available for the Holocene (COHMAP), Pleistocene (CLIMAP, GLARMAP) and Pliocene (PRISM2) but not for the Early Cretaceous.

In an attempt to circumvent these difficulties, downscaling techniques for GCM outputs have been developed. One method of downscaling is to use a physically based climate model with a higher spatial resolution. These models may be with a grid that is variable, so that the resolution can be optimised for the regions of interest (Deque and Piedelievre, 1995; Renssen et al., 2001).

This paper describes the results from a new palaeoclimate modelling experiment run for a specific Wealden time slice (the Barremian) using a Limited Area Model (LAM). The use of a LAM significantly increases the horizontal resolution of the model allowing for the better representation of coastlines and mountains and behaviour of mid-latitude storms. Climate model output from this new high-resolution Wealden simulation is compared to geological proxy data in an effort to evaluate the robustness of the model predictions and to provide new perspectives on proposed palaeoenvironmental reconstructions for the Weald during the Early Cretaceous.

2. Methods

2.1. Atmospheric General Circulation Model (AGCM)

A global scale Barremian experiment was performed with the HadAM3. The particulars of the HadAM3 are well documented (e.g., Pope et al., 2000). However, some discussion of the model itself and how HadAM3 differs from HadAM2 is necessary. HadAM3 was developed at the Hadley Centre for Climate Prediction and Research, which is a part of the UK Meteorological Office. The horizontal resolution of the model is 2.5° in latitude by 3.75° in longitude. This gives a grid spacing at the equator of 278 km in the North–South direction and 417 km East–West. The atmospheric model comprises 19 layers. It has a time step of 30 min and includes a new radiation scheme that can represent the effects of minor trace gases (Edwards and Slingo, 1996). A parameterization of simple background aerosol climatology by Cusack et al. (1998) is also included. The convection scheme has also been improved according to Gregory et al. (1997). A new land-surface scheme includes the representation of the freezing and melting of soil moisture. The representation of evaporation now includes the dependence of stomatal resistance on temperature, vapour pressure and CO_2 concentration (Cox et al., 1999). The above changes have resulted in the atmospheric model being capable of a realistic simulation of the surface heat-flux.

2.2. Climate modelling using a Limited Area Model (LAM)

HadLAM3 was also used in this study. The model was developed at the Hadley Centre for Climate Prediction and Research. The grid resolution of the model is 0.44° of longitude by 0.44° of latitude (approximately equivalent to a 40 km resolution) and the model has a 15 min time step. The physics of the model is almost identical to HadAM3 except that the horizontal diffusion is modified. A domain was used which broadly covered the European sector and upstream areas, as they existed during the Early Cretaceous. This domain included 229 grid boxes in the x-direction and 132 in the y-direction. In the LAM, a co-ordinate transformation is used which shifts the co-ordinate axis so that the LAM domain is at or near the co-ordinate Equator. The benefit of using a LAM is that the high resolution is able to resolve the detailed structure of the coastlines and the palaeotopography. This application of the LAM is only appropriate if such data exist. Cretaceous environments of the Weald have been extensively studied by Earth Scientists. Therefore, the palaeogeography at high resolution is relatively well known. The impact of resolution of the global model and LAM is illustrated in Fig. 1.

In our Barremian experiment, the LAM uses 3-hour updates of all the prognostic variables predicted by the global HadAM3 GCM time-varying fields as boundary conditions. These include surface pressure, horizontal velocities, temperature and moisture. The prognostic variables in the LAM are relaxed towards the lateral boundary conditions, in a zone of four grid rows towards the margin of the domain. Therefore, it is important to recognise that the LAM results near the margins of the

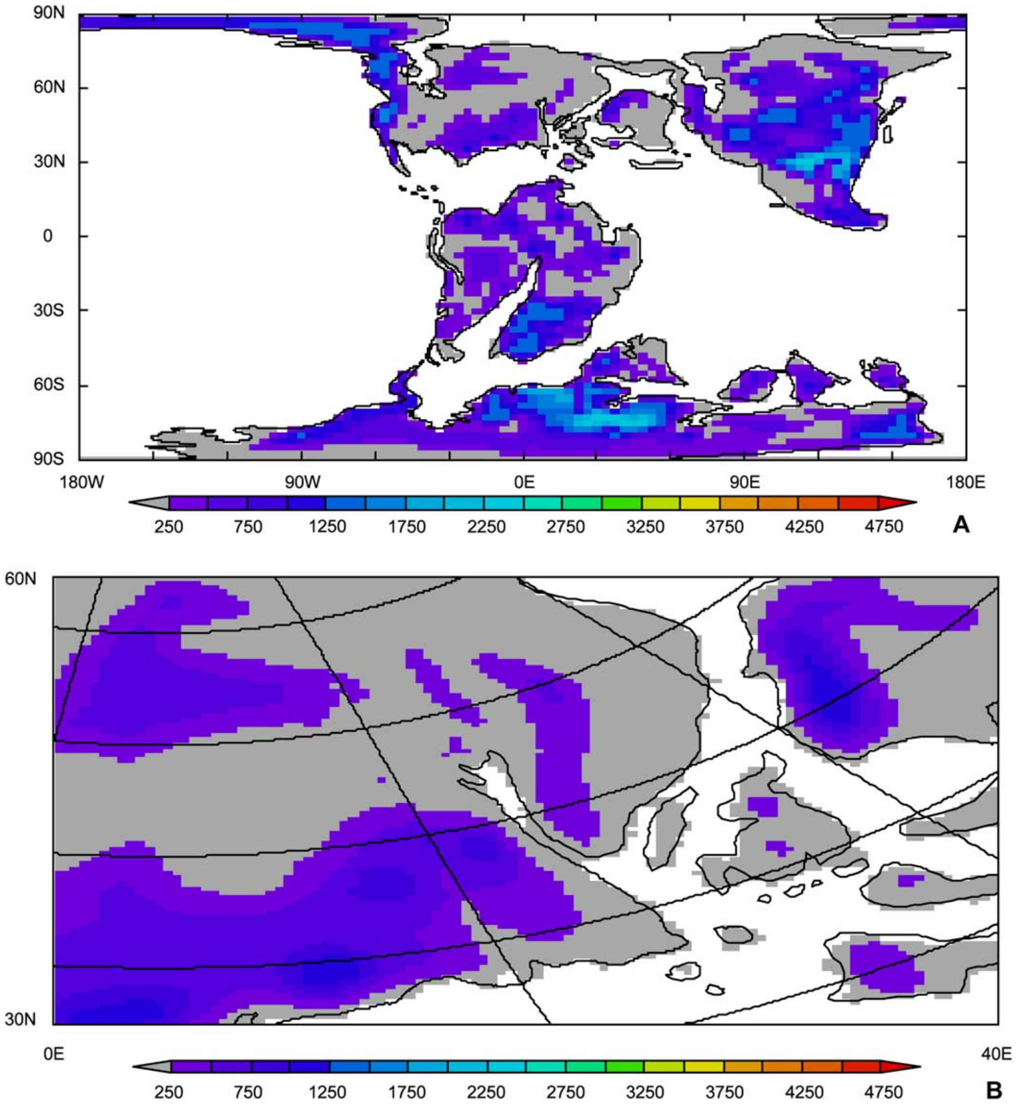


Fig. 1. Land–sea mask and orographic height (m) as imposed boundary conditions in the A, global (HadAM3) and B, LAM (HadLAM3) Barremian experiments; modified from an original Aptian reconstruction by Markwick (unpublished).

specified domain may be unrealistic due to the nesting procedure; thus, they are not shown. Additionally, it is important to understand that the LAM provides a high-resolution, dynamically consistent regional climate, but which is driven by the large-scale global model. Thus any systematic error in the large-scale model will also be reflected in the LAM results.

2.3. *Experimental design*

The Early Cretaceous experiment was carried out in the following manner. Firstly, a global Barremian experiment was run using the HadAM3 for a total of 12 simulated years with the last ten years of the model run being utilised to compute the required climatological means. The model was then run for a further two simulated years, but this time the climatological means were not averaged. All prognostic variables from this part of the HadAM3 run were stored and then passed to the HadLAM3, which was then run for a further 2 simulated years to generate the required high-resolution model output.

Boundary conditions used within the modelling experiment include atmospheric CO_2 levels set at ×4 pre-industrial concentrations; CH_4 concentrations were maintained at pre-industrial levels. Utilised sea surface temperatures (SSTs) were considerably warmer than modern values and reflect recent reconstructions based on oxygen isotope measurements (Pearson et al., 2001) and coupled ocean-atmosphere GCM experiments (conducted by Valdes, unpublished). A Barremian land/sea mask and palaeogeography was generated to reflect continental and shoreline positions as well as the topography that existed at this time by modifying an existing Aptian reconstruction (produced by Markwick, unpublished). This was possible due to the similarity between the two periods. Global vegetation cover was estimated from the BIOME 4 vegetation model (see Kaplan, 2001; Haywood et al., 2002).

3. Climate results

3.1. Surface temperature (°C) and total precipitation rate (mm/day)

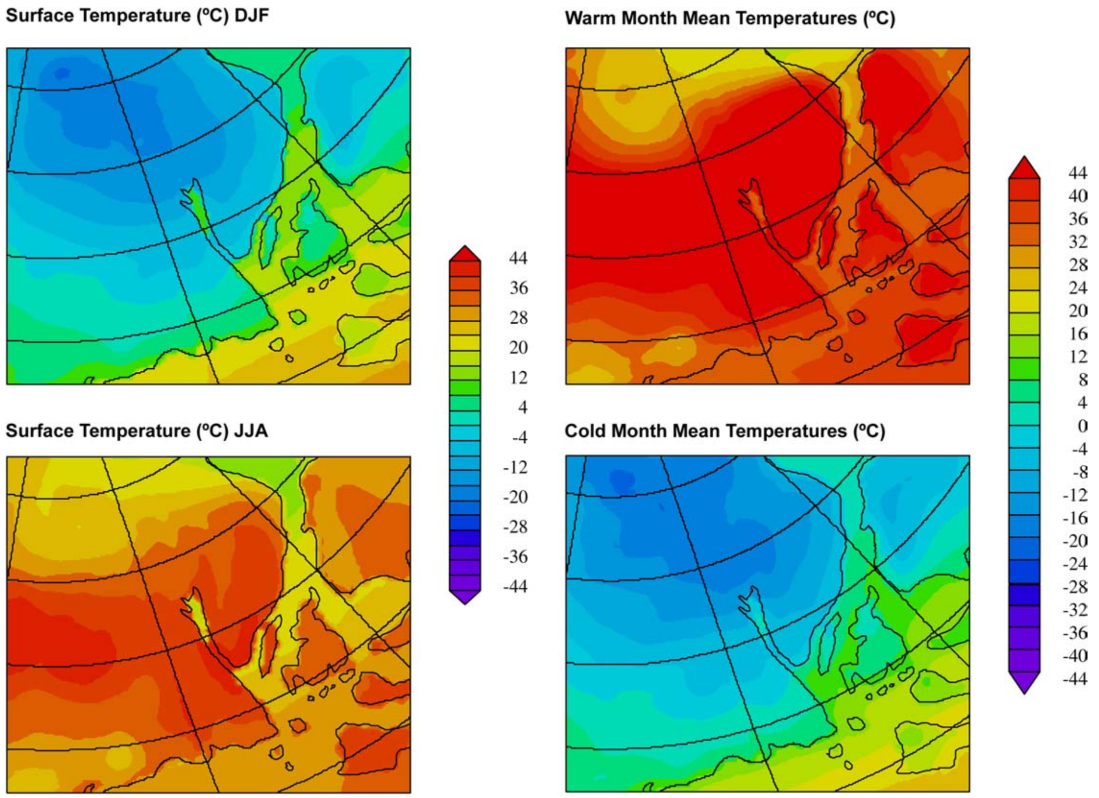
A seasonal surface temperature regime for the Wealden region during the Barremian is suggested by the HadLAM3 predictions. During the coldest month, mean surface temperatures are 4–8 °C. During the warmest month, mean surface temperatures are 36–40 °C (Fig. 2). During the Northern Hemisphere spring season (March, April, May: MAM), average temperatures are 12–16 °C. During the summer months (June, July, August: JJA) average temperatures are 32–36 °C. During the autumn (September, October, November: SON) and winter (December, January, February: DJF) seasons average temperatures are predicted as being 24–28 °C and 8–12 °C respectively (Fig. 2). Surface temperatures do not fall below freezing during any month of the year. Globally, as an annual average, Barremian surface temperatures are 10.2 °C warmer than model predictions for present-day (as predicted by the HadAM3 global simulation).

Model predictions indicate that precipitation rates (mm/day) remain relatively high (compared to amounts currently observed over the Weald) during all seasons for the Barremian (Fig. 3). During MAM, an average precipitation rate of 4–8 mm/day is common over the Weald. During JJA, over southern areas of England, this precipitation rate is maintained (Fig. 3). A similar pattern is predicted during SON, whilst during DJF precipitation rates of 4–8 mm/day are common but may exceed 16 mm/day (Fig. 3). The strength of the precipitation is a reflection of the very warm surface temperatures which enhance oceanic evaporation and hence precipitation.

These model results do not indicate the presence of a pronounced dry season during the Barremian and thus do not agree with the proposed analogue of a Mediterranean-type climate.

3.2. Precipitation minus evaporation (mm/day) plant water stress levels (%)

When analysing changing moisture budgets in model experiments it is necessary to carefully examine the precipitation minus evaporation field (P−E). For the Barremian experiment the model predicts a strong



Surface Temperature (ºC) DJF

Warm Month Mean Temperatures (ºC)

Surface Temperature (ºC) JJA

Cold Month Mean Temperatures (ºC)

Fig. 2. HadLAM3 predictions of surface temperature (°C) for December, January and February (DJF) and June, July and August (JJA) plus the warm and cold month mean temperatures (°C) over the European sector during the Barremian (Early Cretaceous).

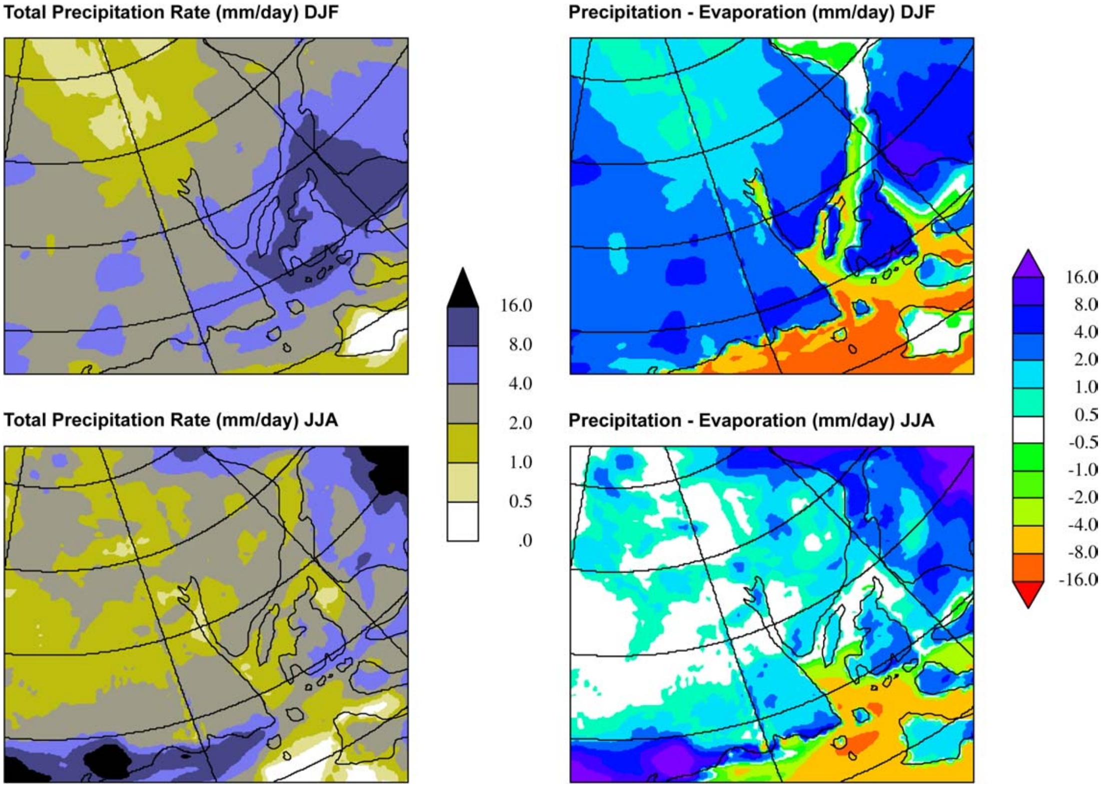


Fig. 3. HadLAM3 prediction of the total precipitation rate and precipitation minus evaporation (mm/day) for December, January and February (DJF) and June, July and August (JJA) over the European region during the Barremian (Early Cretaceous).

gradient in P−E between land and sea (Fig. 2). Over grid boxes specified as water covered, evaporation strongly exceeds precipitation by an average 4–8 mm/day during DJF and JJA. This pattern of evaporation exceeding precipitation over sea areas holds constant during most months and over most areas of water and is a reflection of the warm-specified Cretaceous SSTs, model-predicted surface temperatures, and the availability of moisture for evaporation to occur. Over land areas, precipitation significantly exceeds evaporation, especially during DJF, by as much as 8–16 mm/day (Fig. 3). This result reflects the fact that there is insufficient moisture on the land surface for evaporation to occur. This indicates that although precipitation levels are high throughout the year, the land surface remains water stressed (deficient). The high model-predicted surface temperatures generate this response.

The low moisture availability on the land surface is reflected in the model diagnostic for plant water stress (%). This diagnostic is derived through the calculation of limits of effective moisture in the soil, at what levels moisture becomes unavailable to plants, and therefore the level of water stress to which a plant is subjected. In this context, any moisture level below approximately 30% (depending upon the specified soil type) can be regarded as placing a plant under a high water stress (drought). During DJF, the plant water stress index over the Weald is predicted as being 50%. This indicates only a moderate water stress level (Fig. 3). In contrast, during JJA, the most consistent value is 30–40%, which reflects a high water stress level over the summer months (Fig. 4). Results for the individual months reveal that for August and September water stress levels reach a very high level of 20%. This highlights the fact that although annual average and seasonal precipitation is high, evaporation is so great that little moisture is held within the soil layers for use by plants.

3.3. *Total run-off rates (mm/day), convective cloud (%) and lightning strikes*

The main trends in total run-off rates in mm/day are as follows. During MAM, total run-off rates are predicted at between 1 and 4 mm/day. For JJA, these rates decrease to 0.2–2 mm/day, a pattern that remains constant through SON. During DJF, run-off rates increase to 2–4 mm/day (Fig. 4). Although the model simulates Barremian total run-off rates as being similar to those of present-day for the Weald during JJA and SON, Early Cretaceous run-off is substantially more vigorous during DJF and MAM (by a maximum of 100%). This is a reflection of the amount of precipitation that the model predicts for these months in the Barremian experiment. These results are suggestive of a flashy precipitation regime where heavy rainfall creates high run-off rates. This scenario also helps to explain the P−E field, which

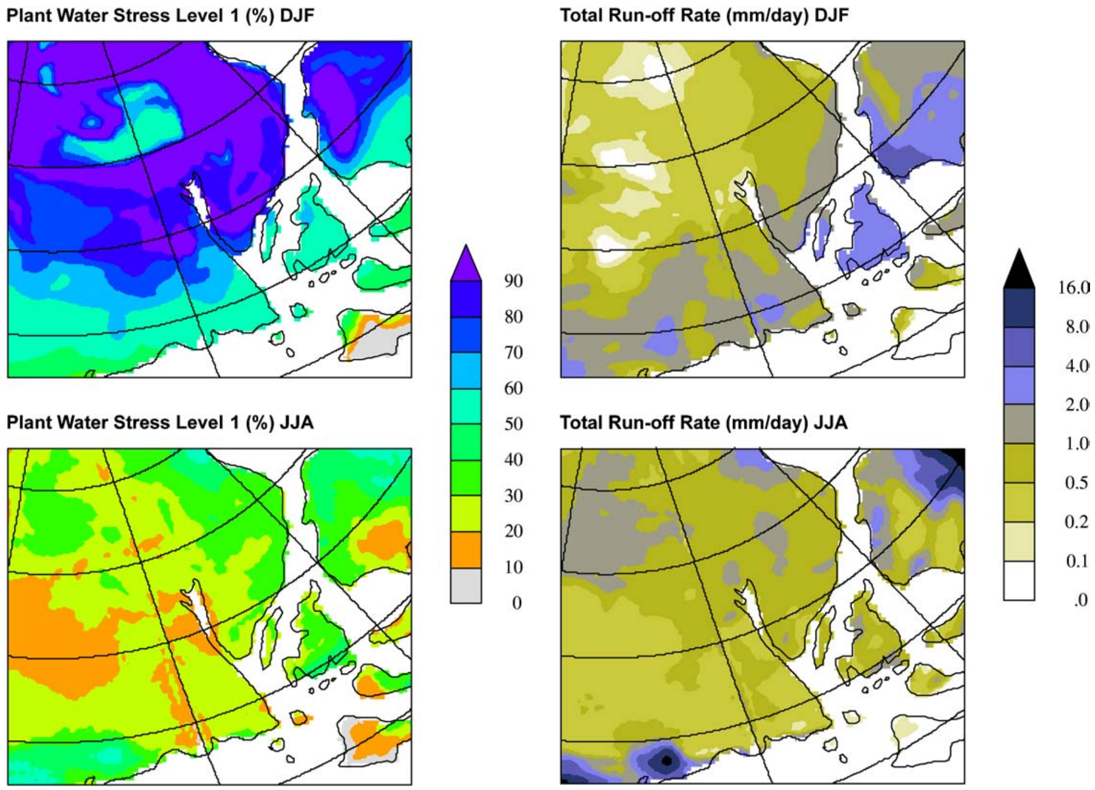


Fig. 4. HadLAM3 predictions of plant water stress (%) and total run-off rate (mm/day) for December, January and February (DJF) and June, July and August (JJA) for the European region during the Barremian (Early Cretaceous).

suggests that during much of the year insufficient water is present at the land surface for evaporation to occur. Under a flashy precipitation regime, the land surface will absorb less moisture and hence the moisture will not be available for the evaporation process or for plant uptake.

Model predictions for convective cloud coverage (%) suggest a clear pattern of enhancement during the Barremian compared to the present-day. For DJF and MAM, Early Cretaceous convective cloud cover, which can be used as a simple proxy for thunderstorm activity, is 1–10% greater than today. During JJA and SON, the increase is more modest (1–5%). This suggests greater thunderstorm activity during the Barremian in the Weald. Since surface temperatures were significantly warmer than now, and moisture availability at the surface was restricted particularly during JJA, this result may indicate that forest fires resulting from lightening strikes might have been a frequent occurrence during the Barremian.

4. Discussion

4.1. Proxies of Early Cretaceous Wealden environments and climates

Many sources of proxy data exist from which the environment and climate of the Weald during the Early Cretaceous has been reconstructed. The following discussion is not designed to provide an exhaustive review of all palaeoenvironmental information published on the Weald but rather to provide a representative sample of published materials.

Robinson et al. (2002) documented the character and stable-isotope geochemistry of calcrete nodules from Barremian non-marine Wealden Beds (Wessex Formation) of southern England. Field evidence suggests that the calcretes were formed mostly under semi-arid Mediterranean-type climatic conditions. Radley and Barker (2000a) described the molluscan palaeoecology and biostratinomy in a Lower Cretaceous meander-plain succession of the Wessex Formation of the Isle of Wight, southern England. Five categories of shelly sediment were documented in the Barremian part of the alluvial section and were interpreted as being deposited in a warm to very hot meander-plain environment. Thick, regularly spaced growth lines in some bivalves probably reflect alternating wet and dry phases. Autochthonous concentrations characterise well-oxygenated pond or lake deposits. Radley and Barker (2000a) suggested that these water bodies were subjected to wet-period sediment influx and disturbance and to dry-period desiccation. Poorly sorted muddy conglomerates representing allochthonous mudflow sediments contain closed, variably orientated unionoids, indicating their catastrophic exhumation and subsequent rapid burial during periodic floods. Radley and Barker (2000b) documented the existence of storm coquinas in the Barremian Vectis Formation (coastal lagoon environment) of the Isle of Wight. These storm coquinas provide clear evidence for powerful and widespread coastal storms in the Weald during the Early Cretaceous.

According to Allen (1981), the Wessex and Weald Basins were subjected to heavy storms and flash floods, which left behind quantities of loose bones and other organic debris. Plate-tectonic widening of the Atlantic enhanced the moisture contents and strengths of westerly winds. This may have been accompanied with local changes in massif heights inducing rain-shadow effects that would have been pronounced on the eastern flanks of the massifs (Allen et al., 1998). The Wessex Formation built up as a series of alluvial meander-plains that overran the basin and crossed the Weald by Barremian times. Breaks in the muddy channel-fills of the meandering systems, evidenced by erosion surfaces, sun-cracks, footprints and clay-draped ripples, indicate intermittent fluctuations ranging from drought to storm discharges with splays and overbank flooding (Allen et al., 1998). Some of the flows were catastrophic, leaving unbanked braided networks of sand-bars and confused accumulations of irregularly bedded sands entombing large, fragmented bones, shells, massive forest tree trunks, boulders, cobbles, and pebbles. The Pine Raft beds with *Pseudofrenelopsis* on the Isle of Wight could represent debris from log jams that developed and collapsed during heavy rain after ponding back considerable bodies of water (Allen, 1981).

Batten (1998) examined the palaeoenvironmental implications of plant, insect and other organic-walled microfossils in the Weald Clay Formation in southern England. During Hauterivian–Barremian times in the Weald Sub-basin, the lowlands were vegetated and green during wet periods, brown during droughts, and burnt by lightning-induced fires prior to the onset of the rainy season. Batten et al. (1996) discussed the differentiation, affinities and palaeoenvironmental significance of the megaspores *Arcellites* and *Bohemisporites* in Wealden and other Cretaceous successions. They concluded that the occurrence of probable water ferns in Wealden deposits may support inferences that have been proposed from sedimentological and palaeontological analyses for a climate with pronounced wet/dry seasons. Ruffell and Batten (1990) presented evidence from nine areas in Western Europe, including the Weald Basin, for a phase of aridity which began in the Hauterivian and continued to dominate the climate of the region until the mid-Aptian, although conditions during this period were not uniformly dry throughout.

Studies of the Early Cretaceous insect faunas and palaeoenvironment of the Wealden Group by Jarzembowski (1995) indicated that the Wealden climate was warmer than it is today, possibly subtropical or warm temperate. The English Lower Cretaceous has yielded one species of Isoptera and over 50 species of Blattodea. Jarzembowski (1995) concluded that the abundance but relatively small size of the Wealden Blattodea could be a reflection of a seasonal climate by analogy with Palaeozoic Euramerican cockroach faunas.

4.2. Data/model comparison

The climate model results for surface temperature produced by the HadLAM3 appear to be in good agreement with Barremian palaeoclimate proxy data for the Wealden region, which suggests that the temperature regime was seasonal and hot during certain periods of the year and significantly warmer than now.

Unlike surface temperature, a data/model inconsistency is evident when examining precipitation characteristics. Most interpretations of palaeoclimate proxy data indicate that precipitation, like surface temperature, was highly seasonal with a pronounced dry season similar to the conditions currently experienced in parts of the Mediterranean. The model does not support this assertion. HadLAM3 predicts significant precipitation during all four seasons, peaking during DJF.

There are numerous lines of evidence to suggest that flooding as a result of very heavy precipitation was a common occurrence during the Barremian (see Section 4.1). The model results support this conclusion and indicate that flooding may have been particularly intense during the winter months caused by powerful, but relatively short-lived, storms. The majority of storms would have been blown across the proto-Atlantic and Weald during the autumn, winter and spring seasons by the prevailing westerly and north-westerly winds (strength of 0 to 6 $\mathrm{m\,s^{-1}}$). The existence of storm coquinas and other sedimentary evidence within Barremian sediments of the Weald support this model result.

Evidence from burned insect carapaces and plant material indicate that fires in the Barremian Weald environment may have been frequent (Batten, 1998). Model predictions for the percentage of convective cloud cover suggest that thunderstorms and hence lightening strikes were more numerous during the Barremian, which is in agreement with palaeoclimate proxy data.

4.3. Significance of proposed palaeoclimatic reconstructions

Some suggested palaeoclimatic reconstructions (e.g., Allen, 1975, 1981; Allen et al., 1998) based upon numerous sources of proxy data, have invoked a Mediterranean analogue for Early Cretaceous Weald. The numerical climate model results presented here support this assertion for surface temperature but not for precipitation. In any reconstruction of past moisture regimes from proxy data the balance of two variables, precipitation and evaporation, must be carefully considered. All of the proxies used to reconstruct past moisture conditions for the Early Cretaceous environment of the Weald will not simply record precipitation levels alone but rather the balance of precipitation minus evaporation. Thus, providing that evaporation remains high during one season and exceeds precipitation, it is entirely possible to generate an *apparent* dry season in proxy data sources when in reality precipitation occurred all year round. The predicted high Barremian surface temperatures, combined with the nature of the precipitation itself (intense and short lived storm events), ensure that evaporation (or potential evaporation) exceeds precipitation during the summer months.

A comparison of the Barremian model results to modern predictions of precipitation for the Mediterranean region highlight the dissimilarity between the Weald during the Barremian and the modern Mediterranean. For the modern, the HadAM3 predicts that for the months of May through September (MJJAS), at a global position of 0° East and 40° North (i.e., in the Mediterranean), there are 36 rain days over the five months totalling 96 mm of rain. This generates an average rainfall of 2.6 mm/day on each of the 36 rain days. For the same MJJAS period for the Weald during the Barremian, the HadLAM3 predicts 80 rain days with a total of 653 mm of rain falling. This averages as 8.16 mm/day on each of the 80 rain days. These predictions indicate a 214% increase in rain per rain day for the Barremian and a 122% increase in the number of rain days during the MJJAS period compared to model predictions for the present-day Mediterranean. Thus, during the Barremian there were more rain days during the MJJAS period and on the days it did rain, the rainfall was far more intense than is presently experienced in the Mediterranean.

The Barremian model outputs indicate that for the 150 days which make up the MJJAS period, approximately half were rain days, the other half were dry. This result should not be construed as supporting the existence of seasonal Barremian droughts. Even though 75 days of the MJJAS period were dry they did not occur concurrently but rather sporadically throughout the five months.

Although the results of this study have highlighted alternative reconstructions of the Early Cretaceous climate of the Weald, it is important to remember that the model outputs represent a snap-shot of geological time and do not consider the temporal variability of climate that occurred during the entire period when Wealden facies were deposited. Palaeoclimate analyses using spectral gamma-ray data from Barremian/Aptian sediments of southern England and southern France (Ruffell and Worden, 2000) suggest that there was a gradual change from a semi-arid climate in the Barremian and early Aptian to a semi-humid climate in the mid-Aptian. Given the limited temporal coverage of the modelling results presented, combined with the low temporal resolution of the geological record itself, it is unclear how truly representative palaeoclimatic reconstructions for the Early Cretaceous Weald are.

5. Conclusions

This paper describes the results from a new high-resolution climate-modelling exercise focussed on the Weald during the Barremian (Early Cretaceous) using a Limited Area Model (LAM). The LAM simulates a similar large-scale climate to HadAM3 but the extra resolution allows us to examine the climate of the Wealden region in detail. It is one of the first uses of a LAM for pre-Quaternary climates and is only appropriate because of the availability of relatively detailed palaeocoastlines and palaeotopography of this region. The model outputs are compared to proxy climate data and the significance of the new results to proposed palaeoclimate reconstructions for the Weald are discussed. The model predicts: (1) a seasonal surface temperature regime varying from 4–8 °C during the coldest month to 36–40 °C during the warmest month; (2) significant precipitation during all seasons (monthly average is 4–8 mm/day) up to a maximum of 16 mm/day during periods of the winter season; (3) an increase in convective cloud cover, and hence a greater potential for lightning strikes; (4) dominant westerly and north-westerly wind direction with a wind strength of 1–6 m s^{-1}.

These results are in broad agreement with proxy climate data with the exception of precipitation where the data have previously been interpreted as suggesting the existence of a seasonally wet, seasonally dry environment. During the summer months, very warm temperatures, heavy but relatively short-lived precipitation and high evaporation led to low moisture availability at the ground surface. This occurred even though there was substantial precipitation during the summer months. This work highlights the importance of considering the moisture budget as a whole when reconstructing past climates from proxy data sources. The research also underlines the usefulness of numerical climate models when used in concert with proxy data to reconstruct past environments.

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