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Jurassic Climates as Inferred from the Sedimentary and Fossil Record [and Discussion]

A. Hallam, J. A. Crame, M. O. Mancenido, J. Francis and J. T. Parrish

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Jurassic climates as inferred from the sedimentary and fossil record

A. HALLAM

School of Earth Sciences, University of Birmingham, Birmingham B15 2TT, U.K.

SUMMARY

A review is presented from the Jurassic terrestrial and marine fossil record, and the record of sediments and clay minerals, insofar as it bears on the two principal climatic parameters, temperature and precipitation. It is shown that there is a generally good agreement between palaeoclimatic data derived from fossils and rocks and the results of modelling experiments, provided a substantially higher atmospheric content of carbon dioxide is assumed for Jurassic times. The Jurassic world was relatively equable compared with the present day, but there were probably strong seasonal contrasts of temperature within the large continental areas, as well as some polar ice. Monsoonal effects were dominant on the continents and rainfall in low and mid latitudes was probably strongly seasonal, with arid conditions prevailing at low latitudes. Significant changes of temperature through the course of the period cannot be discerned, but some evidence tentatively favours a slight increase. A notable spread of aridity in southern Eurasia in the late Jurassic can be related to orographic effects. Some minor cyclicity in the sedimentary sequence may relate to orbital forcing.

1. INTRODUCTION

There has been a general consensus for many years that the climates of the Jurassic, like those of the Cretaceous, were appreciably more equable than today, to the extent that there were evidently no polar icecaps, and cold-intolerant organisms apparently extended over a wider range of latitude (Frakes 1979; Hallam 1975, 1985). The use of the term equable to characterize the climate as a whole has, however, recently been called into question (Crowley & North 1991). In particular, a large supercontinent such as Pangaea, which was coherent for much of the period, is likely to have experienced a considerable seasonal range of temperature.

Although less attention has been paid to Jurassic climates than those of the Cretaceous, both in terms of data gathering and modelling, a substantial body of knowledge exists from which to make reasonably confident statements about general patterns at least. Of the two major climatic parameters, temperature and precipitation, temperature has received the greater attention, but a great deal can be learnt also about the distribution of rainfall on the continents. In the following account the distribution of climatically significant flora and fauna will be reviewed first, followed by the distribution of climatically significant sediments and clay minerals, and brief attention also paid to oxygen isotope data on fossil shells. Subsequently changes through time of inferred Jurassic climate are considered, and the article concludes with a discussion of the relationship between empirical and theoretical studies.

2. FLORAL DISTRIBUTIONS

Among the ferns there are abundant widespread genera whose living relatives cannot tolerate frost. In the Lower Jurassic there is a northern floral zone embracing Greenland, northern and central Europe, Siberia and Japan, and a southern zone extending from Mexico to the Middle East and southern China (Barnard 1973; Wesley 1973). These zones could reflect a degree of latitudinal differentiation, but Barnard (1973) considers that the difference might relate in part to the continentality of the climate, i.e. to the degree of contrast between seasons.

Cycadophytes are latitudinally restricted to a belt more or less corresponding to the more southerly floral zone among the ferns (Vakhrameev 1964, 1991; Wesley 1973). Passing northwards into Siberia, the cycadophyte and conifer floras are much lower in diversity and are instead dominated by ginkgophytes. According to Vakhrameev this signifies a latitudinal climatic gradient in Eurasia significantly less than today, with winter temperatures in Siberia probably never falling below 0°C. The climate of this northern zone appears to have been humid and moderately warm, while that of the southern zone compares with the present humid tropical zone. Vakhrameev detected a slight northward shift of the boundary between the two floral provinces from the early to the mid Jurassic and an appreciably greater northward shift from the mid to the late Jurassic (figure 1). The conifer pollen *Classopolis* is evidently most common in association with evaporites and hence its abundance has been used as an indicator of arid climate.

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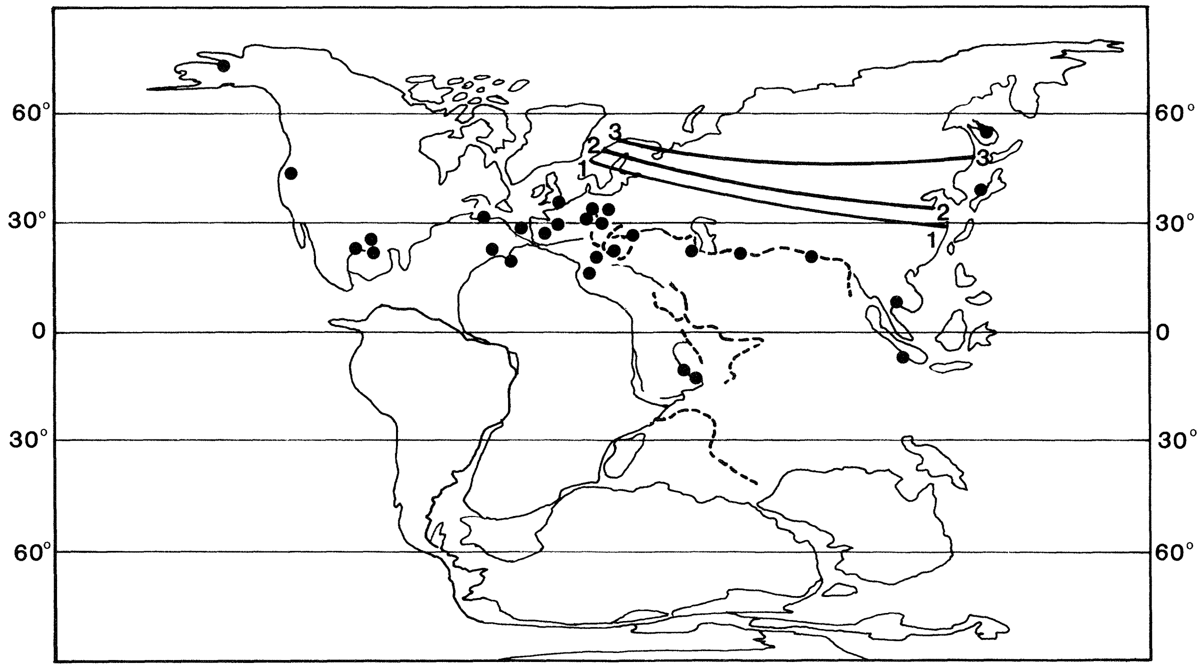

Figure 1. Distribution of Jurassic reefs. Simplified from Flügel & Flügel-Kahler (1992). Also shown is the shift in the boundary of the Indo-European and Siberian floral provices in Eurasia from the early (1) and mid (2) to late (3) Jurassic. Adapted from Vakhrameev (1964).

According to Vakhrameev (1981) it is most abundant in Upper Jurassic sediments, thereby indicating the late Jurassic as a time of maximum aridity during the period. This confirms inferences derived from the sedimentary record (see below).

Turning to the Southern Hemisphere, the floras which contain *Dictyophyllum* differ considerably from those of the Northern Hemisphere, and appear to mark a separate floral province. The wide distribution of this genus between palaeolatitudes 50° and 60°N and S is to Barnard (1973) a strong argument in favour of a relatively warm and equable world. A differentiation between the Northern and Southern Hemispheres has also been recognized among the conifers (Florin 1963) but this is unlikely to relate simply to climate, because climatic control should have given rise to a symmetrical latitudinal pattern of zones with respect to the equator. It is more likely to be due to the increasing separation of Laurasia and Gondwanaland by the Tethys, and inability of pollen to cross the ocean. The Indian floras are significantly different from those in adjacent Eurasia, which presumably relates to the subcontinent's northward migration in post-Jurassic times.

Growth rings of fossil tree trunks also provide valuable climatic indicators. The formation of uninterrupted secondary wood is generally correlated with a uniform, essentially seasonless climate. Wood entirely lacking growth rings is broadly confined to those areas in the tropics in which the climate is relatively seasonless. In a global analysis of fossil wood ranging in age from Lower Jurassic to Lower Tertiary, Creber & Chaloner (1984) were able to recognize a broad equatorial zone ranging in latitude from approximately 30°N to 30°S, in which annual growth rings are either absent or very weakly developed. To the north and south of this zone, pronounced annual growth rings are well developed and are thought to have formed in strongly seasonal climates. This is consistent with broad temperate climatic belts between the poles and 30°N and S. A similar conclusion is drawn by Epshteyn (1978) for the Jurassic floras of northern Asia, where the woods have annual rings indicating a clearly defined seasonal climate.

3. FAUNAL DISTRIBUTIONS

A tropical belt is also clearly recognizable from the distribution of (presumed) hermatypic corals, rudistid and other large, thick shelled bivalves, lituolacean foraminifera and hydrozoans, together with abundant and diverse dasycladacean algae (Hallam 1984*a*). This is well illustrated by a map of the distribution of coral-dominated reefs (figure 1). The only places where they extend well beyond 30°N are in western North America and eastern Asia, but these are in areas of displaced terranes, which have been moved significant distances northward as a result of post-Jurassic tectonic activity (Hallam 1986*a*).

The interpretation of the well known Tethyan–Boreal provinciality among the ammonites and belemnites is more controversial. The traditional interpretation is that, since the boundary between the two realms roughly follows latitude (figure 2) the Boreal Realm signifies a cooler climate. There are, however, a number of arguments against this (Hallam 1975, 1984*a*; Doyle 1987). The taxonomic diversity is not significantly reduced towards the poles, unlike at the present day, and among the belemnites at least appears to increase northwards from the Boreal–Atlantic to the Arctic Province (Doyle 1987). Doyle also records that Arctic endemic belemnites are not

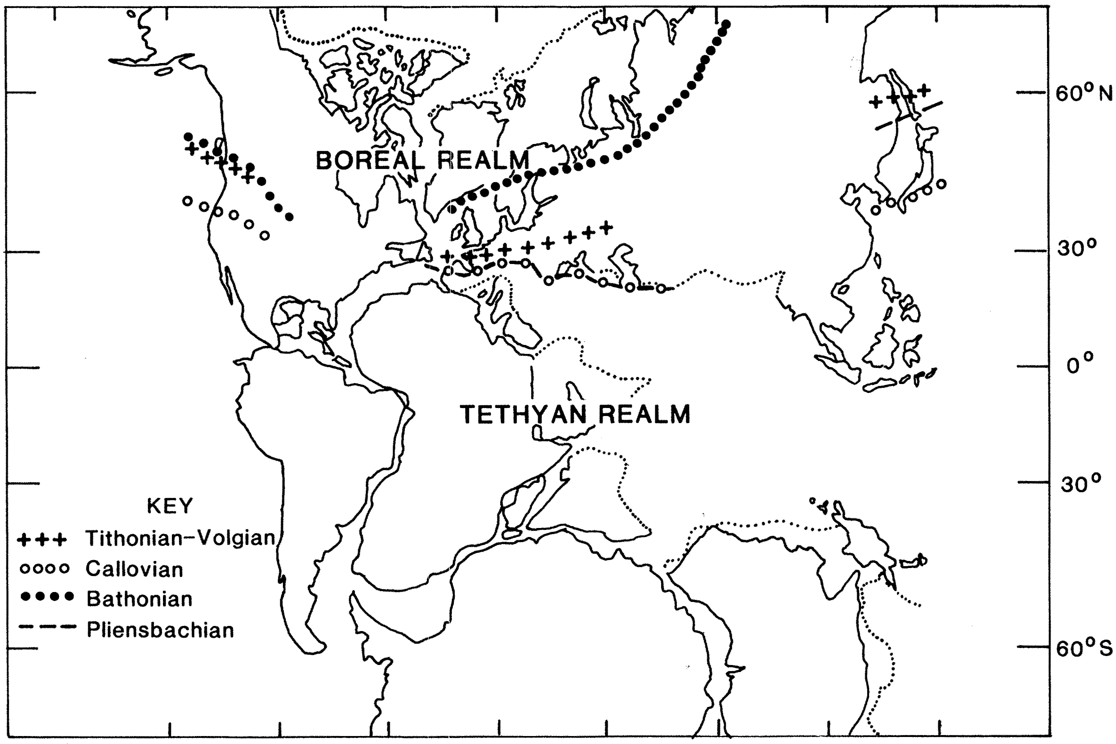

Figure 2. The approximate boundaries of the Tethyan and Boreal realms at different times in the Jurassic. After Hallam (1975).

strictly confined latitudinally, extending down the western side of North America as far as Mexico, mixed with Tethyan ammonites.

The absence of an austral fauna matching the boreal one, argues against a climatic interpretation for the provinciality but Crame (1986) has suggested that the distribution of certain late Jurassic bivalves, including *Buchia*, *Retroceramus* and *Arctotis*, is bipolar. Most occurrences of *Buchia* are north of 30°N palaeolatitude, and in the Spiti Shales of India, located south of 30°S in late Jurassic time. *Buchia* is common in the Antarctic, becoming less common into Andean South America. However, the relevant bivalves have a circum-Gondwanaland distribution, and *Buchia* occurs commonly in North American cordilleran terranes as far south as northern Mexico. Probably palaeogeographic factors including water depth were more significant than temperature. Palaeogeographic restrictions are also invoked by Doyle (1987) to account for the relatively low diversity of belemnites in the Boreal–Atlantic Province of Europe (cf. Fürsich & Sykes 1977). Further north and south (the Arctic Sea, Tethys) more stable habitats allowed a higher diversity, and more open seaways may have persisted between the Arctic and Pacific. Whatever the reasons for the origin and maintenance of the Tethyan–Boreal provinciality, and it probably involves a complex interplay of factors, it seems evident that the provinciality gives us no information on climate that is not better deduced on other grounds. If, despite the evidence to the contrary, some sort of latitudinal effect is thought to be paramount, seasonal changes in illumination or solar radiation could have been possible controlling factors (Reid 1973).

Schaeffer (1970) has discussed the evidence of Jurassic marine fish and concluded that the extensive north–south distribution of ceratodontids and certain actinopterygian groups must signify an essentially uniform climate embracing all the continents. Thus ceratodontid lung fishes have been found in England, the United States, China, Madagascar and Australia. Their living relatives are confined to the tropics and subtropics.

Dinosaurs are the best known of the terrestrial vertebrates. The richest faunas occur in the Upper Jurassic of the United States Western Interior and Tanzania, but scattered occurrences have been recorded over a wide latitudinal range, from the United States, Europe and China to Patagonia and Australia. Charig (1973) was unable to recognize genuine provinciality and several families were cosmopolitan. If dinosaurs were ectothermic, like other reptiles (implying the requirement of an external heat source for their temperature regulation), the wide latitudinal distribution of dinosaur genera would appear to reinforce that of marine fish in implying relative equability.

4. SEDIMENTS

The most important sedimentary rocks that have been used in palaeoclimatic interpretation are limestones, tillites, evaporites and coals, which will be considered in turn, together with a number of other criteria such as clay minerals, ironstones and calcretes.

(*a*) *Limestones*

Ziegler *et al.* (1984) have drawn attention to the fact that most shallow shelf carbonates in the Mesozoic and Cenozoic occur within the subtropics, 5–35°N and S; 99% of occurrences are within 45° of the equator. The carbonate belt evidently did not expand polewards during warmer intervals, suggesting that temperature is not the limiting factor. Year-round light refraction falls markedly at about 35° from the equator, the present poleward limit of Bahamian-type environments. This depositional system relies on algal fixation of $CaCO_3$, either directly or indirectly. Therefore light penetration appears to be the latitude-limiting factor influencing carbonate distribution. The lack of high-latitude Jurassic limestones cannot be accounted for by high rates of siliciclastic sedimentation. Thus the non-calcareous deposits of the Russian Platform signify very low sedimentation rates, as evidenced by thin ammonite zones and abundant glauconite and phosphorite.

(*b*) *Tillites and dropstones*

Older claims of Jurassic tillites in Antarctica and Patagonia have been decisively refuted (Hallam 1975) but more recently the interpretation of a number of pebbly mudstones in the Arctic borderlands of northern Siberia as including glacial dropstones (Epshteyn 1978) has attracted some attention (Brandt 1986; Frakes & Francis 1988; Frakes *et al.* 1992). The deposits in question extend between the West Siberian lowlands and Kamchatka, with examples recorded from the Liassic, Aalenian, Bajocian, Callovian, Kimmeridgian and Volgian. They are described as unstratified, with individual beds ranging from fractions of a metre up to 5–7 m in thickness. Randomly distributed clastic material ranges from sand to gravel, pebbles and even occasional cobbles. Professor L. A. Frakes (personal communication) has personally examined some of these deposits at seven localities concentrated near the headwaters of the Kolyma River and considers that only a Bathonian (or possibly Callovian) example sufficiently satisfies the criteria for identifying a genuine glacial dropstone. Evidently one needs to accept the possibility of some high-latitude ice in the Jurassic, as in the Cretaceous (Frakes & Francis 1988). It could have disappeared in the summer, however, and there is no justification whatever for postulating the existence of polar icecaps substantial enough to generate glacioeustatic changes of sea level (Brandt 1986).

(*c*) *Evaporites, coals and aeolian sandstones*

The distribution of Jurassic evaporites and coals, long established as criteria for the recognition of precipitation patterns, has been plotted by Parrish *et al.* (1982) and Hallam (1975, 1984*b*), the former for two stage intervals, the Pliensbachian and Volgian and the latter for the three subsystems, Lower, Middle and Upper. The area covered by evaporite deposits is second only to that of the Triassic (Gordon 1975), but the geographic range does not seem to have been significantly different from that at the present day.

The only region where reasonably well authenticated Jurassic aeolian sandstones are known is the United States Western Interior, namely the Navajo and Nugget Sandstones of Lower Jurassic age. Part of the Callovian Entrada Sandstone is also apparently of aeolian origin. The measurements on dune bedding orientations are broadly consistent with the region lying in a trade wind belt at the time (Poole 1964; Tanner 1965).

(*d*) *Other climatic criteria*

Compared with evaporites and coals, clay minerals have the advantage of being almost ubiquitously present in sedimentary sequences of a wide range of facies, thereby allowing a much fuller monitoring of changes through time and space. It is generally accepted that kaolinite forms most readily under intensive leaching conditions in acid soils in a climate combining high temperature and precipitation. The climatic significance of this and other clays in fully discussed by Hallam *et al.* (1991) and Sellwood & Price (this volume), who also mention the complications of burial diagenesis.

Ancient soils can be climatically revealing but little attention has been paid to pedogenic deposits in the Jurassic. Deposits of calcrete, signifying formation in warm, semi-arid conditions, have been reported, however, from the Lower Jurassic of New England (Hubert 1978) and the Oxfordian of Portugal (Wright & Wilson 1987).

Wignall & Ruffell (1990) have inferred a change from a humid to a semi-arid style of deposition in the Upper Kimmeridge Clay of southern England using a variety of criteria. A decline in kaolinite abundance is matched by a decline in offshore sedimentation rate, softground fauna being replaced by hardground faunas and dolostones formed in the mechanogenic zone giving way to calcite nodules. Their inference is supported by palynological data. The work of Wignall & Ruffell is a good example of using data from a multiplicity of sources to infer a history which could not be safely inferred from one criterion alone.

5. OXYGEN ISOTOPIC COMPOSITION OF SHELLS

Serious doubt has been cast on the adequacy of oxygen isotope measurements obtained from Jurassic marine shells because of the problems of 'vital effects' and meteoric diagenesis (e.g. Hallam 1975; Epshteyn 1978). Some more recent work is, however, rather encouraging. The excellent preservation of calcareous invertebrates and phosphatic vertebrates in the Callovian Lower Oxford Clay of central England offers good possibilities for reliable palaeotemperature determinations. The mean $\delta^{18}O$ values for oysters, pendent bivalves and belemnites (all calcitic) and nuculacean bivalves (aragonitic) correspond to precipitation at isotopic equilibrium with non-glacial seawater at temperatures of 15–18°C. The mean isotope palaeotemperature for ammonites (aragonite) is slightly higher (20°C) but is probably not significantly different from those of other calcareous macroinvertebrates. Preliminary oxygen isotope results on phosphate extracted from bones, teeth and gill rays correspond to palaeotemperatures of 12–20°C (Hudson & Martill 1991; Anderson *et al.* 1992). These results are in good agreement with palaeotemperature estimates based on Jurassic biotic distributions, and tentatively suggest also the likelihood of temperature stratification of the water column, at least for part of the year.

6. CHANGES IN JURASSIC CLIMATES THROUGH TIME

The dramatic disappearance of reefs from the Austrian Alps at the end of the Triassic has been used to argue for a significant fall of temperature at this time. This interpretation is not borne out, however, by oxygen isotope analysis of a well dated and apparently complete carbonate sequence across the Triassic–Jurassic boundary in the Salzkammergut, which indicates no detectable temperature change (Hallam & Goodfellow 1990).

There is no convincing evidence of any notable global temperature change through the course of the Jurassic. The best evidence available concerns the areal distribution of terrestrial plant provinces in Eurasia. Vakhrameev (1964) detected a slight northward shift of a boundary between northern and southern floral provinces through the period, continuing into the Cretaceous (figure 1), which implies a slight warming trend. As opposed to this, it could be argued that the ocurrence of glacial dropstone deposits in northern Siberia marks the beginning of a cooler time from the mid Jurassic onwards. This was in fact done recently by Frakes *et al.* (1992). These authors maintain that the Siberian dropstones recorded by Epshteyn (1978) signify a relatively cool interval extending from the Bajocian to the Albian. Actually Epshteyn cites work mentioning Liassic dropstones in addition, but in view of the scepticism now expressed by Frakes there is bound to remain some doubt about the reality of the supposed cool interval. Furthermore it needs to be borne in mind that the late Jurassic marked a time of significant geographic spread of carbonates and associated reef deposits (Hallam 1975). Clearly further evaluation is required of both the palaeobotanical and sedimentological evidence.

The distribution of evaporites, coals and other climatic criteria reveals a Jurassic world in which the western part of Pangaea in low to mid latitudes experienced an arid climate. The more easterly parts of Laurasia and Gondwanaland were more humid, at least seasonally, and high latitudes were persistently humid. The principal change took place towards the end of the period, when arid conditions extended across southern Eurasia (Hallam 1984, 1985; figure 3).

The general pattern of this change is outlined by Hallam (1984*b*) and a more detailed study of Jurassic–Cretaceous boundary beds in western Europe, using the proportion of kaolinite in the clays as the most continuous monitor, was undertaken by Hallam *et al.* (1991). The kaolinite proportion works quite well as a correlation tool within south eastern France and Switzerland but breaks down in detail over a more extensive region. Thus a shift in age of the inception of kaolinite depletion from late Oxfordian–Kimmeridgian in south eastern France to late Kimmeridgian–Portlandian in Dorset suggests some diachronism in the onset of arid conditions, beginning earlier in the south and slowly moving northward. The Lower Purbeck beds marks the maximum development of the Tithonian arid phase, with kaolinite disappearing completely and palygorskite occurring as well as evaporites. The co-existence of evaporites with coniferous trees and abundant insects and molluscs suggests a highly seasonal, Mediterranean-type climate (Francis 1984). Whereas the onset of more arid conditions in southern England can be dated as Upper Kimmeridgian *hudlestoni* zone (Wignall & Ruffell 1990) it occurred slightly later in north eastern Scotland, in the *rotunda* zone (Wignall & Pickering 1993).

The wide extent of arid conditions in western

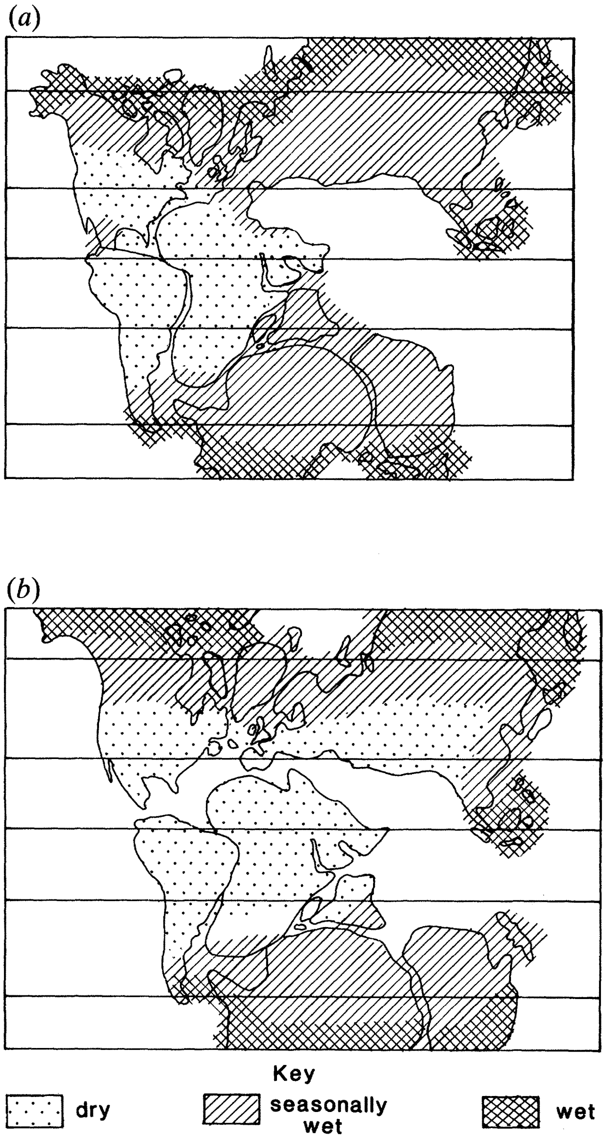

Figure 3. Continental humid and arid belts in the Jurassic. (*a*) Early Jurassic; (*b*) Late Jurassic. After Hallam (1985).

Pangaea is readily explicable by reference to high pressure trade wind belts in conjunction with a huge landmass. The late Jurassic spread of arid conditions in southern Eurasia is most probably an orographic effect rather than due to a southward shift of Eurasia, a rain shadow resulting from the collision of the Cimmerian landmass and concomitant disappearance of Palaeotethys (Hallam 1984*b*; Sengör *et al.* 1988; figure 4).

Cyclicity

In view of the current interest in orbitally forced climatic rhythms it is only natural that small-scale cyclicity in the Jurassic should be attributed to this (e.g. House 1985; Hallam 1986*c*). However, as Algeo & Wilkinson (1988) point out, cycles in the Milankovitch range can be produced by a variety of mechanisms independent of orbitally modulated climatic change. In the absence of a clearly defined mechanism for translation of orbital variations into cyclic sedimentation during non-glacial times, orbital forcing cannot be assumed.

A promising beginning, using some form of time-series analysis, has nevertheless been made in a few cases. Olsen (1986) has studied a series of lacustrine strata in the Newark Supergroup (Upper Triassic–Lower Jurassic) in the north eastern United States. These are characterized by repetitive sequences known as Van Houten cycles. In general, a Van Houten cycle consists of an ordered series of facies indicative of lake deepening and shallowing. Olsen has calibrated continuous sections with both radiometric dates and varve counts to obtain an average value for effective accumulation rates. Fourier analysis indicates that the sections are dominated by periodicities that correspond well to the orbital theory of climatic change.

The gamma method is a new method for testing periodicity within cyclic strata (Kominz & Bond 1990). Time–thickness relations of the facies within individual cycles are used to estimate ages. It is thus possible to address quantitatively the question of whether the cycles that make up these strata are periodic. In the Newark Supergroup, it is claimed that both precessional and eccentricity cycles are recorded (Kominz & Bond 1990; Kominz *et al.* 1991).

Weedon (1985) applied Walsh power spectrum analysis to the limestone-shale sequence of the Blue Lias (Hettangian–Lower Sinemurian) of southern England, but was criticized for underestimating the disturbing effects of diagenesis (Hallam 1986*b*). The slightly younger Belemnite Marls of the same region have a comparable facies apparently less affected by diagenesis. Weedon & Jenkyns (1990) believe that they may record precessional cycles, but cycle bundles cannot be linked to changes in eccentricity. Rather they apparently record irregular large-amplitude climatic variations with periods of a few hundred thousand years. In a further study, Weedon (1989) used the same method of analysis to examine three Liassic limestone-shale sequences in Switzerland. He claimed to detect the 21 ka precession cycle in all three cases, the 100 ka eccentricity cycle in two and the 41 ka obliquity cycle in one.

In 1990 the Ocean Drilling Program succeeded in recovering the oldest sediments in the Pacific, extending back in age to the mid Jurassic. The reddish-coloured clayey and cherty sediments from low palaeolatitudes consist of rhythmically bedded layers, alternating in enrichment or depletion of radiolarians, relating presumably to episodes of upwelling and surface fertility of the tropical ocean. The finest scale cycles have a possible periodicity of 20 ka, consistent with precessional control (Shipboard Scientific Party 1990).

A serious problem with all such studies in rocks of Jurassic age is the imprecision of absolute dating, such that the degree of confidence with which one can recognise Milankovitch cycles of a particular type is necessarily limited.

7. COMPARISON OF DATA AND MODELS

The most important advance in recent years in the study of Jurassic climatology has been a number of attempts to introduce modelling for a world of very different geography from that of the present day.

The global climatic model experiments of Kutzbach & Gallimore (1989) for the early Mesozoic (Triassic) Pangaea predict that it would have experienced a strongly monsoonal climate, involving alternating circulation between high pressure in winter and low pressure in summer. Rainfall in consequence is likely to have been strongly seasonal. Most of the landmass at latitudes of less than 40° would have been relatively dry. This modelling is well supported by data on the distribution of coals and evaporites. Parrish *et al.* (1982) utilised two alternative rainfall models to account for such distributions for a number of time intervals in the Mesozoic and Cenozoic. The zonal model predicts coals occurring within latitudes 15°N to 15°S and 45–75°N and S, and evaporites between 15° and 45°N and S. The circulation model takes account of strong seasonality and a monsoonal regime. It is more successful than the zonal model for the Pliensbachian and Volgian, the two Jurassic stages that were studied, a result which is unsurprising bearing in mind that a monsoonal influence has a considerable perturbing effect on latitudinal climatic zones. According to Manabe & Wetherald (1980) large-scale monsoonal circulation is a powerful mechanism for transporting large amounts of latent heat poleward, where high rainfall is to be expected. This could account for the high-latitude coals of the Mesozoic.

Crowley & North (1991) point out that modelling studies indicate that a very large seasonal cycle, with probable winter cooling, is an inescapable feature of Pangaean climates, and they contest the world 'equable' to describe them. A large seasonal cycle might still result even if the snow cover were reduced, because soil moisture depletion leads to the land being heated up faster. Heat loss in continental interiors would occur at a greater rate than could be compensated for by transport from the oceans. The larger the land-

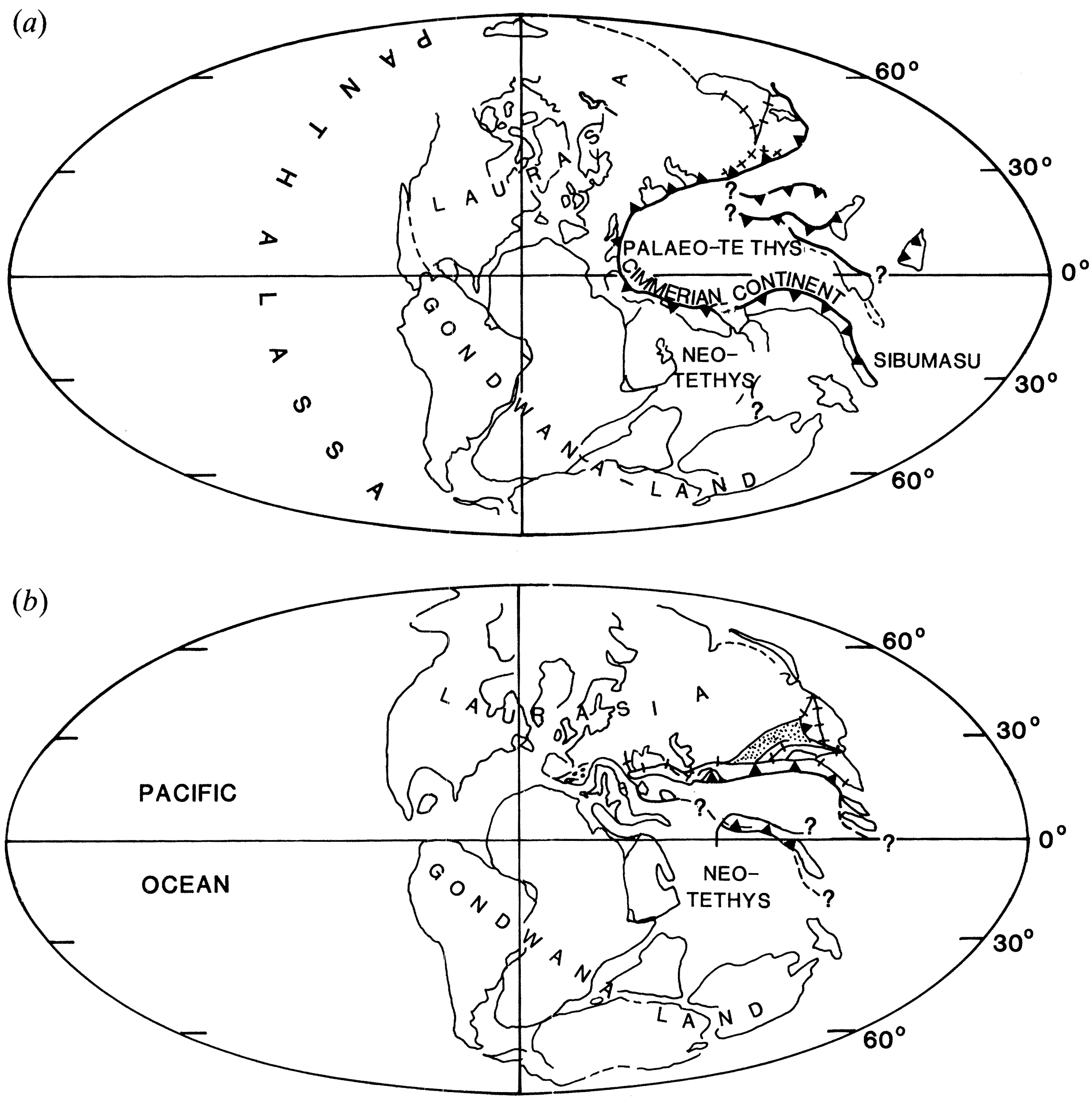

Figure 4. Sketch diagrams to illustrate the collision of the Cimmerian continent with Eurasia in the late Jurassic, with concomitant destruction of Palaeo-Tethys. A, Early Triassic; B, Late Jurassic. Simplified from Sengör *et al.* (1988).

mass, the larger the discrepancy in the energy budget of continental interiors. If at least some of the purported glacial dropstones in northern Siberia can be adequately substantiated it would indicate the existence of high latitude ice, though probably seasonal and in relatively small quantities, in view of all the counter evidence from the distribution of flora and fauna. The presence of such ice would certainly be consistent with a whole series of modelling experiments which suggest that the problem is more to account for the absence rather than the presence of substantial polar ice during geological history (Donn & Shaw 1977; Barron *et al.* 1981; Hunt 1984).

Currently the most popular way of accounting for a more equable world at certain times in the past is to invoke the greenhouse effect caused by greater concentrations of carbon dioxide in the atmosphere. Berner (1991) put forward an isotopic mass balance model for the whole Phanerozoic, expanded to include the effects of changing continental palaeogeography and seafloor area generation rate, together with the changing relative importance of deep sea versus shallow platform carbonate deposition insofar as they affect global degassing. The amount of atmospheric CO_2 was calculated from a weathering feedback function for silicates.

Berner's best estimate of CO_2 for the Jurassic fluctuates around four times the present value, with a slight rise from mid Jurassic times onward and a more marked fall to three times the present value at the Jurassic-Cretaceous boundary. Cerling (1991) argues that the isotopic composition of soil carbonate recorded in calcrete is a faithful monitor of the concentration of atmosphere CO_2. His $\delta^{13}C$ results from Lower Jurassic calcretes in Connecticut are in good agreement with Berner's predictions.

Moore *et al.*'s (1992*a*) analysis of the late Jurassic (Kimmeridgian–Tithonian) world used a general circulation model with two seasonal simulations, one with 280 p.p.m. atmosphere CO_2 concentration (the pre-industrial modern value) and the other four times this value, like Berner's (1991) figure. The 280 p.p.m. simulations produced too cold a world for environmentally sensitive organisms and rocks, but the 1120 p.p.m. simulation fits the stratigraphic record quite well, suggesting in support of Berner that the late Jurassic world possessed an enhanced greenhouse effect. The splitting of Pangaea and flooding of large parts of Eurasia would profoundly have altered the climate, but the three major continental blocks were extensive in area, with interiors whose climate was harsh and arid but not overwhelmingly equable. The distribution of sea ice in the 1120 p.p.m. simulation is largely offshore of the continents and fits the stratigraphic record of no land-based tillites. Moore *et al.* recognize also a massive summer monsoonal circulation that focuses heavy precipitation on south east Asia; there is fairly good agreement between evaporite and coal distributions and rainfall precipitation maps.

There is also generally good agreement between geological and palaeontological data and a relatively detailed, high resolution climatic model produced for the Kimmeridgian by Valdes & Sellwood (1992). Their system predicts no permanent ice cover near either pole but surface temperatures over Siberia and south east Gondwanaland fall below zero for a significant part of the winter, a challenge to Vakhrameev's (1964) interpretation based on fossil plants. The expectation from theory and models is for a moister climate than geological data suggest, which indicate a more arid climate than at present. The reason put forward is that total rainfall was greater but dominant over the oceans. The large-scale, as opposed to convective, rainfall was less, and it is this component that primarily affects the land. Higher surface temperatures in the model were counteracted by increased cloud cover due to a warmer and moister atmosphere.

Topography influences many climatic parameters to varying degrees. The sensitivity tests undertaken both by Moore *et al.* (1992*b*) and Valdes & Sellwood (1992) indicate that, without realistic palaeotopography, flat or idealized continents surrounded by bodies of water do not produce realistic palaeoclimate results. Therefore in palaeogeographic reconstructions the location and extent of mountain ranges and highlands should be established if possible and, ideally, given suitable elevations consistent with their plate tectonic origins, settings and age.

Modelling of the orographic effect on patterns of rainfall and aridity has been undertaken by Hay *et al.* (1982, 1990). In the late Triassic and early Jurassic a complex of rifting-produced half grabens bordered the site of the future central Atlantic. Within the rift complex, the occurrence of evaporites indicates extremely arid conditions along the eastern edge of the central rift, in contrast with synchronous lacustrine, playa and coal deposits in the west, indicating more humid conditions. The observed pattern is generally very similar to that predicted by a topographically controlled climatic model (Hay *et al.* 1982). As air rises it cools and becomes saturated with water; the concomitant rise of relative humidity leads to increased precipitation. As air descends leeward of mountains it warms and the relative humidity diminishes. Air would not have become saturated if the western rift margin had been less than 1.5 km elevation. In this case the entire rift valley might have been arid.

Orographic effects were explored more generally in a series of simulations of the effect of changes in palaeotopography, using an idealised pole-to-pole sector continent 105° of longitude in width (Hay *et al.* 1990). Of the four models run, only elevation of mountains on the eastern border of a continent caused aridity. This result is perhaps relevant to the spread of aridity in western Europe in the late Jurassic. Whereas the Cimmeride mountain collision with Eurasia could account for the aridity further east, by a rain shadow effect, it seems puzzling that western European landmasses enveloped by sea should be similarly affected. Bearing in mind the results of the modelling experiments, it is conceivable that the Cimmerides had the effect of partly isolating Europe from the nearest major body of ocean water, the Tethys.

It would be instructive to model the effects on continental climates of low versus high sea-level stands, such as between the Hettangian and Kimmeridgian, and test the results against the geological record.

REFERENCES

Algeo, T.J. & Wilkinson, B.H. 1988 Periodicity of mesoscale Phanerozoic sedimentary cycles and the role of Milankovitch orbital modulation. *J. Geol.* **96**, 313–322.

Anderson, T.F., Popp, B.N., Ho, L.Z. & Williams, A.C. 1992 The carbon and oxygen isotope records of fossils from the Lower Oxford Clay. *Paleont. Soc. Spec. Publ.* **6**, 7.

Barnard, P.D.W. 1973 Mesozoic floras. In *Organisms and continents through time* (ed. N. F. Hughes) (*Palaeont. Spec. Pap.* **12**), pp. 175–188.

Barron, E.J., Thompson, S.L. & Schneider, S.H. 1981 An ice-free Cretaceous? Results from climate model simulations. *Science, Wash.* **212**, 501–508.

Berner, R.A. 1991 A model for atmospheric CO_2 over Phanerozoic time. *Am. J. Sci.* **291**, 339–376.

Brandt, K. 1986 Glacioeustatic cycles in the Early Jurassic? *N. Jb. Geol. Paläont. Mh.* 257–274.

Cerling, T.E. 1991 Carbon dioxide in the atmosphere: evidence from Cenozoic and Mesozoic paleosols. *Am. J. Sci.* **291**, 377–400.

Charig, A.L. 1973 Jurassic and Cretaceous dinosaurs. In *Atlas of palaeobiogeography* (ed. A. Hallam), pp. 339–352. Amsterdam: Elsevier.

Crame, J.A. 1986 Late Mesozoic bipolar bivalve faunas. *Geol. Mag.* **123**, 611–618.

Creber, G.T. & Chaloner, W.G. 1984 Influence of environmental factors on the wood structure of living and fossil trees. *Bot. Rev.* **50**, 357–448.

Crowley, T.J. & North, G.R. 1991 *Paleoclimatology*. Oxford: Clarendon Press.

Donn, W.L. & Shaw, D. 1977 Model of climate evolution based on continental drift and polar wandering. *Bull. geol. Soc. Am.* **88**, 390–396.

Doyle, P. 1987 Lower Jurassic-Lower Cretaceous belemnite biogeography and the development of the Mesozoic boreal realm. *Palaeogeogr. Palaeoclim. Palaeoecol.* **61**, 237–254.

Epshteyn, O.G. 1978 Mesozoic-Cenozoic climates of northern Asia and glacial-marine deposits. *Int. Geol. Rev.* **20**, 49–58.

Florin, R. 1963 The distribution of conifer and taxad genera in time and space. *Acta Hortic. Bergen.* **20**, 121–312.

Flügel, E. & Flügel-Kahler, E. 1992 Phanerozoic reef evolution: basic questions and data base. *Facies* **26**, 167–278.

Frakes, L.A. 1979 *Climates through geologic time.* Amsterdam: Elsevier.

Frakes, L.A. & Francis, J.E. 1988 A guide to Phanerozoic cold polar climates from high-latitude ice rafting in the Cretaceous. *Nature, Lond.* **333**, 547–549.

Frakes, L.A., Francis, J.E. & Syktus, J.I. 1992 *Climate modes of the Phanerozoic.* Cambridge University Press.

Fürsich, F.T. & Sykes, R.M. 1977 Palaeobiogeography of the European Boreal Realm during Oxfordian (Upper Jurassic) times: a quantitative approach. *N. Jb. Geol. Paläont. Abh.* **155**, 137–161.

Gordon, W.A. 1975 Distribution by latitude of Phanerozoic evaporite deposits. *J. Geol.* **53**, 671–684.

Hallam, A. 1975 *Jurassic environments.* Cambridge University Press.

Hallam, A. 1984*a* Distribution of fossil marine invertebrates in relation to climate. In *Fossils and climate* (ed. P. J. Brenchley), pp. 107–125. London: Wiley.

Hallam, A. 1984*b* Continental humid and arid zones during the Jurassic and Cretaceous. *Palaeogeogr. Palaeoclim. Palaeoecol.* **47**, 195–223.

Hallam, A. 1985 A review of Mesozoic climates. *J. geol. Soc. Lond.* **142**, 433–445.

Hallam, A. 1986*a* Evidence of displaced terranes from Permian to Jurassic faunas around the Pacific margins. *J. geol. Soc. Lond.* **143**, 209–216.

Hallam, A. 1986*b* Origin of minor limestone-shale cycles. Climatically induced or diagenetic? *Geology* **14**, 609–612.

Hallam, A. 1986*c* Role of climate in affecting late Jurassic and early Cretaceous sedimentation in the North Atlantic. In *North Atlantic palaeoceanography* (ed. C. P. Summerhayes & N. J. Shackleton), pp. 277–281. Oxford: Blackwells Scientific Publications.

Hallam, A. 1992 Phanerozoic sea-level changes. New York: Columbia University Press.

Hallam, A. & Goodfellow, W.D. 1990 Facies and geochemical evidence bearing on the end-Triassic disappearance of the Alpine reef ecosystem. *Historical Biol.* **4**, 131–138.

Hallam, A., Grose, J.A. & Ruffell, A.H. 1991 Palaeoclimatic significance of changes in clay mineralogy across the Jurassic-Cretaceous in England and France. *Palaeogeogr. Palaeoclim. Palaeoecol.* **81**, 173–187.

Hay, W.W., Behensky, J.F., Barron, E.J. & Sloan, J.L. 1982 Late Triassic-Liassic paleoclimatology of the proto-central North Atlantic rift system. *Palaeogeogr. Palaeoclim. Palaeoecol.* **40**, 13–30.

Hay, W.W., Barron, E.J. & Thompson, S.L. 1990 Results of global atmospheric circulation experiments on an Earth with a meridional pole-to-pole continent. *J. geol. Soc. Lond.* **147**, 385–392.

House, M.R. 1985 A new approach to an absolute timescale from measurements of orbital cycles and sedimentary microrhythms. *Nature, Lond.* **315**, 721–725.

Hubert, J.F. 1978 Paleosol caliche in the New Haven Arkose, Newark Group, Connecticut. *Palaeogeogr. Palaeoclim. Palaeoecol.* **24**, 151–168.

Hudson, J.D. & Martill, D.M. 1991 The Lower Oxford Clay: production and preservation of organic matter in the Callovian (Jurassic) of central England. In *Modern and ancient continental shelf anoxia* (ed. R. V. Tyson & T. H. Pearson) (*Geol. Soc. Spec. Publ.* 58), pp. 363–379.

Hunt, B.G. 1984 Polar glaciation and the genesis of ice ages. *Nature, Lond.* **308**, 48–50.

Kominz, M.A. & Bond, G.C. 1990 A new method of testing periodicity in cyclic sediments: application to the Newark Supergroup. *Earth Planet. Sci. Lett.* **98**, 233–244.

Kominz, M.A., Beavan, J., Bond, G.C. & McManus, J. 1991 Are cyclic sediments periodic? Gamma analysis and spectral analysis of Newark Supergroup lacustrine strata. *Kansas geol. Surv. Bull.* **233**, 319–334.

Kutzbach, J.E. & Gallimore, R.G. 1989 Pangaean climates: megamonsoons of the megacontinent. *J. geophys. Res.* **94**, 3341–3357.

Manabe, S. & Wetherald, R.T. 1980 On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. *J. atmos. Sci.* **37**, 99–118.

Moore, G.T., Hayashida, D.N., Ross, C.A. & Jacobson, S.R. 1992*a* Paleoclimate of the Kimmeridgian/Tithonian (Late Juassic) world: I Results using a general circulation model. *Palaeogeogr. Palaeoclim. Palaeoecol.* **93**, 113–150.

Moore, G.T., Sloan, L.C., Hayashida, D.N. & Umrigar, N.P. 1992*b* Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: II Sensitivity tests comparing three different paleotopographic settings. *Palaeogeogr. Palaeoclim. Palaeoecol.* **95**, 229–252.

Olsen, P.E. 1986 A 40-million-year lake record of Early Mesozoic orbital climatic forcing. *Science, Wash.* **234**, 842–848.

Parrish, J.T., Ziegler, A.M. & Scotese, C.R. 1982 Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. *Palaeogeogr. Palaeoclim. Palaeoecol.* **40**, 67–101.

Poole, F.G. 1964 Palaeowinds in the Western United States. In *Problems in palaeoclimatology* (ed. A. E. M. Nairn), pp. 394–405. London: Interscience.

Reid, R.E.H. 1973 Origin of the Mesozoic 'Boreal' realm. *Geol. Mag.* **110**, 67–69.

Schaeffer, B. 1971 Mesozoic fishes and climate. *Proc. N. Am. Paleont.* Conv. Sept. 1969, Chicago, Part D, 376–388.

Sengör, A.M.C., Altiner, D., Cin, A., Ustaömer, T. & Hsü, K.J. 1988 Origin and assembly of the Tethyside orogenic collage at the expense of Gondwanaland. In *Gondwana and Tethys* (ed. M. G. Audley-Charles & A. Hallam), pp. 119–181. Oxford University Press.

Shipboard Scientific Party 1990 Site 800. *Proc. O.D.P. Init. Repts* **129**, 33–89.

Tanner, W.F. 1965 Upper Jurassic paleogeography of the Four Corners region. *J. sedim. Petrol.* **35**, 564–574.

Vakhrameev, V.A. 1965 Jurassic and Early Cretaceous floras of Eurasia and the paleofloristic provinces of this period. *Tr. Geol. Inst. Moscow* **102**, 1–263. [In Russian.]

Vakhrameev, V.A. 1981 Pollen *Classopolis*, indicator of Jurassic and Cretaceous climates. *Palaeobotanist* **28**, 301–307.

Vakhrameev, V.A. 1991 *Jurassic and Cretaceous floras and climates of the Earth.* Cambridge University Press.

Valdes, P.J. & Sellwood, B.W. 1992 A palaeoclimate model for the Kimmeridgian. *Palaeogeog. Palaeoclim. Palaeoecol.* **95**, 47–72.

Weedon, G.P. 1985 Hemipelagic shelf sedimentation and climatic cycles of the basal Jurassic (Blue Lias) of south Britain. *Earth Planet. Sci. Lett.* **76**, 321–335.

Weedon, G.P. 1989 The detection and illustration of regular sedimentary cycles using Walsh power spectra and filtering, with examples from the Lias of Switzerland. *J. geol. Soc. Lond.* **146**, 133–144.

Weedon, G.P. & Jenkyns, H.C. 1990 Regular and irregular climatic cycles and the Belemnite Marls (Pliensbachian, Lower Jurassic, Wessex Basin). *J. geol. Soc. Lond.* **147**, 915–918.

Wesley, A. 1973 Jurassic plants. In *Atlas of palaeobiogeography* (ed. A. Hallam), pp. 329–338. Amsterdam: Elsevier.

Wignall, P.B. & Ruffell, A.H. 1990 The influence of a sudden climatic change on marine deposition in the Kimmeridgian of north west Europe. *J. geol. Soc. Lond.* **147**, 365–371.

Wignall, P.B. & Pickering, K.T. 1993 A palaeoecological and sedimentological analysis of fault-controlled deposition in the Kimmeridgian (Late Jurassic) of N.E. Scotland. *J. geol. Soc. Lond.* **150**, 323–340.

Wright, V.P. & Wilson, R.C.L. 1987 Parabolic carbonate facies and source rocks, Upper Jurassic, Portugal. *Soc. econ. Paleont. Mineral., midyear meeting, Abstract Vol.* Austin, Texas, 93.

Ziegler, A.M., Hulver, M.L., Lottes, A.L. & Schmactenberg, W.F. 1984 Uniformitarianism and palaeoclimates: inferences from the distribution of carbonate rocks. In *Fossils and climate* (ed. P. J. Brenchley), pp. 3–25. Chichester: Wiley.

Discussion

J. A. Crame (*British Antartic Survey, Cambridge, U.K.*). Professor Hallam has cast doubts on both the existence of bipolar molluscs, and their palaeoclimatic significance. The genus *Buchia*, however, is of particular note, occurring both in the northern and southern palaeo-hemispheres, and with an amphitropical distribution (generally not occurring in association with typical Tethyan benthos). The palaeoclimatic significance of such distributions should not be over-emphasized, however.

M. O. Manceñido (*La Plata Natural Sciences Museum, Argentina*). I wish to draw attention to the possible existence of a Southern Hemisphere Austral Realm, in terms of molluscan distributions (both bivalves and ammonites).

A. Hallam. The comments of Dr Crame and Dr Manceñido concerning the possible existence of bipolar elements in Jurassic bivalve faunas are intriguing and I would not wish to deny this possibility. I fail to see, however, that it has much bearing on the question of Jurassic climates, because no-one denies that the temperatures at the poles were cooler than in the tropics. The only interesting question in this respect is the degree of equability.

J. Francis (*Department of Earth Sciences, University of Leeds, U.K.*). The part of Mesozoic Antarctica which would have been located in the continental interior of Gondwana (and most likely experienced seasonally extreme temperatures, as the models suggest) is at present covered by thick ice. Palaeoclimatic evidence is, at present, unavailable. Early Cretaceous sediments on the eastern side of Antarctia are arc-related and in facies unsuitable for glendonite preservation.

A. Hallam. I thank Dr Francis for her explanation of the apparent absence of Mesozoic glendonites from Antarctica.

J. T. Parrish (*University of Arizona, U.S.A.*). Unpublished data suggest a bimodal distribution of dinosaur diversity by latitude (maximum diversity in northern and southern mid-latitudes with an equatorial minimum and peri-polar decline). If the pattern is not monographic it might reflect low-latitude dryness.

A. Hallam. I welcome the possibility of bimodal dinosaur distribution as being consistent with a likely paucity of food for large herbivores in low latitude regions, at least during the Jurassic.