

A review of Mesozoic climates

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SUMMARY: There is overwhelming evidence, based on the distribution of distinctive sediments and fossils and oxygen isotope data, that the climate of the Mesozoic world was appreciably more equable than that of today, with no polar ice caps, but precise quantitative data are not available. Except for an episode of late Cretaceous cooling there is no good documentation of any significant change in global temperature distributions through the era. The distribution of coals and evaporites, together with other criteria, indicates a pattern of humid and arid zones appreciably different in important respects from that of today. During the Triassic and Jurassic, western Pangaea in low to middle latitudes was largely arid, but in the early Cretaceous the lands on the margin of the newly opening Central Atlantic and western Tethys experienced a humid climate. By late Cretaceous times arid zones had become very restricted in extent. Because of insufficient suitable data, attempts at climatic modelling have had only modest success, and only to a limited extent can the major long-term changes in climate between the Permian and the present be explained in terms of changing geography. The most probable explanation of Mesozoic equability is an increased atmospheric CO₂ content. A number of enigmas remain, such as the existence of flourishing forests in polar palaeolatitudes. Whereas for the late Cenozoic short-term climatic changes can be related successfully to variations in the geometry and mechanics of the earth–sun system, there is a long way to go before comparable success can be claimed for the Mesozoic.

Imbrie (1982) identifies a succession of stages in the study of ancient climates. In the early, descriptive stage the primary task is to provide a narrative of past events. Initially, explanations are likely to be qualitative in nature and difficult to test, but eventually there may be sufficient data available and enough insight into causal mechanisms to allow the development of numerical models. These models can then be used to make retractions of system behaviour over some past interval of time for which the climatic forcing functions are known.

Unlike for the Quaternary, the study of Mesozoic climates has not got far beyond the descriptive phase, and although increasing attention is being paid to at least qualitative modelling, the results of this approach so far can hardly be described as highly successful and no comprehensive simulations have yet been achieved. Problems arise for several reasons (Barron 1983). There is uncertainty about the key forcing factors, the climatic response to modifying influences and the interpretation of palaeoclimatic data, most of which have only an indirect relationship to the forcing factors, whether involving variations in solar radiation, atmospheric composition or palaeogeography. In consequence, the best we can hope to achieve at present, for a world of very different palaeogeography and climate from today, is a general qualitative account of climatic zones and their changes in space and time, and more or less tentative interpretations of the principal controlling factors, pointing up problems which, as yet, defy satisfactory solution.

The broad patterns of climate can be determined in terms of latitudinal temperature distributions and distributions involving the amount of precipitation on the continents. This is attempted on the basis of lithological and palaeontological data plotted on best estimates of past palaeogeography, utilizing geometric, geological and palaeomagnetic information (Frakes 1979; Habicht 1979).

The best palaeontological evidence concerning temperature distributions is that from terrestrial plants, which are more climatically sensitive than most marine organisms. Thus, there are many Mesozoic ferns whose living relatives are confined to the tropics and are intolerant of frost (Barnard 1973). Utilizing the principles of taxonomic uniformitarianism (Dodd & Stanton 1981) means that the precision and reliability of our knowledge declines with increasing age. Therefore, only from the mid-Cretaceous onwards can one utilize the percentage in given floras of angiosperm tree leaves with entire margins, which has been shown to correlate very well with mean annual temperature at the present day (Wolfe 1978). Similarly, living crocodiles and alligators are cold-intolerant and therefore confined to the tropics and the distribution of Mesozoic forms accordingly provides useful climatic information, whereas there is some uncertainty about the climatic significance of dinosaur distributions, although it is extremely unlikely that these mainly large reptiles could have tolerated severe winter cold. In the marine realm the distribution of organic build-ups and various associated organisms,

including giant and thick-shelled molluscs, provides a reasonably good indicator of a tropical belt, but there is uncertainty about the interpretation of faunal provinces in terms of temperature distributions (Hallam 1984b).

As regards sedimentary rocks, the absence from the Mesozoic of well-authenticated tillites and associated striated pavements—the best indicators of glaciation—has frequently been remarked upon. Taking into account present-day distributions, Frakes (1979) has utilized phosphorites as indicators of warm seas but, strictly speaking, their presence in abundance relates primarily to zones of upwelling. The distribution of limestones has sometimes been used in a similar way, and indeed limestones are sparse in high Mesozoic latitudes. Such a likely temperature effect apart, the prime factor controlling limestone abundance through the Mesozoic was variations in sediment runoff from the exposed continents, related to (a) the extent of epicontinental sea and (b) the extent of continental humid zones (Hallam 1984c). Thus, many low latitude zones have a low limestone abundance.

The claim has recently been made that glendonites are a criterion for cold conditions (Kemper & Schmitz 1981; Kemper 1983). Glendonites are pseudomorphs of calcite after thenardite (Na_2SO_4), with characteristically stellate crystal aggregates occurring only in mudrocks. Recent glendonites are apparently restricted to the Arctic Ocean and adjacent seas. On this basis cold polar climates comparable to the present day are claimed for various Mesozoic intervals such as the Pliensbachian, Valanginian and late Aptian–early Albian. This result, counter to a wide range of evidence from other fields, should be viewed with scepticism, at least until much more is known about the distribution and factors controlling the formation of glendonite. One would like to know, furthermore, how many of the stellate nodules from high latitude boreal Mesozoic shales can be proved to have originated from the evaporite mineral thenardite, and what their oxygen isotopic composition is. According to Shearman & Smith (in press) we should not dismiss the possibility that the temperatures of marine sediments may be lowered during diagenesis, for example by adiabatic cooling caused by expansion of gases on their release from hydrocarbon-rich sediments.

With regard to the distribution of marine invertebrates, a high diversity zone with organic build-ups is persistently recognizable through the Mesozoic and is identifiable with a warm-water tropical belt. The distribution of the Tethyan and Boreal provinces or realms in the Jurassic and early Cretaceous is not, however, unambiguously interpretable in terms of temperature (Hallam 1984b).

The use of oxygen isotopes of fossil shells as palaeotemperature indicators has been reviewed most recently by Savin (1982). The most reliable results come from Cretaceous foraminifera collected during

deep-sea drilling. Earlier results obtained from Jurassic and Cretaceous belemnites collected from onshore outcrops are subject to considerable error, principally the consequence of post-depositional isotope exchange with connate or meteoric water.

As has long been appreciated, coal and evaporite distributions, respectively, are by far the best criteria for continental humidity and aridity. Supporting criteria for humid regimes are, first, bauxites, which formed in warm, better-drained conditions than coals, and second, kaolinitic clay and chamositic ironstones, which occur commonly in shallow, nearshore marine environments (the kaolinite and iron are continental weathering products in warm, humid regimes). An abundance of ferns in plant-rich mudrocks is a further good criterion of regional humidity.

Supporting criteria for more arid regimes are calcretes and aeolian sandstones, but determination of dominant wind directions from cross bedding measurements in the latter is fraught with hazard, and results should be viewed with some scepticism. Determination of the presence or absence of kaolinite and 'chamosite' (strictly speaking, berthierine (Van Houten & Purucker 1984)) in marine sediments in conjunction with analysis of the distribution of the other sedimentary criteria allows for a more comprehensive monitoring of the humidity–aridity spectrum over the continents than plotting merely of the distribution of evaporites, coals, bauxites and aeolian sandstones, which are confined to non-marine deposits and hence developed discontinuously in most stratigraphic sequences (Hallam 1984c).

Many non-marine sequences do not fall neatly into a humid or arid category, as they contain both minor coals and/or plant beds including logs of wood, and minor evaporites. Abundant sandstones with distinctive sedimentary structures may signify the action of substantial quantities of running water, while calcrete nodules in the intervening mudrocks may signify a drier climate free of perennial fluvial influence. For such mixed facies it is most reasonable to postulate a climate of alternating wet and dry seasons. Depending on the amount of precipitation, the terrains in question range from forest to scrub, and it is very difficult in the present state of knowledge of the Mesozoic to do more than indicate a third, intermediate, category (alternate wet and dry seasons) between humid (more or less wet through the whole year) and arid (more or less dry through the whole year).

Temperature distributions

There is a strong consensus that the Mesozoic era was appreciably more equable than the Quaternary, with temperatures characteristic of the tropics extending into mid-latitudes and polar regions experiencing temperate conditions (e.g. Barnard 1973; Colbert 1964; Frakes 1979; Habicht 1979; Hallam 1975). Thus,

Triassic and Jurassic ferns and gymnosperms signifying subtropical to warm temperate conditions extend up to 60° palaeolatitude, with rich floras in Greenland and Antarctica (Barnard 1973; Wesley 1973). The wide latitudinal distribution of terrestrial tetrapods during these periods (Colbert 1964; Cox 1974) and of thermophilous marine invertebrates such as reef corals provide strong supporting evidence. Furthermore, there is the lack of significant diversity decline from the palaeoequatorial region to the palaeopoles (Hallam 1975).

A similar pattern is apparent for the Cretaceous. Rich fern, gymnosperm and angiosperm floras are known from Alaska, Greenland, Spitsbergen, Siberia and Antarctica, signifying warm temperate conditions in present-day polar latitudes (Smiley 1967; Krassilov 1981; Donn 1982; Jefferson 1982). The boundary between seasonal and non-seasonal floras, reflecting temperature, shifted some 15° poleward with respect to today (Vakhrameev 1975). Barron & Washington (1982) point out that most Cretaceous floras occupy former coastal settings and that climatic modelling

suggests that continental interiors in high latitudes should have experienced winter cold. They concede, however, that the flora from such an interior region, Mongolia, gives no indication of this, but rather is subtropical in character. The occurrence of ectothermic alligators and crocodiles at latitudes higher than 60°N indicates ambient temperatures of at least 20°C (Colbert 1964). At the present day the 20°C isotherm is displaced poleward of 40° only in continental interiors. The distribution of Cretaceous coral reefs suggests a poleward shift of the 21°C isotherm of between 5° and 15° latitude compared with the present (Barron 1983).

Oxygen isotope analysis of benthic foraminifera from deep Pacific cores indicate that low-latitude bottom water temperatures have decreased from >15°C in much of the Cretaceous to 10–12°C at the end of the period, with a subsequent decline to ~3°C at present. There has been a comparable change in low-latitude surface water temperatures, as determined from planktonic foraminifera. Both sets of data suggest a Cretaceous optimum in the Albian (Savin

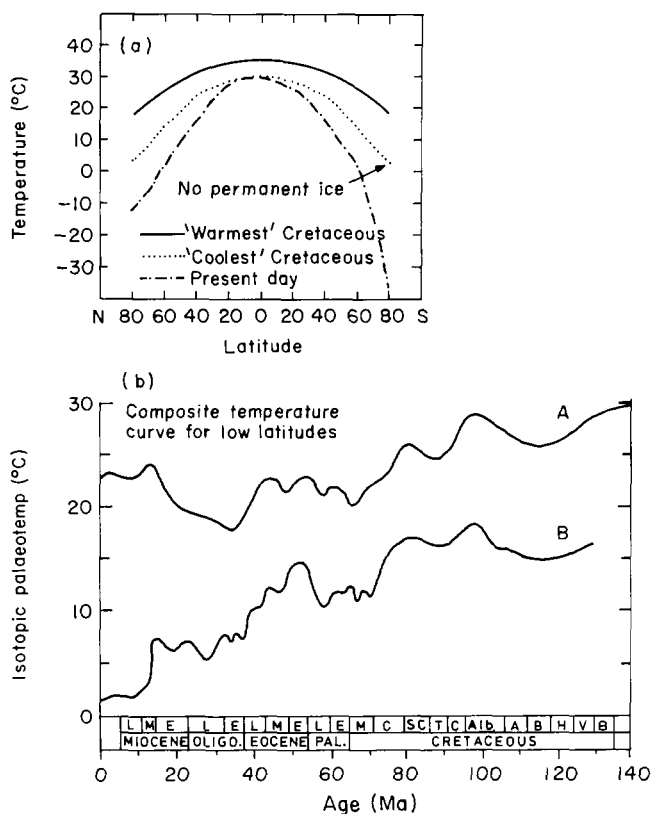


FIG. 1. (a) Estimates of latitudinal surface water temperature distributions in the mid-Cretaceous compared with the present. Simplified from Barron (1983). (b) Temperature curves from the early Cretaceous to the present, based on oxygen isotope data from (A) planktonic and (B) benthic foraminifera from Deep Sea Drilling Project cores. Simplified from Douglas & Woodruff (1981).

1977, 1982 and Fig. 1b). On the other hand, Krassilov (1975) suggests a Cretaceous air temperature optimum in the Campanian, followed by a sharp decline in the ...

... on the basis of analysis of Siberian and North American angiosperm floras (cf. Smiley (1967) for North America). Maximum and minimum estimates of the mid-Cretaceous mean annual surface water temperature distribution with latitude, using data based on isotopes and coral reef occurrences, are presented in Fig. 1a.

While there is good agreement, as just noted, that both air and sea-water temperatures underwent a marked fall towards the end of the Cretaceous, the picture is much less clear for the Mesozoic as a whole. Frakes (1979) proposed that global warming trends occurred during the course of both the Triassic and Jurassic periods, but I know of no changing rock or faunal distributions that provide convincing support for this claim. Jurassic and Cretaceous belemnite isotopic data, as summarized by Stevens & Clayton (1971), provide a confusing picture, with wide disparities in supposed palaeotemperature determinations between different groups of workers. As already observed, much of this confusion is probably due to

the unreliability of the technique as applied to belemnites, but it is worth recording that there is some measure of agreement with the more reliable foraminifera data in two important respects, an Albian optimum and a late Cretaceous fall.

The best evidence of a temporal change in temperature prior to the Albian comes from terrestrial plants. Vakhrameev (1964) distinguished two Jurassic–Cretaceous floral provinces in Eurasia, a low-latitude Indo-European and a high-latitude Siberian. Between the early Jurassic and mid-Cretaceous (Aptian–Albian) the boundary between the two provinces underwent a progressive 10° northward shift. This would appear to suggest a warming trend through this time, although, as Frakes (1979) points out, the results are affected by the way the continents are positioned according to palaeomagnetic data.

Krassilov (1973, 1975, 1981) has also concerned himself with the palaeofloral evidence for temperature change, taking into account the evidence both of diversity and latitudinal shift of 'isoflores', the boundaries of what he describes as ecotones rather than provinces. Three ecotones are distinguished: warm, warm-temperate and temperate, of which the second

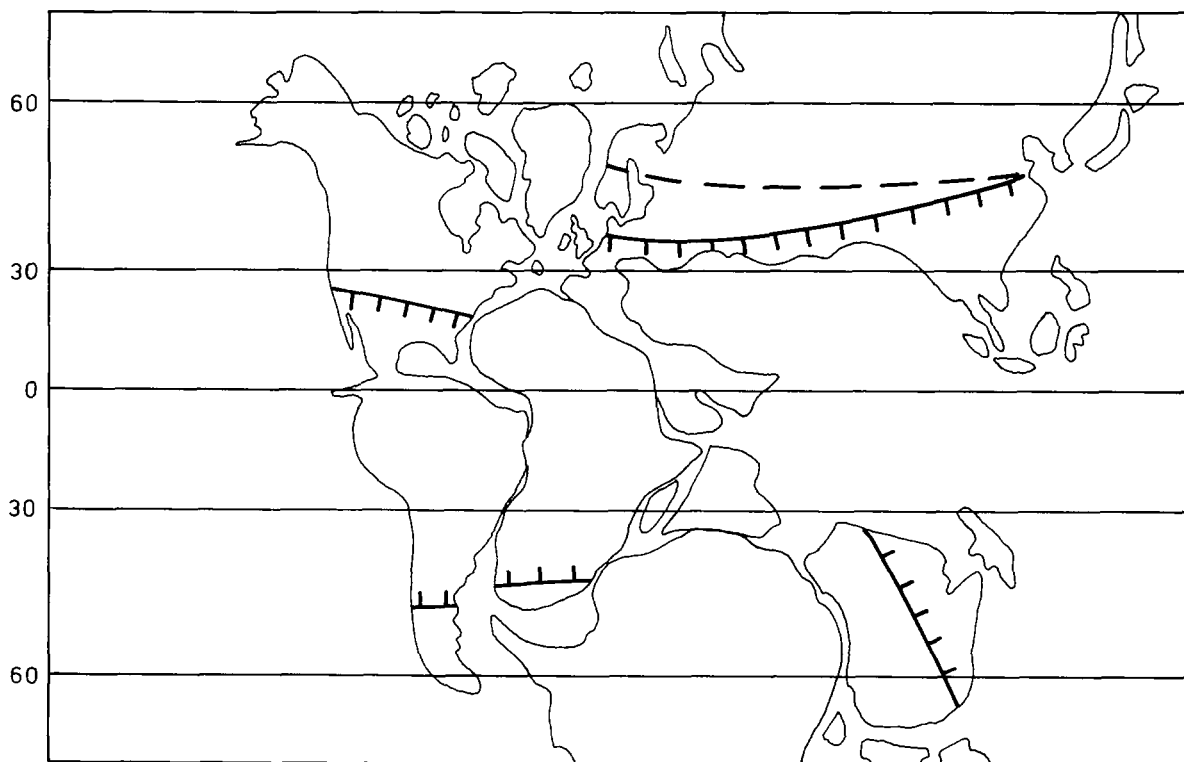


FIG. 2. Floral boundaries for early Jurassic, using reconstruction of Smith & Briden (1977). Broken line = boundary between Indo-European and Siberian floral provinces of Vakhrameev (1964). Continuous line, with bars directed towards inferred tropical zone = boundary between warm and temperate ecotones of Krassilov (1981).

forms only a narrow band between the warm and temperate ecotones. A poleward shift of the boundaries in the middle and late Jurassic is claimed, implying a global rise of mean annual temperature (Krassilov 1981). Krassilov (1973) also argues for a temperature decline in eastern Asia from the Berriasian to the Albian. This is based largely on the decline of cycadophytes during this time interval, yet Krassilov also pointed out that this decline clearly correlates with an increase in angiosperm abundance, which is surely an evolutionary phenomenon. Epshteyn (1978) used the presence of annual growth rings in tree logs as a criterion for determining the tropical-extratropical boundary in Eurasia, and also found evidence for a northward shift in the late as compared with the early and middle Jurassic. Parrish *et al.* (1982), however, argue that this criterion could reflect seasonal rainfall patterns rather than temperature.

Vakhrameev's (1964) and Krassilov's (1981) floral boundaries for three Mesozoic time intervals are plotted in Figs 2-4 on the continental reconstructions of Smith & Briden (1977). They lend some support for a poleward shift, and hence global temperature increase, from the early Jurassic to the Cretaceous, but not for any significant change within the Cretaceous. Note for the early Jurassic the disparity of Krassilov's

boundaries between North America and Eurasia, and the curious result for Australia, which leads one to query the reconstructions or the reliability of the palaeobotanical data base, or both. While the approach of the Russian palaeobotanists appears to offer the best prospect of learning more about Mesozoic continental temperature distributions, it is evident that much more work needs to be done on a global scale to obtain really trustworthy results.

It has been widely assumed that at such times as the Mesozoic, when the equator-to-pole surface temperature gradient was appreciably less than today, the atmospheric circulation was correspondingly sluggish. The model simulations of Barron & Washington (1982) throw this assumption into question. Similarly, their modelling exercises cast doubt on the assumption of a poleward shift of the subtropical high pressure zone during equable periods.

Precipitation on the continents

Much less attention has been paid to Mesozoic precipitation patterns than to temperature distributions. In an important pioneering article Robinson

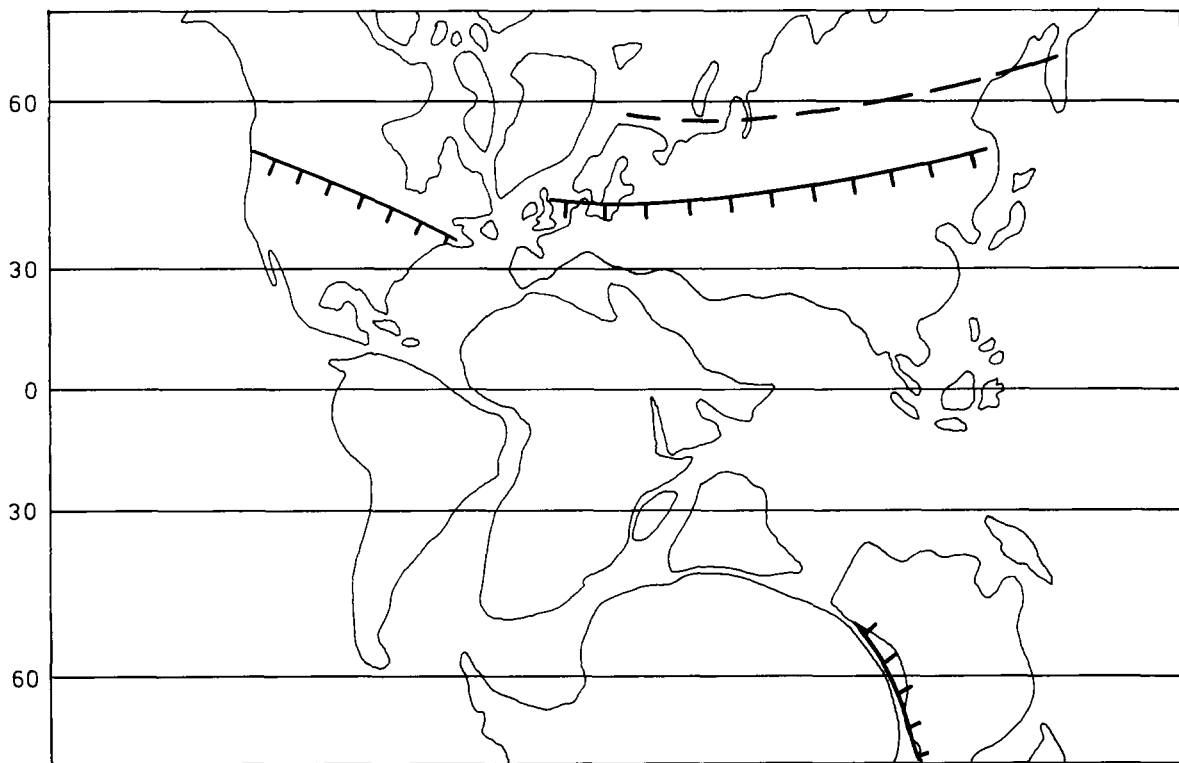


FIG. 3. Floral boundaries for early Cretaceous. For details see caption to Fig. 2.

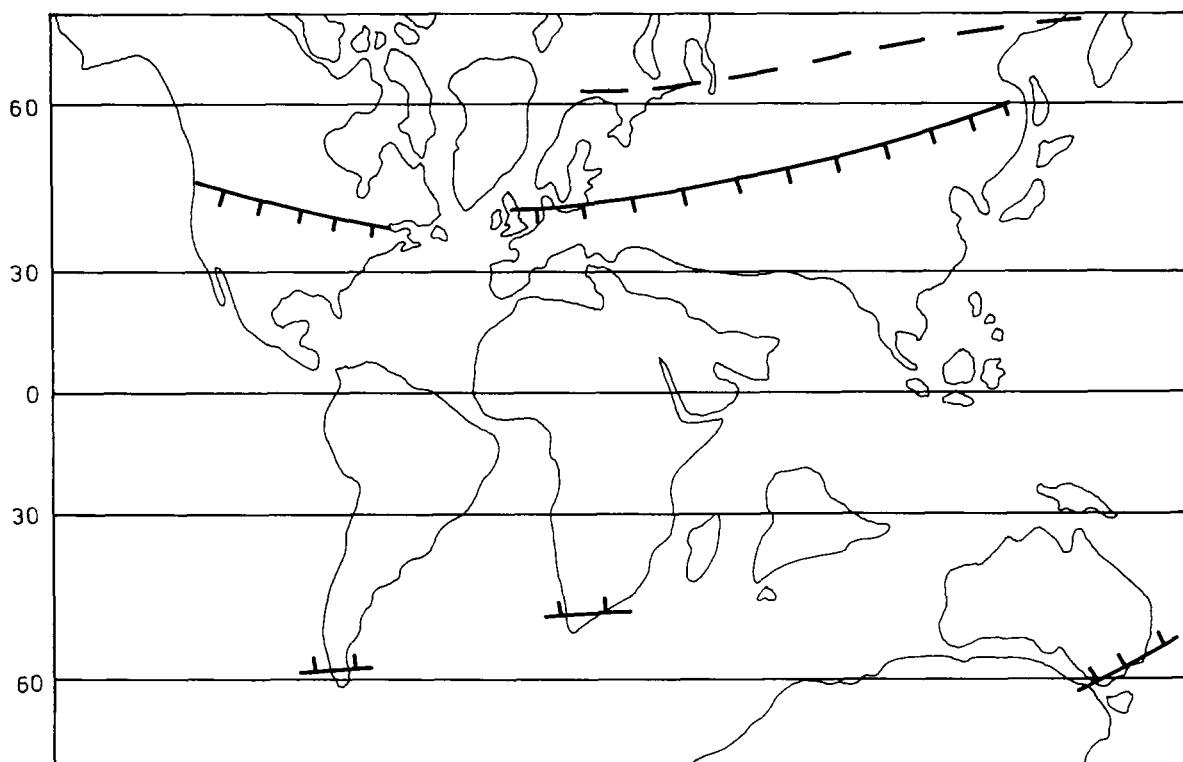


FIG. 4. Floral boundaries for late Cretaceous. For details see caption to Fig. 2.

(1973) pointed out that, because of very different palaeogeography, the pattern of continental precipitation in the Triassic bore only a limited correspondence to that of the present day. The most striking differences were the lack of an equatorial humid zone and the general dominance of a monsoonal effect, with zonal winds being of reduced importance, an interpretation supported by the modelling exercise of Parrish *et al.* (1982). This is primarily the consequence of the major continental areas being gathered together in a coherent Pangaea more or less symmetrically distributed about the equator, with northern and southern 'limbs' flanking a tropical Tethys expanding in width eastwards (Fig. 5). The shape of Pangaea ensured that the trade winds would have tended to follow the arms of the chevron. Therefore they would not have crossed extensive stretches of ocean, which is the primary reason for the absence of a low-latitude equatorial humid belt.

The only humid regions in Robinson's Triassic picture are in high latitudes and on or near westerly or northerly coasts, in the belt of westerlies or polar easterlies. A further probable reason for the aridity of western low latitude Pangaea is the increased importance of the monsoonal effect in the east, with an Australasian promontory to the south as well as an

Asian promontory to the north of Tethys. This would have had the effect of drawing moisture-laden winds away from western Pangaea (Parrish *et al.* 1982).

Robinson thus proposed three broad regions for the late Triassic and found that the distribution of evaporites and coals gave good support to her model: (1) dry at all seasons—low to mid-latitudes of western and central Pangaea; (2) alternate wet and dry seasons (monsoonal)—SE Asia, western India, eastern Arabia, etc; (3) Wet—mid- to high latitudes (eastern Australia, Antarctica, northern Siberia, north American Arctic).

Because Pangaea remained a coherent entity through most of the Jurassic (as with the Triassic, this disregards various displaced or 'suspect' terrains originally located in Panthalassa, which are not considered to affect the general picture), a broadly similar pattern is supported by the distribution of evaporites, coals and other climatic indicators (Hallam 1975). Gordon (1975) demonstrates that the Permian–Jurassic time interval, during which the major continents coalesced into a single supercontinent, is the time of maximum Phanerozoic deposition of evaporites. This is evidently a consequence of reduction of maritime influence over large sectors of continent.

Attempts to recognize changes through time in the

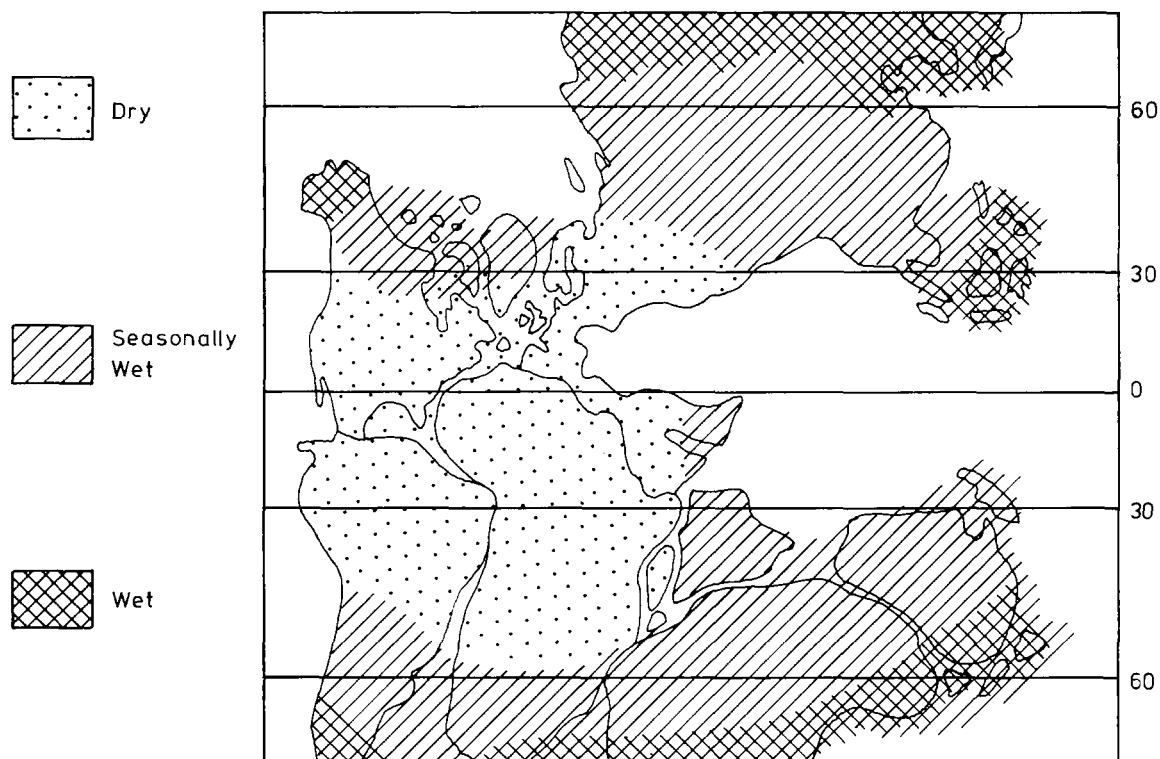


FIG. 5. Schematic presentation of continental humid and arid belts for early Triassic.

pattern of precipitation, in addition to changes in space, have been made for the Triassic by Tucker & Benton (1982) and for the Jurassic and Cretaceous by Hallam (1984c). Details of the distribution of climatically significant criteria are recorded in these papers and need not be repeated here. The maps of Figs 5–8 represent highly schematic, oversimplified attempts to represent Robinson's three major climatic zones for selected time intervals through the Mesozoic (see also Parrish *et al.*'s (1982) rainfall maps for the Induan, Pliensbachian, Volgian, Cenomanian and Maastrichtian). An important point to note about the Triassic and Jurassic maps is that extensive segments of eastern Asia were probably islands in the proto-Pacific or Panthalassa with a warm, humid climate like that of the Philippines today. There is too much uncertainty about their position, however, to make it worthwhile here to attempt any modification of the maps of Smith & Briden (1977).

Both in South Africa and southern South America the climate changed from humid to arid during the course of the Triassic; in the United States Western Interior semiarid conditions were replaced by more humid and then more arid conditions, while along the eastern margins of North America there was a change northeastwards from a seasonally wet to an arid

climate. Hay *et al.* (1982) have invoked an orographic effect in the form of higher relief to account for an inferred wetter climate on the western side of the proto-north Atlantic rift than on the eastern side (NW Africa), a pattern that continued into the early Liassic. Western Europe remained arid through most of the Triassic but shortly before the end of the period, in the late Norian (= Rhaetian), more humid conditions are recorded by the replacement of gypsiferous red beds by plant-rich and coal-bearing paralic sediments and by the introduction of kaolinite into the marine and non-marine mudrocks (Hallam 1984c). Further East in Eurasia, abundant coals signify widespread and persistent humidity.

The precipitation pattern of the early and middle Jurassic was broadly similar to that at the end of the Triassic, but towards the end of the period there was an extensive northward spread of the low-latitude arid zone into a large area of Europe and S Central Asia, marked by a replacement of coals and ironstones by evaporites, with a corresponding spread of limestones at the expense of siliciclastics. The transition to the Cretaceous marked a sudden return to more humid conditions (seasonally wet) over a large region extending from North America via Europe and North Africa to the Middle East, although S Central Asia

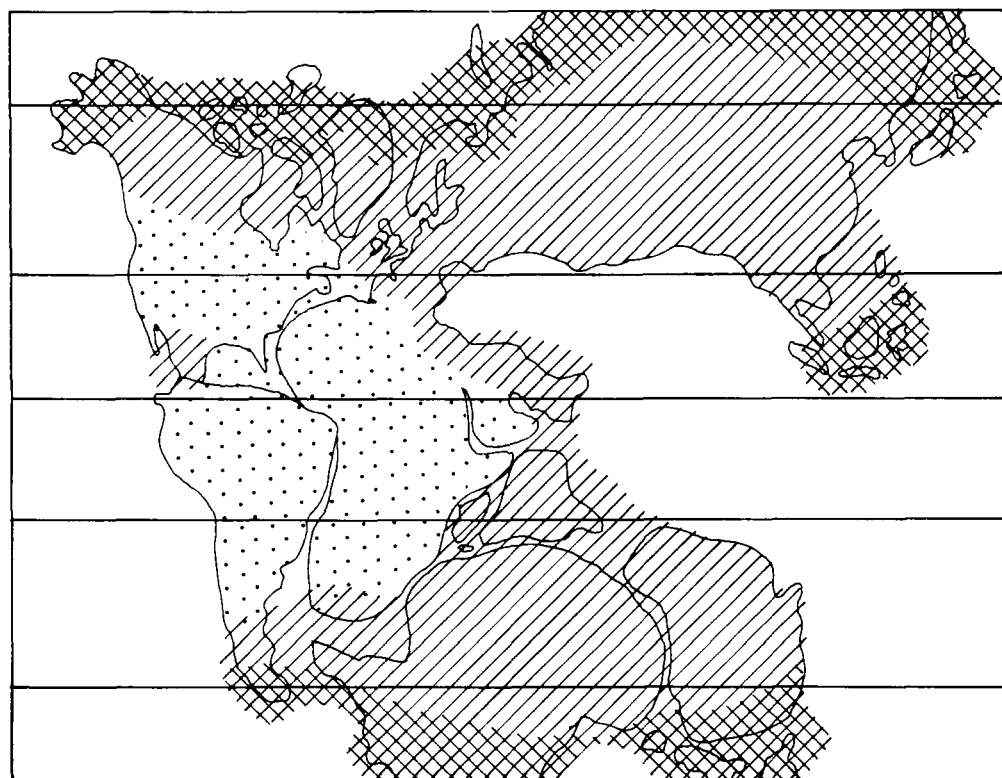


FIG. 6. Continental humid and arid belts for early Jurassic. For key to ornamentation see Fig. 5.

remained dry. This is most strikingly indicated by the sharp replacement of shallow marine and paralic limestones by coarse siliciclastics (Wealden facies). Extensive bauxites and coals indicate widespread humid conditions, and by late Cretaceous times the evaporite-producing arid zones had contracted to a Mesozoic minimum. There is also the first clear evidence of an equatorial humid zone in the form of coals and ironstones in Colombia and Nigeria. Climatic change in the low-latitude South Atlantic zone is especially striking, because thick salt deposits there testify to early Cretaceous aridity.

Independent confirmation that the humid zones of the late Cretaceous were appreciably more extensive than those of the late Jurassic comes from a study of strontium isotope ratios in marine carbonates, which are thought to reflect accurately the sea-water values. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio correlates with the amount of continental runoff, which is controlled by (a) the extent of land and (b) the precipitation on that land. When due allowance is made for the areal spread of epicontinental sea, the ratio in the late Jurassic is appreciably lower than in the late Cretaceous, signifying greater aridity (Hallam 1984a,b).

As the increase in continental humidity in the

Cretaceous appears closely bound up with increasing maritime influence as the continents split up and sea level rose, it appears that monsoonal effects would have been of paramount importance, with a corresponding disturbance of the zonal wind circulation. This result is independently arrived at by Lloyd (1982), who has attempted to model atmospheric circulation for the mid-Cretaceous, but Parrish *et al.* (1982) come to a different conclusion, inferring that a zonal model accounts better for evaporite and coal distributions in the Cenomanian and Maastrichtian.

In the equable world of the Mesozoic the most important climatic change through the year over most of the continents would have been between wet and dry seasons. This has an obvious bearing on the interpretation of growth rings in wood.

Discussion

The outstanding problem concerning Mesozoic climates is the reason for the well-established equability. Donn & Shaw's (1977) pioneering climatic model of northern hemisphere temperature distributions from the Triassic to the present made successful predictions only for comparatively recent times. According to

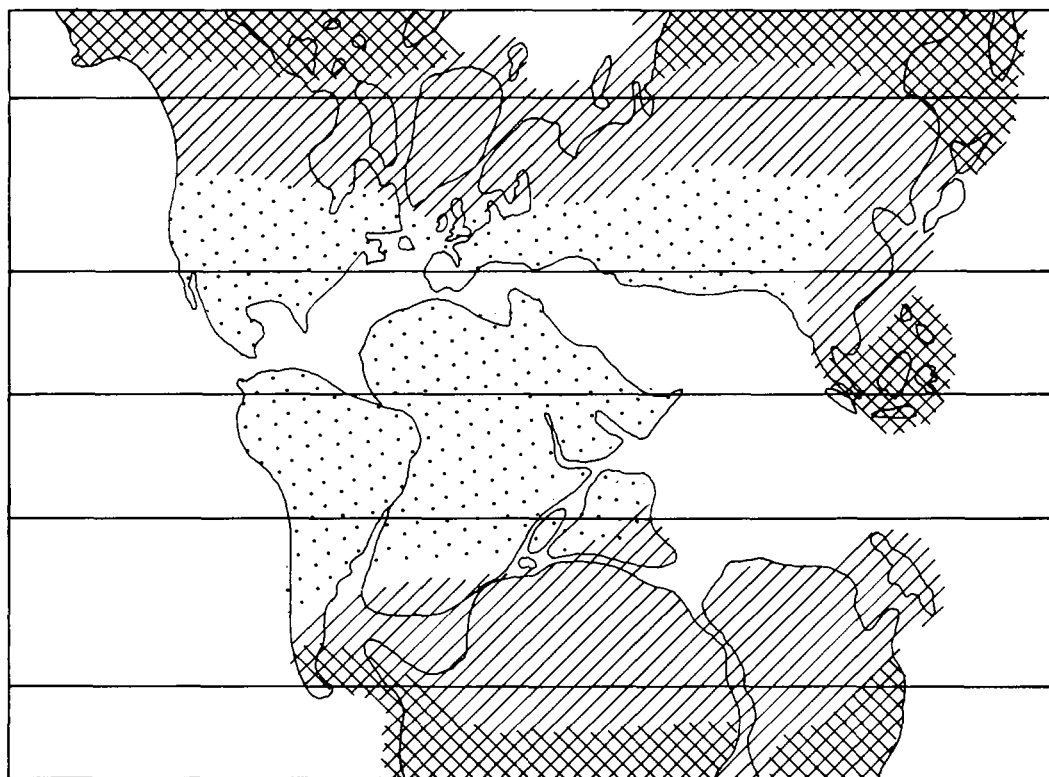


FIG. 7. Continental humid and arid belts for late Jurassic. For key to ornamentation see Fig. 5.

their model, and assuming a reasonable palaeogeographic reconstruction, the computed temperature range for the Arctic in Mesozoic times was 0–10°C, indicating an error of 15°C or more. Subsequent modelling attempts (Barron *et al.* 1981; Hunt 1984) have been no more successful and strongly suggest that the problem is more to account for the absence rather than the presence of substantial polar ice during geological history.

The possible explanations involve variations in the solar constant, palaeogeography and the CO₂ content of the atmosphere. Not only is there no independent evidence of an appropriately long-term variation in solar radiation, but any significant Mesozoic increase should have resulted in higher tropical temperatures than today, which is not borne out by the fossil flora and fauna.

As regards palaeogeography, a popular interpretation relates the long-term appearance and disappearance of polar ice caps to changing continental positions as a result of plate tectonics (Crowell & Frakes 1970; Frakes 1979; Crowell 1982). If continents are located in polar or sub-polar sites, the uplands accrete snow and ice, which reinforces the polar cooling tendency because of the increased albedo. Furthermore, a more

or less landlocked polar ocean such as the present-day Arctic will inhibit the meridional circulation of ocean waters, thereby restricting heat transfer from low to high latitudes. Whereas the palaeogeographic changes within the last 60 Ma, including the isolation of Antarctica and creation of a circum-Antarctic ocean current, seem to accord well with this scenario and provide a reasonably plausible account of the onset of the Cenozoic ice age, a less satisfactory account is provided of the late Permian disappearance of the Gondwana ice cap. This is because there was no significant change in continental position through the Permian and Triassic, although according to the maps of Smith & Briden (1977) the South Pole moved slightly offshore of Antarctica in the late Permian. Another problem is that Hunt's (1984) atmospheric circulation model suggests that high-latitude land is *not* a necessary condition for the initiation of ice ages. Sea ice should form regardless of the presence of land, although either extensive land or shallow sea is required for ice sheets to grow substantially.

As an alternative, Barron *et al.* (1980) argue that the increase in land area in the tropics and subtropics over the last 100 Ma, related to fall of sea level, is the most significant cause of the global cooling trend, pointing

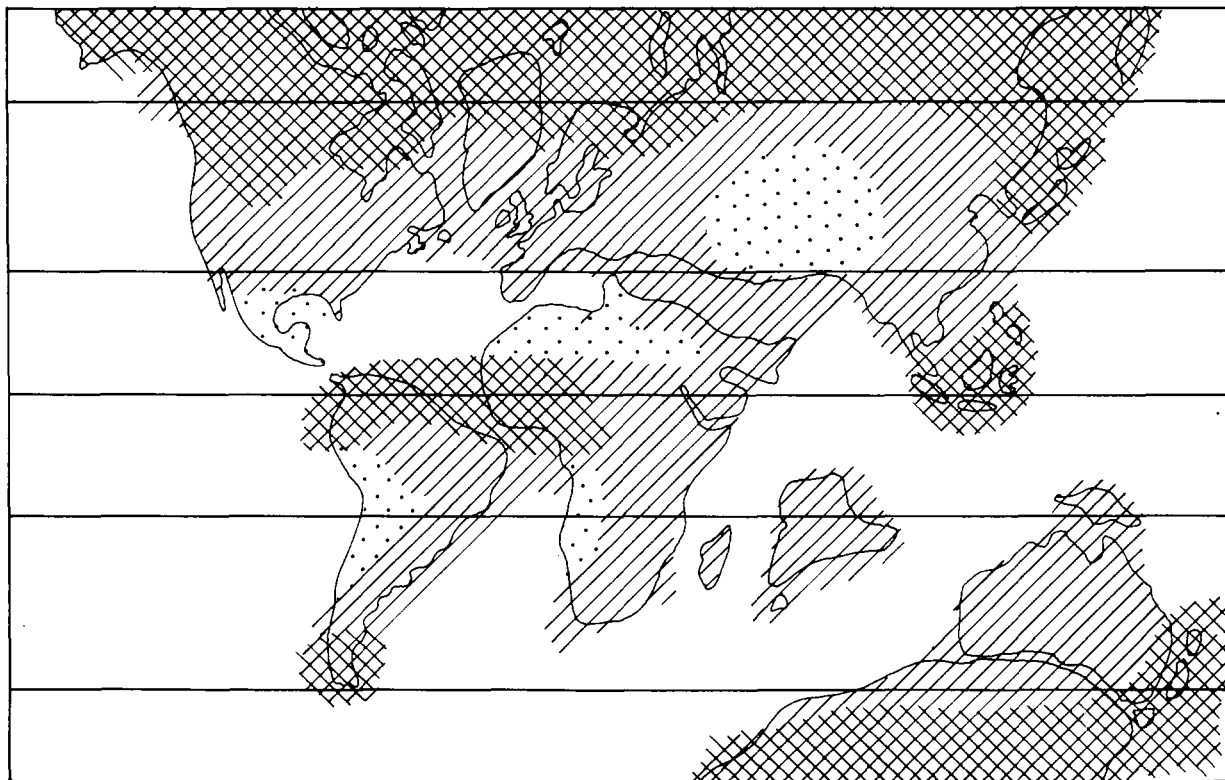


FIG. 8. Continental humid and arid belts for late Cretaceous. For key to ornamentation see Fig. 5.

out that high albedo contrasts at low latitudes may be very significant in terms of modifying the global heat budget. This contrast is a function of the presence of deserts, and an association is claimed between continentality associated with deserts and often with glaciations.

This explanation is no more successful, however, than that involving changing continental positions in accounting for the disappearance of the Gondwana ice sheet, because at the end of both the Permian and the Triassic the extent of epicontinental sea in low as well as high latitudes was significantly more restricted than in the late Mesozoic (Hallam 1984a), while extensive low-latitude deserts existed from the late Permian into the Jurassic.

Atmospheric composition could have been affected, according to Brass *et al.* (1982), by the increased role of warm saline bottom water in the Mesozoic. This would have resulted from high evaporation rates in extensive low-latitude epicontinental seas. Because of their high density, brines so produced would end up in the deep ocean. This could have led to a decrease in bottom ventilation because of the reduced O_2 solubility in the source regions, resulting in widespread anoxia even without any change in circulation. The

decrease in solubility of CO_2 with increasing temperature suggests that the production of warm saline bottom water could have led to an increase in atmospheric CO_2 content. Manabe & Wetherald (1980) have suggested that increased poleward latent heat transfer of water vapour in the atmosphere may account in part for the equable Mesozoic climate, and this could have been caused by the increased CO_2 in the atmosphere.

The reason a higher CO_2 content causes temperature rise is bound up with what is popularly known as the greenhouse effect. CO_2 transmits incoming short-wave solar radiation but absorbs outgoing long-wave earth radiation and returns it to the ground. Hunt (1984) considers that an increased atmospheric CO_2 content is the most plausible way of accounting for the equable Mesozoic climate, and support for this interpretation is provided by Berner *et al.* (1983). They produced a computer model that considers the effects of CO_2 in the atmosphere, Ca, Mg and HCO_3 in the oceans, and various weathering, precipitation and metamorphic reactions involving calcite, dolomite and Ca-Mg silicates. Their results suggest that the CO_2 content is highly sensitive to changes in sea-floor spreading rate and continental land area, and they

infer a level in the late Cretaceous several times higher than today. It would seem desirable to pursue this kind of study back through the Mesozoic, especially bearing in mind that the end-Triassic and end-Permian extents of continental land were comparable to the present day, without there apparently being any polar ice (Hallam 1984a). Unfortunately, there are no sea-floor spreading rate data prior to the late Jurassic.

Another problem that has not been satisfactorily resolved concerns photoperiodicity. Because of the short growing season in polar regions it is difficult to understand how forests could have flourished there. In particular, the detailed tree ring analysis of Jefferson (1982) of early Cretaceous conifer forests in Alexander Island, West Antarctica revealed features indicating rapid growth rate, high climatic sensitivity and seasonality, which are characteristic of trees in warm temperature regions with a long growing season. Furthermore, the close spacing of *in situ* tree stumps implies a shade problem if the angle of incidence of the sun's rays was like that today. Wolfe (1978), faced with a similar problem concerning Eocene forests in Alaska, proposed that the obliquity of the earth's axis was significantly less than today, thereby giving a more uniform distribution of sunlight through the year in high latitudes. As pointed out, however, by Donn (1982), the very low angle of incidence of the sun's rays would yield permanent winter conditions in polar latitudes.

Donn's alternative explanation invokes a marked disparity between the geographic and magnetic poles, due perhaps to relative motion between the outer shell and interior of the earth. Thus, he proposes that if, for the early Jurassic, the North and South Poles are placed in the ocean E and W of Gondwana, then most land would fall into a tropical-temperate belt. Moreover, the occurrence of the poles in the freely circulating ocean would minimize the formation of cold water, and hence cold air, in high latitudes. This novel suggestion, which if true would throw rock magnetism palaeolatitude analysis into confusion, receives no support from study of Mesozoic tropical reef belts, whose position broadly corresponds with that of the present day (Hallam 1984b). Perhaps, however, the palaeobotanical data have been misinterpreted, and the photoperiod problem exaggerated. Axelrod (1983) thus argues that many plants are restricted in their distribution today by temperature rather than light, with numerous shrubs and trees ranging well N of the Arctic Circle.

Axelrod (1981) has also drawn attention to extensive volcanism as an agent contributing to climatic cooling, as a result of volcanic dust in the atmosphere reducing the incidence of sunlight on the earth's surface. He claims that tuffs and bentonites occur with increasing frequency at higher levels in the Upper Cretaceous. This could therefore relate to the end-Mesozoic climatic cooling episode well established

from both palaeobotanical and oxygen isotope studies. Whatever the merits of this particular proposal, varying incidence of volcanism hardly seems plausible as a *general* explanation of climatic change, and is very unlikely to have been the critical factor in the global cooling that has taken place since the Mesozoic, because there is no clear indication that the rate of volcanism has increased substantially within the last 60 Ma.

With regard to the distribution of arid and humid belts, the increased aridity of southern Gondwana and SW Laurasia in the later Triassic can be explained by the northward continental movement that brought South America and South Africa into low latitudes (Tucker & Benton 1982). The converse climatic change from the late Triassic to the early Jurassic in western Europe is likewise correlated with northward movement of Pangaea (Figs 3, 4) but may also reflect to some extent the spread of epicontinental sea. The progressive spread of humid belts at the expense of arid from the late Jurassic into the Cretaceous clearly relates to increasing maritime influence on the continents as they moved apart and sea level rose, causing over a third of the total continental area to be flooded late in the period. However, the northward spread in southern Eurasia of extensive aridity in the late Jurassic cannot yet be satisfactorily explained. The problem is rendered even more difficult using 'conventional' reconstructions such as those of Smith & Briden (1977) which indicate that a major Tethyan Ocean existed directly to the south (Hallam 1984c).

So far no mention has been made of the possible recognition of geologically short-term climatic cycles related to variations in the geometry and mechanics of the earth-sun system, as has been successfully achieved for the late Cenozoic (Hays *et al.* 1976). The cyclic variations in question are the precession of the equinoxes (period ~21,000 years), obliquity of the ecliptic (~40,000) and eccentricity of the earth's orbit (~100,000). Power spectrum analysis of the thickness of the components of Cretaceous limestone-marl sequences has led to the suggestion that these indeed record such periodicities, and are hence expressions of climatic cycles (Fischer 1982; Schwarzacher & Fischer 1982). However, the choice of facies for this type of analysis is unsatisfactory because of the possibility, if not probability, that such lithological cyclicity may be diagenetic rather than sedimentary in origin. The important point to recognize here is that it is not sufficient for this kind of climatic analysis that *some* limestone-marl cycles are sedimentary in origin and hence reflect environmental changes. If only a proportion of these are destroyed by diagenetic overprint in condensed sequences, or others generated in thicker sequences by a kind of rhythmic unmixing of CaCO₃ (cf. Eder 1982), the technique is fatally undermined.

A more promising facies for such analysis is that in which normal, bioturbated mudrocks alternate with

laminated organic-rich shales in decimetre- to metre-thick beds. On the reasonable assumption that the component kerogen-clay couplets of the organic-rich shales are annual, sedimentary cycles in the range of about 10,000–100,000 years have been estimated for a

number of Mesozoic sequences. Cyclic alternations in degree of bottom-water stagnation are clearly implied, which might be bound up ultimately with climatic cycles affecting the degree to which the ocean system is periodically stirred up (Hallam in press).

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