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CRETACEOUS CLIMATE: A COMPARISON OF ATMOSPHERIC SIMULATIONS WITH THE GEOLOGIC RECORD

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ABSTRACT

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Atmospheric simulations using realistic Cretaceous geography (100 million years ago) suggest that paleogeography is an important factor governing the nature of the circulation. The simulated Cretaceous atmospheric circulations are markedly different both from the present-day atmospheric circulation and from the classical hypotheses of a weaker circulation and poleward displacement of circulation features (e.g. the subtropical high). Therefore, they pose specific questions which can be tested against the geologic record. Aspects of the Cretaceous simulations are verified in comparisons with the geologic record. The simulations serve to guide areas of future paleoclimatic research and to formulate better the nature of the problem of warm, equable climates.

INTRODUCTION

There are three basic limitations to understanding the behavior of the atmosphere, ocean and cryosphere system over geologic time. First, paleoclimatic data are insufficient to characterize completely past climates. Second, all the external forcing factors which influence climate (e.g., solar variability, atmospheric composition) and which may be necessary to explain past climates are uncertain. Third, knowledge of the climate system, as represented by models, undoubtedly does not include all the physical processes necessary to understand past climates. Because of these limitations it is uncertain that the climate of any past geologic period can be completely reconstructed. However, model experiments can be designed in order to formulate hypotheses which can be tested by comparison with the geologic record. In this manner we can pose sets of questions and seek answers through additional examination of the geologic record and through additional model experiments.

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Barron and Washington (1982) performed three-dimensional atmospheric simulations with a version of the National Center for Atmospheric Research (NCAR) General Circulation Model (GCM) using mid-Cretaceous geography from Barron et al. (1981). The purpose of these simulations was to examine quantitatively the relationships between paleogeography, surface temperature gradients and the nature of the atmospheric circulation by performing model sensitivity experiments. As discussed by Barron and Washington (1982), the classical hypothesis is that the reduced equator-to-pole surface temperature gradient is a dominant factor controlling the circulation, resulting in (1) a poleward displacement of large-scale circulation features, such as surface westerlies, and (2) a "sluggish" atmospheric circulation in the sense of weaker winds. Neither of these two features are observed in the Cretaceous simulations.

Comparisons of simulations with present-day geography and surface temperature characteristics with two cases with Cretaceous geography, but different surface temperature characteristics indicate that paleogeography is an important factor governing the distribution of large-scale circulation features. In addition, the simulations suggest that knowledge that the equator-to-pole surface temperature gradient was less in the past is insufficient to characterize the intensity of the circulation. In one Cretaceous simulation, polar ocean temperatures of 10°C were assumed, implying a large oceanic heat transport, in order to take into account some of the Cretaceous paleoclimatic data from high latitudes. This assumption did not result in substantial warming of continental interiors at high latitudes. Rather than a globally "uniform" equable climate, ocean—continent thermal contrasts resulted in substantial zonal variability.

As noted by Barron and Washington (1982), these results may be model-dependent and therefore must be considered preliminary. However, the simulations pose specific questions which can be tested against the geologic record. (1) Is the warming due to the change in geography and the implied oceanic heat transport sufficient to explain the paleoclimatic data? (2) Is there any evidence that the atmospheric or oceanic circulation was "sluggish"? (3) Is the predicted pattern of major circulation features consistent with the geologic record? (4) Is there any evidence for substantial climatic contrasts during warm, equable periods?

By examining these questions and attempting to verify the results of the model simulations, these sensitivity experiments can guide future paleoclimatic research. In many cases, this examination only serves to formulate more precisely the nature of the problem of warm, equable climates.

SUMMARY OF MODEL CHARACTERISTICS

The model used here is a three-dimensional time-dependent general circulation model of the atmosphere (Washington and Williamson, 1977) with a simple coupled, mixed layer ocean model with uniform depth. The atmospheric model is based on the hydrodynamic and thermodynamic laws applied to the atmosphere. The vertical extent of the model is 24 km with eight layers and the horizontal grid is a global spherical grid with 5° latitude—longitude resolution. The model has an explicit hydrologic cycle with predictive equations for soil moisture and snow cover. The surface temperature is computed from surface energy fluxes including the diurnal cycle. Cloudiness is diagnostically determined from the relative humidity. The ocean portion of the model is a simple mixed layer with uniform temperature at each grid point predicted by the surface heat balance. If the ocean temperature drops to −2°C, sea ice can form and grow according to the thermodynamic sea ice model of Semtner (1976).

The General Circulation Model (GCM), with some exceptions, favorably reproduces present-day observations (Washington et al., 1979). However, as yet, there are no models which incorporate all the physical processes which may be necessary to predict climatic change fully. The primary purpose of many such mathematical models of climate is to perform sensitivity experiments, by modifying a specified parameter or physical process, and then comparing a "control" with a model "experiment". In this manner insight into the physical system can be obtained. Largely because of constraints on computational time, the standard procedure in GCM climate studies is to perform simulations for a "perpetual" month (solar insolation) until the model approaches equilibrium. Gates (1979) includes several examples of sensitivity studies which serve as examples.

In order to examine the model sensitivity to a change in geography and surface temperature gradients, three simulations were completed (Barron and Washington, 1982) for "perpetual" March (Equinox) insolation: (1) a "control" simulation with present-day geography: (2) a Cretaceous experimental simulation (case 1) with specified mid-Cretaceous geography; and (3) the Cretaceous experiment repeated but with the restriction that the minimum sea surface temperature was constrained to be 10°C (case 2). All of the experiments utilize present-day orbital parameters and solar input.

By comparing a present-day control simulation with two Cretaceous cases with identical geography, but different surface temperature characteristics, the relationships between geography, surface temperature gradients and the nature of the atmospheric circulation can be examined. In addition, model experiments were performed for "perpetual" January and July for Cretaceous experimental case 2, in order to aid the interpretation of the results from the March simulations. In each case the interpretations are based on 30-day averages, with guidance on the statistical significance from Chervin and Schneider (1976a, b).

The Cretaceous geography is taken directly from the 100 million year map of Barron et al. (1981), with the exception that the model includes an estimate of the area of shallow seas on Antarctica in the absence of ice (Tarling, 1978). Continental elevations are assumed to be much more uniform than at present and no permanent ice is specified in the experimental cases.

SUMMARY OF MODEL RESULTS

There are a number of aspects of the atmospheric circulation in the Cretaceous simulations which are notably different from the present-day control simulation and from the classical hypotheses of warm, equable climates. Barron and Washington (1982) directly compared the model simulations with the classical hypotheses of the atmospheric circulation during warm, equable geologic time periods. Here, four characteristics will be examined: (1) the nature of the planetary warming due to changes in geography and the implied oceanic heat transport; (2) the characteristics of the circulation which can be related to the geography; (3) the "intensity" of the circulation; and (4) the equability of the climate.

The nature of the Cretaceous warming

The changes in land—sea configuration and the area of continent above sea level should alter the radiation balance of the earth–atmosphere system, because the albedo is a function of the surface type. Based on experiments with simple climate models (Thompson and Barron, 1981; Barron et al., 1981), the Cretaceous geography results in a planetary warming of approximately 2°C compared to the present day. Calculations based on Cretaceous paleoclimatic data indicate a globally averaged surface temperature which was 6—14°C warmer than at present. Barron et al. (1981) speculate that a 6°C warming could be achieved by incorporating additional climatic feedbacks in the simple model. Thus, the modification of geography in the GCM simulation should result in a significant increase in globally averaged surface temperature.

Cretaceous case 1 has a 3°C increase in globally averaged surface temperature compared to the present-day control simulation. Tropical surface temperatures are approximately 1° higher and the position of the 270°K (—3°C) isotherm has been displaced 5—15° poleward of its present-day position. Northern Hemisphere polar temperatures are approximately 5—10° higher than at present. Antarctic interior temperatures increased only a few degrees (Fig.1). The equator-to-pole surface temperature gradient has decreased slightly in both hemispheres.

The polar temperatures in Cretaceous case 1 are much closer to present-day values than to hypothesized Cretaceous temperatures, which are in the range of 273 to 290°K (0—17°C) (see Barron, 1982, for a review of the paleoclimatic data). This discrepancy between the model calculation and the paleoclimatic data can be ascribed to a number of possible factors. Some other external climatic forcing factors in addition to geography may be

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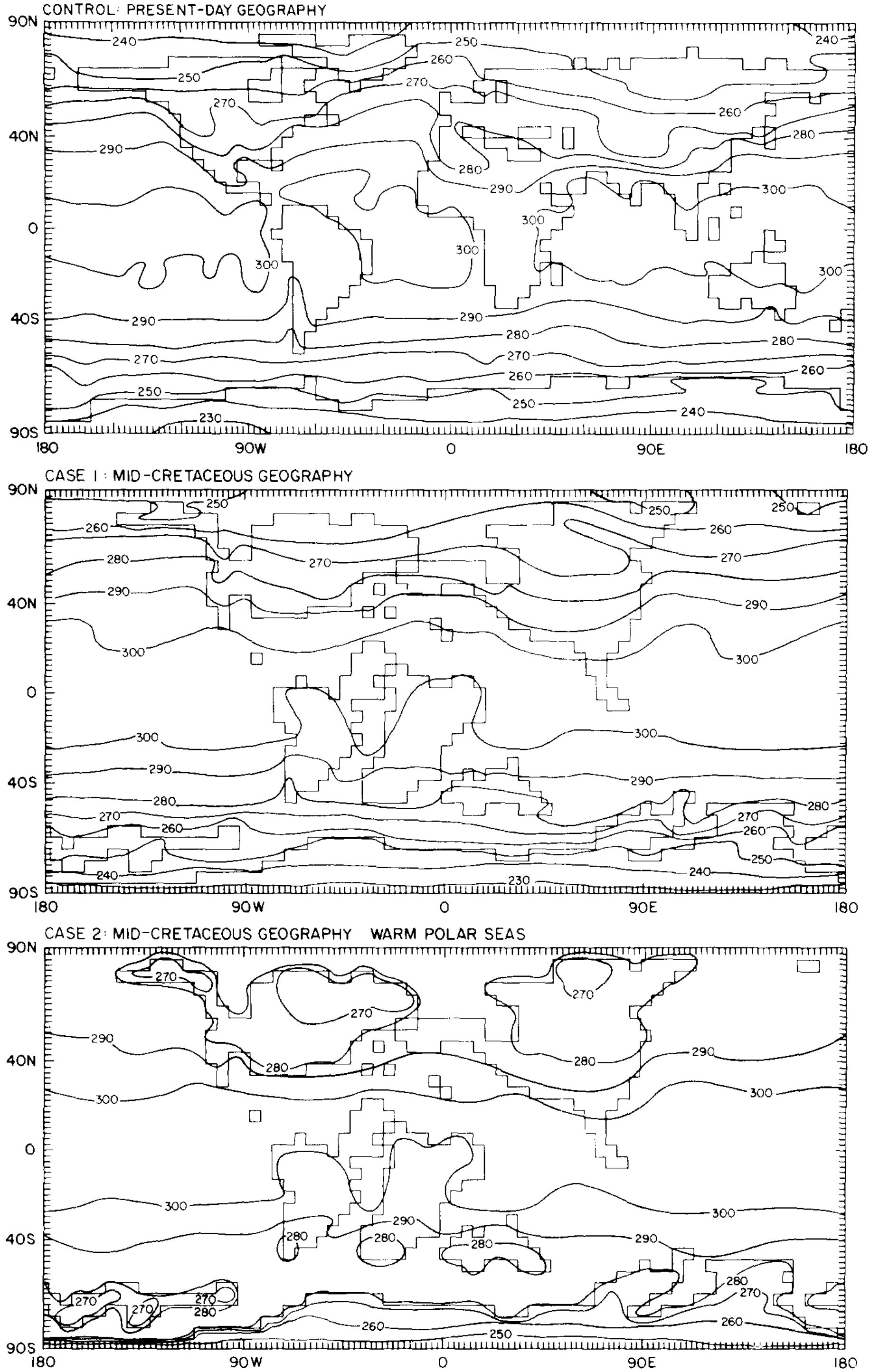
Fig.1. A comparison of the time mean (30-day average) temperature at the ground (mixed layer temperature at ocean grid points) averaged over the diurnal cycle for the March present-day control, Cretaceous case 1 and Cretaceous case 2. The temperatures are given in °K.

TEMPERATURE AT THE SURFACE



required, or some aspect of the model may be inadequate. The primary inadequacy of the GCM simulation is that it lacks a coupled ocean. Mixed layer temperatures are calculated based on a surface energy balance in the control and Cretaceous case 1 simulation. This does not allow for substantial changes in oceanic heat transport which may have resulted because of the characteristics of Cretaceous ocean basins. Numerous authors (e.g. Frakes, 1979) have suggested that oceanic heat transport is an important element in explaining the warmth of Cretaceous polar regions.

In Cretaceous case 2, the case 1 experiment was repeated with the constraint that the minimum allowed sea surface temperature was 283°K (10°C). This is qualitatively the same as prescribing a large oceanic heat transport. In Fig.1, which compares the Cretaceous simulations, it is evident that tropical and mid-latitude sea surface temperatures are substantially similar in Cretaceous case 1 and case 2. The most notable characteristic of the surface temperature distribution in Cretaceous case 2 is that the assumption of increased polar ocean temperatures did not result in substantial warming of the continental interiors at high latitudes. Interior Antarctica, North America and Asia have cold cores which are well below freezing. The strongest temperature gradients are associated with continental margins. This aspect of the surface temperature distribution is accentuated in the January and July Cretaceous case 2 simulations (Fig.2). Apparently, the atmosphere's ability to advect warm air from the surrounding oceanic regions into the continental interiors, at times of low solar radiation, is limited. This result implies that unless other factors are operating (e.g. increased solar input or CO_2) large continents at high latitudes are likely to be characterized by cold interiors, even if polar ocean temperatures are warm. By comparing the model results with the geologic record, it should be possible to verify whether the simulated Cretaceous climate is warm enough.

THE RELATIONSHIP BETWEEN GEOGRAPHY AND THE CIRCULATION

By comparing the present-day control simulation with two Cretaceous experimental cases with identical geography but different surface temperature characteristics, the relationships between geography, surface temperature gradients and the nature of the atmospheric circulation can be examined. Paleoclimatologists have hypothesized that the atmospheric circulation during periods of reduced temperature gradient differed from the present-day in that there was a poleward displacement of large-scale circulation features. This characteristic was not observed in either of the two Cretaceous experimental cases, although the Cretaceous experiments are markedly different from the present-day control. A number of the differences are related to the land—sea distribution.

Particularly in the Northern Hemisphere, the position of the subtropical high in the present-day control simulation is not parallel to latitude and appears to be a function of the continental positions (Fig.3). At polar

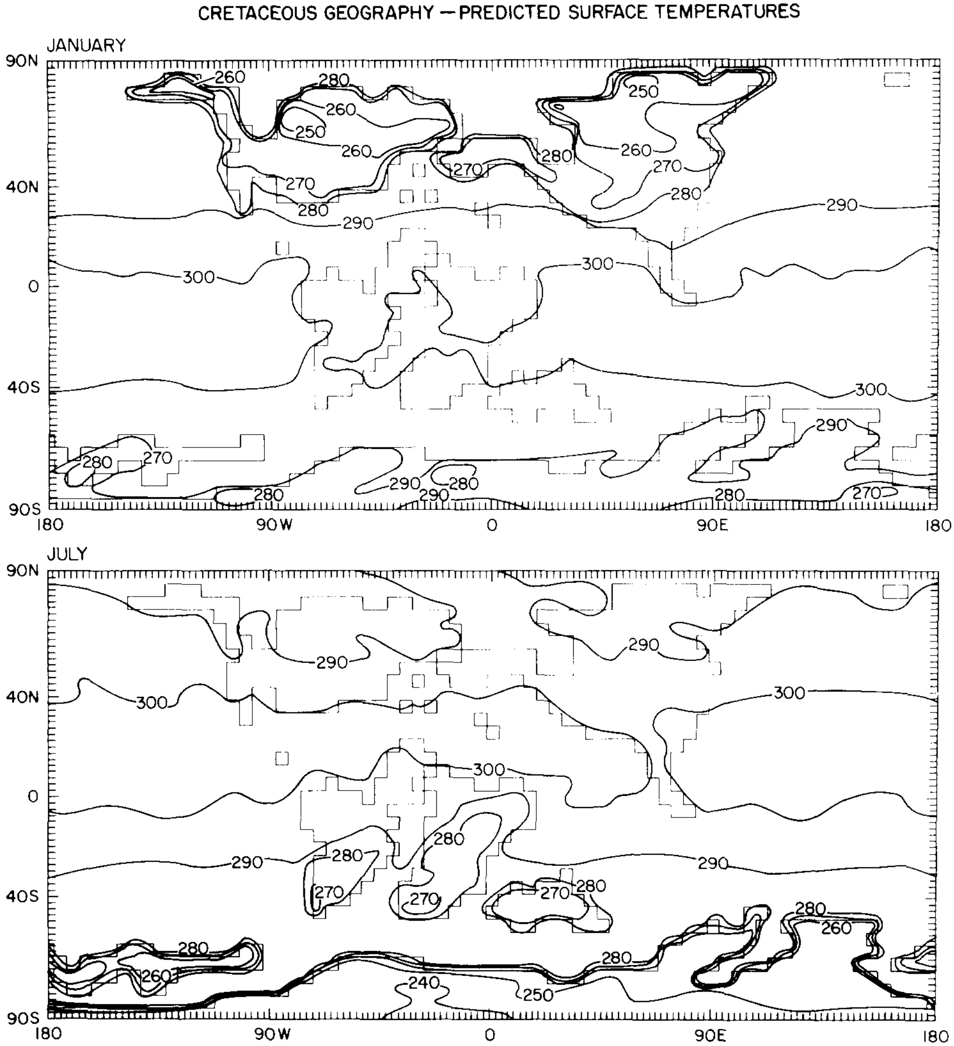
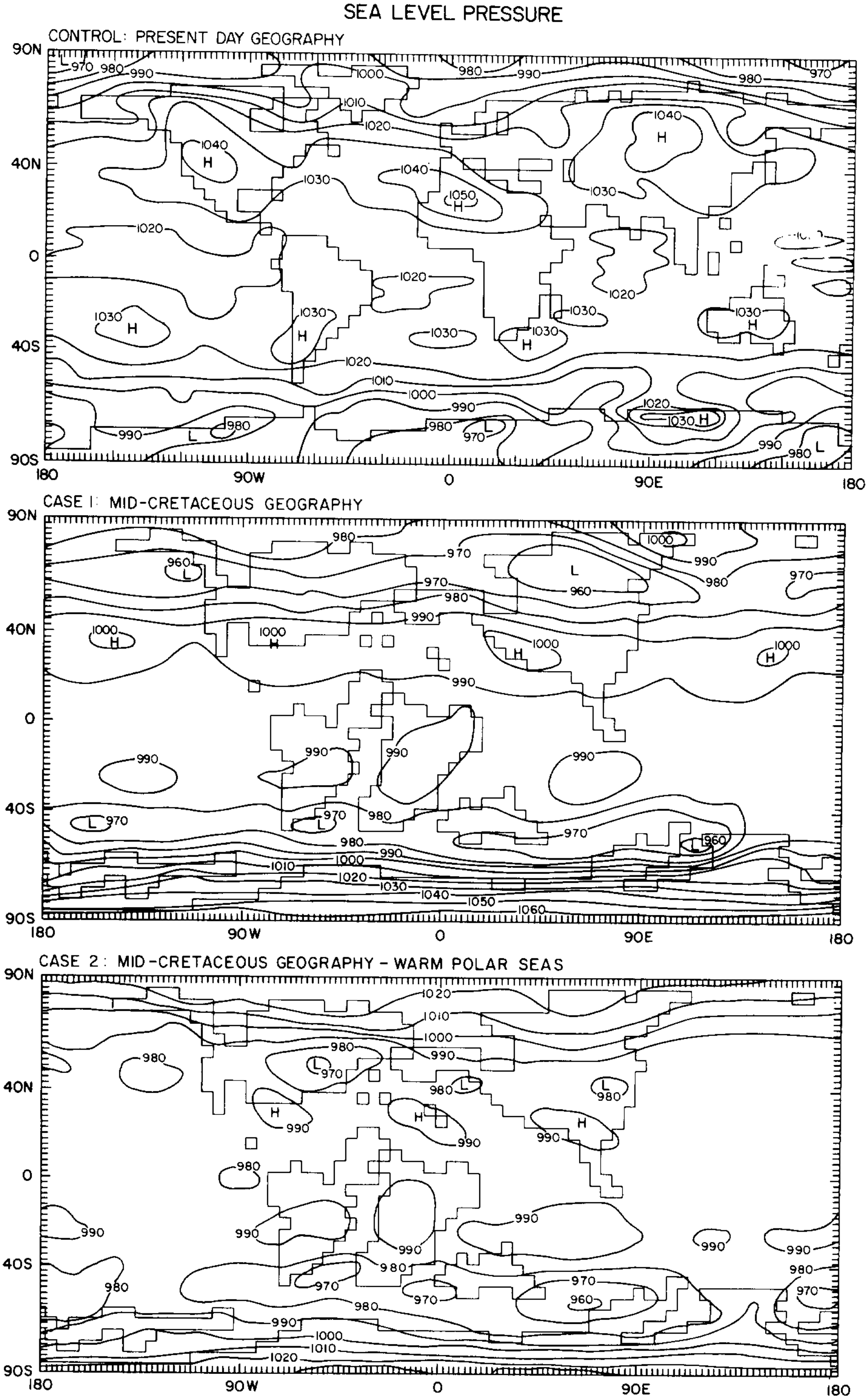


Fig.2. A comparison of the time mean (30-days average) mean temperature at the ground (mixed layer temperature at ocean grid points) averaged over the diurnal cycle for January and July solar insolation and mid-Cretaceous geography with specified warm polar seas. The temperatures are given in °K.

latitudes, in the control, neither a polar high or a polar low dominates the March simulation. In both the Cretaceous experimental cases the poles are characterized by high surface pressure and hence easterly winds. The subtropical high in the Northern Hemisphere of the Cretaceous cases has shifted slightly equatorward to a position associated with the Tethys Ocean. In the Southern Hemisphere the position of the subtropical high is approximately the same in all three simulations. The general pattern of equator-to-pole surface pressure characteristics is very similar in Cretaceous case 1 and 2, although the surface temperature gradient is very different.


SEA LEVEL PRESSURE
CONTROL: PRESENT DAY GEOGRAPHY
CASE 1: MID-CRETACEOUS GEOGRAPHY
CASE 2: MID-CRETACEOUS GEOGRAPHY - WARM POLAR SEAS
90N
40N
0
40S
90S
180
90W
0
90E
180

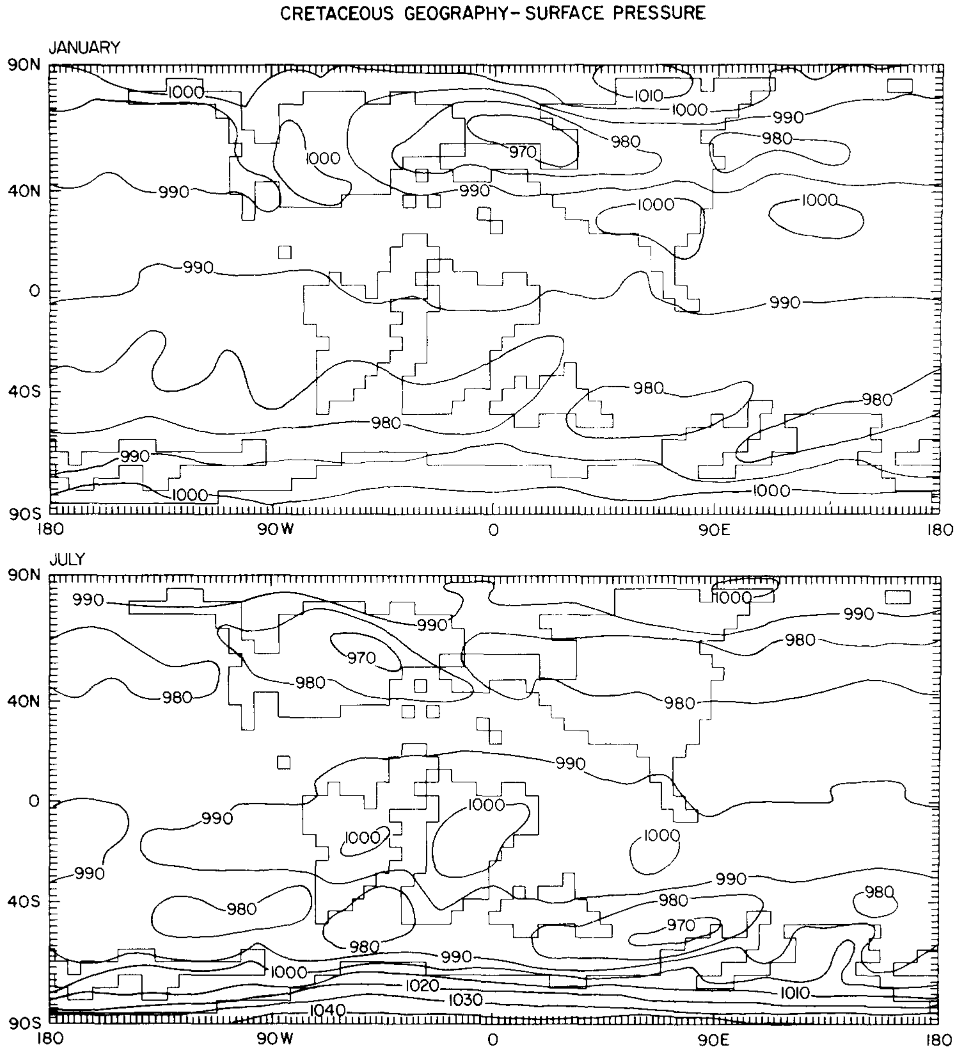


Fig.4. A comparison of the time mean (30-day average) sea level pressure for the January and July solar insolation simulations with mid-Cretaceous geography and warm polar seas. The values are given in mbars.

The difference between the present-day control simulation and the Cretaceous cases, and the overall similarities of the Cretaceous cases, implies that the surface pressure characteristics are related to the paleogeography. The January and July Cretaceous case 2 simulations provide additional evidence indicating that this result is not a function of the specified solar radiation. The polar high in these two simulations is best developed in the winter hemisphere, but is also present in the summer hemisphere (Fig. 4).

Fig.3. A comparison of the time mean (30-day average) sea level pressure for the March present-day control, Cretaceous case 1 and Cretaceous case 2. The values are given in mbar and highs and lows are indicated by H or L, respectively.

The major difference between Cretaceous case 1 and case 2 involves the zonality of the surface pressure characteristics in the mid-latitudes. Cretaceous case 2, with stronger land—sea thermal contrasts has a less zonal surface pressure distribution. For instance, the position of the low pressure belt is more equatorward than in case 1 and borders the zonal ocean in the subtropics. There is a distinct association between the positions of highs and lows in the mid-latitudes. In the Southern Hemisphere the position of the low pressure belt is very similar to case 1, however the lows are intensified over oceanic regions.

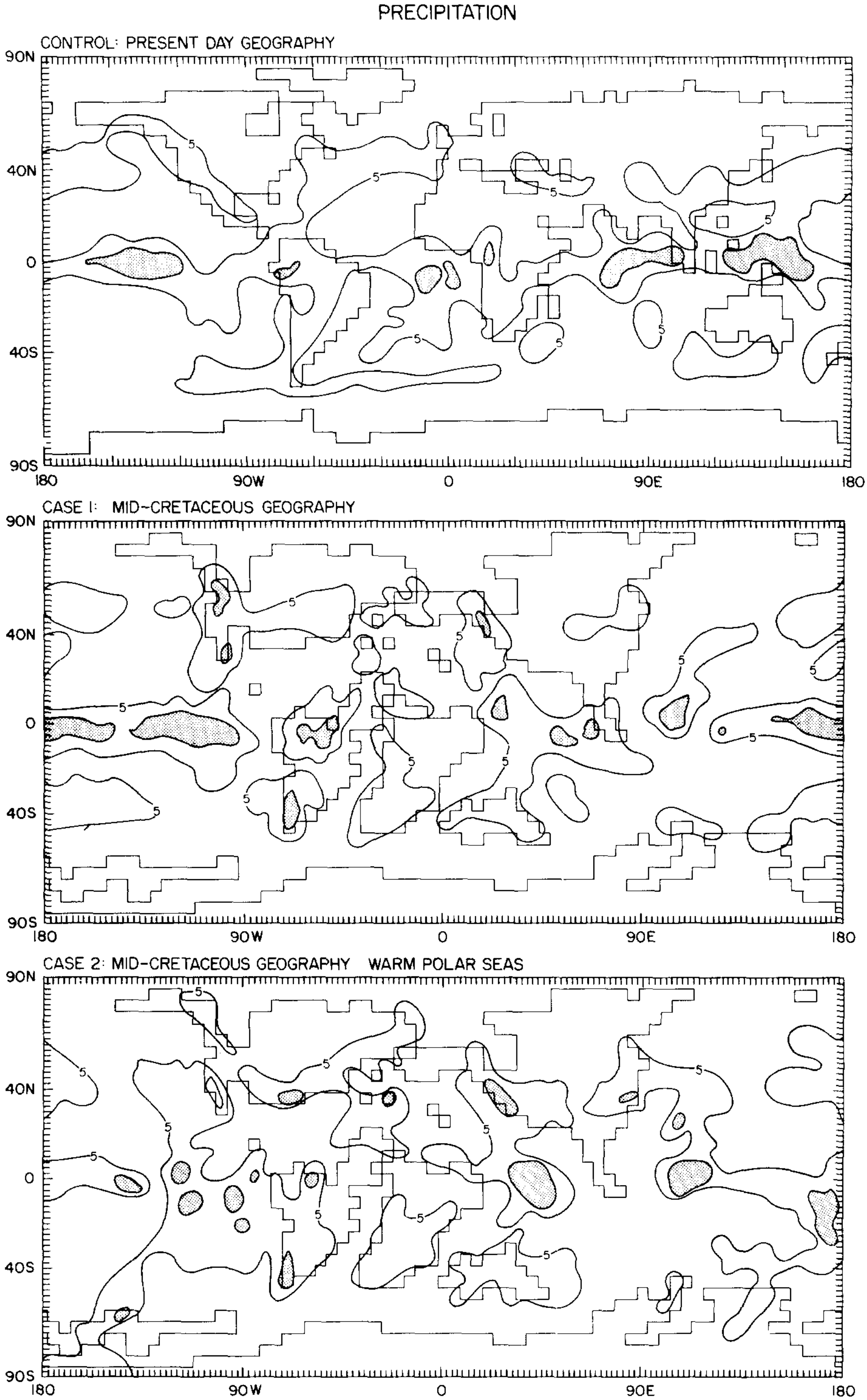
The relationships between paleogeography and the circulation is also illustrated by examining other variables such as precipitation (Figs.5 and 6). The control and Cretaceous simulations are all characterized by a well-developed equatorial rainbelt. In the present-day control simulation there is a secondary maximum in precipitation in the mid-latitudes which is primarily associated with oceanic regions or the western margins of the continents. The mid-latitude rainfall in the Cretaceous cases is greater than in the control, and is more strongly associated with continental regions. With the exception of a decrease in the zonality of the rainfall pattern in case 2, the regions of high rainfall in Cretaceous case 1 and 2 are very similar. In the January case 2 simulation the position of the equatorial high rainfall belt has shifted into the Southern Hemisphere by approximately 10° in latitude. Note however, that the regions of high rainfall in the Northern Hemisphere are very similar to the March Cretaceous case 2 simulation. In the July (Fig.6) Cretaceous case 2 simulation the position of the equatorial rainbelt has shifted into the Northern Hemisphere by 20° of latitude, to a position over the zonal ocean. In particular, the differences between the Southern Hemisphere and the Northern Hemisphere rainfall patterns illustrate the geographic effect of a zonal ocean in the subtropics.

The intensity of the circulation

Paleoclimatologists have hypothesized that during periods of reduced equator-to-pole surface temperature gradients, the intensity of the atmospheric circulation will decrease and therefore the intensity of the wind-driven surface ocean circulation will also decrease. In contrast, the zonally averaged surface wind speeds in the Cretaceous cases decreased at some latitudes but increased at other latitudes. Although the Cretaceous cases are both characterized by a reduced equator-to-pole surface temperature gradient, this decrease did not result in a "sluggish" circulation.

This result occurred for two reasons. First, equatorial temperatures increased slightly. The increased evaporation due to the non-linear relationship between temperature and saturation vapor pressure warmed the tropical

Fig.5. A comparison of the time mean (30-day average) rate of precipitation for the March present-day control, Cretaceous case 1 and Cretaceous case 2. The 0.5 cm/day contour is given and regions with greater than 1.5 cm/day precipitation are shaded.


PRECIPITATION
CONTROL: PRESENT DAY GEOGRAPHY
90N
40N
0
40S
90S
180
90W
0
90E
180
5
CASE 1: MID-CRETACEOUS GEOGRAPHY
90N
40N
0
40S
90S
180
90W
0
90E
180
5
CASE 2: MID-CRETACEOUS GEOGRAPHY WARM POLAR SEAS
90N
40N
0
40S
90S
180
90W
0
90E
180
5

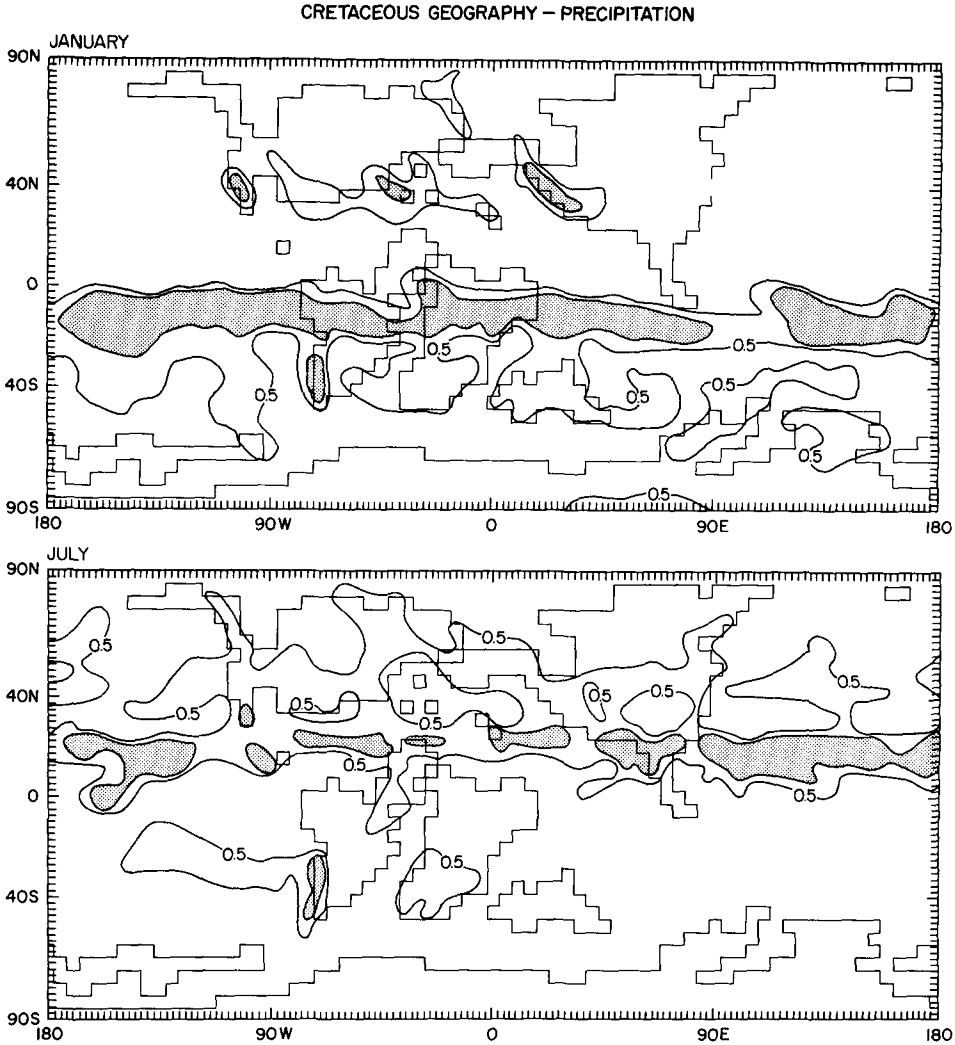


Fig.6. A comparison of the time mean (30-day average) rate of precipitation for the January and July solar radiation simulations with mid-Cretaceous geography and warm polar seas. The 0.5 cm/day contour is given and regions with greater than 1.5 cm/day precipitation are shaded.

atmosphere sufficiently to help maintain the vertically integrated meridional temperature gradient despite the decrease in equator-to-pole surface temperature gradient. Second, in part, the polar warming serves to eliminate the polar temperature inversion without affecting tropospheric temperatures substantially. Thus, the vertically integrated meridional temperature gradient is maintained.

The equatorial warming may be a specific model-dependent result, and therefore it cannot be stated with certainty that the Cretaceous atmospheric circulation was not "sluggish." However, the model suggests that knowledge the equator-to-pole surface temperature gradient was less is insufficient to characterize the intensity of the circulation.

The equability of the Cretaceous climate

Many authors have argued that the thermohaline circulation, the component driven by density differences, was much weaker during warm, equable "ice-free" periods (e.g. Berggren and Hollister, 1974). This idea appears to be a logical extension of the fact that high-latitude cooling and salt exclusion during freezing produces extremely dense cool waters at present. This concept has been extended to suggest that oceanwide stagnation is the key to the interpretation of oceanic sedimentation during warm geologic periods (e.g. Degens and Stoffers, 1976). The widespread uniformity of paleofloras and -faunas are indicative of a more globally uniform climate. The small vertical and horizontal temperature differences measured isotopically on Foraminifera (e.g. Savin, 1977) also imply warm, equable conditions. Several aspects of the Cretaceous simulations suggest that these concepts should not be extended as global interpretations.

First, even the assumption of warm, polar oceans in Cretaceous case 2 did not result in substantial warming of continental interiors at high latitudes (Figs.1 and 2). Although there is a small global range of sea surface temperatures compared to the present-day control simulation, strong thermal gradients are associated with continental margins.

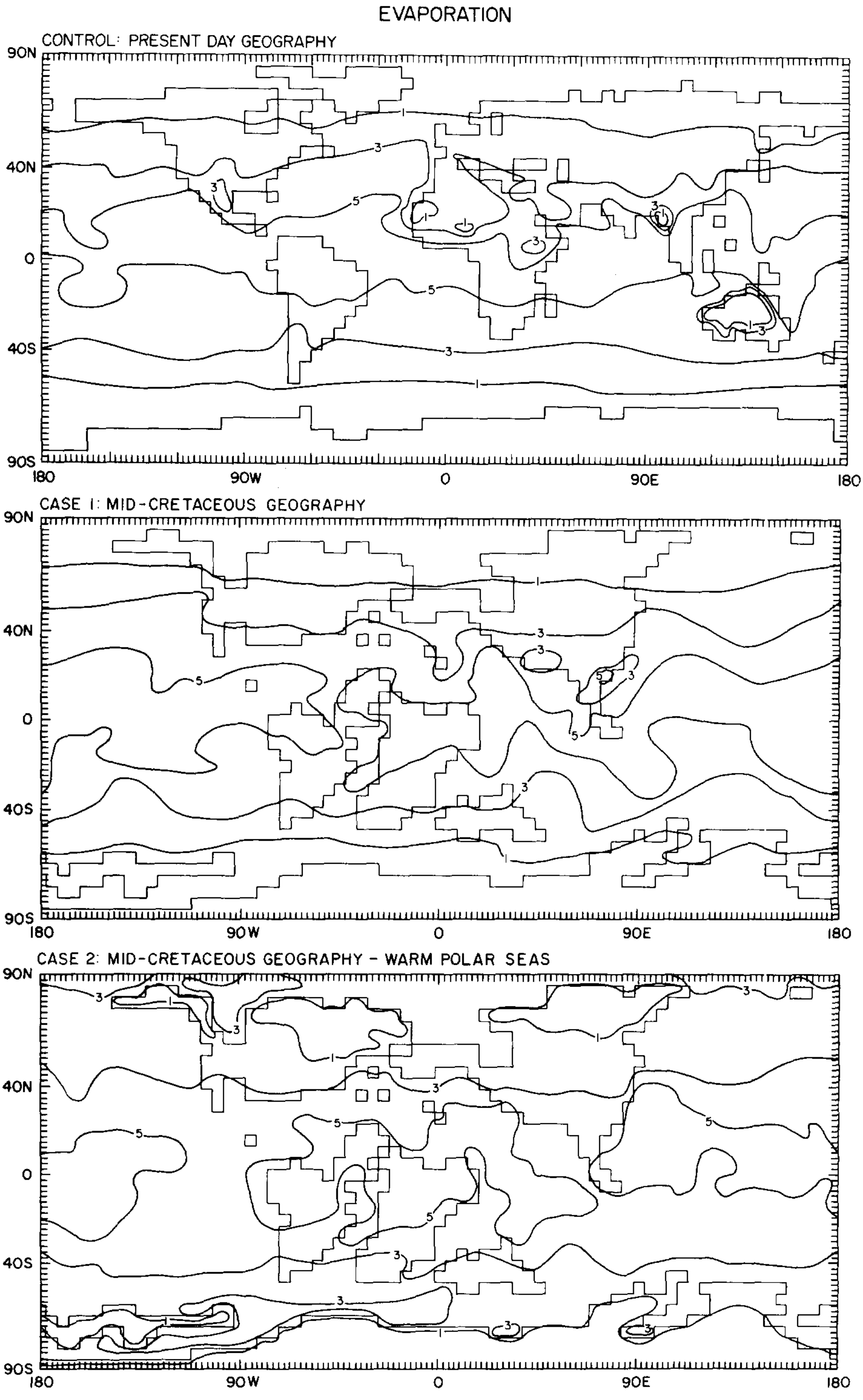
Second, the land—sea thermal contrasts are associated with some decrease in the zonality of the surface pressure pattern and the surface winds compared to Cretaceous case 1. Cretaceous case 2 is characterized by local divergences and convergences of winds in the mid-latitudes.

Third, Cretaceous case 2 is characterized by geographically controlled regions of high rainfall, and strong contrasts between continental margins and continental interiors. Combined with the predicted patterns of evaporation (Figs.7 and 8), which are largely a function of surface temperature, there are relatively large variations in the surface moisture balance. In particular, large variations in the surface moisture balance are associated with continental margins.

The purpose of the Cretaceous simulations is not to provide a comprehensive reconstruction of the mid-Cretaceous climate, but to formulate hypotheses which can be tested by comparison with the geologic record. A number of questions have been raised concerning previous hypotheses and interpretations of warm paleoclimates. These questions must be examined through a comparison with the geologic record.

VERIFICATION OF MODEL RESULTS

The Cretaceous simulations pose specific questions concerning the nature of the circulation during warm, equable periods, which can be tested against


EVAPORATION
CONTROL: PRESENT DAY GEOGRAPHY
CASE 1: MID-CRETACEOUS GEOGRAPHY
CASE 2: MID-CRETACEOUS GEOGRAPHY - WARM POLAR SEAS
90N
40N
0
40S
90S
180
90W
0
90E
180
1
3
5

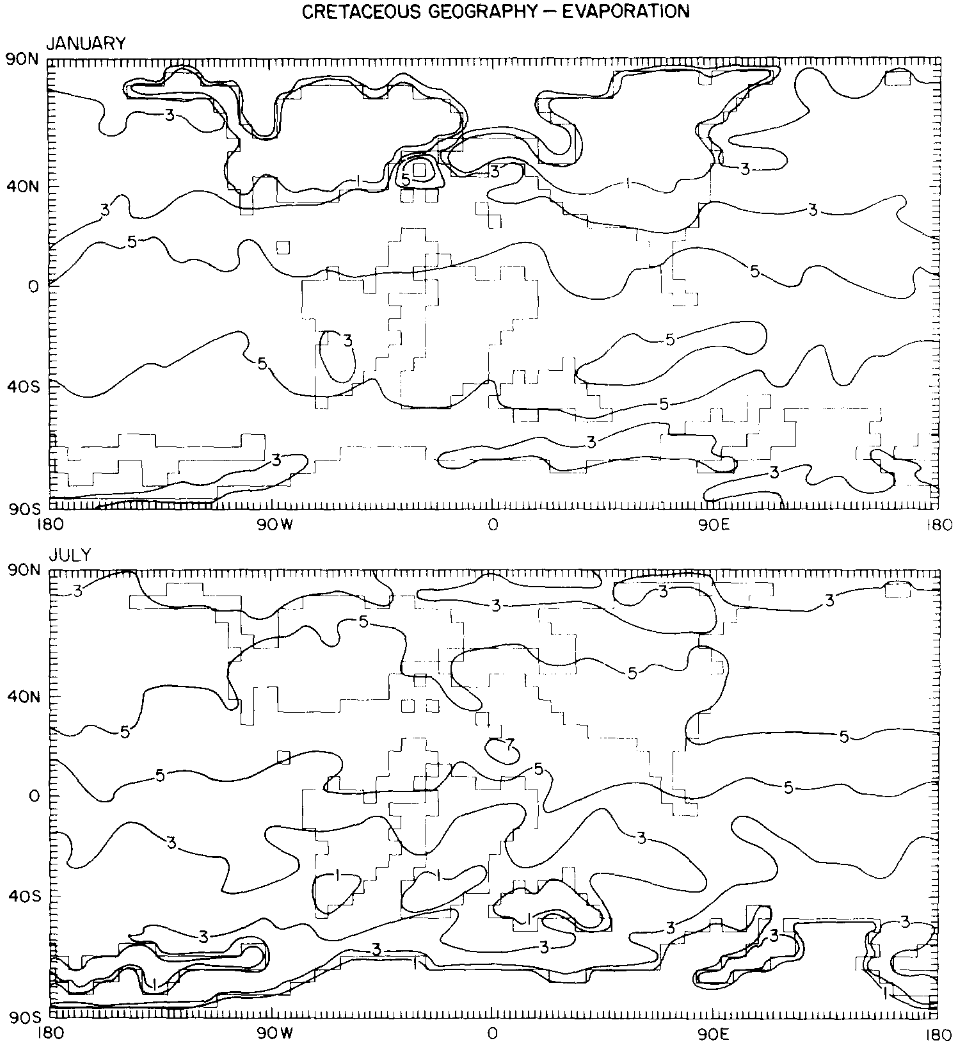


Fig.8. A comparison of the time mean (30-day average) rate of evaporation given in tenths of centimeters per day for the January and July insolation simulations with mid-Cretaceous geography and warm polar seas.

the geologic record. The assumption of higher polar temperatures also implies an oceanic mechanism to explain warm climates. The question is whether this mechanism is sufficient to explain the paleoclimatic data. Four specific questions derived from the model simulations will be considered: (1) Is the simulated Cretaceous climate warm enough to account for the paleoclimatic data? (2) Was the Cretaceous atmospheric and oceanic circulation "sluggish"? (3) Is the predicted pattern of major circulation features (westerlies, easter-

Fig.7. A comparison of the time mean (30-day average) rate of evaporation given in tenths of centimeters per day for the March present-day control, Cretaceous case 1 and Cretaceous case 2.

lies) consistent with the geologic record? (4) Were there substantial climatic contrasts during warm, equable periods? In this manner we can attempt to verify the results of model simulations in order to guide future paleoclimatic research.

Even in considering these broad questions, the geologic record has important limitations. First, the climate is not recorded directly (e.g., as pressure and temperature fields) but rather we must rely on a series of proxy indicators for which their relationship to climate may only be partially understood. Second, the geologic record integrates the climate over thousands of years and often Cretaceous data can be globally correlated only to the level of stages. Even in this regard data from the Albian—Cenomanian (108—92 m.y.) of interest here, is not global in extent. In many cases, the fact that the Albian was a climatic optimum (e.g., Savin, 1977) has been used in supplementing this data with data from other Cretaceous stages to give a more global picture. In some cases, this may be the only evidence presently available from a large region. Unfortunately, it is probably a mistake to ignore the possibility of regional and temporal variability, even during warm, equable "ice-free" periods.

Is the simulated Cretaceous climate warm enough?

The majority of estimates of Cretaceous polar ocean surface temperatures are in the range of 5 to 19°C (e.g., Fairbridge, 1964; Frakes, 1979), well above freezing. There is no evidence for any cold-water faunas. For instance, both evidence from gastropods (Sohl, 1969) and bivalves (Kauffman, 1973) indicate that northern provinces were warm and temperate. Similarly, studies of paleofloras around the Arctic (Smiley, 1967; Krassilov, 1973, 1981; Vakhrameev, 1975) and from Antarctica (Taylor, 1972) are characterized as warm-temperate or thermophilous, even in cases well above 60° in paleolatitude. For these reasons Cretaceous simulations were completed in which the minimum sea surface temperature was constrained to be 10°C. This case assumes that oceanic heat transport is a major component in explaining warm polar temperatures. A major question is whether, with this assumption, the Cretaceous simulation is warm enough to explain the paleoclimatic data. Because higher polar temperatures were specified, verification must be based on temperatures predicted for the continental regions and for the tropical and mid-latitude oceans.

There are numerous isotopic paleotemperature estimates from the mid-latitudes of the Albian—Cenomanian (108—92 m.y. ago). The majority of these measurements are on the calcareous hard parts (rostrum) of belemnites, for which there are several drawbacks (e.g., Stevens and Clayton, 1971). Both depth babitat and the season of shell formation may be difficult to reconstruct. In addition, because both fresh-water dilution and diagenetic alteration tend to result in more negative $\delta^{18}O$ values, a conservative approach is to utilize (Fig.9) only the *minimum* isotopic temperatures measured on

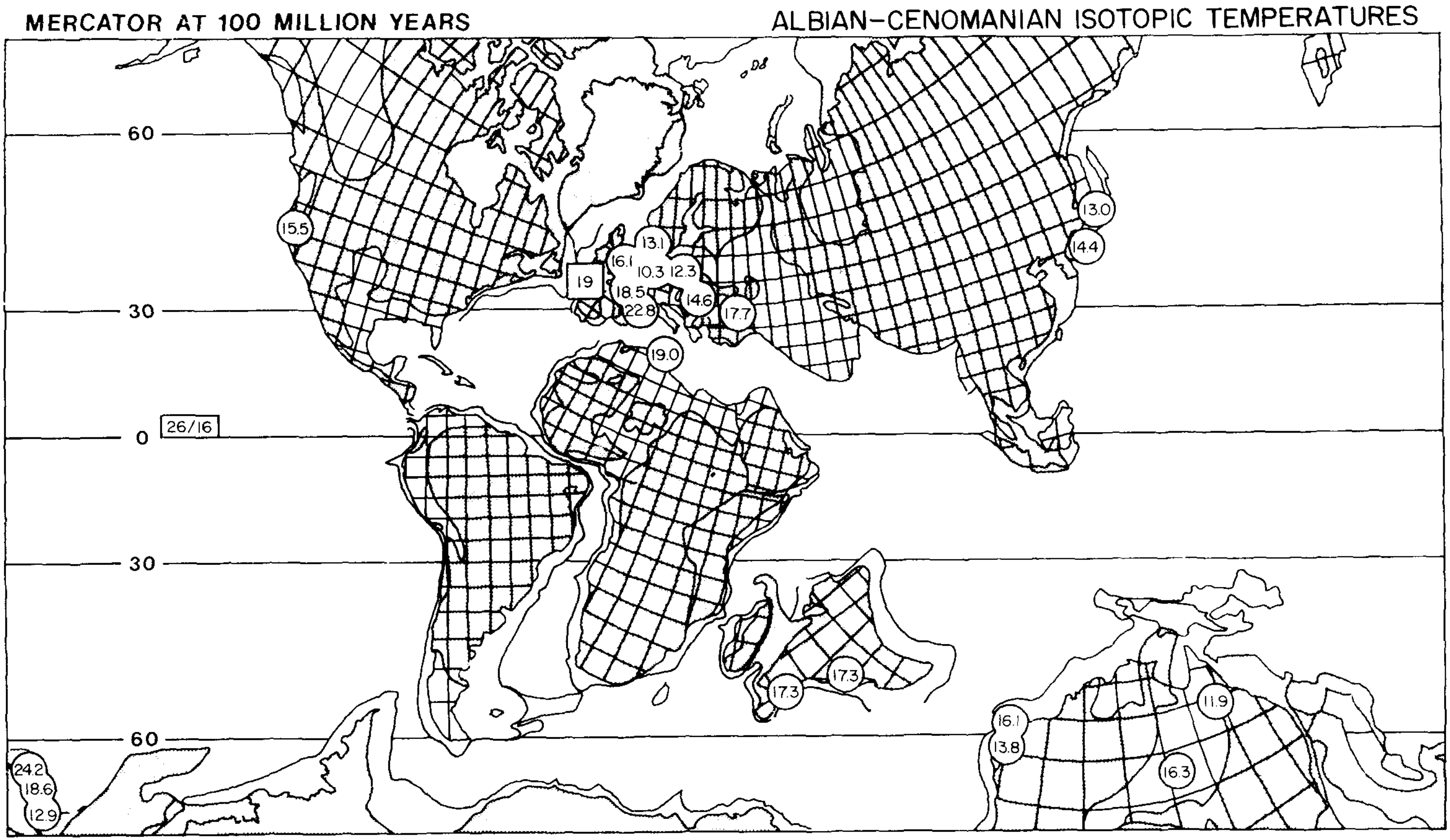


Fig.9. Albian—Cenomanian (108—92 m.y.) isotopic paleotemperatures (°C) from belemnites and planktonic foraminifers plotted on a mid-Cretaceous (100 m.y.) paleogeographic map. The area of land is shaded and the Mercator projection extends to 70° in paleolatitude.

Albian—Cenomanian belemnites by Lowenstam and Epstein (1954), Teis et al. (1957), Bowen (1961a,b), Bowen and Fontes (1963), Spaeth et al. (1971), and Stevens and Clayton (1971). Each temperature has been calculated using the paleotemperature equation of Craig (1965) with a correction of −1.00% for an ice-free earth. The *minimum* isotopic temperatures at various mid-latitude locations range from 10.3°C to 22.8°C. A single measurement from an Albian planktonic foraminifer from the continental margin off France gave a value of 19°C (Letolle, 1979). Douglas and Savin (1975) determined values of 25 to 27°C from planktonic Foraminifera from the Shatsky Rise which was probably within the Pacific tropics during the mid-Cretaceous (Lancelot and Larson, 1975).

In comparison, the minimum allowed model mixed layer temperature is 10°C. In the simulations this value is the mixed layer temperature in much of the mid-latitudes of the winter hemisphere. Model summer temperatures in the mid-latitude European region are between 20 and 27°C. Zonally averaged model temperatures in the tropical ocean seasonally range from 27 to 30°C. Given the fact that belemnites and foraminifers do not reflect surface temperatures, and that only minimum isotopic values have been utilized, the model predicted surface ocean temperatures are probably not distinguishable from the isotopic data.

Even with the assumption of a minimum sea surface temperature of 10°C, the mid-latitude continental regions, such as Asia, and high-latitude regions, such as Antarctica, become cold in winter. In Fig.2, the January 0°C isotherm essentially outlines the Asian continent, extending almost to 30° in paleo-latitude. The assumption of warm polar oceans and the planetary warming due to changes in geography only maintain above freezing conditions along a coastal zone in winter. This reflects the fact that the advection of warm air into the continental interior is limited. On Antarctica some regions remain below freezing all year round and only a narrow warm coastal zone exists in July. This aspect of the simulation may be verified by determining if the floras and faunas of Asia, North America and Antarctica have a temperate character and could survive conditions of frost or prolonged freezing.

Both the rich and diversified flora and fauna from Alexander Island (Taylor, 1972) and the Cretaceous *Globotruncana* from several localities on Antarctica and New Zealand (e.g., Webb and Neall, 1972) are probably indicative of warm oceans adjacent to the continent. However, we know of no data from the interior of Antarctica which bears on this problem.

The data are considerably more abundant from Asia. Vakhrameev (1964, 1975) described a paleofloristic boundary separating a subtropical—tropical flora from a temperate flora of Asia during the Albian (Fig.10). The boundary is similar to that of other authors (e.g., Krassilov, 1981). The paleofloristic boundary is essentially parallel to paleolatitude and not to the continental outline as would be suggested by the model isotherms. More important than the hypothesized boundary are the actual localities of the fossil floras. Most of the localities (Fig.10) are near coastlines when plotted on a paleogeo-

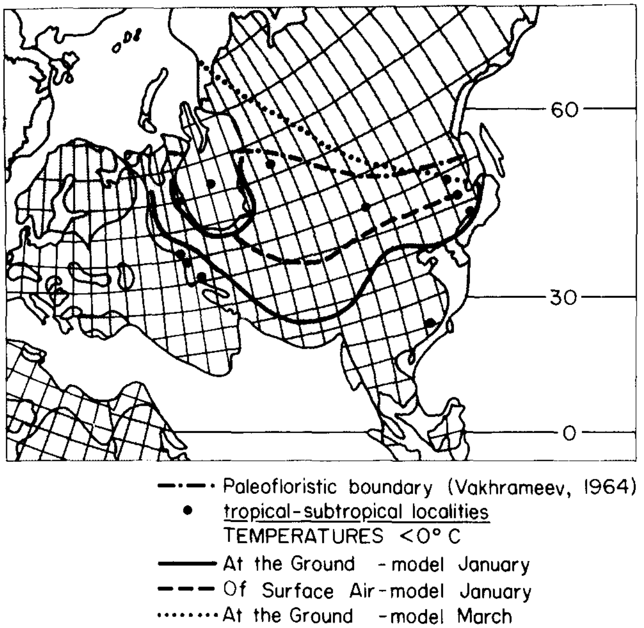


Fig.10. A comparison of the model-simulated 0°C isotherm for March and January with the paleofloristic boundary of Vakhrameev (1964), including the locations of the paleofloras, plotted on a mid-Cretaceous (100 m.y.) paleogeographic map of Asia.

graphic map and can be reconciled with the model simulation. However, one location in Mongolia, in the interior of Asia, has a paleo-floral community which is fairly diverse and has a subtropical character, but a model calculated mean January surface temperature of approximately −10°C. This interpretation may be supported by other data from the Late Cretaceous, such as the presence of crocodiles (Lefield, 1971). If this interpretation is correct, and if the biota cannot withstand seasonally subfreezing temperatures, then we must conclude that the temperatures of the continental interiors in the model simulated climate are not warm enough to satisfy the paleoclimatic data. Such continental interior localities are rare, and thus take on special significance. For instance, the Albian floral localities (Smiley, 1967) of North America are also near coastlines when plotted on paleogeographic maps, with the exception of a site in western Greenland. This site is problematic because the rifting of Greenland from North America occurred in the mid-Cretaceous.

The simulations indicate the importance of data from the interiors of continents. If the data from Mongolia could be ignored, either because of the interpretation or because of errors in the paleogeography (e.g. mountainous regions to the northeast could partially isolate the cold air mass), then the Cretaceous warming may be explained as a result of changes in global geography and in oceanic heat transport. The problem may then reduce to understanding how the oceans could maintain warm polar temperatures. However, if data from continental interiors require more equable conditions, then there exists a more difficult problem. It does not appear reasonable to increase oceanic temperatures beyond a minimum value of 10°C, and therefore we would need to seek other mechanisms, such as increased CO_2, to explain the Cretaceous climate. The difference between a warm Antarctica and a warm Asian interior in winter, compared to a warm coastal zone, would be a major difference in terms of the mechanisms required to explain the Cretaceous climate. Additional data from continental interiors are required to solve this problem.

Was the Cretaceous atmospheric and oceanic circulation "sluggish?"

The Cretaceous model atmospheric circulations were characterized by a reduced intensity of the surface winds at some latitudes but an increase at other latitudes. This reflects many factors, including the position of the continents and the distribution of surface pressure features, as well as the surface temperature characteristics (Barron and Washington, 1982). Barron and Washington (1982) pointed out that although the surface temperature gradient decreased substantially the vertically integrated meridional temperature gradient actually increased at low and mid-latitudes, while decreasing at high latitudes. This result partly occurred because equatorial temperatures warmed slightly. The increased evaporation, because of the non-linear relationship between temperature and saturation vapor pressure, warmed the tropical atmosphere sufficiently to help maintain the atmospheric temperature gradient despite the decreased surface temperature gradient. One basic problem is that the simulated increase in tropical temperatures (1–2°C) may be a specific model-dependent result. Errors in cloud parameterizations, for instance, could account for part of the surface warming. If equatorial regions were cooler (rather than warmer) and the poles were warmer, then the intensity of the surface winds might decrease.

Much of the paleoclimatic literature simply assumes that a reduced equator-to-pole surface temperature gradient will result in a weaker atmospheric circulation and a weaker wind-driven ocean circulation. The model establishes the principle that data on the nature of the surface temperature gradient are insufficient to make a conclusion concerning the intensity of the circulation. Knowledge of the temperatures at each latitude and the change in temperature with height in the atmosphere are a minimum requirement. First it must be determined if tropical surface temperatures were slightly higher than at present and if there is actually any evidence that the Cretaceous atmosphere and oceans were sluggish.

Albian isotopic paleotemperatures from the tropics are rare. Douglas and Savin (1975) determined values from 25°C to 27°C from the Shatsky Rise which was probably within the tropics (Lancelot and Larson, 1975). It may be reasonable to assume that the isotopically lightest measurement (27°C) reflects the shallowest dwelling Foraminifera. Present-day shallow-dwelling forms are about 3°C cooler than the surface and selective dissolution tends to bias isotopic results in the cold direction (Savin et al., 1975). If we can assume that the Foraminifera are unaltered, it seems unlikely that the Cretaceous tropics were cooler than at present. However, the data cannot be interpreted as a paleotemperature with an accuracy as good as 1—2°C.

Based on modern corals (Vaughn and Wells, 1943), values of 35—37°C are required to exceed the temperature tolerances of tropical organisms. The model temperatures are several degrees cooler than this hypothesized maximum tolerance. In addition, we cannot place a physical limit on tropical sea surface temperatures. Newell and Dopplick (1979) suggested that sea surface temperatures reach a limiting temperature of 303°K, based on a balance between radiative energy input and evaporation. This balance ignores any atmospheric feedbacks, and the more detailed GCM simulations with interactive oceans, which include this surface energy balance, do not have such a limit. Increased evaporation due to a change in surface temperature will limit the increase in surface temperature for a net increase in incoming radiative energy. However, the relationship between temperature and saturation vapor pressure only suggests that the change in temperature will decrease for each increment of increased incoming energy. It might be interesting to speculate that slightly warmer tropics would have spawned an increased number of hurricanes, but apparently a physical limit to sea surface temperatures cannot be given.

An increase in the zonally averaged tropical sea surface temperatures of a few degrees does not exceed either biologic or physical limits to surface temperatures. The available isotopic data are not accurate enough to characterize tropical surface temperatures to within 1—2°C. As yet, it is not possible to verify whether the Cretaceous tropics were slightly warmer than at present.

Efforts to verify whether warm, equable periods were characterized by sluggish winds apparently must rely on the ability to recognize aspects of the geologic record which are indicative of the intensity of the circulation. The record of the intensity of surface ocean currents may be preserved on continental margins, where it may be possible to estimate the magnitude and direction of currents. With increased continental margin drilling, current velocities may be based on sediment size, deposition patterns and erosion (e.g., Ledbetter and Johnson, 1976). Such quantitative studies for the Cretaceous are not yet available. Thiede (1981) notes the distinct lack of reworked sediments in Mesozoic sections in the central Pacific. Because of changes in paleodepths and paleolatitude as well as the limited number of Cretaceous sites, this information may not be easily related to the surface circulation.

Wind velocities over continental regions may be determined from sediment size and size distributions in desert regions and adjacent ocean basins (e.g., Leinen and Heath, 1981; Sarnthein et al., 1981). The Cretaceous deserts of China (e.g., Strakhow, 1967) may provide some data, however, it will be very difficult to extrapolate regional conditions to the earth as a whole. Measurements of the aeolian component in deep sea cores in the Pacific Ocean (Rea and Janecek, 1981) indicate that the Albian accumulation rate was greater than at subsequent periods. This was interpreted as an increase in source area because the authors assumed that the winds were sluggish. Careful reconstruction of Cretaceous volcanic ash deposits may also contribute to knowledge of the intensity of the circulation.

The answer to the question of the intensity of the circulation during warm time periods may also require an innovative approach to the geologic record. A "sluggish" ocean and atmospheric circulation has been a basic assumption in the interpretation of much of the data from "ice-free" periods. In many cases it becomes difficult to separate the assumptions from the interpretation of the data. The results from the climate simulations provide an additional hypothesis, and are an incentive to re-examine the data.

Is the predicted pattern of major circulation features consistent with the geologic record?

The March Cretaceous cases are distinctly different from the present-day control in that they have a well-developed polar high and mid-latitude low and the subtropical high has shifted equatorward in the Northern Hemisphere to a position over the Tethys Ocean. The general equator-to-pole distribution of surface pressure highs and lows is very similar in the Cretaceous cases, although the surface temperature gradient is quite different. Barron and Washington (1982) concluded that this surface pressure pattern must be related to changes in the geographic boundary conditions rather than in the surface temperature gradient or polar temperatures. In addition, the previously hypothesized poleward displacement of major circulation features during warm, equable time periods did not occur. The subtropical circulation appears to be a relatively stable feature and the poles are characterized by easterlies rather than poleward displaced westerlies. There is a clear contrast between the previous hypotheses, the present circulation, and the Cretaceous simulations. It seems likely that this aspect of the circulation should be verifiable.

The subtropical high is associated with a large moisture deficit, and therefore arid continents and deposition of evaporites in restricted basins. Previous hypotheses have suggested that the subtropical arid region was displaced poleward 10–15° or more in latitude (e.g., see summary by Frakes, 1979). Both the distribution of evaporites when plotted on a recent paleogeographic map (Barron et al., 1981) and the Cretaceous simulations suggest that very little shift in the subtropical high occurred as a result of a decreased equator-to-pole surface temperature gradient. The model simulations also suggest that the position of the Tethys Ocean was an important control on the position of the subtropical high.

Habicht (1979) plots the locations of all Cretaceous evaporites. Subdivision of the Cretaceous evaporite distribution into stages would provide a more direct comparison of the model simulations with the geologic record. Because these data are from a much longer time span than represented by our mid-Cretaceous boundary conditions, Habicht's compilation will give a greater distribution of evaporites than actually occurred at any one time period. In Fig.11 the evaporites are largely restricted to the Tethys Ocean in the Northern Hemisphere and are found only slightly poleward of 30°S. There appears to be little support for a poleward displacement of the subtropical arid belt, although the atmospheric moisture balance is not the only criterion for the deposition of evaporites.

The distribution of Cretaceous arid regions can also be compared with the model-simulated regions of low soil moisture. The Cretaceous simulations for March and July predict relatively low soil moisture only in China and Southeast Asia in the Northern Hemisphere. Fig.12 gives the area of predicted soil moisture which is less than 10 cm of liquid water equivalent. Much of this region has a predicted March soil moisture of less than 4 cm. This prediction compares favorably with the distribution of arid Cretaceous lithologies as described by Strakhow (1967). Fig.12 also gives the floral localities which place limits on the position of the arid-humid boundary. The discrepancies, which are relatively minor, can be explained by several factors. The arid lithologies have not been divided into stages, thus Strakhow's distribution is probably greater than the actual distribution, and the model does not precisely predict the locations of today's desert regions. In addition, the discrepancy between the simulated arid region and more humid conditions recorded from eastern China may reflect the fact that the paleogeographic reconstruction included part of the Yellow Sea as land, which may not be justified. The model simulation appears to be reasonable, whereas a poleward displacement of the subtropical circulation does not.

The major differences between the Cretaceous and the present-day simulations occur at high latitudes, notably a well-developed mid-latitude rainbelt and a well-developed polar high, and hence easterlies, in the Cretaceous simulations. The westerlies are slightly more restricted in latitude than at present. Again, these differences are relatively large and should be verifiable.

It is interesting to note that Strakhow (1967) described an area of extensive Aptian—Albian bauxite deposits indicative of soil weathering conditions which most likely imply a humid climate (with some relief) on the poleward border of the Northern Hemisphere subtropics. These deposits stretch from Spain well into central Asia. The widespread distribution of these deposits appears to support the idea of a more humid mid-latitude zone than at present. It appears that many areas of the northern margin of Tethys were characterized by extensive rainfall.

It is also important to consider that strong polar easterlies could promote upwelling along the continental margins of the Arctic Ocean (the mass transport of the water in the Northern Hemisphere is 90° to the right of the wind). A weak westerly circulation would be less likely to promote upwelling.

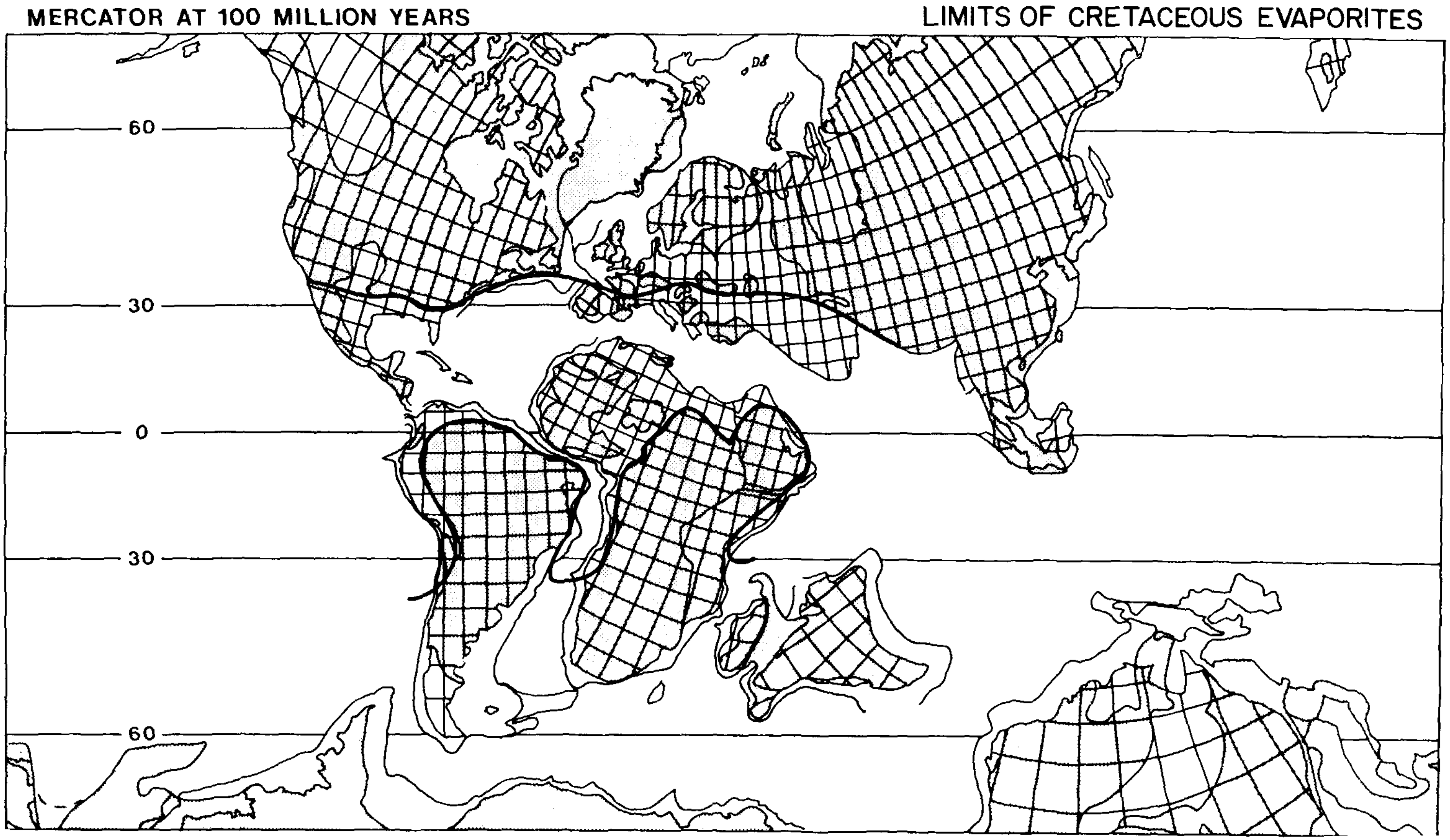


Fig.11. The maximum latitudinal distribution of Cretaceous evaporites (Habicht, 1979) plotted on a mid-Cretaceous (100 m.y.) paleogeographic map.

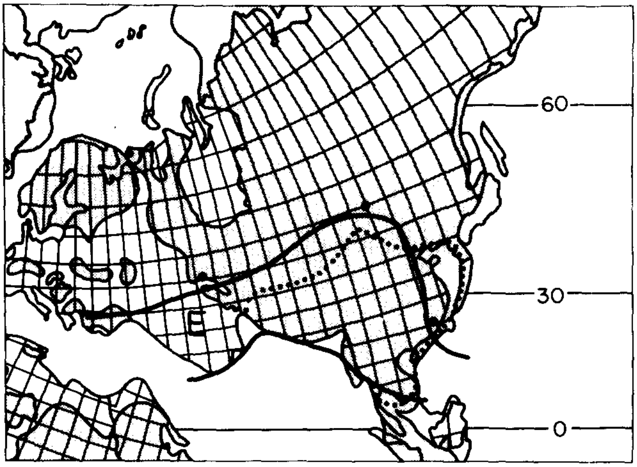


Fig.12. A comparison of the model-simulated area of low soil moisture (see Barron and Washington, 1982) with the area of arid lithologies described by Strakhow (1967) for the Cretaceous of Asia.

Maestrichtian sediments recovered in a core from the Arctic has an assemblage of diatoms and silicoflagellates which have been interpreted as evidence for polar upwelling (Clark, 1977). This aspect of the geologic record is described by Kitchell and Clark in this volume (1982). Unfortunately no mid-Cretaceous sediments were recovered.

Berggren and Hollister (1974) have suggested that paleogeography and circulation patterns are a major control on biogeography. The boundary between the simulated polar easterlies and mid-latitude westerlies, and associated oceanographic divergences and convergences might be expected to result in some floral and faunal distinctions. Cretaceous floras and faunas have largely been separated into only two major realms, a tropical—subtropical realm and a northern temperate realm, and there appears to be no evidence of the simulated boundary between polar easterlies and mid-latitude westerlies. This boundary might not exist, however, if temperature were the major control on the distribution of organisms or if the land—sea contrasts resulted in sufficient zonal variability in the wind patterns. However, it remains an important problem because authors have used the hypotheses of poleward displaced ocean gyres, in response to poleward displaced westerlies, in reconstructing paleobiogeographic patterns (e.g., Gordon, 1973). Reconstructions of opaline silica deposits, reflecting oceanic divergences (upwelling) would be a major indication of the surface circulation patterns.

Were there substantial climatic contrasts during warm, equable periods?

The Cretaceous cases with warm polar seas have considerably more uniform ocean temperatures compared to the present. However, in March and in the winter hemisphere in January and July there exist strong ocean—continent thermal contrasts. The ocean—continent thermal contrast results in the development of quasi-stationary highs and lows along continental margins. There are also considerable variations in precipitation along the margins, which are related to the pressure pattern. In this case the simulated climate cannot be described as "uniform". This aspect of the simulation can be verified by determining if major changes in floral and faunal character occurred with respect to distance from the continental margin and if the floral, faunal and sedimentological character on continental margins and adjacent basins was highly variable, even though the margin might be within a fairly narrow latitudinal zone.

Both the lithologic record and the floral record of Asia suggest a major contrast between the continental margin and the adjacent continental interior. Strakhow (1967) notes that even within the arid belt there existed "wet" coastal regions in China during the mid-Cretaceous. He also notes that this aspect is in contrast with other time periods. Krassilov (1973) separated Cretaceous flood-plain, swamp and stream coastal border floral communities from more "shrub-like" interior communities. Samylina (1967) described similar contrasts in Siberia but suggests that continental relief may be an explanation for these differences. This type of contrast is not unusual today, however, each of these authors suggests that the continental margin—continental interior differences are especially marked during the Aptian—Albian. Kobayashi and Shikama (1961) also suggest that humid coastal regions and more arid interiors became especially pronounced in the Mesozoic record of the Far East. The Cretaceous record in Asia supports the notion of major contrasts associated with distance from the continental margin. However, it is not clear whether this feature can be explained solely by climatic factors and certainly evidence from one continent is insufficient to extend to a global interpretation.

The temperatures of the marine realm in the simulations are much more uniform than at present. However, the distribution of high and low pressure areas associated with the land—sea thermal contrasts result in considerable variations in evaporation and precipitation. Because evaporation and precipitation control sedimentologic processes, we might expect considerable variation in the character and rate of sediment supply along continental margins. It is also possible that different sediment types and salinity might have resulted in some differentiation of paleocommunities. These variations may become apparent only after substantial drilling along continental margins.

Sedimentation in individual ocean basins might also be highly variable under the conditions of the Cretaceous case 2 simulation. High regional evaporation rates combined with strong precipitation contrasts along continental margins might produce a sufficient buoyancy deficit to form dense plumes of warm water (e.g., the Mediterranean today) which become bottom water. The distribution of quasi-stationary highs and lows along continental margins could result in multiple competing sources of deep water forming in the subtropics. The sedimentologic and paleotemperature history in each basin would then reflect the distribution of these sources and the mixing within each of the basins. This description appears to fit the isotopic record for the Late Cretaceous from *Inoceramus* in the South Atlantic and Pacific (Saltzman and Barron, 1982), which indicates that each basin may be characterized by a different deep water temperature. In addition, if anoxic sedimentation is related to warm, saline bottom water (Brass et al., 1982) which has a low oxygen solubility, then the simulations would predict that the record of "anoxic events" (e.g., Schlanger and Jenkyns, 1976) would not be globally synchronous. This must be tested by careful stratigraphic comparison of Deep Sea Drilling Project sites and by additional drilling.

SUMMARY

The paleotemperature data from the Cretaceous oceanic regions are consistent with the predicted mixed layer temperatures of the Cretaceous simulations. However, temperature estimates accurate to a few degrees cannot be obtained from paleoclimatic data. Temperature departures of a few degrees from the present in the tropics may be significant in terms of the change in the vertically integrated meridional temperature gradient, and hence the intensity of the atmospheric circulation during warm equable climates. The model simulations predict tropical temperatures 1—2°C above the present. In this case the atmospheric temperature gradient is maintained despite the decrease in the equator-to-pole surface temperature gradient. This model result cannot be disregarded based on physical or biologic limits on tropical sea surface temperatures. Most importantly we cannot assume that the atmospheric circulation was sluggish because the equator-to-pole surface temperature gradient was less in the past. A minimum requirement for inferring the intensity of the atmospheric circulation is knowledge of the surface temperatures, and the change in temperatures with height in the atmosphere (lapse rate). We must seek direct evidence as to whether the intensity of the Cretaceous atmospheric circulation was reduced compared to the present.

The assumption of warm polar oceans in the Cretaceous simulations implies that oceanic heat transport may be important in explaining warm, equable climates. Warm polar temperatures do not result, according to the model simulation, in substantial warming of continental interiors. We can test whether the climate can be explained by oceanic heat transport by examining the climatic record at Cretaceous sites which were located in continental interiors. Such sites are rare and it is apparent that most Cretaceous paleoclimatic data, which are located near ancient coastal zones, could be explained by warm adjacent oceans. One site in Mongolia is an exception. The Cretaceous subtropical floras and faunas at this continental interior location suggest that the warm oceanic mechanism may be insufficient to explain continental interior climates. It is difficult to judge this problem based on data from a single site. The difference between a warm Antarctica and a warm Asian interior, even in winter, compared to a warm coastal zone would be a major difference in terms of the mechanisms required to explain the Cretaceous climate.

There is some evidence that the Cretaceous climate could have had substantial variability, especially associated with continental margins, even though oceanic temperatures may have been much more uniform than at present. Establishing this point requires a careful analysis of coastal and continental margin paleocommunities and comparison of sedimentologic characteristics along a continental margin within a fairly restricted latitudinal zone. This latter analysis may require information from continental margin drilling.

The geologic data supports the results of the model simulation that the subtropical high was not displaced poleward, in contrast to previous hypotheses. However, the development of strong polar easterlies in the Cretaceous simulation is more difficult to verify. If the position of the boundary between westerlies and easterlies should have been a major floral or faunal boundary, then this aspect of the circulation appears to receive little support from the geologic record. However, with more uniform ocean temperatures this boundary may not be important in oceanic regions. Careful paleobiogeographic analysis may be required to differentiate between the classical hypothesis (polar westerlies), characteristics similar to the present circulation (regions of polar easterlies and polar westerlies), and the model simulations (polar easterlies).

The Cretaceous simulations suggest several types of additional paleoclimatic data are required to understand the nature of the problem of warm, equable climates. Specifically, data bearing on tropical temperatures, climatic conditions in continental interiors, the intensity of the circulation, and the distribution of easterlies and westerlies are essential.

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