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Modeling Late Cretaceous climate and vegetation

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With 3 figures in the text

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Abstract: The Late Cretaceous was much warmer than today. There was no significant ice at high latitudes, meridional thermal gradients were low, and continental interiors remained warm during winter. Late Cretaceous atmospheric CO_2 concentrations were about four times greater than today and an enhanced "greenhouse" effect contributed to the overall warmth of the Late Cretaceous. However, increases in atmospheric CO_2 tend to increase temperatures at all latitudes and do not explain the very low thermal gradients recognized in the geologic record. Increased poleward ocean heat transport has been cited as a mechanism for maintaining low meridional thermal gradients during the Cretaceous. However, ocean heat transport values larger than the present day are difficult to reconcile. In addition, low meridional thermal gradients suggest sluggish atmospheric circulation, implying that the advection of heat from the warm oceans into the continental interiors was limited. In general, paleoclimate simulations using Atmospheric General Circulations Models (AGCMs) have not been successful in simulating the low meridional thermal gradients and warm winter continental interiors of the Cretaceous, forcing the concept of "equability" to be questioned.

Until recently, the physical effects of vegetation on pre-Quaternary climates have largely been ignored. Terrestrial ecosystems influence global climate by affecting the exchange of energy, water, and momentum between the land surface and the atmosphere. In a new approach to pre-Quaternary paleoclimate modeling, Campanian (80 Ma) climate and vegetation have been simulated using a global climate model (GENESIS Version 2.0), coupled to a predictive vegetation model (EVE), resulting in a realistic simulation of Late Cretaceous climate. The predicted distribution of Late Cretaceous vegetation played an important role in the maintenance of low meridional thermal gradients, polar warmth, and equable continental interioirs. High latitude forests reduced albedo, especially during snow-covered months, and increased net surface radiation and latent heat flux.

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Increased atmospheric moisture augmented latent heat transport by the atmosphere and enhanced the water vapor feedback component of the greenhouse effect.

Introduction

The geologic evidence for a generally warm, ice-free Late Cretaceous climate includes the latitudinal expansion of thermophillic organisms (e. g. KAUFFMAN 1973, HUBER et al. 1995), the expansion of dinosaurs into polar latitudes of both hemispheres (e. g. COLBERT 1973, OLIVERO et al. 1991, CRAME 1992), and the poleward migration of vegetational provinces (VAKHRAMEEV 1991). Meridional thermal gradients were low in the oceans (HUBER et al. 1995) and on land (PARISH & SPICER 1988, UPCHURCH & WOLFE 1987). The Campanian stage of the Late Cretaceous was not as warm as the mid-Cretaceous thermal maximum. However, Campanian mean annual surface temperatures were still much warmer (~10 °C) than today (DeCONTO 1996).

Atmospheric CO_2 is an import "greenhouse" gas, affecting the radiation energy balance of the Earth. Estimates of Late Cretaceous atmospheric CO_2 fall between 1.5 and 9 times larger than present day values (BERNER et al. 1994, CERLING et al. 1991, ANDREWS et al. 1995). Early General Circulation Model (GCM) studies of Cretaceous climate (BARRON & WASHINGTON 1984) suggested that an increase in atmospheric CO_2 of four times present day values provides a plausible explanation for Cretaceous warmth. However, changing atmospheric composition alone was not enough to account for all the warmth or the low meridional thermal gradients recognized in the geologic record.

The Late Cretaceous physical environment was very different from today. The distribution of continents reflected the recent break-up of Pangea. Sea level was about 200 m higher than today (HAQ et al. 1987), flooding the continental interiors and coastal zones and reducing total land area by 20 % from that of today. The Cretaceous distribution of land and sea has been cited as an explanation for Cretaceous warmth (DONN & SHAW 1977) because of the different thermal characteristics of land and ocean and their different responses to the seasonal insolation cycle. However, subsequent modeling studies (BARRON et al. 1993a) showed that the role of paleogeography is secondary to forcing from increased atmospheric CO_2.

The oceans play an important role in regulating the planetary energy budget, by contributing approximately as much poleward heat transport as the atmosphere (PEIXOTO & OORT 1992). Increased ocean heat transport has been cited as a means of maintaining low meridional thermal gradients during the Cretaceous (COVEY & BARRON 1988, RIND & CHANDLER 1992, BARRON et al. 1993b). However, a viable mechanism for increasing ocean heat transport beyond present day values, in a world with reduced meridional thermal gradients, has not been explicitly defined (SLOAN et al. 1995). In addition, the reduced thermal gradients of the Cretaceous may have weakened the atmospheric circulation, limiting the zonal transport of heat from the oceans to the continental interiors. Winter, radiative cooling of the continental interiors cannot be compensated by a weak inflow of warm air from the oceans. In model simulations of mid-Cretaceous climate, BARRON et al. (1993) showed that despite elevated atmospheric CO_2 and increased ocean heat transport, very cold (~ -30 °C) temperatures developed in the continental interiors during winter. Cold seasonal temperatures contradict evidence from the Late Cretaceous geologic record, including tropical and para-tropical vegetation in non-marine North America (UPCHURCH & WOLFE 1987), palms in the Asian interior (VAKHRAMEEV 1991), and Mongolian crocodiles (LEFIELD 1971). Understanding how the comprehensive climate system was able to maintain the overall warmth, low meridional thermal gradients, and warm winter continental interiors of the Cretaceous has become a classic problem of paleoclimatology.

GENESIS Version 2.0 and EVE

Climate models test the sensitivity of climate to external forcing, such as variations in solar luminosity and orbital parameters, and to internal forcing from changes intrinsic to the Earth's surface and atmosphere. However, climate is the result of complex interactions and feedbacks between the atmosphere, hydrosphere, cryosphere, biosphere and the solid-earth, with each element operating on a different time scale. The GENESIS Global Climate Model is an Earth system model, designed to simulte climate by allowing interaction between individual models of climate system components. GENESIS Version 2.0 (THOMSON & POLLARD 1997) includes evolutionary improvements over GENESIS Version 1.02 (POLLARD & THOMPSON 1995), which has been used in prior modeling studies of the Cretaceous (BARRON et al. 1993a, 1993b). GENESIS uses an AGCM as its core component, coupled to a non-dynamical slab ocean model and multi-layer models of soil, snow, and sea-ice. A Land-Surface-Transfer Scheme (LSX) serves as the interface between the AGCM and the land surface, calculating fluxes of heat, radiation, moisture, and momentum between the ground surface (soil and snow), vegetation, represented by two canopy layers "grass" and "trees", and the atmosphere. The GENESIS Version 2.0 AGCM has 18 vertical layers and a spectral resolution of T31, approximately (3.75° X 3.75°). The resolution of the land-surface model (LSX) is 2° X 2°.

The Equilibrium Vegetation Ecology (EVE) model (BERGENGREN & THOMPSON submitted) predicts plant community structure as a function of climate and fundamental ecologic principles, and provides a description of the vegetation for the land-surface model component of GENESIS. EVE is driven by seven ecoclimatic predictors that describe the annual and seasonal characteristics of climate in each 2° X 2° land-surface grid cell. The predictors are derived from 12 monthly mean values of temperature, precipitation and relative humidity, provided by the AGCM. The basic vegetation units in EVE are called **lifeforms.** Lifeforms define the individual components of a plant community, like the individual and species levels of vegetation, but are based on their physiognomic and ecologic characteristics at the biome level. The 110 lifeforms in EVE are defined physiognomically and not taxonomically, allowing EVE to be applied to the simulation of pre-Quaternary vegetation with only minor modifications.

Not all the lifeforms found in today's terrestrial biosphere existed 80 million years ago, requiring the lifeforms in EVE to be compared with the Late Cretaceous fossil record of vegetation. Only those lifeforms with known Late Cretaceous physiognomic analogs were included in the Campanian simulation. The most notable exclusions were the graminoids, narrow-leaved herbs with well developed root stocks, including grasses (Gramineae) and sedges (Cyperaceae). Although Gramineae may have existed in the Late Cretaceous (CREPET & FELDMAN 1991), grasslands as we know them today did not exist until the mid-Tertiary. Before the advent of grasslands, the dry continental interiors were dominated by other lifeforms. Forbs (broad-leaved herbaceous angiosperms), ferns, and shrubs provided the dominant fractional cover in the climate niche occupied by grassland today (DeCONTO 1996). The term "forb-fern prairie" replaces "grassland" in the Campanian biome map shown below.

Boundary conditions

Boundary conditions for paleoclimate simulations include atmospheric chemistry, the solar constant, orbital parameters, and solid-earth boundary conditions including the distribution of land and sea, topography, and vegetation. Highly resolved and accurate paleogeographic reconstructions are critical to the simulation of realistic paleoclimates. Therefore, a new high resolution paleogeography was constructed on a 2° X 2° grid, specifically for the climate and oceans simulations shown here.

The Campanian paleogeography consists of a global plate tectonic reconstruction, with shoreline locations and elevations superposed on the tectonic model. The plate tectonic reconstruction is based on a new global tectonic model for the Cretaceous (HAY et al. in press). The new tectonic model is significantly different from other global tectonic models of the Cretaceous, which assumed that large continental blocks consisting of Eurasia, Greenland, North America, South America, Africa, India, Australia and Antarctica were completely separated by the mid-Cretaceous, with wide, deep ocean passages between them.

The position of paleoshorelines, representing a Late Cretaceous highstand of sea-level, were mostly reconstructed from the Atlas of Lithological-Paleogeographical Maps of the World (RONOV et al. 1989). The RONOV et al. (1989) data were digitized and superposed on the global plate tectonic model. Some shoreline data were modified to include newly recognized land areas, like those around the Kerguelen Plateau-Broken Ridge-Ninetyeast Ridge. The flooding of continental crust in the Late Cretaceous results in a global land area about 20 % smaller than today, with a substantial reduction in northern hemisphere continentality.

Global topography is another important boundary condition for paleoclimate simulations, because prescribed topography can affect the zonal mean circulation, monsoonal circulation, storm track position, precipitation patterns and snow line. Like the shoreline data, Campanian elevations were reconstructed largely from the RONOV et al. (1989) paleolithological map of the Late Cretaceous. Average elevations were applied to orogenic zones (1000-3000 m), intermontane basins (500-1000 m) and areas of continental erosion (200-500 m) and deposition (0-200 m). The data were superposed on the tectonic model and contoured with the paleoshorelines providing sea level (zero elevation). The resulting Campanian paleogeography is shown in Fig. 1, with shorelines and elevations superposed on the tectonic model and plotted on an equidistant grid.

The present day solar constant, defined as the incident solar flux at the top of the atmosphere, is 1365 W m^{-2}. However, the Sun's luminosity was smaller in the Cretaceous having risen steadily since the beginning of Main-sequence evolution about 4.7 X 10^9 years ago. Campanian (80 Ma) solar luminosity was calculated from a standard model of solar evolution (GOUGH 1981), resulting in a value of 1355.7 W m^{-2} (0.632 % less than present day). Orbital parameters were prescribed with a mean orbital configuration, in which eccentricity was prescribed as zero and obliquity as 23.5°.

Long-wave radiation emitted by the warm surface of the Earth is partially absorbed and then re-emitted by water vapor (the biggest contributor), naturally occurring trace gases (mainly carbon dioxide, methane, nitrous oxide, and ozone), and aerosols in the troposphere and stratosphere. Of the trace gases, CO^2 is the largest contributor to the "greenhouse effect". A linear interpolation between estimates of Cretaceous (CERLING 1991, ANDREWS et al. 1995) and Eocene (CERLING 1991) atmospheric CO^2, determined from the isotopic composition of soil carbonate in paleosols, suggests an average decrease of about 20 ppm atmospheric CO^2 per million years throughout the Cretaceous and Early Cenozoic. Extrapolating to the Campanian yields a value of about 1600 ppm (4.6 times present). The CO^2 atmospheric volume mixing ratio used in solar and infrared radiative calculations in GENESIS was prescribed conservatively as 1500 ppm.

The ocean model in GENESIS transports heat as a linear diffusion down the local ocean temperature gradient as a function of latitude and the zonal fraction of land vs sea. The multiplicative of the oceanic heat diffusion coefficient in the slab ocean model component of GENESIS can be prescribed to effectively alter the efficiency of the oceans ability to move heat poleward. This multiplicative was initialized as 4, resulting in ocean heat transport values similar to the present day observed values (about 2.0 X 10^{15} W m^{-2}) and about 2 x present day GENESIS V.2 control values.

Interactive paleoclimate-vegetation modeling

Atmospheric inputs of energy and water affect the structure and function of terrestrial ecosystems. In turn, terrestrial ecosystems influence global climate by altering the fluxes of momentum, radiation, heat and water vapor at or near the ground surface. Terrestrial ecosystems differ greatly in structure and physiology. Canopy roughness, leaf area index (the area of one-sided leaf surface as projected on a flat surface, per unit area of land surface), seasonality of leaf display, and the partitioning of sensible and latent heat through transpiration, all affect the climate system. Because the Late Cretaceous was ice-free, the entire land surface was vegetated, amplifying the importance of feedbacks in the coupled climate-vegetation system.

Instead of prescribing a fixed reconstruction of Campanian vegetation from a fragmented fossil record, EVE was applied as an interactive component of the Campanian climate simulation. EVE provides the seasonal

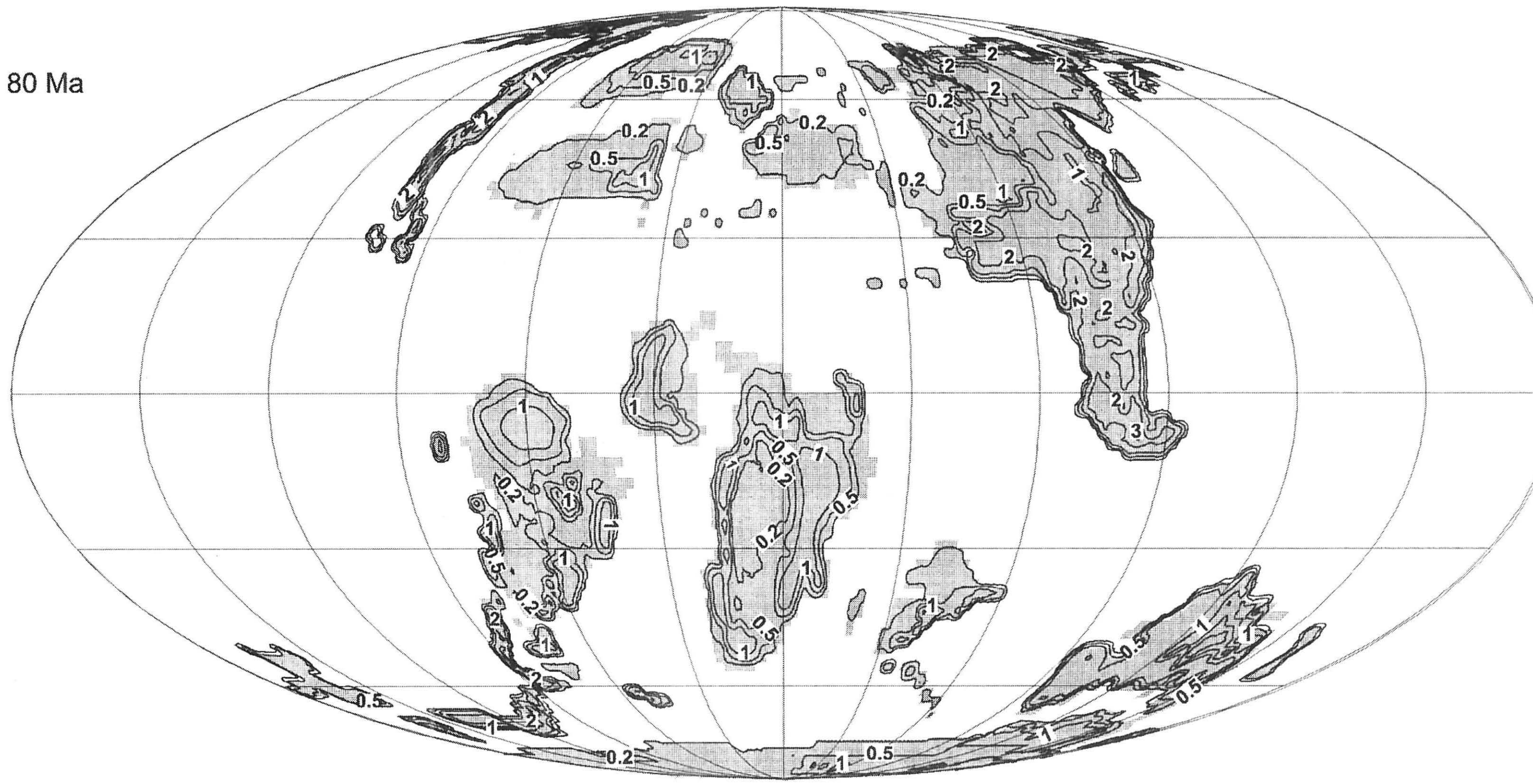


Fig. 1. The Campanian paleogeography providing the solid-earth boundary conditions for the climate-vegetation model simulation. Elevations are shown in contour intervals of 0.2, 0.5, 1.0, 2.0, and 3.0 km.

phenology and physical characteristics of the two canopy vegetation layers specified within each 2° X 2° surface grid cell. In turn, the global distribution of predicted vegetation is updated according to the previous year's 12 month climatology provided by GENESIS. In this way, the GENESIS simulated climate is affected by the EVE predicted vegetation and vice versa, allowing feedbacks between climate and vegetation.

Campanian climate-vegetation model results

GENESIS and EVE were run coupled with the boundary conditions described above. After 20 model years of integration, a climate-vegetation equilibrium was reached. Fig. 2 shows the simulated distribution of Campanian vegetatino, with the fractional cover of lifeforms broken down into biomes. The simulated Campanian vegetation was dominated by forest, with evergreen needleleaf trees providing up to 80 % of the ground cover in the interior of Antarctica and Asia.

Fig. 3 shows January (a), July (b), and zonally averaged mean annual surface temperature (c), simulated by GENESIS. The simulated Campanian climate is well correlated with proxy climate data at all latitudes. The coldest monthly mean temperatures in the continental interiors are -12 °C, sufficient to allow substantial snow fall (predicted winter fractional snow cover reached 100 % over most land areas poleward of 60°), but still in keeping with the concept of an "equable" Late Cretaceous. Areas of subzero Mean Annual Temperatures (MATs), limited to northeast Asia and the higher elevations of East Antarctica, are much reduced from prior simulations of Cretaceous climate (BARRON et al. 1993a, 1993b, VALDES et al. 1996). The simulated Campanian climate can be described as warm and wet, with a global MAT of 24.1 °C (about 9 °C warmer than today) and a global Mean Annual Precipitation (MAP) of 3.9 mm/day (about 25 % wetter than today). Precipitation was seasonally steady, resulting in large areas of saturated soil. Meridional thermal gradients were extremely low (<0.3 °C per degree of latitude) over land and ocean. Polar MATs were 8 °C and 2 °C in the north and south, respectively. Despite substantial predicted snowfall at high latitudes caused by the high moisture holding capacity of the warm Late Cretaceous atmosphere, no snow survived through the summer months implying that no ice sheets would have formed.

The predicted distribution of Campanian vegetation played an important role in the maintenance of low meridional thermal gradients and warm continental interiors. High latitude needleleaf forests in continental Antarctica, North America, and Asia, masked the high albedo of snow cover in the winter and spring, prior to snow melt. Annual net radiation, surface to atmosphere latent heat flux, and atmospheric moisture were significantly higher over forest than tundra at the same latitudes, heating the overlying atmosphere (mean annual temperatures were 8 °C warmer over forest than tundra at the same latitude). Increased high latitude warmth, especially in winter and spring, moderated seasonal cooling of the high latitude oceans. This, in turn, reduced summer continental cooling from the influence of the seasonal thermal lag of the oceans. Warm high-latitude and polar summer temperatures maintained healthy forest and limited tundra development. Increased atmospheric moisture, mainly from an in-

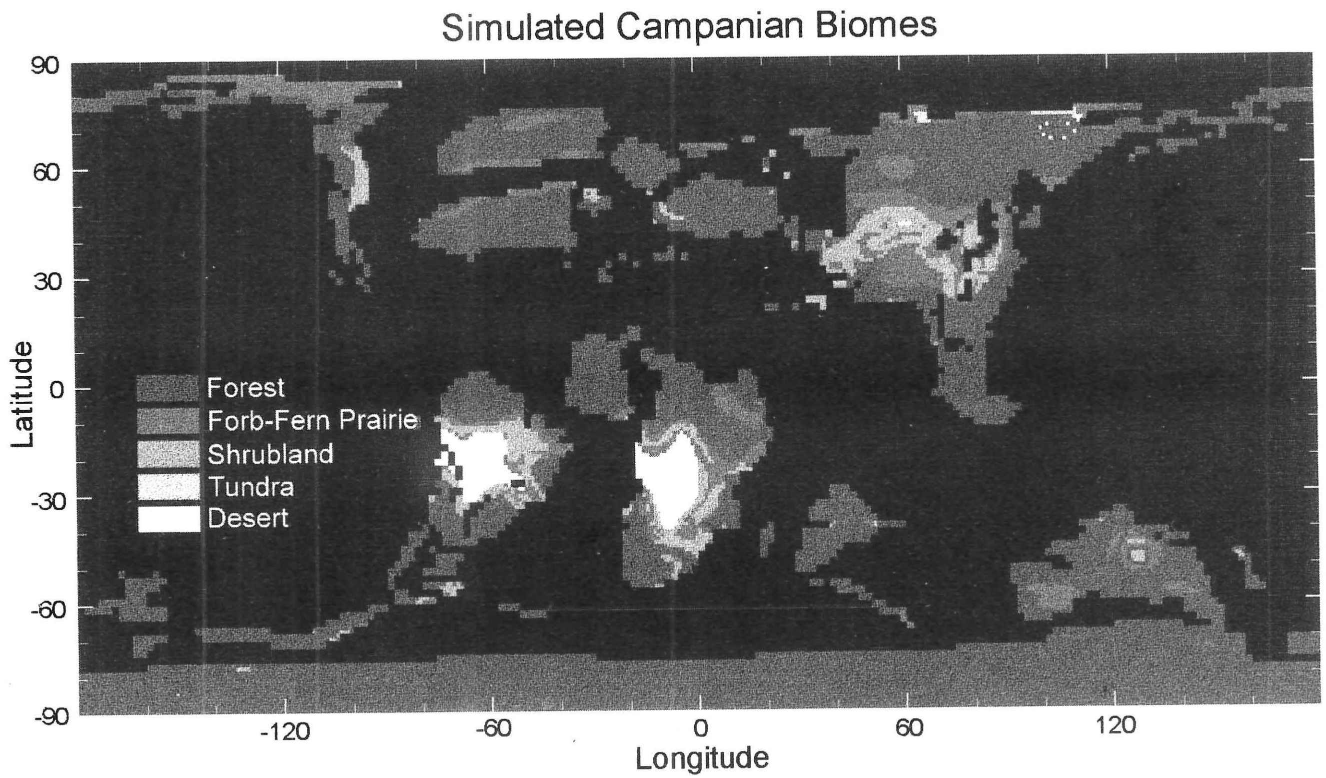
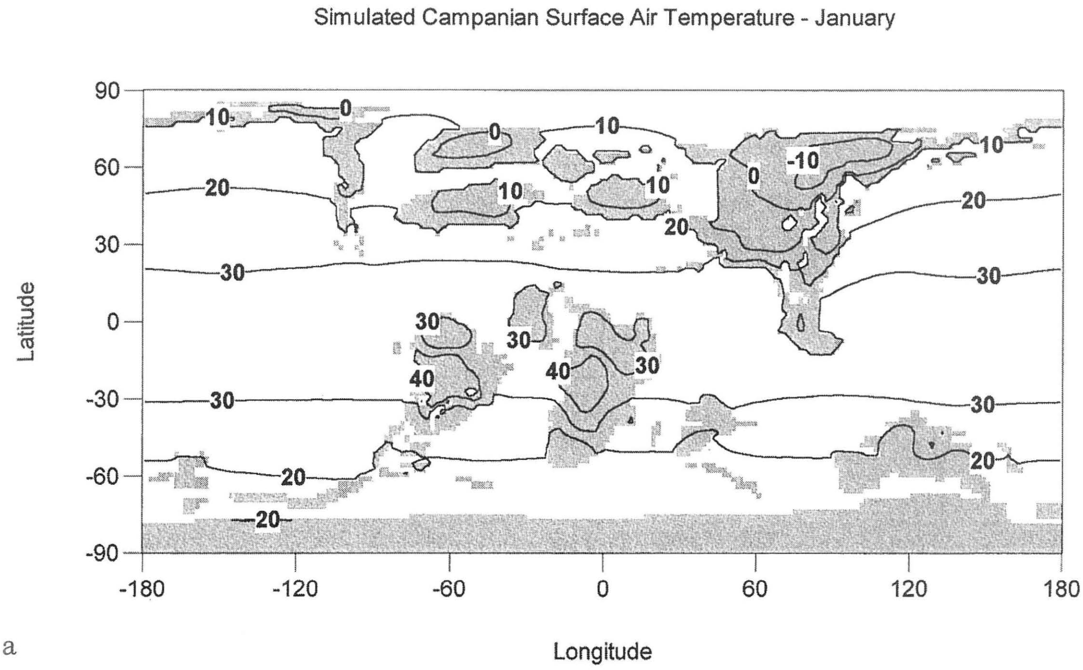


Fig. 2. Campanian biomes predicted by the interactive vegetation model (EVE) component of GENESIS. "Forb-Fern Prairie" occupies the climatic niche occupied by grassland today. Forests, with evergreen trees providing up to 80 % of the fractional cover in some areas, dominate the mid-high latitude continental interiors.



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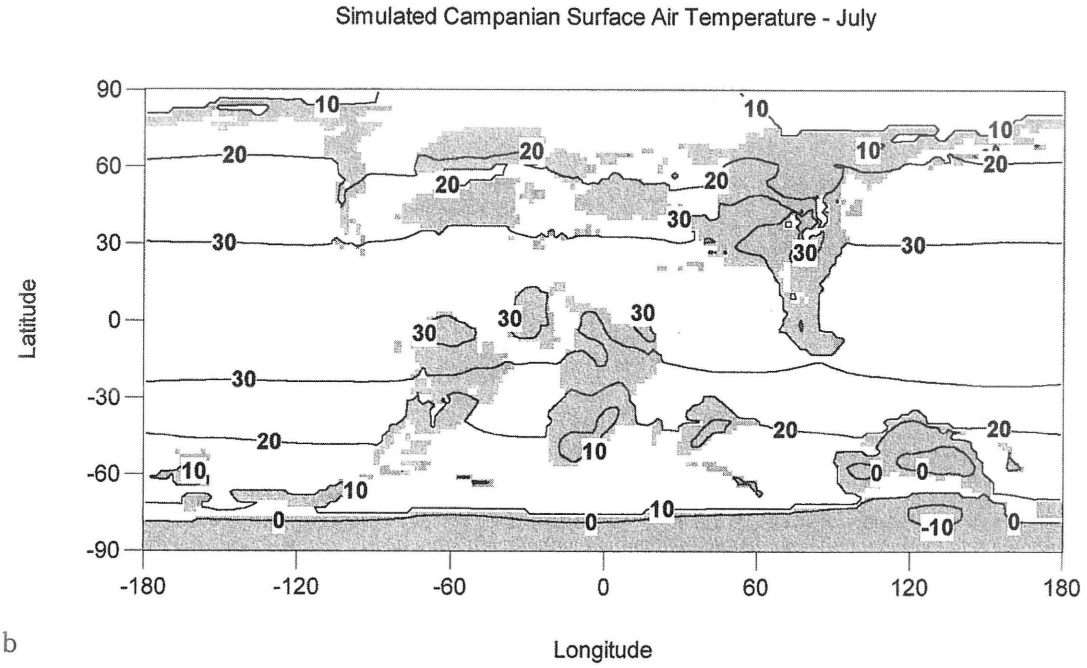

b

Fig. 3. January (a) and July (b) surface temperatures (°C) predicted by GENESIS. The areas of sub-zero winter temperatures are much reduced from prior simulations of Cretaceous climate. The coldest winter temperatures (about -12 °C) occur over the tundra dominated, higher elevations of Northeast Asia and East Antarctica. Zonally averaged MATs (c) clearly show the overall warmth and low meridional thermal gradients simulated by the model. The simulation is well correlated with a compilation of Campanian temperature proxies (shaded area) at all latitudes.

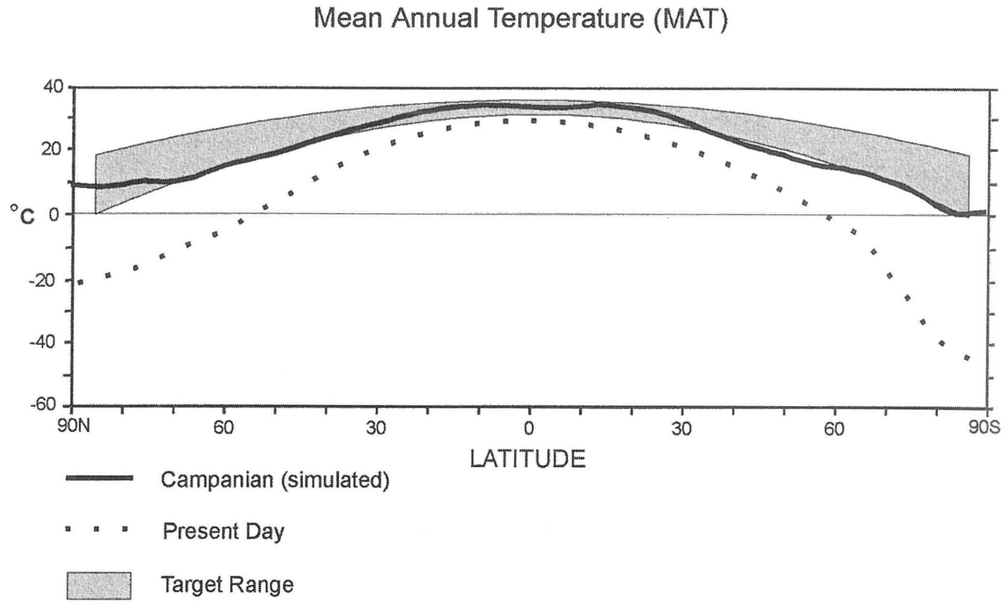

Fig. 3c. Legend see p. 1441.

crease in transpiration over forest, enhanced the latent heat transport potential by the atmosphere and added to the water vapor feedback component of the "greenhouse" effect. Mean annual surface to atmosphere latent heat flux was ≈25 W m^{-2} greater over high latitude forest than tundra. The large radiative flux over forested land areas aided low-level convergence over the continents, drawing in warm moist air from the oceans and contributing to continental warmth.

Conclusions

Recent advances in paleoclimate modeling, including interactive vegetation models, better treatment of land surface-atmosphere processes, and more detailed reconstructions of paleogeography, are helping to narrow the gap between model-data comparisons of pre-Quaternary paleoclimates. Only through understanding the interactions between climate system components can the mechanics of extreme paleoclimates be understood.

The interactive climate-vegetation simulation of the Campanian has reproduced the overall warmth, low meridional thermal gradients and warm winter continental interiors characteristic of the Late Cretaceous, without resorting to extreme prescribed values of atmospheric CO_2 or poleward ocean heat transport. Terrestrial ecosystems played a fundamental role in the maintenance of Late Cretaceous equability. Late Cretaceous forest dominated the mid to high latitude continents. The forests reduced surface albedo, especially during late winter and early spring prior to snow melt, and increased net radiation and latent heat flux. This moderated winter cooling of high latitude sea surface temperatures and increased atmospheric moisture at high latitudes, augmenting latent heat transport by the atmosphere, aiding the advection of heat into the continental interiors, and adding to the water vapor feedback component of the greenhouse effect.

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