FIRST CASE STUDY

Plate Tectonics and Climate— Episodes of Extensive Glaciation and Extreme Global Warmth

The most persuasive evidence for global climatic change in Earth history is the record of extensive glaciations separated by periods for which there is little or no evidence of year-round ice (Figure 2). From an Earth-history perspective, the climate of today is distinctly glacial. Much of the research that attempts to explain the major changes in climate, illustrated in Figure 2, focuses on periods of the greatest contrast. The warm climate of the Cretaceous period (approximately 100 million years ago) exhibits the largest well-documented contrast to the present glacial climate.

The evidence for global warmth comes from every facet of the geologic record including paleontology, geochemistry, and sedimentology. More than 400 plant species are recorded from latitudes above the Arctic Circle, and these polar floras are indicative of seasonal conditions with mean annual temperatures between 5 and 10°C. Fossils of large ectotherms (cold-blooded organisms) are found at latitudes as high as 60 degrees, whereas we know that modern relatives (alligators and crocodiles) become inactive below 20°C and are restricted to much lower latitudes. In the marine realm, no evidence of cold-water faunas from Cretaceous time has been discovered. Paleotemperature data suggest that deep ocean temperatures were between 15 and 17°C, compared to modern values of 1–2°C. Tropical surface temperatures were evidently similar to modern values,

or a few degrees higher. A combination of these data (Figure 3) suggests that the globally averaged surface temperatures were 6–12°C higher than at present, with polar temperatures 20–50°C higher.

Not only did the Cretaceous show substantially greater warmth over millions of years, but the transition from the warm climatic conditions of the Cretaceous to the modern glacial climate occurred slowly, over tens of millions of years. This evidence argues for a causative mechanism that operates over a long time. Since the formulation of the plate tectonic theory of crustal evolution, the changing distribution of continents has become a frequently cited explanation for the occurrence of glacial and nonglacial climates. The following sections explain how.

Plate Tectonics and the Surface Earth

Earth's crust (lithosphere) consists of a series of rigid plates that are in extremely slow but constant motion. Plate tectonics is defined simply as the interactions between these plates. Three types of interactions occur: (1) two plates diverge, and new lithospheric crust is created from hot molten rock that moves up from below; (2) plates converge, forcing one beneath the other in a process known as subduction; and (3) two plates slide past each other without
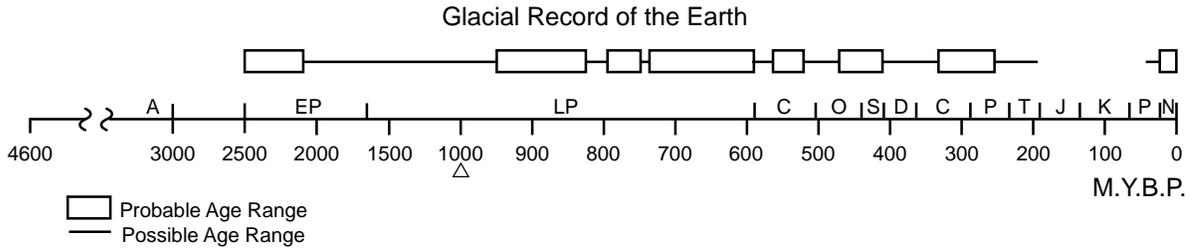
Glacial Record of the Earth

Figure 2, above and right. The probable time range of glacial episodes during Earth history. Times of uncertainty in interpreting the record are given as possible ranges of glaciation.
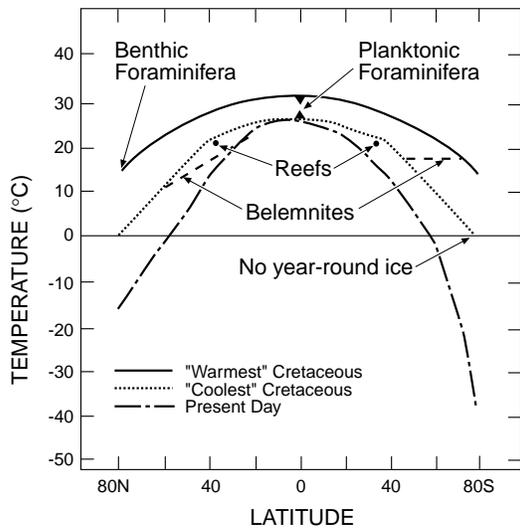

Figure 3. Mean annual surface temperatures in Cretaceous times, compared with modern values (after Barron, 1983). Some of the major constraints are based on oxygen isotopes (in benthic and planktonic Foraminifera, bottom-dwelling and floating microorganisms that secrete a CaCO$_3$ shell, and belemnites, ancient relatives of a nautilus), reef distribution, and the absence of year-round ice.

Geologic Time Scale

Era	Period	Epoch	Years Before the Present
Cenozoic	Quaternary	Holocene (Recent)	
			11,000
		Pleistocene (Glacial)	
			1,600,000
	Tertiary	Pliocene	
			5,300,000
		Miocene	
			23,700,000
		Oligocene	
			36,600,000
		Eocene	
			57,800,000
		Paleocene	
			66,400,000
Mesozoic	Cretaceous		
			144,000,000
	Jurassic		
			208,000,000
	Triassic		
			245,000,000
Paleozoic	Permian		
			286,000,000
	Carboniferous — Pennsylvanian (Upper Carboniferous)		
			320,000,000
	Carboniferous — Mississippian (Lower Carboniferous)		
			360,000,000
	Devonian		
			408,000,000
	Silurian		
			438,000,000
	Ordovician		
			505,000,000
	Cambrian		
			570,000,000
Precambrian	Proterozoic		
			2,500,000,000
	Archean		3,800,000,000

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convergence or divergence. The idealized plate in Figure 4 includes both continental and oceanic crust. The plate is growing with the addition of new material (accretion) at the midoceanic ridge on the right, and oceanic crust is being destroyed (subducted) where the idealized plate converges with the adjacent plate on the far left. Throughout the world, subduction is indicated by the distribution of deep-sea trenches, by explosive volcanism, and by deep-seated earthquakes. In Figure 4, the ocean basin to the right of the continent is growing in area while the ocean basin to the left of the continent decreases in size.

One consequence of plate tectonics is that the distribution of continents is continually changing. The Atlantic Ocean first formed about 165 million years ago, at which time the world consisted of a single megacontinent, Pangaea, and a single super-ocean called Panthalassa. We can find times in Earth history when Greenland straddled the equator and times when the Sahara Desert was at the South Pole.

The topography or elevation of the continents is also governed by plate tectonics. With continued motion of the plates, collision between continents is inevitable. Usually, the thinner and more dense oceanic lithosphere is subducted beneath the thicker and less dense continental lithosphere. For example, the existence of the Andes mountain range is a direct consequence of South America's being at the boundary of an active or converging plate. The Himalayan-Tibetan Plateau region, the highest topography in the world, is the product of the collision of India and Asia nearly 50 million years ago.

Plate tectonics also influences sea level. At boundaries where new crust is created (predominately at midocean ridges), hot, thick lithosphere is accreted to the margins of diverging plates. Over tens of millions of years the thick lithosphere cools and contracts. In fact, the new crust is clearly evident as ridges (midocean ridges) on maps of the depth of the ocean. Consequently, at times when new sea floor is created more rapidly by faster spreading at divergent boundaries or increased length of midocean ridges, the holding capacity of the ocean basins decreases and some continental flooding occurs. For example, most estimates suggest that during the middle Cretaceous new sea floor was created at a rate twice as fast as it is today. The theory of lithospheric cooling and contraction suggests that such a fast sea-floor spreading rate would yield a global sea-level rise of 200 to 300 meters (this may be compared with 65 meters if we melted the modern ice caps). In fact, almost 20% of the modern continents was covered by ocean in the middle Cretaceous (Figure 5). In short, plate tectonic processes affect not only the distribution and elevation of the continents, but also the area of continents above sea level.
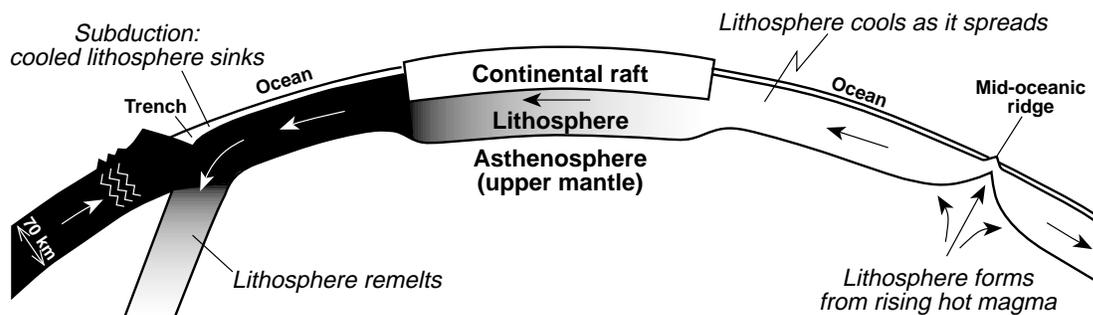

Figure 4. From right to left, the motion of lithospheric plates in response to mantle convection.
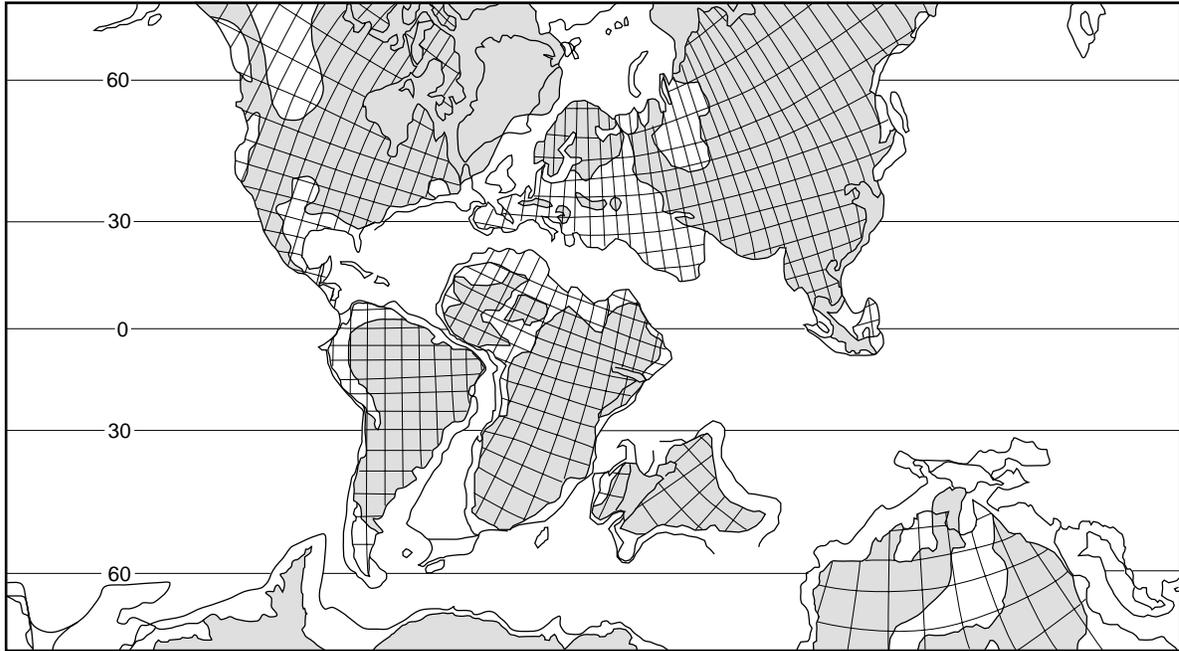
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*Figure 5. A reconstruction of mid-Cretaceous geography extending to 70°
north and south latitudes (Barron et al., 1981). Present continental outlines
and the 2,000-m depth contour are included with mid-Cretaceous continental
area (shaded). Paleolatitude lines are given at 30˚ intervals, and the continents
include their present-day latitude/longitude lines for reference.*

How Can Plate Tectonics Influence Global Climate?

The distribution, elevation, and areal extent of the continents each influence climate. In addition, plate tectonics influences climate by modifying the atmospheric concentration of carbon dioxide.

Continental Distribution

In assessing the effects of the distribution of continents on global climate, five major factors must be addressed: differences in surface albedo, land area at high latitudes, the transfer of latent heat, restrictions on ocean currents, and the thermal inertia of continents and oceans. Each of these factors is explained below.

Albedo. Different types of surfaces reflect different amounts of incoming solar radiation; for example, a snow-covered field reflects more sunlight than a dark soil. The amount of energy that a surface reflects is called its albedo. The albedo of a land surface is very different from that of an ocean surface. The average albedo of a tropical ocean is near .07 (7% reflected, 93% absorbed), while that of a desert region may approach .25. Considering that the amount of incoming solar energy is very different at different latitudes (it is greatest at the equator), the latitudinal distribution of land and sea has a strong potential to influence the total energy budget of Earth.

High-latitude land area. Land at high latitudes provides a surface for the accumulation

of snow and year-round ice. Snow and ice have a very high albedo; for fresh snow it approaches .65 to .80. Consequently, high-latitude land area, if snow-covered, can also dramatically influence the energy budget of the atmosphere-ocean system.

R = Net Solar and IR Radiation (W/m^2)
E = Evaporation/Transpiration (W/m^2)
S = Sensible Heat (W/m^2)
$\alpha \equiv$ Surface Albedo

Subtropical Land
$\alpha \equiv$ **0.25**

50   **15**   **35**

Subtropical Ocean
$\alpha \equiv$ **0.07**

85   **80**   **5**

Near-Equatorial Land
$\alpha \equiv$ **0.12**

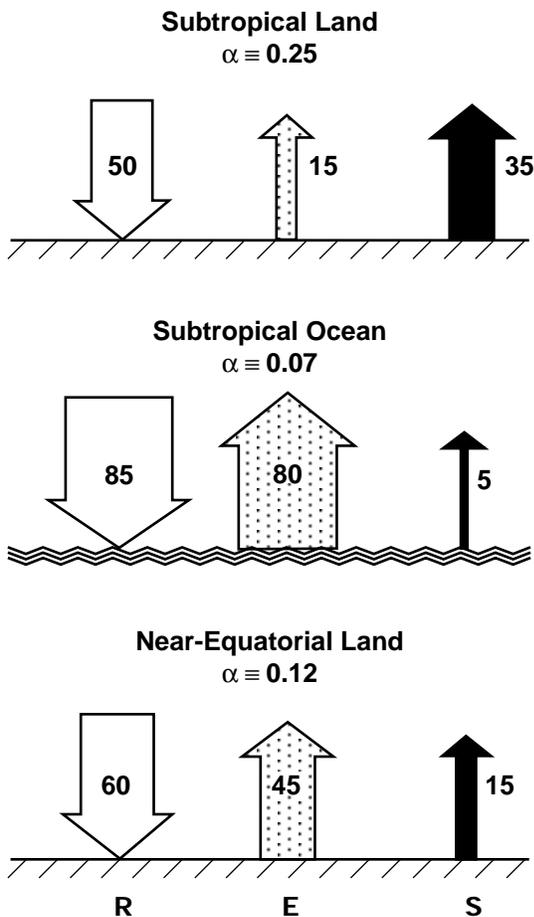**60**   **45**   **15**

R   **E**   **S**

Figure 6. Heat balances for some representative surface types. On average, net radiative heating of the surface is balanced by evaporative and sensible heat loss. Evaporation is the preferred mode of heat loss at warm temperatures; thus subtropical oceans lose heat mainly through evaporation.

Transfer of latent heat. Changes in albedo are not the only mechanism by which continental distribution affects the global energy budget and, hence, the global climate. An examination of the surface energy budget, in terms of sensible and latent heat fluxes (Figure 6), reveals a third means by which continental distribution influences climate. The largest energy fluxes at the surface of Earth involve moisture (latent heat flux). Clearly, the distribution of land and sea will influence evaporation and precipitation and therefore the total energy budget of the atmosphere.

Restrictions on ocean currents. Continents act as barriers to the flow of oceanic currents. The oceans transport a substantial amount of heat poleward (a maximum of 2–4 x 10^{15} watts at latitudes of 20–30 degrees, representing one-third to one-half of the total poleward heat transport by the oceans and the atmosphere). The distribution of land can block poleward heat transport by the ocean and may influence polar climates and the subsequent extent of ice and snow cover. Thus, the shape and size of the ocean basins become a factor in controlling global climate.

Thermal inertia. A continental surface has little thermal inertia. Basically, a continental surface responds rapidly to the current solar input. In contrast, the oceans have a large heat capacity. They store solar energy in summer and release it in winter. Therefore, the thermal inertia of the oceans tends to moderate the role of the seasonal cycle of insolation. The range of summer or winter temperatures could influence whether or not snow accumulated in the winter or melted in the summer. Again, in this example, the distribution of land and sea may be a controlling factor in the occurrence of glacial or nonglacial climates.

Continental Elevation

Climate is also influenced in a number of ways by the elevation of continents. Examples of this factor include temperature change and varying moisture content with changing elevation, the effect of mountains on large-scale atmospheric circulation, the effect of mountains on regional climate, and influences of topography on the general circulation of the atmosphere.

Effects of changing elevation. Atmospheric temperature decreases with height, a decrease referred to as the lapse rate. The average lapse rate is 6.5°C per kilometer of height. The colder temperatures at higher elevations promote snow accumulation, and therefore mountains become a base region for glaciation. Again, snow and ice have a very high albedo, so the occurrence of year-round snow and ice promotes cooling through modification of the energy balance.

Effects on large-scale circulation. The distribution of mountains influences the large-scale circulation of the atmosphere. In the simplest form, this influence is analogous to that of a large rock in a stream. The rock acts as a barrier to the flow of the fluid, and the current pattern is modified around and downstream from the barrier. The positions of the continents and oceans (causing differences in heating) and the distribution of regions of high topography control the position of the large-scale waves in the atmosphere, such as the jet stream, and therefore control the pattern of the weather. A change in topography may well control the distribution of cold air masses or the track of winter storms. Such changes could initiate glaciation in a particular region by promoting even greater cooling, or they could warm high-latitude regions which may otherwise be cool.

Effects on regional climate. The regional differences in climate associated with topography might be considered a third mechanism of climatic change. The windward sides of mountains tend to be much wetter, while a rain-shadow effect occurs in the lee of mountains. On the windward side the air is forced upward, cooling with increasing elevation. Since cooler air can hold less moisture, the cooling air mass reaches saturation and precipitation occurs. In the lee, deserts develop because the sinking air warms and therefore the level of saturation decreases as the air descends. For this reason, the different sides of mountain belts tend to have very different climates.

Effects on general circulation. Topography can exert an influence on the general circulation of the atmosphere or large-scale wind patterns. The general circulation is very complex, but it can be understood by a series of thought experiments. First, imagine a nonrotating Earth. On average, the air near the equator is heated the most and the air near the poles the least. In response to this, the cold, dense air at the poles sinks and spreads toward the equator, while the air over the equator rises and moves toward the poles. In this case the Northern Hemisphere winds near the surface would be from the north and the winds at higher altitudes would be from the south.

What happens if Earth rotates about its axis? Every point on Earth makes a complete circuit in a day. Near the poles, each point on the Earth's surface hardly moves; points on the equator, being farthest from Earth's axis, move most rapidly. What does this mean for the wind? Consider the case of air moving northward from the equator. The surface north of the equator moves more slowly, so the air moves toward the east—the winds are now from the southwest instead of the south. Similarly, the sinking cold air at the poles has almost no eastward speed, but south of the pole, the surface beneath moves eastward faster. Thus the polar air, which started out moving southward, begins to turn southwestward. The winds are from a northeasterly direction.

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Because of the rotation of Earth, the circulation in each hemisphere tends to be broken up into three cells. On the surface of the Northern Hemisphere, the winds near the poles are from the northeast (the polar easterlies), and the winds near the equator are from the northeast (the northeast trade winds). They are separated by a broad zone of west winds in the middle latitudes (the midlatitude westerlies). The easterlies and westerlies exert a frictional drag on the surface of the earth that must balance.

Now let's add mountain belts. A mountain belt in the easterly wind belt would exert a westward frictional drag on the winds. The opposite would occur in the region of the westerlies. Differences in pressure across mountains would play a role similar to the frictional drag. Therefore, the strength and the distribution of the easterlies and westerlies would change for an Earth with fewer mountains or a different distribution of mountains.

Carbon Dioxide and Plate Tectonics

There are numerous mechanisms by which aspects of plate tectonics directly modify the atmospheric or oceanic circulation, or directly influence the surface energy balance (albedo changes). Plate tectonic processes also modify the carbonate-silicate geochemical cycle.

Increased sea-floor spreading rates and increased plate destruction by subduction (faster plate tectonic processes) should result in greater outgassing of carbon dioxide from volcanoes. On long time scales, carbon dioxide production is balanced by consumption during weathering of igneous and metamorphic rocks. To maintain the atmospheric carbon dioxide concentration, the amount of carbon dioxide consumed by silicate weathering would also have to increase. Many researchers suggest that during the Cretaceous the rate of sea-floor spreading was nearly twice as great as the modern rate.

In addition, as stated earlier, higher rates of plate accretion are associated with higher sea level. For those times for which much higher

sea-floor spreading rates are hypothesized, increased continental flooding should occur (e.g., covering 20% of the present-day continental area in the middle Cretaceous). Consequently, not only was it likely that volcanic outgassing of carbon dioxide was higher than today, but the area of continental rocks exposed that would consume atmospheric carbon dioxide through the weathering of silicate rocks was substantially less.

This simple argument suggests that changes in the rates of plate tectonic processes can produce changes in the atmospheric concentration of the important greenhouse gas carbon dioxide. Such changes would occur on a time scale of tens of millions of years. Interestingly, the times of high sea level are often associated with planetary warmth and the times of low sea level are associated with cooler climates. This association may reflect the fact that atmospheric carbon dioxide concentration is tied to plate tectonics as part of the carbonate-silicate cycle.

Modeling to Explain the Extreme Warmth of the Cretaceous

A large number of mechanisms related to plate tectonics may be responsible for, or contribute to, the occurrence of major glaciations or extreme climatic warmth in Earth history. Climate models provide an opportunity to probe whether any specific forcing factor has been important in regulating past climates. Models are mathematical representations of the climate system. By changing a specific factor, such as land-sea distribution, a scientist can examine the model response and compare it with the information derived from the geologic record.

Evaluation of all the mechanisms described above is not straightforward. In fact, multiple mechanisms may be responsible for changes in climate, and there is no reason to suppose that the same mechanism produced each of the major climatic episodes illustrated in Figure 2. Since the changes in Cretaceous geography are

large and well known (Figure 5), study of the effects of the distribution of land and sea is a logical starting point to try to explain Cretaceous warmth. In order to assess the importance of geography, the model results can be compared with the surface temperature data plotted in Figure 3.

Paleogeography and Cretaceous Warmth

A hierarchy of climate models, from simple two-dimensional models that consider only the equator-to-pole temperature contrast to three-dimensional models that simulate the atmospheric circulation, has been applied to the study of the extreme climatic warmth of the Cretaceous. The results from each type of model simulation suggest that Cretaceous land-sea distribution is an important factor contributing to the extreme warmth. For example, one of the most comprehensive models of the atmosphere has been utilized to simulate the climate for the Cretaceous, based on the geography illustrated in Figure 5. The global average temperature for a simulated Cretaceous climate, based on this geography and without polar ice
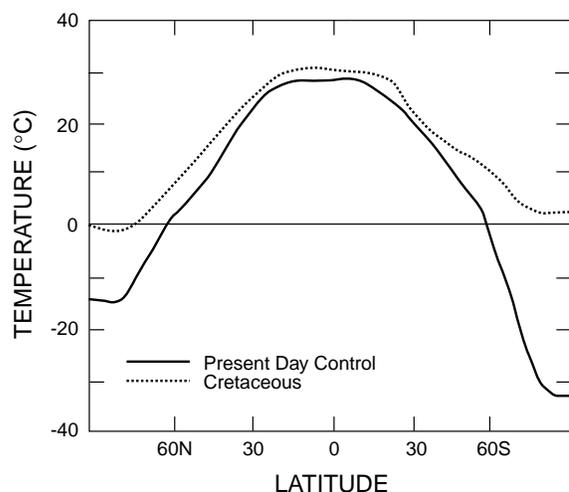

Figure 7. A comparison of the zonally averaged surface temperature (averaged across latitudinal belts) for the present-day control and "realistic" Cretaceous simulation.

caps, was 4.8°C higher than for a present-day control simulation. The warming was accentuated at high latitudes (Figure 7 shows a 15°C and 35°C increase at high northern and southern latitudes, respectively), corresponding very closely to the sense of the warming estimated from the geologic record. However, this result is problematic. Even though the warming is in the right sense, the magnitude is only half of what is required to explain the geologic evidence.

Interpreting the result is more difficult because the simulated Cretaceous warming includes changes in several different model parameters at once (continental positions, topography, sea level, and removal of the ice caps), relative to the present-day control simulation. What factors are responsible for the 4.8°C warming? Modelers attempt to dissect such complex cause-and-effect relationships by repeating the experiments, changing only one variable at a time to determine which were most responsible for the net change.

Interestingly, as Figure 8 shows, the warming of the Southern Hemisphere was due almost entirely to the removal of the Antarctic ice cap. (Remember that the difference between warm, ice-free climates and glacial climates is what we are trying to explain, yet the total simulated temperature difference at high southern latitudes seems to be associated with the removal of ice rather than some geographic factor!) Most of the Northern Hemisphere warming can be attributed to the difference in the amount of high-latitude land. The model showed no sensitivity to sea level, and although topography played an important role in governing regional climates, removal of all modern-day topography did not result in a substantial change in the global temperature.

The results of the climate model experiments are of considerable interest, and there are several possible ways to interpret them. First, assume that the model simulations are accurate. Clearly, then, the actual geographic changes result in only a modest Northern Hemisphere

warming and the cause of the difference be-tween global warmth and glaciation remains unsolved. Some additional mechanism would be required to explain the extreme warmth of the Cretaceous. Alternatively, assume that the geologic data is in substantial error. Certainly many difficulties are associated with determin-ing the temperatures prior to the historical
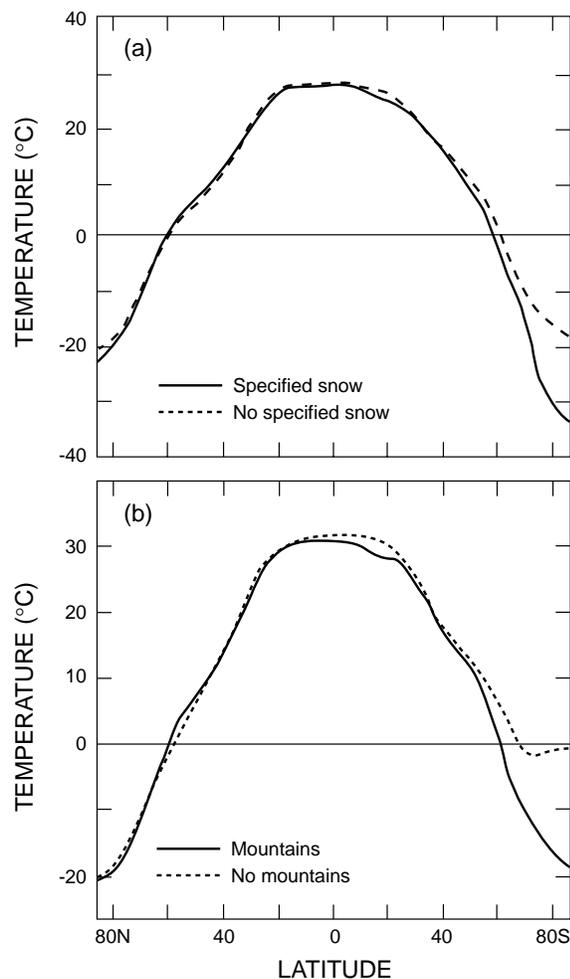

Figure 8. (a) A comparison of the zonally averaged surface temperature for the present-day simulation with and without specified permanent snow (fixed high albedo) on Antarctica and Greenland. (b) A comparison of the zonally averaged surface temperature for the present-day simulation with mountains and without mountains.

record. However, the model-simulated warming deviates considerably from the ob-servations; the simulations are well below even the lower limit of the geologic interpretations.

Second, assume that the modern climate models that are used here to simulate the Cre-taceous climate may be missing some funda-mental process or feedback mechanism, and therefore are unable to correctly simulate cli-mates very different from today's. This is a very real possibility as mathematical models are highly idealized representations of the climate. For example, the role of the oceans and the characteristics of the ice caps are poorly repre-sented in many climate models. Some research-ers have suggested that the role of the oceans, with their tremendous ability to store heat, is a key to the problem. Because of this storage of heat, oceanic regions have a smaller seasonal change in temperature than land areas at the same latitude. Using an energy balance climate model, Thomas Crowley and his colleagues demonstrated that the presence of oceanic re-gions near the poles can reduce summer tem-peratures over adjacent polar continental regions in comparison with situations of high polar continentality (see their article in Recom-mended Additional Reading). These research-ers suggested that cooler summer temperatures may not melt winter snow and ice, thus initiat-ing glaciation. The results suggest that the role of geography has not yet been fully explored and that the models must link the oceans, the atmosphere, and the ice caps in order to pro-vide an understanding of the history of Earth's climate.

What is the solution? Is the geologic record misinterpreted? Are models far too inaccurate? Do we need some additional forcing factor? The geological record and the model simulations provide one additional clue that helps to focus the investigation. Remember that global warmth appears to be well correlated with times of high sea level, yet the climate model results described earlier exhibited almost no response in an experiment that flooded 20%

of the area of the continents. This point suggests that something fundamental is missing from our simulation. We then remember that times of continental flooding are associated with rapid sea-floor spreading rates, and presumably higher carbon dioxide degassing rates.

Carbon Dioxide and Cretaceous Warmth

Although the geochemical models of the carbonate-silicate cycle indicate that changes in atmospheric carbon dioxide levels are plausible
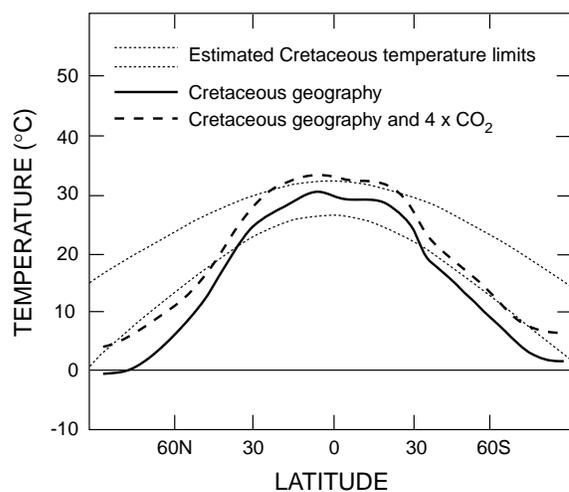

Figure 9. A comparison of the estimates of Cretaceous temperature limits (dotted lines) with predicted zonally averaged surface temperatures for Cretaceous geography (solid line) and for Cretaceous geography plus quadrupled carbon dioxide (dashed line). Predicted temperatures were derived from a general circulation model of the atmosphere (Barron and Washington, 1984).

and that higher levels in the Cretaceous are likely, there are no accurate measurements of atmospheric gas concentrations for periods tens of millions of years ago. However, continued experimentation with the climate model suggests that quadrupling the atmospheric carbon dioxide level in the Cretaceous, in addition to the differences in geography, could produce an 8°C increase in temperature compared to the present. For the first time the model-simulated temperatures (Figure 9) are close to the limits of the observations from the geologic record. A quadrupled level of carbon dioxide for the Cretaceous is well within the limits suggested by the geochemical models of the carbonate-silicate cycle.

Of course, improved models may give very different results. The carbon dioxide level required to achieve the extreme climatic warmth of the Cretaceous may be greater than or less than four times the present level. More importantly, the experiments suggest that several factors are required to explain the climate of a single time period, and, significantly, the mechanisms are interrelated. Earth's internal heat engine, which drives plate tectonics, alters climate directly through interactions of the atmosphere and oceans with the surface of Earth, and indirectly through geochemical interactions that alter the greenhouse character of the atmosphere. Both the direct effects of plate tectonics and the influence of plate tectonics on geochemical processes are required, in concert, to explain the large-scale changes in climate—from episodes of extreme warmth to the major periods of polar glaciation.