seen, the points overlap each other, and in general show a factor of about 3 between the optical and radar data. This describes the agreement between the two independent measurements of atmospheric propagation (*4*).

A comment is in order on Fig. 10. The calculation of the profile depends on adjustment of the radar cross sections by means of a series of empirical constants. A principal contributor is the humidity, which is obtained from coordinated rawinsonde launches. Difficulties with this coordinated data reduced the overlap between the time sequences of radar and optical data. The +'s and x's on the figure indicate data taken with east- or west-directed radar beams, respectively.

This is the only direct measurement of the phase front statistics on vertical path propagation that is available. Other experiments have generally produced measurements of log-amplitude fluctuations that were used to infer the phase statistics. The matching of the power spectral distributions obtained on several hundreds of passes shows that the theoretical predictions regarding the inertial theory of turbulence are correct. In fact, this experiment has shown the presence of small jogs in the phase power spectrum that have been predicted theoretically and indicates an interchange of energy between log-amplitude scintillation and phase power content.

In conclusion we can say that this current work provides a reliable body of experimental data that supports the theoretical predictions of the inertial theory of turbulence. Furthermore, this work establishes levels for the statistical behavior of the atmosphere on the basis of direct optical measurements. From the nature of the measurements and the correlation with the very-high-frequency measurements, it is seen that averaged thermosonde sounding of the atmosphere to establish propagation data is of such a nature that it does not adequately describe the optical propagation observations.

The above-stated numbers described a possible average state of the atmosphere. Because the measurements generally fitted normal distribution over about 95 percent of the range, it can be presumed that these measurements characterize the atmosphere, within the latitude range studied, quite well. No significant difference would be expected for different geographic locations. Since the weighting with altitude for the upward-going spherical wave case studied here requires very little weighting at low altitudes, this indicates little dependence on local orographic turbulence characteristics, as would be expected. The consistency of the data that were taken both in the mountains and the deserts and shore area confirmed this behavior.

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Terminal Cretaceous Extinction
Scenario for a Catastrophe

Stefan Gartner and James P. McGuirk

A number of mechanisms have been proposed for the massive extinction of biota at the Cretaceous-Tertiary transition some 65 million years ago. Most of them were reviewed recently (*1*). Two additional mechanisms have been proposed, however, since that review was compiled—the "greenhouse" mechanism (*2*) and the Arctic spillover model (*3*). In the first of these, McLean has proposed that the large land and marine reptiles as well as the marine plankton (plant and animal) and many marine invertebrates became extinct at the end of the Mesozoic era because of an increase in surface temperature of the earth, this increase being the result of an elevated carbon dioxide level in the atmosphere (greenhouse effect). McLean's mechanism is at variance with data regarding this event (*4*) and it presents a line of reasoning that is subject to debate (*5*). The second mechanism, proposed by Gartner and Keany, requires that the entire world ocean was covered by a layer of low density water that originated from a fresh or brackish Arctic Ocean, and that the drastically reduced salinity at the surface and intense oxygen depletion beneath the surface water caused the more or less instantaneous extinction of much of the marine biota. Citing recent studies of the paleomagnetic record across the Cretaceous-Tertiary boundary (*6–8*) and a detailed assessment of the vertebrate succession (*9*), Gartner and Keany concluded that the marine extinctions and the terrestrial extinctions probably were not simultaneous. This conclusion may have been incorrect (*10*), and here we will explore this point more fully.

Briefly, the mechanism proposed by Gartner and Keany requires that the Arctic Ocean became essentially isolated from the world oceans in latest Cretaceous (late Maastrichtian) time, probably by a combination of tectonism and a gradual regression of shelf seas. Because of excess precipitation and runoff, the salt water was flushed from the basin making the Arctic Ocean a fresh or brackish body of water. When rifting was initiated between Greenland and Norway some 65 million years ago, salt water from the North Atlantic intruded into the Arctic basin, while at the same time the lighter Arctic Ocean water spilled out over the North Atlantic and beyond into the South Atlantic and, through the Tethyan and Caribbean seaways, covering the entire ocean surface with a layer of water of low salinity. This low salinity layer caused the extinction of most of the stenohaline planktonic organisms that lived at the surface, whereas beneath the surface layer depletion of dissolved oxygen had a severe impact on organisms with a high oxygen requirement, benthos as well as nekton (*11*). Stable isotope data from late Cretaceous

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mollusks of the western interior of North America and from Greenland (*12*), and from across the Cretaceous-Tertiary boundary in deep-sea sediments (*13-14*), are in good agreement with this mechanism.

Outline of the Problem

The temperature structure of the late Cretaceous world oceans was vastly different from what it is today. Oxygen isotope data suggest that the vertical and, hence, the latitudinal temperature difference was perhaps not much more than 10°C, or less than half what it is today (*13*). On land, tropical vegetation extended to 45° to 50° north of the equator (*15, 16*) and, no doubt, an equal distance to the south; this vegetation points to a relatively small latitudinal temperature contrast. Nonetheless, an isolated Arctic Ocean, centered roughly around the North Pole much as it is today, would have been substantially colder than the rest of the world oceans, although how much colder is as yet unknown. If the temperature difference from equatorial to high latitudes within the contiguous oceans was 10°C, then it is probably not unreasonable to think that the isolated Arctic had a temperature lower by perhaps 15°C than that prevailing in Cretaceous tropics. For the purpose of our discussion, we assume such an initial temperature difference.

As the Arctic Ocean was flushed by intruding North Atlantic water, mixing would have occurred, the exact amount of mixing being determined by the density contrast of the water masses and by the size of the opening. We also assume that the volume of the water mass of the Arctic Ocean was approximately doubled by mixing with an equal volume of North Atlantic water during the flushing and spreading, and that the temperature difference was thereby reduced to 10°C.

Actual mixing would be far more complicated because the temperature contrast between the two mixing water masses (North Atlantic normal salinity water and Arctic Ocean fresh or brackish water) would be only about 5°C. Therefore, even if the Arctic Ocean water were mixed with two or three times as much North Atlantic water, the surface temperature reduction at the equator resulting from the spreading out of the Arctic Ocean water over the surface of the world oceans would still be greater than 10°C. In lower latitudes, mixing would occur with warmer waters; also a certain amount of solar heating of the cooler Arctic Ocean water would occur during the spreading. However, both of these are relatively less important than is mixing at the passage between the North Atlantic and the Arctic basin. The assumption of a 10°C temperature drop on the surface of most of the world oceans, though perhaps overly simplified, does not seem wholly unreasonable.

With the above conditions and assumptions as a starting point, we have attempted to assess the climate change that might have resulted on continents from such a rapid cooling of the ocean surface.

Climatic Impacts of the Arctic Spillover

Virtually nothing is known about the atmosphere's general circulation of 65 million years ago. Two major obstacles to a reliable reconstruction of the general circulation, over and above the dearth of data, are the following.

1) Continental and oceanic configurations were notably different from those of today. The uncertainty includes the position and height of major mountain ranges.

2) What little we know or can project about forcing on the Cretaceous atmosphere (from inferred surface climate) suggests an atmospheric regime so dissimilar to that of today that any attempted analog based on present-day circulation may be unrepresentative.

In view of the rather broad constraints and lack of hard data, a number of equally likely general circulations could be generated, and the one chosen may bear little resemblance to the actual circulation of the period. It is necessary only, however, that these circulations must be capable of describing the climate as we know it and, from a global point of view, they must at least be energetically consistent; that is, energy in and out of the atmosphere or in and out of the planet must balance. The hypothesized circulation is probably sufficiently close to the actual circulation with regard to energy processes, so that an assessment of first-order changes in climate can be made. Secondary changes (either in kind or in atmospheric parameters) may not be negligible and, in fact, may overwhelm the hypothesized changes in the hypothesized circulation.

We assume that incoming solar radiation (insolation) did not differ significantly 65 million years ago from what it is today. Surface albedo (reflectivity) probably was significantly less than what it is at present. Total planetary albedo was probably not greater than it is today. The oceans covered a somewhat larger proportion of the earth's surface as indicated by more extensive shelf seas; major deserts probably did not exist (except perhaps in Mongolia); and extensive snow and ice cover in high latitudes was lacking. An important ingredient to total albedo is cloud albedo; but there is no reliable way to make an accurate assessment of late Cretaceous cloud albedo. The average surface temperature of the earth is now about 288°K (15°C) and Cretaceous surface temperatures probably were reasonably close or slightly higher—tropical and subtropical ocean surface temperatures of about 295°K (22°C) with the more poleward oceans cooler and the continental surface somewhat warmer. The effective radiative temperature, a composite of the surface temperature and atmospheric temperature, is currently 255°K (*17*), and during the latest Cretaceous this temperature is assumed to have been approximately the same.

It has been suggested that during the middle Eocene, when vegetational zones were probably similar to late Maastrichtian vegetational zones, the existence of a diverse broad-leaved evergreen forest 60° north of the equator requires that the tilt of the earth's axis of rotation was less than 10° (compared to 23.5° today) so that these plants would receive sufficient light throughout the year to survive (*18*). Such a small tilt would also allow for a much more uniform annual distribution of insolation in polar regions. The net atmospheric cooling rate by radiation (insolation minus infrared radiation) is now about 1°K per day. The absence of ice in the polar areas during Maastrichtian—indeed during most of geologic time—indicates that this level of cooling was not maintained for long periods of time,

Summary. All the biotic changes that occurred at the end of Cretaceous time, including the extinction of the dinosaurs, may be the result of a single terrestrial catastrophe. The Arctic spillover model, first proposed to explain the marine extinctions, would have caused a rapid and intense change in the earth's climate including a lowering of temperature and of precipitation. This change in climate may have triggered a series of ecological disasters that included the radical change in the distribution of vegetation on the earth as well as the extinction of the dinosaurs.

which, also indicates that polar areas were not without sunshine during many days of the year.

Let us consider the effect of a 10°C drop in the surface temperature of most of the ocean area on the global energy balance of the atmosphere and of the planet.

Since the atmosphere cools radiatively, its temperature is maintained by latent and sensible heat flux from the surface. A cooler surface temperature will reduce this heat flux, and the atmosphere can be expected to cool by about the same amount as the ocean surface within a month or less, or essentially instantaneously. The effective radiative temperature will, therefore, probably decrease below 255°K. Again, if we assume a decrease of 10°K (10°C) in the earth's radiative temperature and no change in albedo, the incoming solar radiation will exceed the outgoing long-wave radiation by 36 watts per square meter. At this rate, it will take approximately 400 days for the top 30 meters of the ocean to return to its predisturbed temperature. Thirty meters is the minimum thickness of a layer formed by the assumed volume of the water in the Arctic Ocean. As indicated above, this volume and, hence, the thickness of the layer, could be increased two-, three-, or fourfold by mixing without raising the temperature significantly. The atmospheric heating process will, however, be controlled by an exponential-like decrease in heating rate, so that the actual time required for the ocean surface to return to its initial temperature will be of the order of a decade or more.

Late Cretaceous Climate

Before an estimate can be made of the change in atmospheric circulation or climate, it is necessary to first estimate the preexisting circulation and climate. In the late Cretaceous the general circulation probably was simpler than today. Considering the inferred temperature contrast between equator and pole and between ocean and continent during the Cretaceous, laboratory experiments suggest a circulation dominated by thermally driven cellular convection; that is, rising motion over warm areas, sinking motion over cool areas, and horizontal motion to satisfy continuity. This circulation is vastly different from the present-day general circulation, which is controlled by the polar front. However, the hypothesized circulation is similar to the present-day tropical Hadley cells.

The isothermal tropical ocean surface, such as is inferred for the latest Cretaceous, suggests convective circulation of the maritime atmosphere with, at best, weak horizontal organization—for example, a Benard-like convection. Persistent cloud cover would act to depress sea-surface temperatures under the convection, keeping horizontal temperature variations small. The remainder of the circulation is assumed to be dominated by extensive land-sea breezes close to continents and, possibly, additional circulation cells over the oceans, particularly over the vast Pacific Ocean. These cells were not driven by diurnal temperature changes like modern sea breezes but by permanent land-sea temperature differences (dictated by the assumption of no seasons). The weather conditions would be similar to the wet tropical monsoons of today. The continents, which would have been warmer than oceans, would be covered by extensive masses of slowly rising air; the oceans close to continents would be covered by slowly sinking air. Close to the ground (below about 4 kilometers), moist air would move inland. In the rising air, thunderstorms would be generated and the moisture would fall out on the continents. The dry air would return to the oceans in the upper atmosphere.

With respect to energy exchange, the air is warmed over continents through latent heat release and sensible heating (in the proportion of about 2 to 1 if the conditions are similar to those of today); and the energy input to the atmosphere by this process would be just the amount required to make up the atmosphere's radiative deficit.

Haurwitz (*19*) constructed a model based on Bjerkne's circulation theorem which predicts the intensity of a thermally driven circulation if the horizontal temperature contrast, the horizontal length scale of the circulation, and the friction are specified. On the basis of the behavior of modern thermally driven circulations and a scant knowledge of late Cretaceous climate, we can make a judicious choice of these parameters. If a particular vertical distribution of atmospheric moisture is assumed, a knowledge of the circulation intensity (which comes from the model) permits an estimate of mean continental precipitation. This precipitation amount then allows an independent check of the consistency of the circulation through the global energetics. For a length scale of 1600 km (a circulation that penetrates about 1600 km inland) and a land-sea temperature contrast of 8°C (22°C for oceans, 30°C for continents), a steady-state horizontal windspeed from ocean to land of 2.2 m/sec results. The mean precipitation generated by this circulation is 135 centimeters (53 inches) per year over land. The heat released by the condensation process amounts to a warming of the atmosphere of 0.9°K per day over the continental areas. Sensible heating accounts for about 0.45°K per day (because we have assumed a 2 to 1 ratio). The total heating over land is 1.35°K per day. Since only about 1°K per day is needed, heat will be returned to the maritime atmosphere to help compensate for its radiative deficit. To complete the energy balance, oceanic precipitation heating must have had a value on the order of 0.4°K per day. Thus, the oceanic precipitation would be about 60 cm/year. The resulting mean global precipitation (75 cm/year) would have been on the lower end of estimates of current values (*20*).

The model cannot resolve the distribution of precipitation but, barring topographic barriers, precipitation would be significantly greater than 135 cm/year close to the ocean and would decrease gradually as the distance from the moisture source increases.

Effect of Oceanic Cooling on Continental Climate

We assume that the modification to the ocean will not significantly alter the form of the circulation. (Even though this assumption may not be valid, that is not necessarily detrimental to the argument because we are considering only the minimum change that would result.) If the continents cooled about the same as the oceans, then the driving temperature differential between continents and oceans would remain unchanged. Therefore, the intensity of the circulation should remain unchanged. However, the precipitation must decrease because the cooler air cannot hold as much moisture as did the warm air before the general cooling. The amount of decrease in precipitation depends on the atmospheric water vapor distribution; however, for a reasonable vertical distribution, the primary dependence is on ocean surface temperature. Under these circumstances the estimated temperature change (10°C) would result in a decrease in precipitation to about 55 cm/year over continental areas (41 percent of predisturbed values), again with greatest precipitation near the coast and decreasing with distance from the ocean. The concomitant atmospheric heating by condensation will be reduced to 0.4°K per day; however, the radiative losses will also decrease, by about 0.15°K per day, because of the cooler effective radiation temperature. If the sensible heating remains unchanged (that is, 0.45°K per day), the net atmospheric heating over continents would provide no heat for export in the maritime atmosphere compared to conditions before the general cooling. The required amount of heat, by analogy with the predisturbed atmospheric balance, would be 0.25°K per day. This imbalance could be made up by modestly (i) increased oceanic precipitation, (ii) intensified circulation, or (iii) adjusted horizontal and vertical temperature distributions. A reduction of precipitation by 59 percent under the conditions outlined above, therefore, need not induce any large increase in the intensity of the circulation, nor need it trigger a radical reorganization of the circulation, although neither possibility should be ruled out.

Prior to the disturbance, precipitation of 135 cm/year is a typical value but not the maximum that can be expected. For example, there will be no theoretical upper limit to the amount of moisture in the air and, therefore, no upper limit to the amount of precipitation, except as determined from energy considerations and saturation of the entire atmosphere. Such a condition would require, however, that the atmosphere would always be marginally unstable and saturated (a situation where a thunderstorm is never far from a particular point, in space or time) in which case the following values result. With a sea-surface temperature of 22°C, the precipitation would be an average 170 cm/year. If the sea-surface temperature were reduced by 10°C, precipitation would drop to 51 percent of the value before disturbance, or 87 cm/year. However, precipitation and sensible heating in the atmosphere prior to the disturbance would be 1.7°K per day, which is somewhat large compared to today's value of about 1°K per day. Precipitation and sensible heating after the disturbance would be reduced to about 1.4°K per day. The resulting discrepancy in energetics may indicate changes in circulation that cannot be easily anticipated, such as changes in intensity, scale, or even kind of circulation. It should, therefore, be taken only as the upper limit of precipitation change possible in the system. The model makes no attempt to include such modifications as cloud-albedo effects, transient effects, or changes in general circulation regime, any one of which could conceivably overwhelm the assumed change.

The above discussion does not elucidate the specific details of the late Cretaceous climate. It is only one possible or likely scenario. Moreover, the predicted changes in climate associated with a substantial drop in sea-surface temperature, such as might result from flushing a fresh or brackish Arctic Ocean onto the world ocean, can only be outlined in the most general way. Nevertheless, it is apparent that the continental climate would become considerably cooler and drier.

An even more severe climatic perturbation might have resulted after the low salinity surface water had heated; the water may have become warmer than it was before the flushing episode because heating would reinforce the density stratification. This overheating may increase precipitation according to the model outlined above, or it may act to reduce the intensity or scale of the circulation because of a reduced temperature contrast between the ocean surface and land surface, which would conceivably result in an even more severe drought.

Support for the Model

The climate we have hypothesized for the late Cretaceous (Maastrichtian) world may seem too generalized, and the hypothesized change as a consequence of an Arctic spillover is only one of several possible alternatives. However, there is little doubt that the direction of the change we have hypothesized is compatible with the fossil record for terrestrial plants as well as for vertebrates. In western North America, tropical and subtropical floras were replaced by floras indicative of a temperate or seasonal climate (or both). The late Maastrichtian flora at Morgan Creek in southern Saskatchewan has its closest modern analog in the rain forests of the southeastern Asian-Indomalaysian region (*15*). Across the Cretaceous-Tertiary boundary it is estimated that about 60 percent of the plant species were replaced (*21*), and, in terms of the pollen record the ". . . change is perhaps reflected in part in an apparent trend from large, ornamented pollen types typical of animal vector pollination to smaller less ornamented pollen types common to wind pollinated plants" (*15*). The latter is ". . . an adaptation to seasonality, both in the dry-wet sense and in the cool-warm sense" (*15*). Some investigators do not consider this change as particularly drastic, or as requiring an extraordinary biological process (*21, 22*), although others hold an opposite view (*16*). Van Valen and Sloan (*9*) have summarized the available floral data from eastern Montana and suggest that the dominantly tropical and subtropical flora was replaced by a dominantly temperate flora. The proportion of entire margined leaves decreased, suggesting a decrease in temperature (*9, 18*). In Sakhalin, a very important turnover in the flora has been recorded across the Cretaceous-Tertiary boundary, one that also suggests a change to a cooler climate (*16*).

The widespread and impressively thick coal beds of the early Paleocene (such as those in Wyoming and Montana) may suggest that an even more humid climate prevailed after the Cretaceous-Tertiary transition than during the Maastrichtian. This is not necessarily incompatible with the scenario we have outlined. A worldwide drought that lasted for not more than a decade could have severely impacted the plant and animal communities without leaving any substantial evidence in the sedimentary record.

It may be significant that the floral changes appear to have been in two distinct stages, indicated by a transitional assemblage separating the typical Maastrichtian from the typical Paleocene pollen assemblages (*23*). Moreover, the floral changes were not transient but persisted beyond the early Danian (earliest Cenozoic) time. This could be interpreted to mean that the climate of the earth was altered radically and in such a way that it did not return to its predisturbance state soon, if ever. It is not certain that this alteration was caused solely by the climatic catastrophe we have outlined. Other factors such as continued regression of shallow shelf seas, altered oceanic circulation and the gradual rearrangement of continents may have acted to effect long-term climatic changes (*24*). Nevertheless, widespread destruction of the Maastrichtian tropical and subtropical rain forest, although a short-term event, could itself have contributed to longer term modification of the climate because of an associated increase in surface albedo reinforced by positive feedback (*25*).

Vertebrate Succession Across the Cretaceous-Tertiary Boundary

The reptile-dominated communities were in singularly good health during the late Cretaceous and, although these communities were seemingly in a decline during Maastrichtian time, they had experienced and survived several similar and far more severe declines during their long history (*1, 26, 27*). Van Valen and Sloan (*9*) concluded that the dinosaur-dominated fauna was replaced in an orderly manner in latest Maastrichtian time by the *Protungulantum* fauna which contained no dinosaurs. However, their evidence can also be interpreted to mean that some members of the dinosaur community survived the initial catastrophe and continued on into the earliest Cenozoic provided that the Cretaceous-Cenozoic boundary is lowered from its arbitrarily assigned level at coal bed "Z" to just below the appearance of the *Protungulatum* community within the Hell Creek Formation [figure 3 in (*9*)]. Paleomagnetic analyses of sections in Montana may indicate whether such moving of the boundary is justified.

It has been pointed out that it is the large animals on land that were decimated most completely at the end of Cretaceous time, while the smaller reptiles and the generally smaller mammals managed to survive (*2, 26*). This is precisely what would be expected in case of a drought that persisted for a whole decade or more. The reptiles of late Cretaceous time were adapted to an equable climate with a year-round constant food supply, and it is unlikely that they developed migratory habits such as are associated with seasonally variable food supplies. It is possible that these reptiles were highly territorial and that when food or water ran out in their territory, most of them simply died.

It is equally enlightening to consider which reptiles survived into Tertiary time. Prominent among these are the turtles, the lizards, the snakes, the crocodiles, and the crocodile-like *Champsosaurus*. The turtles and crocodiles would be the least likely to have been exterminated by drought. In upland areas they would, of course, die. Both groups could survive in relatively small bodies of fresh water, in the coastal areas, and in environments of the salt-marsh type, even though such environments may be too restricted to support a community of large dinosaurs that were herbivorous or carnivorous (or both). The turtles and crocodiles could, of course, survive handily if they were adapted to existence in salt water or in brackish water, unless their food chain was destroyed. Snakes and lizards also would have been affected far less severely by a prolonged drought than their giant cousins, especially if their habits were at all like those of their modern representatives.

How then did the dinosaurs end their days? We suggest that the climatic disturbance (a severe, prolonged drought of perhaps a decade or more accompanied by a general cooling, which may also imply greater seasonality) that was a consequence of the Arctic spillover may have been directly responsible for the extinction of many dinosaurs. The initial climatic disturbance may also have triggered a major climatic reorganization which led to a change in the composition of the flora over large parts of the world, and this may well have contributed to the decline and ultimate demise of many species that survived the initial climatic catastrophe. Some members of the late Cretaceous dinosaur community might have survived even this, but they were unable to adapt to, or find a place in, the rapidly evolving early Tertiary mammalian community, as has been suggested by Van Valen and Sloan. It appears, then, that the dinosaurs may have succumbed to a series of ecological disasters, some dying of thirst, others of hunger, and the stragglers may have perished because the reduced population density rendered the community unviable.

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