Environmental Effects of an Impact-Generated Dust Cloud: Implications for the Cretaceous-Tertiary Extinctions

Abstract. *A model of the evolution and radiative effects of a debris cloud from a hypothesized impact event at the Cretaceous-Tertiary boundary suggests that the cloud could have reduced the amount of light at the earth's surface below that required for photosynthesis for several months and, for a somewhat shorter interval, even below that needed for many animals to see. For 6 months to 1 year, the surface would cool; the oceans would cool only a few degrees Celsius at most, but the continents might cool a maximum of 40 Kelvin. Extinctions in the ocean may have been caused primarily by the temporary cessation of photosynthesis, but those on land may have been primarily induced by a combination of lowered temperatures and reduced light.*

The discovery of a high concentration of iridium at the Cretaceous-Tertiary (K-T) boundary (*1*) led to the suggestion that the earth was struck by a huge (~ 10 km in diameter) asteroid (*1*) or comet (*2*) 65 million years ago. This impact hypothesis is supported by the worldwide occurrence of the iridium anomaly in shallow (*1*) and deepwater marine sediments (*2*) as well as in freshwater sediments (*3*) and the concurrent enrichment of other noble metals and the depletion of rare earth elements (*4, 5*). Alvarez *et al.* (*1*) proposed that the impact event caused a massive amount of fine dust to be ejected into the stratosphere; the resulting debris cloud blocked sunlight and caused photosynthesis to cease for several years, leading to extensive marine and terrestrial extinctions. We conducted a series of aerosol physics and radiative transfer calculations to determine the time history of a massive dust cloud, its blockage of sunlight, and its impact on surface temperatures.

A one-dimensional (vertical), time-marching model of aerosol physics was used to evaluate the evolution of the concentration, altitude profile, and size distribution of the impact ejecta (*6*). This model includes the following physical processes: sedimentation, coagulation, horizontal spreading, vertical eddy transport, and rain-out. It is based on models that have accurately reproduced some observed characteristics of current stratospheric aerosols (*7*), noctilucent clouds (*8*), and meteoritic debris (*9*). We attempted to pick reasonable values for the model parameters (standard case), but this is a difficult task and, as indicated in Table 1, alternative choices for several parameters lead to significant modifications of our results.

The temporal evolution of the dust cloud's optical depth (*10*) for the standard case and a number of alternative cases with horizontal transport are shown in Fig. 1. A useful measure of the cloud's history is provided by the duration over which it has an optical depth greater than 10 (large optical depths), since little sunlight would reach the surface at such times. Large optical depths are sustained for about 3 months in the standard case. This interval is determined by the time it takes for tiny particles to coagulate together into larger particles and for the larger particles to fall out of the atmosphere (*6, 7*).

In the standard case, we assumed that

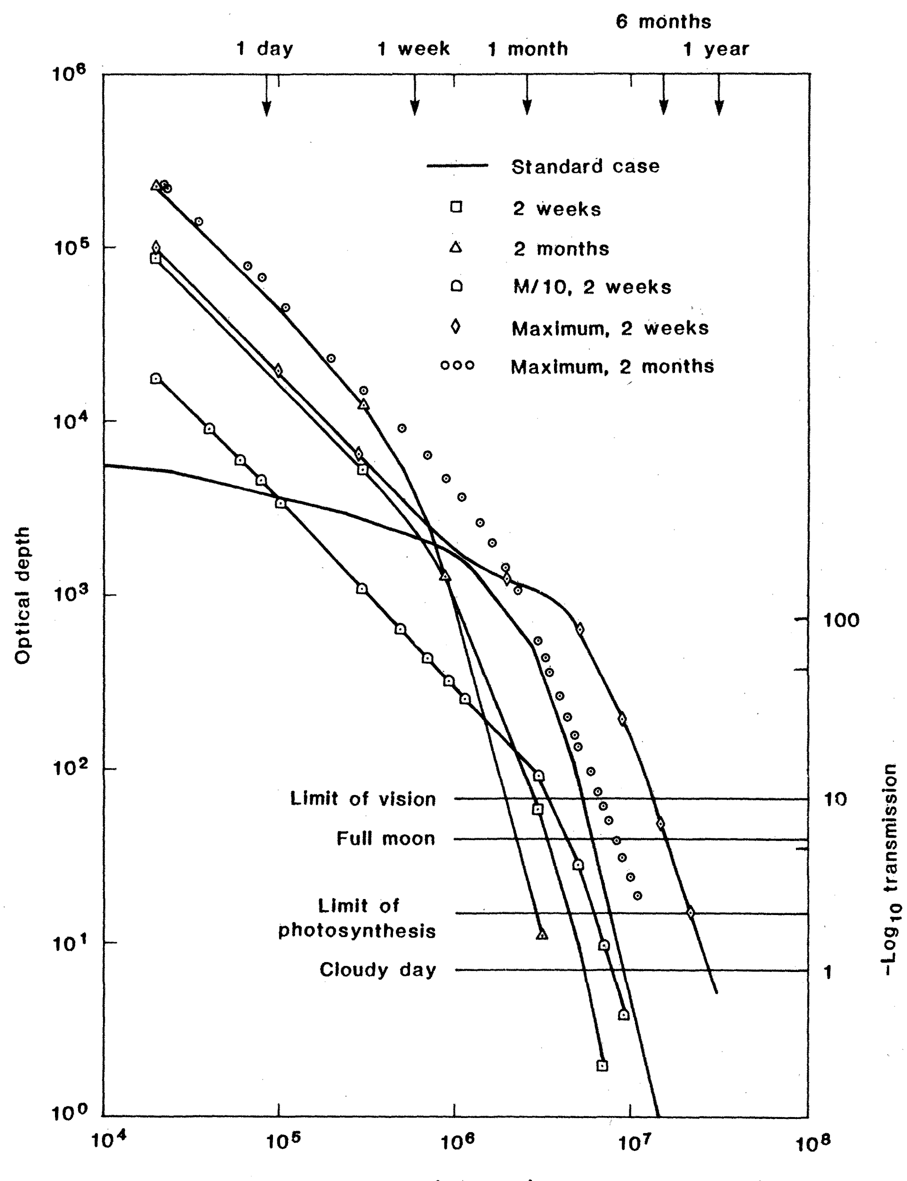

Fig. 1. Optical depth at a wavelength of 0.55 μm and atmospheric transmission at a wavelength of 0.48 μm as a function of time after the impact event for several different scenarios (see Table 1). In the standard case, the dust cloud is instantaneously dispersed over the entire globe. In the other cases, spreading occurs on various characteristic time scales. The initial mass density was chosen so that it would result in a dust loading of 1 g cm^{-2} if the cloud were uniformly dispersed with no loss. The case with *M*/10 refers to a reduction by a factor of 10 in the initial mass loading. Maximum cases correspond to situations where the particle density and coagulation efficiency are set equal to 1 g cm^{-3} and 0.1, respectively, and neither rainfall nor vertical mixing occurs. The plots represent a region near the impact site. Other areas of the earth are subject to the same temporal behavior once the cloud reaches them, but, depending on the spreading times, they do not experience the initial phases.

the dust was instantaneously distributed worldwide, as might occur if there were multiple impacting objects or if a single giant event sufficiently disturbed the atmosphere (*2, 6, 11*). Alternatively, the ejecta might have been confined initially to a small area and spread quickly because of strong positive feedback between dust heating and wind speed under conditions of large optical depths (*6, 12*). A good, physically appropriate analogy to such rapid spreading is provided by Martian dust storms, which grow from local to global proportions in only 1 to 2 weeks (*12*). As shown in Fig. 1, large optical depths can be sustained near the impact site for periods ranging from ~ 1 month to ~ 1 year for horizontal spreading times of ≤ 2 months.

The fraction of the incident sunlight (diffuse plus direct) that reaches the ground was determined by incorporation of the predicted size distributions and optical depths of the aerosol model in a numerically accurate radiative transfer program (*13*), with some allowance for the effects of nonsphericity on the single scattering properties of the particles (*14*). The optical constants of typical crustal rocks and volcanic ash were used (*15*), because excavated terrestrial material would be the dominant component of the impact ejecta (*11*). In Fig. 1, the atmospheric transmission at a wavelength of 0.48 μm is shown for the standard case; virtually identical transmission scales hold for the other curves, and the wavelenth dependence is slight at visible wavelengths.

The amounts of light on a cloudy day, at night, with a full moon, for zero net photosynthesis in the current marine environment (*16*), and for the limit of dark-adapted vision for humans (*17*) are shown in Fig. 1. For dust loadings in excess of 0.1 g cm^{-2}, after an impact event, the light level would be below that needed for human dark-adapted vision for 1 to 6 months with the most likely duration below this level being 2 months (*6*). For dust loadings of greater than 0.01 g cm^{-2}, the light level is below our adopted threshold for photosynthesis for 2 months to 1 year, with 3 months being the most likely duration below this level. Estimates of several years for this interval (*1*), based on the longevity of volcanic stratospheric debris, are inappropriate because during all but the first few months volcanic aerosols are composed chiefly of sulfuric acid generated in situ (*6, 7*).

The change in the earth's radiation budget and the changes in atmospheric and surface temperatures that would have resulted from the debris cloud were evaluated with a one-dimensional, time-marching, radiative-convective model (*6, 13, 15, 18*). Separate calculations were performed for continents and oceans; the surface temperatures of the continents were assumed to adjust instantaneously to the air temperature at the ground, and ocean surface temperatures were assumed to be limited in response by a 75 m deep, mixed layer. The temporal evolution of surface temperatures for several cases with different visible absorption coefficients (*15, 18*) and aerosol model parameters are illustrated in Fig. 2. The oceans cool by only a few degrees because of their large heat capacity. However, the continents cool by as much as 40 K, with this maximum cooling occurring 2 to 5 months after the impact. Atmospheric heat transfer from the oceans to the continents might cause the amplitude of the continental cooling to decrease—by no more than 20 or 30 percent in the interior of large continents and by a factor of two or three within several hundred kilometers of the coastline (*20*).

Under conditions of heavy dust loading, the surface cools because it receives virtually no sunlight and because it is hotter than the overlying stratospheric dust and thus loses energy by thermal radiative exchange with the atmosphere. No warming by a greenhouse effect is

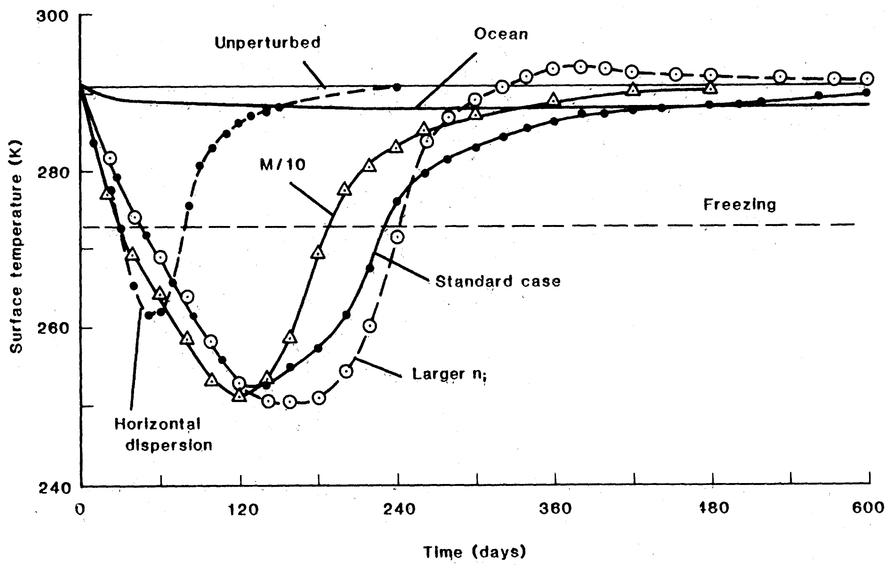

Fig. 2. Ocean and continental surface temperatures as a function of time after a large impact. Calculations were performed for two alternative choices for the imaginary index of refraction of dust in the visible, n_i (*15*). The horizontal dispersion case had a spreading time of 2 weeks (see the legend to Fig. 1 for case descriptions).

Table 1. Parameters used in the aerosol model.

Parameter	Standard	Variation	Sensitivity
	Atmospheric structure		
Vertical mixing	Current earth diffusion coefficients	No mixing	Slight
		Increased mixing in lower stratosphere	Potentially large (*24*)
Rain-out rate	Current earth profile	No rain	Slight
Horizontal transport time	Not included	2 weeks	Large
		1 month	
		2 months	
	Particle properties		
Density	3 g cm^{-3}	1 g cm^{-3}	Moderate
Coagulation efficiency	1.0	0.1	Slight
		0.0	Large
	Initial conditions		
Injection altitude	12 to 42 km	60 to 88 km	Slight
Mass injected	1 g cm^{-2} (*25*)	10 g cm^{-2}	Slight
		0.1 g cm^{-2}	Slight
		0.01 g cm^{-2}	Slight
Size distribution*	0.5 μm (*26*)	0.005 μm	Slight
		5 μm	Large

*Mode radius (log-normal with standard error of the mean, 1.8).

possible under these conditions, despite the greatly enhanced infrared opacity of the atmosphere. Rather, the surface temperature tends asymptotically toward the effective temperature at which the planet radiates to space.

The extensive extinctions that occurred near the end of the Cretaceous appear to be a combination of gradual extinctions over millions of years due to slowly changing environmental conditions and abrupt extinctions near the K-T boundary (*21*). Our calculations (Fig. 1) are consistent with the suggestion that the marine extinctions at the K-T boundary resulted principally from sunlight being blocked by a dust cloud, which caused a temporary cessation of photosynthesis and the collapse of food chains (*1*). Numerical experiments for such a situation in current marine ecosystems suggest that widespread, but not total, extinction would occur if photosynthesis were interrupted for several months (*22*). The high metabolic rates and lack of adaptations to seasonable variability of tropical marine organisms (*22*) may explain the observed preferential extinctions in tropical waters (*21*).

Cessation of photosynthesis may have affected terrestrial plants and animals less than marine ones because the biological carbon cycle on land has a turnover time scale of years, not months, as in the ocean (*23*). For terrestrial extinctions at the K-T boundary, we suggest that two other factors played dominant roles. First, the persistence of very low light for a few months might have reduced vision to such a degree that most animals, especially large ones, had difficulty locating adequate food. Second, the occurrence of substantially reduced temperatures for several months would have killed organisms that were not adapted to the cold or were not able to burrow underground. Small animals may have been better able to cope with both reduced light and temperature (*6*).

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25. The standard value for the injected mass is based on the typical thickness of the clay layer at the K-T boundary (*1*).
26. The size distribution is the same as that of volcanic dust (*27*) similar to that measured in airborne debris produced by nuclear explosions (*28*). The latter provides a good analog to hypervelocity impacts (G. Shoemaker, private communication).
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The Use of Strontium-87/Strontium-86 Ratios to Measure Atmospheric Transport into Forested Watersheds

Abstract. *Strontium-87/strontium-86 ratios indicate the sources of strontium in samples of natural waters, vegetation, and soil material taken from watersheds in the Sangre de Cristo Mountains of New Mexico. More than 75 percent of the strontium in the vegetation is ultimately derived from atmospheric transport and less than 25 percent from the weathering of the underlying rock. Much of the airborne strontium enters the watersheds by impacting on coniferous foliage, but deciduous foliage apparently traps little, if any, strontium-bearing aerosol. The strontium and presumably other nutrients are continuously recycled in a nearly closed system consisting of upper soil horizons, forest litter, and the standing crop of vegetation.*

The presence of vegetation on land surfaces complicates measurements of aerosol deposition from the atmosphere. The efficiency of foliage in trapping aerosols may differ from that of artificial collectors used to measure deposition (*1*). In addition to aerosol-derived material, any sample of natural foliage or throughfall (precipitation that has contacted foliage) contains an unknown proportion of material that has been carried from the roots to the foliage via the transpiration stream of the plant (*2*). Under favorable geographic and geologic circumstances, the isotopic composition of natural Sr may be used to distinguish aerosol and transpiration components and to allow direct measurement of present-day and long-term mean aerosol inputs to a forested watershed.

Radiogenic ^{87}Sr is continuously being added to ambient ^{87}Sr by the β decay of ^{87}Rb (half-life, 4.9×10^{10} years); ^{86}Sr is nonradiogenic, both Sr isotopes are stable, and the $^{87}Sr/^{86}Sr$ ratio can be measured with very high precision (*3, 4*). The $^{87}Sr/^{86}Sr$ ratio of soils and most near-surface continental rocks typically lies between 0.709, the ratio in modern ocean water, and about 0.720, the ratio in streams draining ancient Rb-enriched regions, such as the Canadian Shield (*5*). In old rocks that are enriched in Rb, such as Precambrian granite, the $^{87}Sr/^{86}Sr$ ratio may be much higher than the crustal average; young volcanic rocks may be