ENVIRONMENTAL EFFECTS ASSOCIATED WITH IMPACT EVENTS. E. Pierazzo, Planetary Science Institute (1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719, U.S.A.; betty@psi.edu).

Introduction: Impacts are among the most important mechanisms for the evolution, distribution and destruction of life in the solar system. They may have distributed primitive life forms in the solar system [1] and contributed directly to the evolution of life through extinction events [2], when they did not destroy it [3]. In particular, it was the wealth of studies of the Chicxulub (or KT) impact event and its connection to the end-Cretaceous mass extinction that brought to attention the important long-term consequences of large impacts on the climate.

Destructive effects of impact cratering: Environmental catastrophes occur when abrupt changes in the environment lead to extinction of living organisms. The event's abruptness is a crucial factor in producing an environmental catastrophe; large climate changes that develop over million of years do not seem to cause significant mass extinction events. Climate perturbations from large impacts would occur at most over few years, with the potential to trigger local or even global environmental catastrophes.

Most asteroid and comet impacts will result in localized effects, not global-scale extintions. The low energy end of impact events is based on comparison to nuclear blasts. Impacts with energies less than few thousands of Mt TNT equivalent (1 Mt = 4.184×10^{15} J) may cause at most a small to medium size crater. The airblast is likely the most destructive impact effect beyond crater formation and ejecta distribution. Using scaling from nuclear explosion data, Kring [6] estimated that the Meteor Crater impact event (20-40 Mt) would have cause total destruction 1 to 2 km away from the point of impact; trees would have been flattened by the blast wave over a radial distance of about 14 to 19 km, with up to 50%. casualty rates for human size mammals up to 9 to 14 km from the impact.

Several structures larger than 100 km in diameter are known on Earth today, but the only undisputed case of a large impact event that coincides with a mass extinction (KT) is the Chicxulub structure. Qualitative assessments of impact-related environmental and climatic effects abound, but a comprehensive quantitative investigation is still mostly lacking. The widespread effects caused by large impact events are usually divided into short term and long term [7].

Short-term effects extend up to few weeks after the impact, and are generally believed to have little influence on the long-term evolution of the climate. They include the localized direct effects of shock waves generated by the impact in the atmosphere, blast waves, and at the Earth's surface, such as earthquakes and tsunamis. More widespread effects include the production of toxic gases like NO_x, and HNO_3 by shock heating of the atmosphere from the entering projectile. Re-entering ejecta interacting with the atmosphere can cause intense frictional heating of the upper atmosphere. The resulting infrared heating could have been strong enough to ignite surface biomass [8]. This model is supported by evidence of soot at several KT boundary sites [9]. The fires, in turn, fill the lower atmosphere with smoke, dust and pyrotoxins in a scenario reminiscent of a nuclear winter [10].

Long-term effects extend over months to decades after the impact, and can have profound effects on the environment directly and indirectly by perturbing the overall climate. They include the radiative effects from stratospheric loading of small size dust [2,11] and climatically active gases. Release of climatically active gases is very dependent on the characteristics of the target: CO_2 and SO_x are released from sediments, while large amounts of water is released in oceanic impacts.

The effect of atmospheric dust-loading was first explored using simple numeric models of the atmosphere's radiative balance [12] for the KT impact. Results indicated that even a rapidly coagulating and settling dust layer may cause sub-freezing temperatures in continental interiors for few months after the impact and a global loss of photosynthesis for about half that time. A 3D atmospheric general circulation model simulation indicate a strong and "patchy" cooling on land, with temperature declining by up to ~12ºC, and a mild cooling over the oceans, accompanied by a collapse of the hydrologic cycle [11]. Later, it was realized that only the stratospheric portion of the fine (submicron) dust from an impact can affect the climate on a global scale for a significant period. The amount and size distribution of dust injected in the atmosphere by a large impact is still not well constrained [13].

Today, CO_2 is one of the main culprits of global warming. Impacts into terrains rich in carbonates could abruptly release large amounts of CO_2 in the atmosphere. Modeling studies of the KT impact [14,15] indicate that the impact does not release a significant amount of CO_2 when compared to the end-Cretaceous atmospheric inventory. However, a bigger contribution to the atmospheric CO_2 inventory may come from impact-related wildfires. Estimates from the identified soot layer at the KT boundary suggest the possibility of doubling the pre-impact CO_2 inventory [7]. This may cause a global warming of ~2ºC [15]. Lomax et al. investigated the global-scale response of terrestrial ecosystems to large increases in atmospheric CO_2 from the KT impact with a dynamic vegetationbiogeochemistry model [16,17]. Results suggest that a 4- to 10-fold increase of the atmospheric end-Cretaceous CO_2 inventory causes spatially heterogeneous increases in net primary productivity, and a biotic feedback mechanism that would ultimately help climate stabilization. They then artificially reduced the mean annual temperature by 6°C for 100 years, to addres the cooling effect of dust/sulfates, and added the effects of wildfires by burning 25% of the vegetation carbon (CO_2 concentration set to 10 times pre-impact levels) [17]. Model results indicate an initial collapse of the Earth's net primary productivity with total recovery within a decade. In their model, changes in productivity and vegetation biomass were larger at low latitudes, consistent with terrestrial paleobotanical data.

The release of SO_x and water vapor in the stratosphere results in the production of sulfate aerosols, as documented by volcanic eruptions. Sulfate aerosols scatter short-wave radiation, and can be strong absorbers of long-wave radiation (if >1 μm in diameter), causing a net cooling of the Earth's surface. The effect of injecting SO_x and H_2O in the stratosphere has been investigated with simple 1D atmospheric models combined with coagulation models. Using 2×10^{17}g (200 Gt) of SO_2 and water vapor, Pope et al. [18,19] found a significant reduction of solar transmission for about 8–13 years after the impact, causing a negative forcing about two orders of magnitude larger than CO_2 forcing. This would cause continental surface temperatures to approach freezing for several years [19]. Using a similar approach, Pierazzo et al. [20] obtained a slightly shorter duration of the sulfate effect, with a 50% reduction in solar transmission for 4 to 5 years after the impact, with a stronger overall forcing.

Oceans are a crucial component of the climate system. Their role in the long-term response of the radiative perturbation from a KT-type dust loading of the atmosphere were investigagted with a 2D, zonally averaged dynamic ocean circulation model [21]. Results indicate a sea surface temperature drop of several degrees in the first year post-impact, with strongest effects in equatorial regions. Deep-sea temperatures started to change only after ~100 years, and never exceeded few tenths of °C. Overall, the structure of the ocean circulation was not affected by the impact.

Constructive effects of impact cratering: Impact cratering can affect environments in a positive way, creating niches for life to florish. Modeling work on this aspect of impact cratering range from the potential delivery of complex organic molecules to planetary surfaces [22,23] to the creation of the conditions for a habitat more conducive to life [24,25].

The suggestion that a substantial fraction of the Earth's prebiotic inventory of organic molecule may have been delivered by infalling comets and asteroids is now about a century old [26]. Modeling studies have provided contrasting results. Recent modeling work using high resolution hydrocode simulations of impact cratering, indicate that at the time of the origin of life on Earth cometary impacts could have delivered large amounts of certain complex organic material, thus boosting the concentration of organic molecules crucial for the origin of life [22]. The same does not seem to have occurred on other planetary bodies, like Mars and the Moon, where most of cometary material and related surviving organics would reach escape [23].

Since the realization that hydrothermal systems are possible sites for the origin and early evolution of life on Earth (e.g., [24]) much attention has been directed to impact-related hydrothermal systems at the site of impact events. Evidence of hydrothermal circulation underneath terrestrial structures abound, as well as suggestions that hydrothermal systems could have formed underneath large Martian impact structures. Sophisticated computer models have been used to model the evolution of impact-related hydrothermal systems on Earth and on Mars [25,26], while modeling work is on its way to better characterize the early post-impact conditions that are conducive to the development of the hydrothermal system [27]. Modeling results suggest that heat generated in large impacts could drive substantial hydrothermal activity for hundreds of thousands of years, even under cold climatic conditions, supporting the idea that impact events may have played an important biological role on early Earth and on Mars [25,26].

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