Final Report for NASA Grant NAG5-10592, E. Pierazzo PI:
"Impacts and environmental catastrophes: A study of the effects of impact events on the climate system"

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Abstract

The goal of this work is to investigate the perturbation of the climate system due to large impact events.

Impacts are among the most important mechanisms for the evolution, distribution, and destruction of life in the universe. However, the possible climatic effects of an impact were not seriously considered until 1980, when Louis and Walter Alvarez suggested that the profound end-Cretaceous extinction might have been caused by the impact of an asteroid or comet about 10 km in diameter. Since then, the climatic change associated with the end-Cretaceous impact has become one of the most interesting and still unresolved questions in linking the well-known Chicxulub impact event and the end-Cretaceous mass extinction. While the end-Cretaceous impact offers the best-documented case of an impact affecting the Earth's climate and biota, even smaller (and more frequent in time) impacts could introduce significant perturbations of the climate comparable, if not larger, to the largest known volcanic perturbations.

We propose to study the mechanical and thermal state of the atmosphere following an impact event. This will be done by using both one-dimensional and three-dimensional climate models. When necessary, modifications of the state-of-the-art general circulation models will b e carried out.

We want to use the end-Cretaceous impact event as a case study. This allows us to take advantage of the extensive modeling of this impact event that has already been carried out through a previous Exobiology grant (NAGW-5159). Furthermore, a large experimental dataset, that can be used to constrain and test our models, is associated with the end-Cretaceous mass extinction (one of the largest of the Phanerozoic) and impact event.

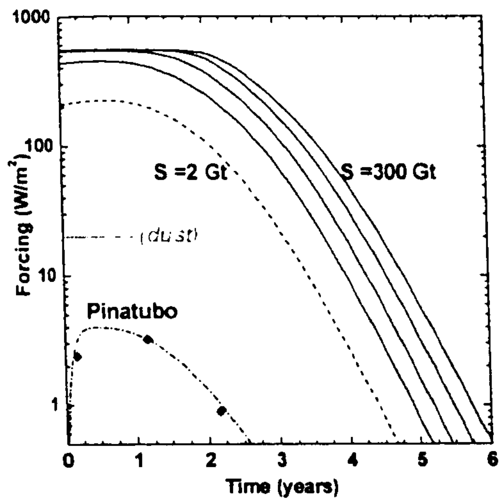
1. Research Results

In this project we have focused on characterizing climate forcing (change in the Earth's total radiative balance at the tropopause; [W/m^2]) and climate sensitivity (mean change in global surface temperature occurring in response to a specific radiative forcing; [K]) of impact-related loads of S-bearing gases into the stratosphere using one-dimensional (1D) atmospheric models from the National Center for Atmospheric Research (NCAR, Boulder, CO) coupled to a simple sulfate aerosols model. Some of the results have been summarized in a paper that was published in Astrobiology as part of the Rubey colloquium proceedings (Pierazzo et al., 2003). This paper also serves as a general review of modeling work done in the past to understand abrupt climate perturbation associated with large impact events and nuclear wars.

Results of forcing and sensitivity studies using 1D atmospheric models include:

Saturation Effect: Estimated K/T impact-related injection of S-bearing gases from the sedimentary layer range from about 20 to 100 Gt, causing a negative forcing of a few hundred W/m^2, about two orders of magnitude stronger than the Pinatubo volcanic eruption, for up to two years after the impact. The simulations indicate a *"saturation effect"*, Fig.1: the magnitude and duration of the forcing does not depend on the amount of S injected for loads above about 25-30 Gt. The forcing due to S-loading from the projectile alone is around one order of magnitude larger than for Pinatubo. Rough estimates of the forcing due to injection of dust (Fig. 1; Covey et al., 1994) are about one order of magnitude inferior to those relative to S-loading. For comparison, we estimated that the positive forcing (heating) from the impact-related injection of CO_2 is ~1-3 W/m^2, similar to the estimated forcing from greenhouse gases due to industrialization.

Fig. 1: Climate forcing (cooling) for various stratospheric S-loadings (20% SO_3, 80% SO_2). *Solid lines*: 10, 30, 100, 300 Gt; *dashed lines* (2 Gt): Maximum loading from the projectile. Modeled forcing form a Pinatubo-like injection (20 Mt SO_2, *dot-dashed line*) and observed Pinatubo forcing (*diamonds*; McCormick et al., 1995) are shown for comparison. *Gray line*: dust loading (Covey et al., 1994).



Residence Time: The stratospheric residence time of gases and particulate affects the duration of the forcing. Our initial assessment of climate forcing associated with the impact event assumed a stratospheric residence time typical of a steady-state atmosphere that is around 2 years. However, in an impact-perturbed atmosphere heating of the upper atmosphere and cooling of the surface may cause a stronger atmospheric stratification and favor smaller aerosol sizes. In this case, the stratospheric residence time for tracer gases ad sulfate aerosol may be much larger than in the unperturbed atmosphere. This increases the overall duration of the impact-related effects. Tests with the Sulfate Aerosol Model (SAM) coupled to the Column Radiation Model (CRM) from NCAR indicate that the main effect of increasing the stratospheric residence time by a factor of 2 to 5 (corresponding to between 4 and 10 years) from the adopted baseline value is a significant increase in the duration of the impact-related effects but hardly affects the maximum change in the net radiative fluxes at the tropopause (i.e., the radiative forcing).

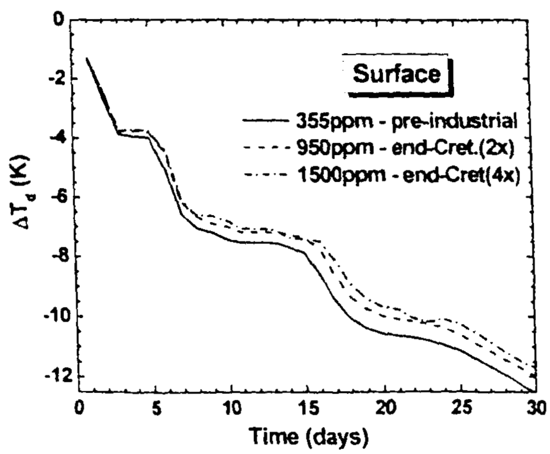
Aerosols' Characteristics: In this study we use a constant sulfate aerosol density of 1.83 g/cm^3 (corresponding to a pure sulfate aerosol). In reality, the density of sulfate aerosols depends on the sulfate-water solution, which, in turn, varies with temperature. We found that varying the density between 1.5 g/cmg^3 (equivalent to a solution of 60% H_2SO_4 and 40% H_2O) and 2 g/cm^3 (due, for example, to the addition of impurities to the sulfate aerosols) introduces at most an uncertainty of 15% in the forcing. The aerosols optical parameters (extinction coefficient, single scattering albedo, asymmetry parameter, and forward scattering fraction) needed for the atmospheric models are estimated using Mie theory. Small impurities, especially dust and soot, strongly affect the optical properties of the aerosols, especially in the visible and near-infrared, by modifying the imaginary part of the index of refraction. This in turn affects the transmission in the aerosol layer. The overall effect, however, does not appear to be dramatic, and it has few repercussions on the overall radiative forcing.

S-bearing Gases: While there is little doubt that significant amounts of S-bearing gases were released in the impact event, the distribution of S among various S-oxides is not well characterized (e.g., Ohno et al., 2003). Our results indicate that the release of S mainly as SO_3 causes an early production of sulfate aerosols, thus maximizing the abruptness and magnitude of the climate forcing. The release of sulfur as SO_2 slows down the sulfate-formation process, resulting in a smaller initial forcing that extends overall over a longer period. In particular we find that although the overall aerosol production for the SO_2 case is almost two orders of magnitude smaller than that of the SO_3 case the maximum radiative forcing decreases to only about two-thirds of the SO_3 case (in agreement with the saturation effect discussed in point *a)*).

Climate Sensitivity: As a next step in complexity, we coupled the SAM to NCAR's single column model, SCCM. Although this does not provide a complete assessment of the mean change in global surface temperature in response to the atmospheric S-loading, it allows us to investigate the immediate response of the atmosphere to perturbation from impact-related sulfate aerosols. SCCM is equivalent to a grid column of the more complete global climate model CCM3 (Kiehl et al., 1996) where the performance of the parameterized physics for the column is evaluated in isolation from the rest of the large-scale model. While lacking the more complete feedback mechanisms available to an atmospheric column imbedded in the global model, it provides an inexpensive first look at the response of the system to the forcing introduced by a particular parameterization. The lack of horizontal feedbacks, however, implies that we can only evaluate climate sensitivity immediately following the injection of the S-bearing gases, up to about a month or two after the impact loading. Any longer-term climate sensitivity can only be investigated with a fully coupled climate system model.

The presence of the S-bearing gases and sulfate aerosols (strong LW absorbers) initially in the upper atmospheric layer of the model produces a significant change in the atmospheric radiation fluxes. This results in a strong heating of the stratosphere accompanied by a strong cooling at the Earth's surface (Pierazzo & Hahmann, 2001; Pierazzo et al., 2003). Compared to a Pinatubo-

Fig. 2: Combined impact-related S (100 Gt) and CO_2 loading at 37°N, 97°W (North America) for present (pre-industrial= 280 ppm; solid line) and end-Cretaceous atmospheric CO_2 (2×pre-industrial= 580 ppm; 4×pre-industrial=1120ppm).



type eruption, the model estimates that in the uppermost layer the temperature increases by (at least) several tens of degrees, more than an order of magnitude that associated with Pinatubo. At the surface the impact-produced cooling is around several degrees, again at least an order of magnitude that associated with Pinatubo. Temperature changes are strongest over continental interiors than over the oceans, regardless of latitude or season. Even at coastal location the nearby vicinity of the oceans act to mitigate the temperature changes due to the stratospheric aerosols. At the top of the atmosphere, however, the influence of the oceans below is minimal, and latitudinal (high versus low) and seasonal (summer versus winter) effects become the main factors influencing the magnitude of temperature changes due to stratospheric aerosols. Adding the impact-loading of CO_2 to the S-loading effect mitigates only slightly the overall effect, as shown in Fig. 2.

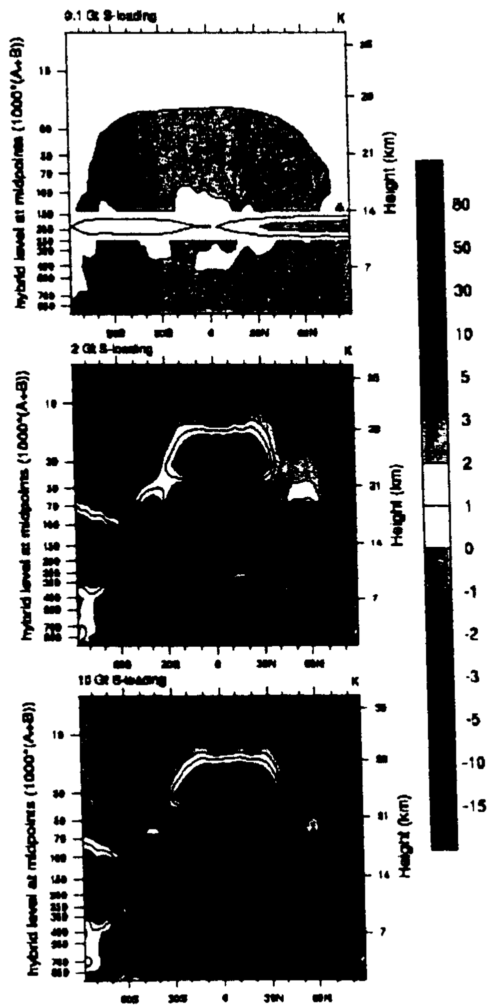


Fig. 3: Zonal average temperature deviations from the unperturbed case for a 0.1, 2, and 10 Gt S-loading in the upper stratosphere 8 days after injection, from CCM3 test runs.

<u>CCM3 testing</u>: We have begun testing of NCAR's three-dimensional (3D) atmospheric model CCM3 (Kiehl et al., 1996) after coupling the sulfate aerosol model. Contrarily to the 1D atmospheric codes, the 3D code has continuously been updated to improve the various physics components and code coupling. Therefore, the coupling of the SAM to the 3D code is not the same as for the 1D code, and had to be further tested and refined. Preliminary tests have highlighted few problems that have helped in improving the overall code. Figure 3 shows CCM3 test runs results for various S-loads before the 10 Gt case blows up (8days). The size of perturbations associated with the impact is already revealing limitations of some parameterizations used in the atmospheric model. For example, in CCM3 the parameterization of the saturation vapor pressure of water is valid for temperatures up to 375.16K; however, impact-effects can cause stratospheric temperature increases above that maximum limit, causing the model to crash. This parameterization must be adjusted to allow for a wider temperature range. It is also becoming clear that the vertical resolution of CCM3 in the stratosphere is too coarse. This makes the model less stable when very large perturbations are involved. A higher vertical resolution in the stratosphere may help stabilize the simulation all together, but this requires a different atmospheric model and the availability of large and fast computers.

References:

Covey C., Thompson S.L., Weissman P.R., MacCracken M.C. (1994) *Global climatic effects of atmospheric dust from an asteroid or comet impact on Earth*, Global Planet. Change **9**, 263–273.

Kiehl J.T. et al. (1996) *Description of the NCAR Community Climate Model (CCM3)*, NCAR/TN-420+STR, 152 pp, Nat. Center. Atmo. Res., Boulder, CO.

McCormick M.P., L. W. Thomason, C.R. Trepte (1995) *Atmospheric effects of the Mt. Pinatubo eruption*, Nature **373**, 399.

Ohno S., Sugita S., Kadono T., Hasegawa S. Igarashi G. (2004) *Sulfur chemistry in laser-simulated impact vapor clouds: implications for the K/T impact event*, Earth Planet. Sci. Lett. **218**, 347-361.

Pierazzo E. (2001) *Climate forcing from the stratospheric injection of impact-produced sulfur*, 32nd Lunar Planet. Sci. Conf., Abst. #1196, Houston, TX.

Pierazzo E. & Hahmann A.N. (2002) *Chicxulub and Climate: Investigating the climate sensitivity to stratospheric injections of impact-generated S-bearing gases* 33rd Lunar Planet. Sci. Conf., Abst. #1269, Houston, TX.

Pierazzo E. & Hahmann A.N. (2001) *Investigating the climate sensitivity of stratospheric injections of large amounts of S-bearing gases*, AGU Fall Meeting, Abst. #6301, S. Francisco, CA.

Pierazzo E., Hahmann A.N., Sloan L.C. (2003) *Chicxulub and Climate: Effects of Stratospheric Injections of Impact-Produced S-bearing Gases*, Astrobiology **3**, 99-118.

2. Relevant Publications and Presentations associated with this grant

Papers:

1. Pierazzo E.: *Climatic effects associated with the Cretaceous-Tertiary Impact Event.* Invited for the Encyclopedia of Paleoclimatology and Ancient Environments (Kluwer Academic Publ. Earth Science Series). In Press.
2. Pierazzo E., Hahmann A.N., Sloan L.C.: *Chicxulub and Climate: Radiative perturbations of impact-produced S-bearing gases*, Proceedings of the Rubey Colloquium. Astrobiology 3, 99-118, 2003.

Abstracts:

1. Pierazzo E.: *Assessing atmospheric water injections from oceanic impacts*, 36th LPSC (2005) Abst #1987.
2. Pierazzo E., A.N. Hahmann: *Chicxulub and Climate: Investigating the climate sensitivity to stratospheric injections of impact-generated S-bearing gases*, 33th LPSC (2002) Abst. #1269.

3. Pierazzo E., A.N. Hahmann: *Investigating the climate sensitivity of stratospheric injections of large amounts of S-bearing gases*, AGU Fall Meeting 2001 (2001), Abst. #6301.
4. Pierazzo E. *Climate forcing from the stratospheric injection of impact-produced sulfur*, 32nd LPSC (2001) Abst. #1196.

Invited Presentations to meetings and symposia:

1. Pierazzo E.: *Assessing atmospheric water injections from oceanic impacts*, 36th LPSC (Houston, TX) March 14-18, 2005. Oral Presentation.
2. Pierazzo E.: *Environmental catastrophes associated with large impact events: The Cretaceous/Tertiary boundary impact event* Short Course on "Role of Water: The Geophysical and Geochemical Constraints on the Distribution, the State and Reaction of Water in the Earth" (Sendai, Japan) November 13, 2004. Guest Lecturer.
3. E. Pierazzo: *Modeling the KT Cratering Event, Major Terrestrial Impacts: Modelling and Visualization*. Open Colloquium of the American Museum of Natural History (New York) Jan. 17, 2003. Invited Oral Presentation.
4. E. Pierazzo: *Modeling the Cretaceous/Tertiary impact event: The onset of an environmental catastrophe,* Mesozoic-Cenozoic Bioevents: Possible links to impacts and other causes. International Symposium (Berlin, Germany) Nov. 21-23, 2003. Invited Oral Presentation.
5. E. Pierazzo: *Impacts and the evolution of planetary biospheres*, Bioastronomy 2002: Life Among the Stars, IAU Symposium 213 (Great Barrier Reef, Australia) July 8-12, 2002. Invited Oral Presentation.
6. Pierazzo E., A.N. Hahmann: *Chicxulub and Climate: Investigating the climate sensitivity to stratospheric injections of impact-generated S-bearing gases*, 33th LPSC (Houston, TX) March 11-15, 2002. Oral Presentation.
7. E. Pierazzo: *Chicxulub and Climate: Effects of stratospheric injections of impact-produced S-bearing gases*, Rubey Colloquium (UC Los Angeles) Feb. 9-10, 2002. Invited Oral Presentation.
8. Pierazzo E., A.N. Hahmann: *Investigating the climate sensitivity of stratospheric injections of large amounts of S-bearing gases*, AGU Fall Meeting (S. Francisco, CA) December 10-14, 2001. Poster.
9. Pierazzo E.: *Climate Forcing of an impact-related sulfur loading of the Stratosphere*, 6th Annual CCSM Workshop (Breckenridge, CO) June 26-28, 2001. Poster
10. Pierazzo E.: *Climate forcing from the stratospheric injection of impact-produced sulfur*, 32nd LPSC (Houston, TX) March 12-16, 2001. Oral Presentation.