ASSESSING ATMOSPHERIC WATER INJECTION FROM OCEANIC IMPACTS.

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Introduction: Collisions of asteroids and comets with the Earth's surface are rare events that punctuate the geologic record. Due to the vastness of Earth's oceans, oceanic impacts of asteroids or comets are expected to be about 4 times more frequent than land impacts. The resulting injections of oceanic water into the upper atmosphere can have important repercussions on Earth's climate and atmospheric circulation. However, the duration and overall effect of these large injections are still unconstrained.

This work addresses atmospheric injections of large amounts of water in oceanic impacts.

Impacts on Earth: Earth is continually hit by a variety of solid debris leftover from the solar system formation. Of this, rare large extraterrestrial debris pierce through the atmosphere and hit the Earth's surface, creating craters tens to hundreds of kilometers in size. These impacts will trigger a series of events that may produce significant long-lasting environmental effects and may affect the evolution of life. Many possible effects of large impacts have been investigated to date [1], but their importance and duration, as well as their connection with evidence from the geologic record is still highly incomplete. Presently, the only case of a clear coincidence of an impact event and a major mass extinction on Earth is the end-Cretaceous impact that created the famous 180-km diameter Chicxulub structure (Yucatan, Mexico).

Several short-term and long-term environmental effects result from a large impact event [1]. Short-term effects, extending up to few weeks after the impact, are believed to have little influence on the long-term evolution of the climate. Long-term effects extend over months to decades after impact, and can have profound direct and indirect effects on the environment by perturbing the overall climate. Among the most important long-lasting environmental/climatic effects of impacts are radiative effects from the stratospheric loading of small size dust [2,3,4,5] and greenhouse gases such as CO_2 and water vapor. Unique to the Chicxulub impact is the climatic effect of sulfur-bearing gases [6,7], whose importance has been inferred from the climatic effects associated with major volcanic eruptions. S-rich target rocks are not common on Earth, covering only about 5% of Earth's surface. The Chicxulub event may thus have triggered uncommonly lethal environmental perturbations that may help explain its connection with a major mass extinction.

Oceanic Impacts: Over 70% of the Earth's surface is covered by oceans and seas, making oceanic impacts about four times more likely than land impacts. In oceanic impacts, injection of dust in the stratosphere, and the associated thermal pulse and radiative effects, occurs if the impactor strikes the ocean's floor. Zahnle [8] identifies a threshold for sig-

nificant production of dust in an oceanic impact by equating the mass of a spherical impact to the mass of water encountered in its motion in the ocean. For a typical asteroid density of 2.5 g/cm^3 and ocean depth of 4 km (mean depth of Pacific and Atlantic oceans) this corresponds to an asteroid 2.5 to 5 km in diameter (lower limit corresponds to a vertical impact, upper limit to an impact angle of ~30º from the surface). Overall, the amount of dust produced in a large oceanic impact, is bound to be a fraction of the dust that would be produced in a land impact, thus reducing radiative and friction heating effects. It is improbable that a Chicxulub-size oceanic impact would inject enough dust in the stratosphere to induce global fires [9] as well as a darkness-at-noon scenario [2].

The short-term and most famous environmental effect of oceanic impacts is the generation of tsunami. The importance of waves generated by explosions at or below sea surface or by impact events have received considerable attention over the years, but conclusions are still mixed. Some studies raise the hazard of impact-generated tsunami [10,11], others de-emphasize the overall effect [12,13]. The consequences of impact-generated tsunami depend also on local conditions, like distance from impact, ocean's depth and coastal configuration (offshore slopes), and cannot be addressed easily in a general context. In the end, although bearer of potentially devastating effects in coastal regions a tsunami constitute a short-term, mostly localized effect of an oceanic impact.

A global effect of oceanic impacts that can perturb the global climate for a significant period of time is the injection of large amounts of water into the atmosphere. This is a still a highly unexplored impact perturbation effect. Toon et al. [1] estimated that an impactor around 5 km in radius would vaporize about 4 times its mass of ocean water.

3D impact simulation with the hydrocode SOVA [14], coupled to tabular versions of the ANEOS equations of state [15], have been carried out to model the impact of a 6km-radius asteroid and a 6.5km-radius comet impacting at 15 and 25 km/sec, respectively and 45º (most probable angle of impact) a 4 km deep ocean. A spatial resolution of 20 cells-per-projectile-radius is maintained over a central region around the impact point, followed by progressively lower resolution. Tabular versions of ANEOS equations of state for granite [16], water [17], and a tabular air equation of state are employed to model the Earth's crust, ocean, and atmosphere, respectively. For accurate estimates of material's volumes over 1,000,000 lagrangian tracers mark each computational target cell around the impact point. Threshold pressures for estimating incipient and complete melting of pure granite are 46 and 56 GPa,

and for incipient and complete vaporization of water are 10 and 40 GPa.

The results indicate that the amount of water vaporized is ~2.5 to 3 times the impactor mass. About half of this vapor is injected in the upper atmosphere early (<10 s after impact), before the injection of significant rock ejecta. An equivalent amount of liquid water is injected into the upper atmosphere at the same time, for a total of ~3.3 Gt of water delivered to that region. Crustal material is injected in the upper atmosphere at a later time.

Water Injections and Climate: Water vapor is the dominant greenhouse gas in the atmosphere and provides the largest known feedback mechanism for amplifying climate change [18]. It influences the atmosphere's heat budget and radiative balance. Overall, the hydrologic cycle is one of the environment's key components. Any change in precipitation, evapotranspiration or runoff may seriously affect the local and global evolution of the biosphere [19].

The water content of the atmosphere is relatively small (~0.3% by mass and 0.5% by volume of the atmosphere). Most of the atmospheric water resides in the troposphere. The present upper atmosphere has a water vapor mass of about 6×10^{-4} g/cm^2; based on temperature and saturation vapor pressure estimates, it could hold up to about 0.2 g/cm^2 or ~1000 Gt. Thus, the oceanic impact of a large object can deliver to the upper atmosphere more than 3 times the amount of water vapor it can hold almost instantaneously.

The evolution of the post-impact atmosphere is highly unconstrained. Friction heating from ejecta will heat the upper atmosphere, which in turn will be able to hold more water (the equilibrium vapor pressure of water increases rapidly with temperature). Excess water vapor will condense out thus releasing further heat to the atmosphere; liquid water (ice if temperatures are low enough) will form clouds. Water is a strong absorber of infrared radiation. Thus, water vapor and clouds will trap a large fraction of the outgoing terrestrial radiation in the atmosphere. On the other hand, clouds, especially ice clouds in the upper atmosphere, block incoming solar radiation from reaching the Earth's lower atmosphere and surface. These two effects are opposite to each other. The prevalence of one or the other determines the final effect on the climate (cooling or warming), depending on the amount of water and the characteristics of the stratospheric clouds (ice/liquid and size of particles). As water condenses it will slowly move through the atmosphere, and temporarily increase the humidity of the troposphere. While it is expected that atmospheric perturbations will be long-lasting, it is unclear that they can last long enough to affect the response time of the oceans (>10 years), the ultimate drivers of climate change.

Atmospheric Chemistry: Another important consequence of large injections of oceanic water into the upper atmosphere is the potential perturbation of stratospheric chemistry. Recently, it has become evident that atmospheric chemistry has an important effect on the climate system. Water vapor is the source of free radicals OH and HO$_2$ which participate to ozone chemistry, contributing to its destruction. OH further contributes to ozone destruction by activating Cl while deactivating NO. Furthermore, seawater is a solution of salts, contributing to an average salinity of ~35‰ (35g of salts per kg of water). Salts in today's seawater are mostly Cl (~55%), Na (~30%) and SO$_4$ (~8%)[20]. The injection of about 3.3×10^{15} kg of seawater in the stratosphere thus provides roughly 64 Gt of Cl and 3 Gt of S (mainly as SO$_4$). The latter is larger than that injected by the Pinatubo volcanic eruption in 1991. Much work is still needed to understand the effects of such injections and the overall importance for the Earth's climate system.

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Figure 1: Normalized volumes of water and crustal material injected in the upper atmosphere (>8 km) for a Chicxulub-size oceanic impact. Water is shown in blue, crustal material in black. Solid and lines represent an asteroidal impact (v=15 km/s), dashed lines represent a cometary impact (v=25 km/s).