IMPACT TRIGGERING OF THE SNOWBALL EARTH DEGLACIATION? C. Koeberl,[1] B. A. Ivanov[2], and J. Goodman[3]. [1]Center for Earth Sciences, University of Vienna, Althanstrasse 14, Vienna, A-1090, Austria, (christian.koeberl@univie.ac.at), [2]Institute for Dynamics of Geospheres, RAS, 119334, Moscow, Russia, (baivanov@idg.chph.ras.ru), [3]Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA (jgoodman@whoi.edu).

Introduction: Observational evidence supports the idea that the Precambrian Earth's history has episodes of total ice coverage of the planet (e.g. [1, 2]). The Snowball Earth hypothesis [1] states that the Sturtian (about 710 Ma) and Marinoan glaciations (about 635 Ma) were of global extent and lasted for several million years each. A variation of this hypothesis, called the Slushball Earth, requires milder conditions without substantial equatorial sea ice [3, 4]. The Snowball Earth glaciations would have ended abruptly in a greenhouse environment, whereas the Slushball would have experienced a slower deglaciation. A variety of reasons for initializing global glaciation have been discussed, including decreased solar luminosity [5], a continent breakup [6] and the passage of the Solar System through a molecular cloud [7]. Not only is the cause of a possible glaciation unclear, but the cause and mechanism of deglaciation is also debated (e.g. [8]).

The goal of our study is to investigate if it is conceivable that a large-scale impact event might have triggered the deglaciation. The problem of the climatic effects of large impact events is not clear, as previously a Chicxulub-scale impact was suggested to induce global freezing [9].

Impact Probability: Fig. 1 presents in the cumulative form the terrestrial cratering rate as the global number of craters of a certain diameter would be accumulated globally (impacts into the ocean are presented with an equivalent crater diameter on land).

If one assumes tentatively that the "critical" impacts would only occur late into a "snowball period", the estimated "snowball" phase duration of 4 to 30 Ma [2] results in estimated probable maximum crater diameter of ~70 km. This provides the limit for our estimates.

The scaling laws of impact cratering allow estimating the projectile diameter, provided the impact velocity corresponds to an average asteroidal value of ~18 km/s, which results in asteroid diameters of ~5 to 7 km. This range of projectile size is used for the reconnaissance numerical modeling of impacts.

Numerical Modeling 1: The hydrocode SALEB has been used for our numerical modeling experiments. The hydrocode has the limited ability to compute multi-material problems. Currently SALEB can handle 3 materials, provided that the mixed cells contain only materials #1 and #2, or materials #2 and #3. This fact forces us to use a set of modeling to study the motion of the rock basement, water/ice, and terrestrial atmosphere in a set of trial runs.

Set # 1 includes the modeling of rocky asteroid impact into the layered target: H_2O layer (ocean water and/or ice cover of continents) over the crystalline basement. Equations of state are ANEOS-computed tables for multi-phase H_2O (water, water vapor, and 7 ice phases [10]), granite and dunite [11]. In this set the atmosphere is not represented, so that the model set #1 allows us to estimate the maximum amount of H_2O ejected above a given altitude.

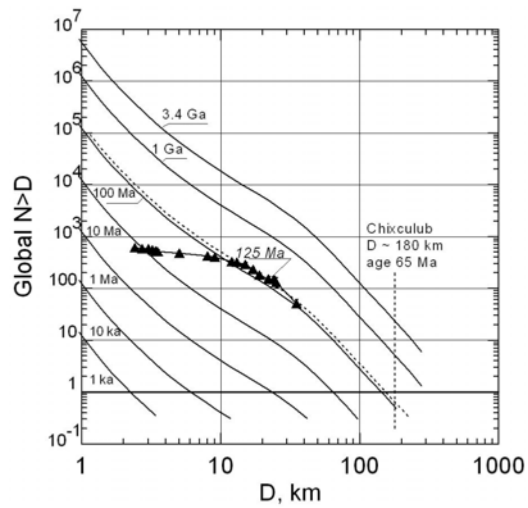

Fig.1. The cumulative global number of impacts, measured in equivalent crater diameter on land, for various time periods. The estimated accuracy is a factor of ~2. During the characteristic time period of 10 Ma a few (3±2) impacts are probable with energy suitable to create a 40 to 50 km crater on land. Black triangles are for dated terrestrial craters [12].

Numerical Modeling 2: To estimate the influence of the atmosphere on the evolution of the H_2O plume we used set #2 of target geometries: air (in the form of an ideal gas) representing the atmosphere above the ice/water layer. In the latter case we are forced to use pure ice target over the rigid bottom, as the atmosphere is described as a separate material and the SALEB code cannot currently handle rock/H_2O/air mixture in a single computational cell

Numerical Modeling 3: The case of a vertical impact is computed using the axisymmetric SALEB code. Qualitative estimates of oblique impacts were done in the planar case.

Preliminary Results: The reconnaissance modeling of the high velocity impact into a "snowball" Earth reveals first estimates of processes and the amount of vaporized water, delivered into the atmosphere and above. In the "modest" case of a 5-km-diameter asteroid impact into an ocean 3 km deep, the mass of water vapor delivered above 20 km reaches 2×10^{15} kg. A larger projectile diameter of 10 km (slightly smaller than the K-T boundary case) increases this estimate about 4 times.

An impact into 800-m-thick ice over a granitic basement produces ~ 4 times less water vapor in the plume (for the case of the 5-km-diameter asteroid).

What follows next in terms of the development of the water vapor in the plume depends on the interaction with the atmosphere. We can approximately model the early plume collapse over the atmosphere (Figs. 2, 3). In the later case our model with the widest spatial boundaries (500 km above the target level and 2000 km from the impact point) results in the pushing out of the upper atmosphere as far as >1000 km outside of the impact location within 400 seconds. The resulting "warm spot" in the atmosphere has a diameter of 2000 km; it initially fills with warm water vapor (which will condense after cooling), and could be a reasonable agent of excitation for a further atmospheric circulation disturbance and cloud formation.

The oblique impact with the most probable impact angle of 45^{o} (modeled here preliminarily only in the planar approximation) demonstrates the same general behavior of evaporated ice/water as for the steam plume in the case of a vertical impact. The unimportance of the projectile wake results in an enhanced forward plume expansion in the upper atmosphere after the oblique impact. However the main outcome of the model is the same: an impact into a water/ice layer uplifts an appreciable amount of initially evaporated H_2O over the top of the terrestrial atmosphere.

Conclusions: In terms of cratering rates, it is statistically plausible that the impact of a ~5 km diameter asteroid occurs during a "snowball period" with a duration of several Myr. Most probably is an impact into the ice-covered ocean. In such a case a vapor plume with a total mass of $n\times10^{15}$ kg will rise up and then collapse over the atmosphere, creating a transient "hot spot". The more indirect consequences may include a global enrichment of the upper atmosphere with water vapors, dust and sea salt particles (in the case of an impact into ocean). Photochemical reactions should be taken into account for a further climatic modeling. At this point our simulations do not allow a conclusion if an impact of a realistic magnitude could cause deglaciation of a Snowball Earth.

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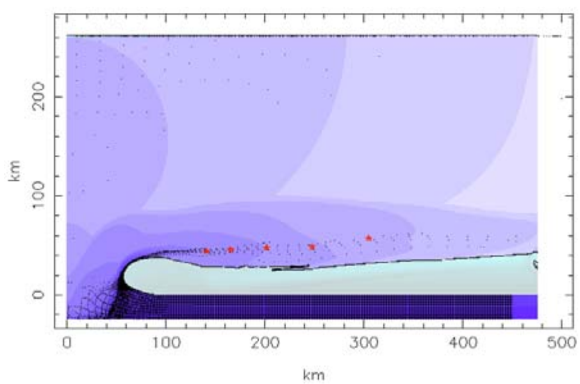

Fig. 2. The snapshot of the H_2O vapor cloud 30 seconds after an impact of a 10-km body into ice. The blue levels logarithmically reflect rarification of expanding vapors. Atmosphere (bluish gray) is trapped under falling and expanding vapors. Red stars show tracers with detailed thermodynamic history recording.

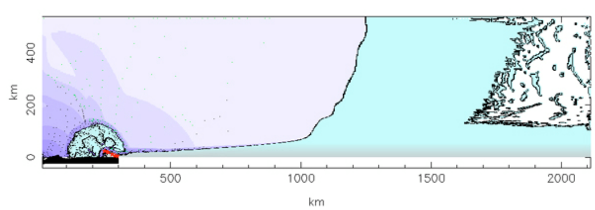

Fig. 3. The same run as in Fig. 2, but 370 seconds after the impact. The vapor cloud expanded to distances > 1000 km from the impact point. The trapped atmosphere at distances of 100 to 300 km has "blown up", what looks like a numerical artifact is caused by incomplete treatment of small volume concentrations in mixed cells. The vapor plume ballistically drops down to the atmosphere, reaching the condensation state at the plume/atmosphere boundary.