GLOBAL MODELING OF IMPACT-INDUCED GREENHOUSE WARMING ON EARLY MARS. T. L. Segura[1] and A. Colaprete[2], [1]Northrop Grumman Aerospace Systems One Space Park, Redondo Beach, CA 90278 teresa.segura@ngc.com, [2]NASA Ames Research Center Mail Stop 245-3 Moffett Field, CA 95035 tonyc@freeze.arc.nasa.gov

Introduction: There have been several recent mineralogical and geomorphological discoveries of evidence for surficial liquid water and/or rainfall in the earliest history of Mars (e.g. [1,2]). However, the presence of liquid water at the surface early in Mars' history presents a conundrum. The early sun was most likely approximately 75% fainter than it is today implying that about 65-70 degrees of greenhouse warming is required to bring surface temperatures to the melting point of water. To date climate models have not been able to produce a continuously warm and wet early Mars [3]. But this may be because the "warm and wet" period was relatively short (~10^2-10^5 years as opposed to ~10^6-10^8 years) and episodic (e.g. [1,2,4,5]) as evidenced by morphological and mineralogical data.

It is widely accepted that even relatively small impacts (~10 km) have altered the past climate of Earth to such an extent as to cause mass extinctions [6]. Mars has been impacted with a similar distribution of objects, and the impact record at Mars is preserved in the abundance of observable craters on it surface. Therefore, impact-induced climate change must have occurred on Mars.

The Environmental Effects of Impacts: The delivery of an impact's tremendous kinetic energy to a planet manifests itself in the destruction of the impactor itself, creation of its crater, and production of ejecta. The ejecta are made up of impactor and target materials and may be in the form of solid rock, melt, or vapor [7] at high temperatures. For example, an object with a diameter of 100 km will result in a global melt/vapor debris layer approximately 10 cm thick [7,8].

Volatiles such as water are also vaporized with the target and impactor materials. Following the impact, the thermal pulse that travels downward into the regolith may release additional water from subsurface reservoirs adding to the total liquid water amount at the surface.

Water vapor is an excellent greenhouse gas and works to trap the impact generated heat within the atmosphere resulting in periods of warmth. Segura et al. (2008, [9]) demonstrated that asteroids with diameters 30-100 km could warm the surface of Mars for several decades to centuries. However the simulations conducted by Segura et al. [9] were limited 1-D and thus only considered impacts which would have a thick (> several cm) global debris layers. There are, however, more than 1000 craters with diameters larger than 60 km on Mars. A 60 km crater would result from an impactor with a diameter of approximately 6 km.

General Circulation Model (GCM) Simulations: The obvious limitations of the 1-D calculations of Segura et al. [9] are the absence of dynamics and the inability to model smaller impacts that do not have thick global debris layers. An accurate assessment of the effects of impacts on the climate will need to include the transport of both heat and water vapor, and the proper simulation of the debris layer localized to the impact site. Reported here are the results of post-impact climate simulations using the Ames Mars General Circulation Model (MGCM). A hydrological cycle has been incorporated into the Ames MGCM that includes the formation of clouds, precipitation, and surface and regolith reservoirs. In these simulations, impacts by objects smaller than 10 km diameter can be simulated. Each simulation is initialized to represent the conditions just following an impact. After a period of simulation time, an impact debris layer and atmospheric thermal plume is emplaced at any location in the model. The impact debris layer thickness and extent, and the thermal plume temperature and extent, is defined as a function of impact diameter [7]. Regolith water abundance and distribution can be specified for each simulation. If regolith temperatures rise above freezing, water is allowed to diffuse to the surface at a fixed rate. Infiltration of the subsurface by surface water is not currently modeled. Both H_2O clouds (wet and cold microphysics) and CO_2 clouds are modeled. The radiative effects of H_2O clouds (warming and cooling effect), CO_2 clouds (warming and cooling effect), and dust (predominantly cooling effect) are included, as well as water cloud coalescence which induces the formation of large-scale convective cumulus clouds, a strong regional cooling forcing. Latent heat effects for both CO_2 and H_2O cloud condensation and surface frosts are also included. In this presentation results are shown for an early Mars atmosphere containing 300 mbar of CO_2 and a solar flux that is 75% current levels.

Results and Conclusions: There are several key results stemming from these simulations. The first is the confirmation of the results found by Segura et al. [9] that a metastable warm climate is observed for at least decades (Figure 1) that is maintained by the greenhouse effects of the water vapor, CO_2, and the radiative effects of clouds of both types. Thus although the dust and clouds can induce cooling effects, in our simulation the overall effect is to warm. The 3-D model simulates seasonal effects and sustains the water in the atmosphere: if the water precipitates out and then freezes in the winter hemisphere, for example, the seasonal return of warmth and humidity allows the cycle to continue. Inter-hemispherical atmospheric transport appears important to maintaining sufficient water vapor concentrations for greenhouse warming. This elevated state of humidity (around 40-60% on average globally), along with the existing 300 mbar of CO_2 results in a stable but temporary "warm and wet" climate. In the MGCM after 20 years there was no indication of the climate returning to its previous "cold and dry" state. The system will finally collapse and return to pre-impact conditions when sufficient water is removed from the system (by surface infiltration, for example), but computing limitations have so far prohibited running of the 3-D model to this state. Indeed, this altered warm climate state was observed for at least centuries in the 1-D model [9] with no indication of collapse at the end of simulation time.

The second result is that tens of meters of rainfall, in several places across the Martian globe are produced in the years following impact, able to carve river valleys, transport sediment, and form mineralogical signatures (Figure 2). The third is that the warming effects of the impact are reduced as the surface pressure declines. This is shown in Figure 3 where both the maximum global surface temperature and the average global surface temperature observed in simulations decline as the surface pressure declines. This is due to two factors: 1) a higher surface pressure allows for greater inter-hemispherical mass transport of water vapor, from the summer hemisphere to the winter hemisphere, thereby maintaining atmospheric water vapor concentrations, and 2) decreased CO_2 pressure decreases absorption in the CO_2 bands, resulting in cooler temperatures and lower humidity, reducing the water vapor greenhouse effect as well. Thus the effects of impacts are not as dramatic today as they were in Martian past when the surface pressure was probably higher.

References: [1] Moore J. M., and A. D. Howard (2005) *JGR, 110(E4)*, E04005. [2] Irwin R. P., III, et al. (2005) *Geology, 33(6)*, 489– 492. [3] Haberle R. M. *JGR 103*, Issue E12, p. 28467-28480. [4] Jerolmack D. J., et al. (2004) *Geophys. Res. Lett., 31(21)*, L21701. [5] C. Barnhart et al. (2009) in press. [6] Toon O. B. et al. (1997) *Rev. Geophys., 35*, 41–78. [7] Sleep N. H., and K. Zahnle (1998) *JGR 103*, pp. 28,529– 28,544. [8] Melosh, H. J. (1989), Oxford Univ. Press, New York. [9] Segura T. L. et al. (2008) *JGR 113*, E11007, doi:10.1029/2008JE003147.

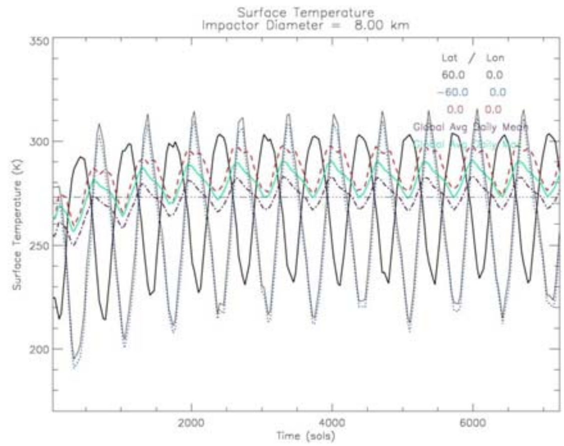

Figure 1. Surface temperature at 3 locations (black, blue, red) plus global average daily mean (purple) and global average daily max temperatures (aqua) for several years following impact with an 8 km diameter object.

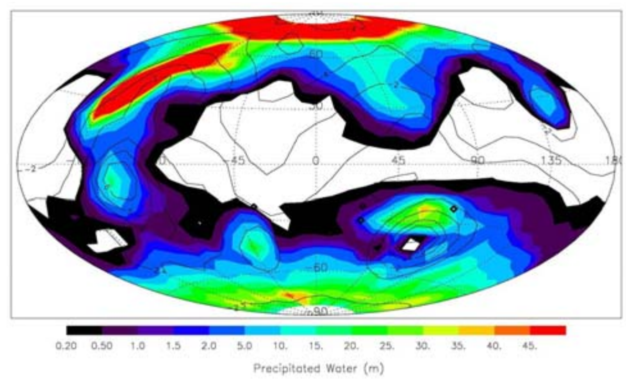

Figure 2. Total precipitated rain (meters) across the Martian globe for an 8 km diameter impactor.

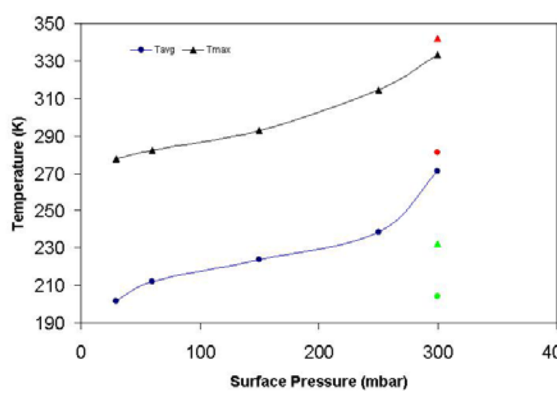

Figure 3. The global daily average (blue) and daily maximum (black) surface temperatures as a function of total CO_2 surface pressure following an 8km impact. The red and green points show the global minimum and maximum surface temperature extent for the 300 mbar case.