**Effects and Lifetime of Ocean Induced $CO_2$ Pulses on Mars: Implications for Fluvial Valley Formation**; Virginia C. Gulick, Daniel Tyler, Robert M. Haberle, and Christopher P. McKay; NASA-Ames Research Center; MS 245-3; Moffett Field, CA 94035. email: gulick@barsoom.arc.nasa.gov

Baker et al. [**1**] proposed that a variety of anomalous geomorphological features on Mars can be explained by episodic ocean formation [**2**] triggered by extensive Tharsis volcanism and the associated massive hydrothermal system. The rapid outpourings of ground water from outflow channel discharges are assumed to release $CO_2$ dissolved in the ground water, adsorbed on the regolith and resident in the north polar cap into the atmosphere. These pulses of $CO_2$ relatively late in Mars' climatic history are suggested to be responsible for short greenhouse periods that Baker et al. believe to be evident in the geologic record. Here we investigate the climatic effect of instantaneous pulses of $CO_2$ added to the martian atmosphere at 1 and 2Ga. We find that such pulses can indeed produce short periods of modest greenhouse warming and significantly increase the saturation vapor pressure. Therefore, significantly greater snowfall at higher elevations is possible than under current climatic conditions [**3**]. This snowfall, in conjunction with melting of snow by localized geothermal heating, might be responsible for late periods of fluvial erosion and glacial activity.

To test the impact of a single injection of $CO_2$ into Mars' atmosphere relatively late in the planet's history, we adapted the climate model of Haberle *et al.* [**4**]. This model was originally used to explore the evolution of the equilibrium surface temperature of Mars from 4.5Ga to present with various initial $CO_2$ boundary conditions. The model draws on published estimates of the main processes believed to affect the atmospheric inventory of $CO_2$ during this period: chemical weathering, regolith uptake, polar cap formation, and atmospheric escape. The model accounts for the variation of solar luminosity with time, the greenhouse effect, and a polar and equatorial energy budget. The $CO_2$ loss processes, with the exception of atmospheric escape, are controlled by the equilibrium surface temperature which is calculated using a modified version of the Gierasch and Toon [**5**] energy balance model that accounts for $CO_2$ condensation.

Our model begins with a nominal 1 bar $CO_2$ atmosphere at 4.5Ga. We find model results to be insensitive to initial $CO_2$ abundance since weathering reduces the exchangeable inventory of $CO_2$ to very similar amounts by the time of the pulse. Haberle et al. [**4**] conclude that initial $CO_2$ inventories of 0.5 to 1.0 bar result in best overall agreement with present day $CO_2$ reservoirs on Mars. An instantaneous 0.5, 1.0, or 2.0 bar pulse of $CO_2$ is then added to the model at either 1 or 2 Ga and the evolution allowed to continue. For each case we varied the percentage area of Mars (5, 10, 20, or 27%) that is covered with water. Pollack et al. [**6**] assumed 5% coverage, Baker et al. calculate a maximum ocean size of approximately 27% of Mars' surface area.

After the $CO_2$ pulse injection, the equilibrium surface temperature rapidly rises, the weathering rate increases, and the $CO_2$ decays. In all cases, except for the injection at 1Ga with 5% water coverage, the atmosphere returns to the buffered regime (permanent polar ice caps) at the present epoch. In the exceptional cases, the weathering rate is too slow and the atmosphere does not collapse. Therefore, even late injections of $CO_2$ into the atmosphere are compatible with the current observed Martian climatic regime, assuming a sufficiently large areal extent of surface water.

The duration of elevated temperatures is more sensitive to the size of the oceans than either the amount of $CO_2$ in the pulse or the time of pulse injection. Depending upon the model, greenhouse warming induced by the $CO_2$ pulse may last for 300 to 1,000 million years. For the 0.5 bar pulse at 1 Ga with 10% water coverage, temperatures rise approximately 25 K above the background temperature to approximately 250 K and then slowly decay over a period of $6 \times 10^8$ years before the atmosphere collapses. For a 2.0 bar pulse, temperatures rise nearly 50 K and then decay more rapidly over $7 \times 10^8$ years to the background temperature. Assuming 27% water coverage, roughly equivalent to the maximum ocean size reported by Baker *et al.* [**1**], the atmosphere collapses in approximately $2 \times 10^8$ and $3 \times 10^8$ years respectively. For the same pulses injected at 2 Ga results are similar although peak temperatures are about 5K less owing to the fainter sun.

The temperature increases triggered by the $CO_2$ pulses are generally not sufficient to raise the equilibrium surface temperature above freezing, except for a 4 bar pulse. In this extreme case, global temperatures are elevated above 273K for several $10^6$ years. Unlike early Mars, such conditions are permissible at later times because the sun is brighter.

Except for possibly the 4 bar case, the temperature increase associated with an ocean-induced $CO_2$ pulse would not alone be sufficient to produce rainfall and fluvial erosion. However as the ocean sublimates, precipitation as snow is possible. Gulick and McKay [3] explored a model in which water vapor from a sublimating frozen lake or ocean is carried to higher altitudes and precipitates onto a snowfield. The ability of the atmosphere to transport water as snow depends critically upon the atmospheric temperature and somewhat on the wind speed. They found that for current martian conditions and wind speeds of 1 to 5 m/s, sublimation rates of the frozen lake are in the range of 0.3 to 3 cm/year. This results in a maximum net accumulation of 1 cm/year of equivalent water depth of snow at a site located 2 km higher than the lake. However an atmospheric temperature rise of 25 or 50K would allow accumulation of 10 or 100 cm of equivalent water depth per year, respectively.

If precipitation rates of 10 to 100 cm/yr persisted over several million years and if the snow could be melted, fluvial erosion would result [3]. Therefore the transient greenhouse model can seemingly produce the higher temperatures necessary for snow accumulation at higher elevations, but another mechanism would still be required to locally melt the snow. Geothermal heat fluxes exceeding 1 $W/m^2$ are commonly measured over areas of $10^3$ $km^2$ in terrestrial hydrothermal regions and would be capable of melting 10 cm/yr of snow. Such heat fluxes are also consistent with Martian hydrothermal systems according to the modeling results of Gulick [7]. The resulting localized melting would account for relatively isolated regions of later Martian valley erosion, such as the flanks of Alba Patera. Regions lacking vigorous hydrothermal systems and easily erodible surfaces would not be subjected to melting snow and subsequent fluvial erosion. Furthermore, the rate of snow accumulation is comparable to that required to form glaciers in the higher southern latitudes as suggested by Kargel and Strom [8] and Baker et al. [1].

However, fluvial erosion at lower elevations (e.g., lower on the flanks of volcanos, near large impact craters, or near intrusive volcanics) or occurring earlier in Mars' geological history can be more directly explained by hydrothermal ground-water outflow. Hydrothermal systems can circulate and discharge large quantities of ground water to the surface without relying upon an atmospherically driven hydrological cycle. Many of the characteristics of the martian fluvial valleys, including the sapping-dominated morphology, the lack of associated runoff valleys, and the clustered distribution of valley networks in the heavily cratered terrain [7,9] may be more straightforwardly explained by hydrothermally driven ground-water outflow.

We have considered whether the $CO_2$ pulses predicted by the episodic ocean hypothesis of Baker et al. would be sufficient to significantly affect the martian climate. We conclude that such pulses do raise the mean surface temperature of the planet for periods of $10^7$ to $10^8$ years, depending on the areal extent of the ocean. However, barring exceptional cases, the mechanism cannot produce mean temperatures over the freezing point of water. Nevertheless, the elevated greenhouse temperatures do significantly increase the carrying capacity of the atmosphere and may allow for significant snowfall at higher elevations. Coupled with a substantial, localized heat source (i.e., hydrothermal systems), such a mechanism could be responsible for the late forming martian valleys. Furthermore, geochemical evidence from the SNC meteorites [10] points to the circulation of $CO_2$-rich ground water in the near surface environment, an observation consistent with the ocean hypothesis and the operation of hydrothermal systems on Mars.

**References:**

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