FORMATION OF MARTIAN GULLIES BY THE ACTION OF LIQUID WATER FLOWING UNDER CURRENT MARTIAN ENVIRONMENTAL CONDITIONS. J. L. Heldmann[1], O.B. Toon[2], W.H. Pollard[3], M.T. Mellon[2], J. Pitlick[2], C.P. McKay[1], and D.T. Andersen[4], [1]NASA Ames Research Center, Moffett Field, CA, jheldmann@mail.arc.nasa.gov, [2]University of Colorado, Boulder, CO, [3]McGill University, Department of Geography, Montreal, Canada, [4]SETI Institute, Mountain View, CA.

Introduction: Images from the Mars Orbiter Camera (MOC) on the Mars Global Surveyor (MGS) spacecraft show geologically young small-scale features resembling terrestrial water-carved gullies (Figure 1). An improved understanding of these features has the potential to reveal important information about the hydrological system on Mars, which is of general interest to the planetary science community as well as the field of astrobiology and the search for life on Mars. The young geologic age of these gullies is often thought to be a paradox because liquid water is unstable at the Martian surface. Current temperatures and pressures are generally below the triple point of water (273 K, 6.1 mbar) so that liquid water will spontaneously boil and/or freeze. We therefore examine the flow of water on Mars to determine what conditions are consistent with the observed features of the gullies.

The Model: We numerically simulate the flow of liquid water within a Martian gully channel. Our goal is to determine whether liquid water can flow over sufficient distances to carve the observed channels and also to place constraints on the flow rate and salinity of the water. This model is first developed to simulate a well-observed terrestrial example of channel flow in the High Canadian Arctic. This environment is an analog to the one commonly assumed by other researchers who have suggested the Martian flow occurred in a different climatic regime with higher pressures so that the liquid did not rapidly evaporate during its flow.

We developed a model of channel flow by dividing the channel into equally spaced parcels and performed an energy balance on each individual parcel. The flow is modeled as a Newtonian fluid whose downslope velocity is determined by a balance between the weight of water in each parcel and the turbulent shearing resistance. Changes in channel shape or bed elevation due to erosion and sediment transport are ignored, although these processes may be important in forming the gullies initially. Energy source terms calculated for each parcel include solar insolation, radiative and sensible heating by the atmosphere, and the latent heat of fusion based on ice formation. Energy loss terms include the latent heat of vaporization as water evaporates, radiative cooling of the liquid, and thermal conduction from the liquid to the ground.

For cases where the atmospheric pressure is greater than the vapor pressure of water (i.e. terrestrial cases and Mars cases involving brines), evaporation rates are calculated using a bulk aerodynamic term for vertical kinematic turbulent water vapor flux. The water vapor mass flux due to evaporation (E_1) is thus calculated using

$$E_1 = C_e\, v_h(r)|[\rho_v(z_o) - \rho_v(z_r)] \qquad (1)$$

where C_e is the bulk transfer coefficient of water vapor, v_h is the horizontal wind velocity, and ρ_v is the total atmospheric density at the surface (z_o) and at a reference height (z_r) of typically 10 m [2].

For cases where the atmospheric pressure is less than the vapor pressure of the water (i.e. Martian cases involving pure water), the liquid water loss rate is calculated using kinetic theory, assuming evaporation under vacuum [3, 4]. The resulting evaporation mass flux (E_2) is given by

$$E_2 = \alpha V_s[\rho_v(z_o) - \rho_v(z_r)] \qquad (2)$$

where V_s is the mean molecular speed of the molecule, ρ_v is the water vapor density, and α is an empirical coefficient which has a value near unity [5].

The drop in temperature of the liquid water caused by the evaporation is calculated from the mass evaporation flux and the latent heat of vaporization. The ice that forms from the freezing of the brine within each parcel is observed to accumulate at the edges of the channel in the Arctic case due to the relatively low flow velocities and hence forms an ice cover which inhibits further evaporation [6]. For the Mars case the high flow velocities due to the relatively steep channel slopes as well as vigorous evaporation of the water in some cases does not allow for ice accumulation within the channels and so the ice that forms within the model is nominally considered lost from the system and does not form an ice cap over the channel. Variable input parameters for both the terrestrial and Martian cases related to the flow itself include flow rate, channel volume, initial outlet temperature, and initial salinity of the liquid.

Results for Earth: We tested our model using known flow parameters and environmental conditions of perennial saline springs in the Mars analog environment of the Canadian High Arctic. The springs at Gypsum Hill on Axel Heiberg Island are located at 79°24'30"N, 90°43'05"W in a polar desert environment where the mean annual air temperature is 258 K and winter temperatures of 218 K are common [7, 8, 9]. This High Arctic site is classified as a polar desert since evaporation exceeds the low annual precipitation [8].

Numerical simulations for this standard Arctic case indicate that liquid brine simultaneously evaporates and freezes which increases the salinity of the remaining liquid within the channel. In this model the behavior of the liquid brine is divided into three phases which include 1) cooling down to the freezing point, 2) the mutual coexistence of ice and liquid below the freezing point but above the eutectic point, and 3) the precipitation of salt from the solution at the eutectic point. At the end of Phase 1, the water cools down to the freezing point of the solution which is dependent on the mole fraction of solute present in the liquid. During this phase, liquid water is lost only via evaporation. Once the liquid reaches the freezing point, ice begins to form in the channel. More liquid water mass is lost once the solution reaches the freezing point and ice begins to form. The amount of ice formed is governed by an energy balance among evaporation, cooling, and ice formation. The amount of ice formed also depends on the relationship between temperature and mole fraction of solute through the freezing point depression curve. The amount of ice formed is determined by a convergence of the energy balance and freezing point depression equations. As ice forms, the remaining liquid solution becomes more concentrated and hence ice forms at increasingly lower temperatures due to the increased freezing point depression. This process continues until the solution reaches the eutectic point where salt begins to precipitate out of the solution as ice forms and the salinity remains constant at this maximum value.

The resulting modeled channel for this standard Arctic case spans 624 m in length before all the liquid is lost to evaporation and ice formation. The maximum distance the liquid brine flows at the Gypsum Hill springs during the winter months is 600-625 m [6] and so our calculated runout value is in excellent agreement with the physical dimensions of the Arctic spring system.

Results for Mars: In our simulations, a range of initial flow rates is used to represent channel depths ranging from 0.15 m - 1 m. A range of initial salinities from pure water to highly saline brines similar to the Arctic brines (~5 times the salinity of seawater) is also used to place constraints on the concentration of a possible brine. The average gully channel length is 500 m [10] and therefore our goal is to simulate flows spanning this distance since these measured channel lengths are indicative of the distance of liquid water flow on the Martian surface.

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Numerical simulations conducted for the standard Mars case using an initial outlet salinity of 0.02 with a conservatively low flow rate corresponding to a channel brine depth of 0.5 m result in channel runout distances spanning tens of kilometers. Liquid water is lost mainly by the formation of ice as the channel freezes. Such long runout distances are consistent with early modeling efforts of *Wallace and Sagan* [3] and *Carr* [11] to explain the formation of the valley network systems. In their models pure liquid water is inhibited from rapidly escaping to the atmosphere due to the formation of a protective ice cover whereas in this work such evaporation rates into the atmosphere are decreased by the presence of soluble salts. In each case, however, the end result is the same; liquid water can run for extensive distances (i.e. tens of km) on the Martian surface if this evaporation is suppressed.

We now consider the case for pure liquid water on Mars where evaporation is allowed to rigorously occur. Results from a simulation of channel flow on Mars using a flow rate of 30 m^3/s (0.3 m water depth in a channel 10 m wide with a flow velocity of 10 m/s) for pure water indicate that the liquid water flows for a distance of 546 m which is approximately the average length of a gully channel on Mars.

Simulations are run for a variety of flow rates for the pure water case. As shown in Figure 2, flow rates ranging from 15 m^3/s - 60 m^3/s (0.15 m - 0.6 m water depth) result in channel runout lengths of 272 m - 1092 m. These distances are consistent with the channel lengths of observed Martian gullies. Using the measured length of individual channels, the minimum flow rate of individual gullies can thus be determined.

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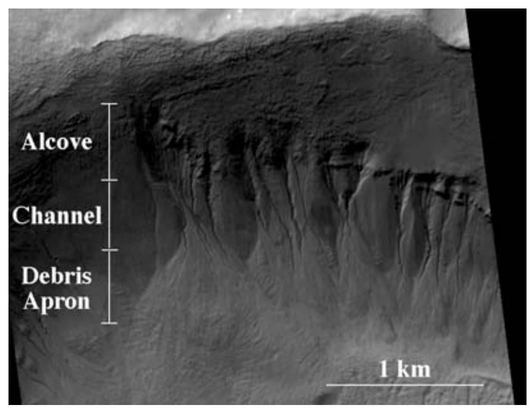

Figure 1. Portion of MOC image M17-00423 located at 200.86°W, 39.16°S showing the alcove, channel, and debris apron structures of recent gullies on Mars. Scale bar is 1 km.

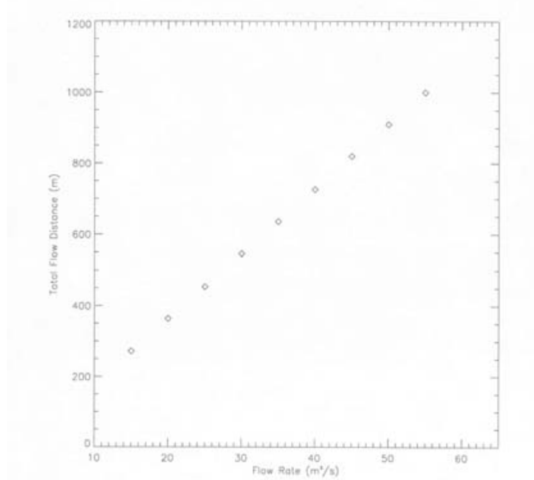

Figure 2. Flow rate versus channel runout distance for the Mars case.