CATASTROPHIC EVENTS: POSSIBLE SOLUTIONS TO THE EARLY MARS ENIGMA(S) ?

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Introduction:

Since the 1970s, there have been a growing number of evidences that liquid water flowed on early Mars: high erosion rates, sedimentary deposits, hydrated minerals and geomorphological clues, including dry river beds and lakes.

However, 3D climate modeling under ancient Mars conditions (faint young Sun, CO_2-dominated atmospheres thicker than today, various obliquities), and performed with a water cycle taking into account water vapor and clouds, have not been able to produce liquid water or at least significant precipitations by climatic processes anywhere on the planet (Forget et al. 2013, Wordsworth et al. 2013). This result holds in fact whatever the CO_2 atmospheric pressure, obliquity, and even when maximizing the scattering greenhouse effect of CO_2 ice clouds.

It has been suggested therefore that warm conditions required to explain the formation of ancient valley networks could have been transient and produced in response to extreme events of various nature: meteoritic impacts, volcanism, groundwater discharges … (Baker et al. 1991, Mangold et al. 2004, Segura et al. 2002,2008,2012, Toon et al. 2010, Wordsworth et al. 2013,2015)

We present below results of 3D Global Climate modeling of the environmental effect of various types of extreme events.

The LMD Generic Global Climate Model:

The studies were lead with the 3 Dimensions LMD Global Climate Model. Simulations of the early martian climate (following extreme events) were performed with resolution grids up to 96x96x30 (in latitude x longitude x altitude). We used both the present-day MOLA and ancient Mars topographies (Bouley et al. 2016), when appropriate.

The model works with a water cycle that includes the formation of water and CO_2 ice clouds. Moist convection was implemented following a moist convective adjustment that derives originally from the 'Manabe scheme' (Manabe and Wetherald, 1967; Wordsworth et al., 2013). In our scheme, relative humidity is let free but limited to 100%, since it is not accurate here to use empirical values for relative humidity (as a function of altitude) that comes from Earth observations, as proposed in the original Manabe scheme.

Generalized radiative transfer (including radiative effects of clouds) is taken into account following the correlated-k approach. Compared to the radiative transfer calculations used in Wordsworth et al. (2013), we use here a more recent spectroscopic database (HITRAN 2012) and built new correlated-k coefficients suited for wet atmospheres (water vapor volume mixing ratios up to 100%).

The processes that are taken into account to simulate the fate of extreme events are summarized in Figure 1.

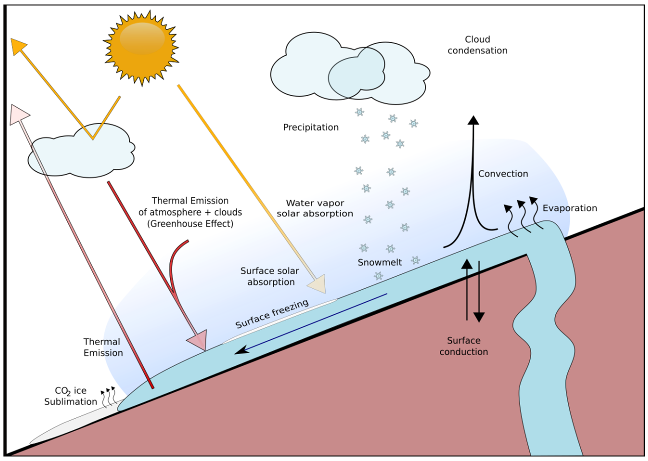

Figure 1: Schematic drawing of the physical processes taken into account in our 3D GCM simulations, following here the case of an outflow channel formation event. Credit: Turbet et al. 2017

Environmental effect of outflow channel formation events:

During late Hesperian epoch, large outflow channels observed around Chryse Planitia (Baker 1982, Carr et al. 1996) are thought to have been carved by catastrophic, sudden warm water floods. It has been speculated that such events may have altered the climate, at least locally and episodically, and could have induced precipitations and even rain that could potentially explain the formation of Late Hesperian valley networks under a cold contemporaneous climate (Mangold et al. 2004).

We performed multiple simulations all starting from a converging initial state with stabilized surface water ice reservoir (Wordsworth et al. 2013). We assumed that a warm source of liquid water (volumes of water up to 10^7 km³ and released at temperatures up to 320 Kelvins) was suddenly released in the region of Echus Chasma, flowing on the slopes of the largest of the Circum Chryse outflow channels: Kasei Vallis (Figure 2).

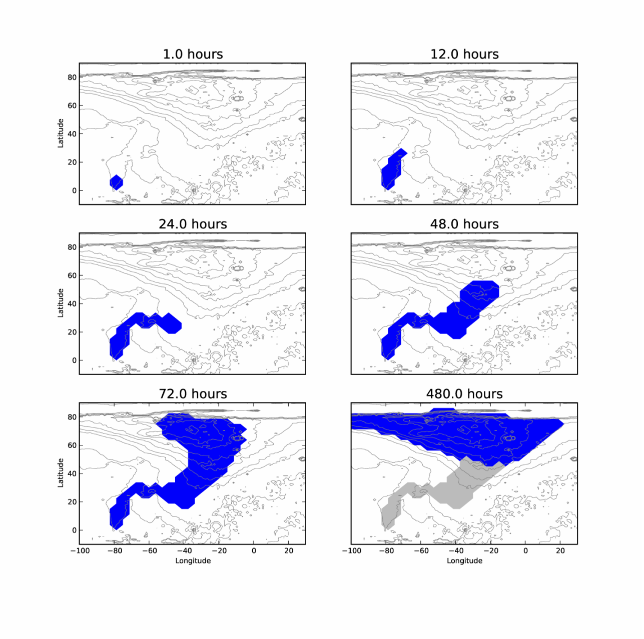

Figure 2: Time lapse of the runoff of the outflow channel event occuring in Echus Chasma, and flowing from Kasei Vallis down to the Northern Plains main topographic depression. The blue area corresponds to the position of the flow. The grey color was used to represent the 'wet' regions where the flow passed through but did not accumulate. Credit: Turbet et al. 2017

We find that the most intense of these outflow channel formation events – even the ones that exceed by far in power the most recent estimates (Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008) - cannot trigger long-term greenhouse global warming, regardless of how favourable are the external conditions (e.g. CO_2 atmospheric pressure, obliquity and seasons). The intensity of the response of these events is significantly affected by the atmospheric pressure, a parameter that is not well constrained for the Hesperian era.

Thin atmospheres ($P < 80$ mbar) can be heated efficiently because of their low volumetric heat capacity, triggering the formation of a convective plume very efficient in transporting water vapor and ice at the global scale, as previously suggested by Kite et al. 2011.

Thick atmospheres ($P > 0.5$ bar) have difficulty in producing precipitation far from the water flow area. Yet, hey are more efficient in generating snowmelt.

In any case, outflow channel formation events for any atmospheric pressure are unable to produce rainfall or significant snowmelt at latitudes below 40°N.

As an example, for an outflow channel formation event (under a 0.2 bar atmospheric pressure and 45° obliquity) releasing 10^6 km³ of water heated at 300 Kelvins and at a discharge rate of 10^9 m³ s^{-1} , the water flow reaches the lowest point of the northern lowlands (around ∼70°N, 30°W) after ∼3 days and forms a 200m-deep lake of 4.2×10^6 km² after ∼20 days; the lake becomes fully covered by an ice layer after ∼500 days.

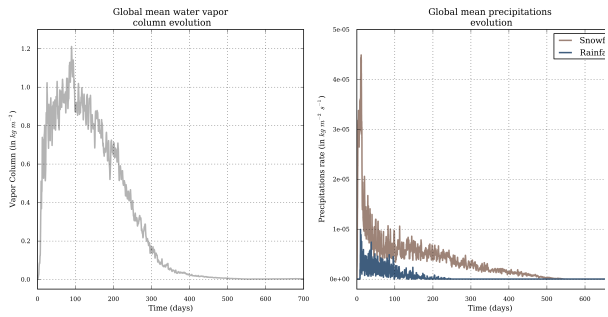

Figure 3: Evolution of the global mean water vapor column (left) and the precipitation (right), during the year following an outflow channel formation event (10^6 km³ of water released at 300 K in Echus Chasma, under a 0.2 bar CO_2-dominated atmosphere). Credit: Turbet et al. 2017

Over the short term, such an event leaves 6.5×10^3 km³ of ice deposits by precipitation (0.65% of the initial outflow volume) and can be responsible for the melting of ∼80 km³ (0.008% of the initial outflow volume; 1% of the deposited precipitation).

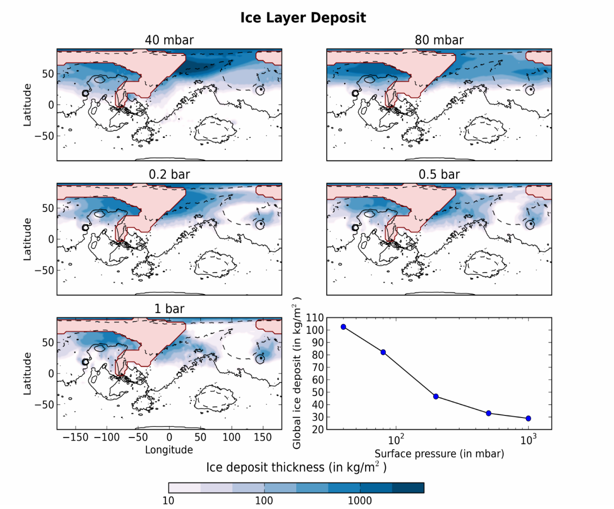

Figure 4: Final Ice layer deposit map (in kg m−2) after 1 martian year of simulations, for five different surface pressures (40 mbar, 80 mbar, 0.2 bar, 0.5 bar and 1 bar). The pink color denotes the regions where the flow passed through on the way to the northern lake/ocean. Credit: Turbet et al. 2017

Furthermore, these quantities decrease drastically (faster than linearly, in fact) for lower volumes of outflow waters.

Over the long term, our results indicate that the presence of the ice-covered lake has a climatic impact very similar to a simple body of water ice located in the Northern lowlands. For an obliquity of ~45° and atmospheric pressures > 80 mbar, we find that the lake ice is transported progressively toward South through the mechanisms of sublimation and adiabatic cooling. At the same time, and as long as the initial water reservoir is not entirely sublimated (lifetime of 10^5 martian years for the outflow channel event described above), ice deposits remain in the West Echus Chasma Plateau region where hints of hydrological activity contemporaneous with outflow channel formation events have been observed (Mangold et al. 2004).

However, seasonal melting related to solar forcing seems difficult here partly because the presence of high albedo snow at the surface has a significant cooling effect. The global temperatures after outflow events can in fact easily be lowered by few Kelvins, making the possibility of solar melting even more difficult. Therefore, our results indicate that localized warming such as geothermal activity or meteoritic impacts would be required to explain the formation of these observed Late Hesperian valley networks.

Environmental effect of meteoritic impact events:

It has been suggested that the warm conditions required to explain the formation of the valley networks - most of them being ~3.8 Gyrs old - could have been transient and produced in response to meteoritic impact events (Segura et al., 2002, 2008; Toon et al., 2010) that peaked during the contemporaneous Late Heavy Bombardment (LHB). The authors of these studies argued that the high precipitation rates under post-impact conditions could be sufficient to carve valley networks similar to those that are observed today on the highlands of Mars.

Segura et al. 2012 have even shown, using a 1D radiative convective climate model, that the largest of the recorded impact events could produce hot, steam atmospheres that (according to their results) should be long-lived due to a strong decrease in thermal IR cooling to space with surface temperature.

We explored here the environmental effect of impact events of various intensity on early Mars, for a wide range of external conditions (atmospheric pressure, obliquity), using 3D GCM simulations. In particular, we simulated the climatic effect of ~100km diameter impactors hitting the surface of Mars at ~10km/s by forcing initially the atmosphere/surface/subsurface at temperatures up to 600 Kelvins, and by vaporizing up to several bars of H_2O.

Our main result is that, whatever the initial impact-induced temperatures and water vapor content injected, warm climates cannot be stable and are in fact short-lived (lifetime of ~ 5-7 martian years per bar of water vapor injected). The results of Segura et al. 2012 seem unconsistent with our findings, which are in fact in good agreement (in term of OLR) with recent studies on the Runaway Greenhouse. It would indeed require extreme supersaturation of water vapor to reproduce the results of Segura et al. 2012 ...

When a hot, steam atmosphere forms on Early Mars, our 3D GCM simulations shows that the IR thermal emission to space is roughly 200W/m² higher than the incoming stellar radiation (under FYS), everywhere on the planet. At the altitude of IR emission to space, water vapor condenses and release ~ 200W/m² of latent heat, everywhere on the planet. Therefore, a 100%, thick cloud cover forms, producing precipitation (rainfall, here) uniformly on the planet.

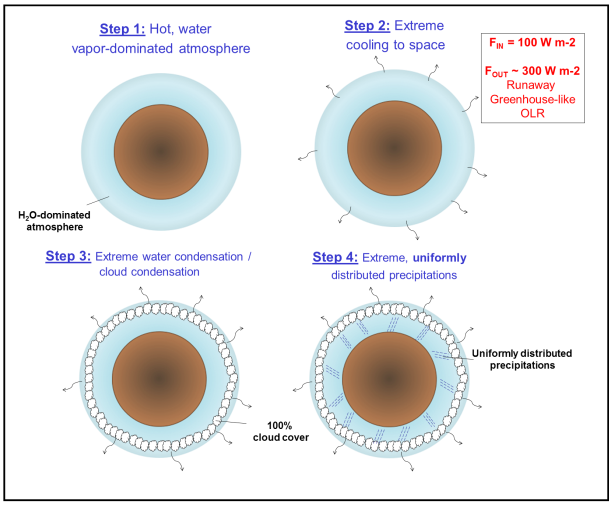

Figure 5: Sketches of the physical processes occuring after a post-impact hot, steam atmosphere forms on Early Mars. From Turbet et al. 2017, in prep.

Warm & wet conditions that follow the largest impacts recorded on Mars should not only have been short-lived, but they should also have produced thick 100% cloud coverage, responsible for precipitation patterns uniformly distributed on the planet (Figure 6).

Ongoing work on impact events:

We believe that moderate-size impact events (5km < $D_{impactor}$ < 50km, N_{events} ~ $3x10^3$) being much more numerous, they are potentially the best candidates to form the valley networks. They could in fact melt the ice that tends to accumulate preferentially in the regions where the rivers were sculpted ('Icy Highlands' scenario – Wordsworth et al. 2013, Bouley et al. 2016). This scenario is particularly appealing because this would be a very efficient mechanism of recharge of the valley network water sources between two impact-induced melting events.

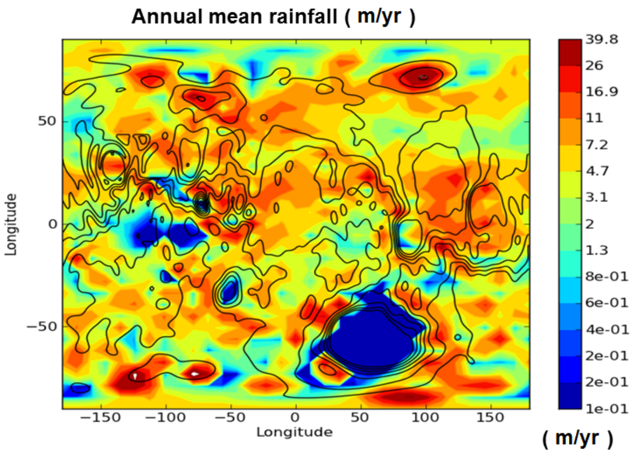

Figure 6: Annual mean rainfall rate following an impact event occuring on Early Mars (initially 1bar CO_2-dominated atmosphere, obliquity of 45°). From Turbet et al. 2017, in prep.

We will present preliminar estimates of the amount of rainfall/snowmelt that should be expected after moderate-size impact events depending on their size, composition, velocity, … For this, we use the SOVA hydrocode for short-term modelling of impact cratering. It provides us with post-impact temperature fields, injection of volatiles, ejecta and dust distribution (Figure 7) that serve as input for the LMD-GCM.

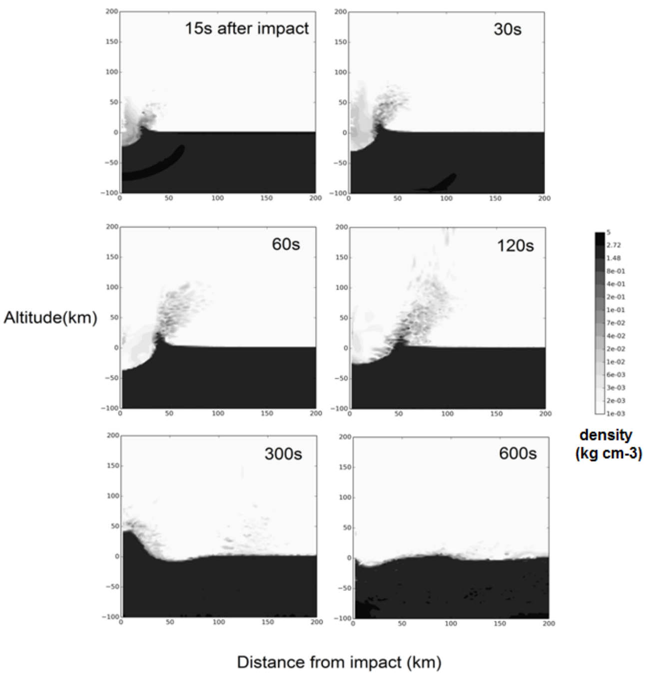

Figure 7: Time lapse of SOVA hydrocode simulations showing the volumetric density of materials following a ~15km diameter comet hitting the surface of Mars at 10km/s. From Turbet et al. 2017, in prep.

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