Icarus 288 (2017) 10–36

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

3D modelling of the climatic impact of outflow channel formation events on early Mars

Martin Turbet[a,*], Francois Forget[a], James W. Head[b], Robin Wordsworth[c]

[a] Laboratoire de Météorologie Dynamique, Sorbonne Universités, UPMC Univ Paris 06, CNRS, 4 place Jussieu, 75005 Paris, France
[b] Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA
[c] Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA

ARTICLE INFO

Article history:
Received 13 September 2016
Revised 25 January 2017
Accepted 26 January 2017
Available online 27 January 2017

ABSTRACT

Mars was characterized by cataclysmic groundwater-sourced surface flooding that formed large outflow channels and that may have altered the climate for extensive periods during the Hesperian era. In particular, it has been speculated that such events could have induced significant rainfall and caused the formation of late-stage valley networks. We present the results of 3-D Global Climate Model simulations reproducing the short and long term climatic impact of a wide range of outflow channel formation events under cold ancient Mars conditions. We find that the most intense of these events (volumes of water up to 10^7 km^3 and released at temperatures up to 320 K) cannot trigger long-term greenhouse global warming, regardless of how favorable are the external conditions (e.g. obliquity and seasons). Furthermore, the intensity of the response of the events is significantly affected by the atmospheric pressure, a parameter 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 that is very efficient in transporting water vapor and ice at the global scale. Thick atmospheres ($P > 0.5$ bar) have difficulty in producing precipitation far from the water flow area, and are more efficient in generating snowmelt. In any case, outflow channel formation events at any atmospheric pressure are unable to produce rainfall or significant snowmelt at latitudes below 40°N. As an example, for an outflow channel event (under a 0.2 bar atmospheric pressure and 45° obliquity) releasing 10^6 km^3 of water heated at 300 K and at a discharge rate of 10^9 m^3 s^{-1}, the flow of water reaches the lowest point of the northern lowlands (around ∼70°N, 30°W) after ∼3 days and forms a 200 m deep lake of 4.2×10^6 km^2 after ∼20 days; the lake becomes entirely covered by an ice layer after ∼500 days. Over the short term, such an event leaves 6.5×10^3 km^3 of ice deposits by precipitation (0.65% of the initial outflow volume) and can be responsible for the melting of ∼80 km^3 (0.008% of the initial outflow volume; 1% of the deposited precipitation). Furthermore, these quantities decrease drastically (faster than linearly) for lower volumes of released water. Over the long term, we find that the presence of the ice-covered lake has a climatic impact similar to a simple body of water ice located in the Northern Plains.

For an obliquity of ∼45° and atmospheric pressures > 80 mbar, we find that the lake ice is transported progressively southward through the mechanisms of sublimation and adiabatic cooling. At the same time, and as long as the initial water reservoir is not entirely sublimated (a 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. However, because the high albedo of ice drives Mars to even colder temperatures, snowmelt produced by seasonal solar forcing is difficult to attain.

1. Introduction

During the Late Hesperian epoch of the history of Mars (about 3.1-3.6 Gyrs ago; Hartmann and Neukum, 2001), the large outflow channels observed in the Chryse Planitia area are thought to have been carved by huge water floods caused by catastrophic and sud-

* Corresponding author.
E-mail address: mturbet@lmd.jussieu.fr (M. Turbet).

http://dx.doi.org/10.1016/j.icarus.2017.01.024

den release of groundwater (Baker, 1982; Carr, 1996). It has been speculated that such events could have warmed the climate and possibly explain the contemporaneous formation of dendritic valley networks observed in the nearby Valles Marineris area and on the flanks of Alba Patera, Hecates Tholus, and Ceraunius Tholus, and that have been interpreted to be precipitation-induced (Gulick and Baker, 1989; 1990; Baker et al., 1991; Gulick et al., 1997; Gulick, 1998; 2001; Mangold et al., 2004; Quantin et al., 2005; Weitz et al., 2008; Santiago et al., 2012). Although the Late Hesperian epoch is thought on the basis of geology and mineralogy to have been cold (Head et al., 2004; Bibring et al., 2006; Ehlmann et al., 2011), the characteristics of these dendritic valleys suggest that the valleys were formed under persistent warm conditions (.e.g, Mangold et al. 2004). First, their high degree of branching is interpreted to indicate formation by precipitation. Second, their high drainage densities – evidence of their high level of maturity – and the presence of inner channels favor the presence of stable liquid water for geologically long periods of time (Craddock and Howard, 2002). Third, sedimentary morphologies observed in the region of Valles Marineris (Quantin et al., 2005) suggest a fluvial and lacustrine environment. Under this hypothesis, the warm liquid water floods that formed the outflow channels would inject water vapor into the atmosphere, a powerful greenhouse gas that could trigger a significant warming period possibly leading to long lasting pluvial activity (rainfall).

In this paper, we use a 3-Dimensional Global Climate Model (LMD GCM) to explore the global climatic impact of outflow channel water discharge events on a Late Hesperian Mars over a range of temperatures and atmospheric pressures. These bursts of warm liquid groundwater outflows onto the surface can trigger strong evaporation, possibly leading to global climate change. How warm and how wet was the atmosphere of Late Hesperian Mars after such major outflow channel events? The climatic effect of relatively small and cool groundwater discharges has been studied on a regional scale (Kite et al., 2011a) and localized precipitation is indicated. In this contribution, we investigate the climatic impact at a global scale of a wide range of possible outflow channel events, including the case of the most intense outflow events ever recorded on Mars (Carr, 1996). Our work focuses on both (1) the direct short-term climate change due to the initial strong evaporation of water vapor and (2) the long-term change of the water cycle due to the presence of liquid water and ice at non-stable locations.

When a warm liquid water flow reaches the surface, strong evaporation occurs and the total evaporation rate increases with the temperature and the surface area of the flow. In term of energy budget, a 300 K warm liquid water flow can potentially convert ∼5% of its total mass into water vapor before freezing starts. The injected water vapor will have a major role on the radiative budget of the planet. First, water vapor is a greenhouse gas that can absorb ground thermal infrared emission efficiently. Second, water vapor can condense to form clouds. In the process, large amounts of latent heat can be released in the atmosphere. The clouds can reflect the incoming solar flux as well as contribute to an additional greenhouse effect, depending on their height and the opacity of the background atmosphere, which depends on the total atmospheric pressure.

To study the global climatic effect of localized outflow channel events, 3D Global Climate Models are particularly relevant because they not only model the physical processes described above, but also the 3D dynamical processes that play a major role in climatic evolution. In particular, we show in this paper that 3D dynamical processes (horizontal advection, in particular) are key to understanding the relaxation timescale of the Late Hesperian martian atmosphere immediately following major outflow channel events.

2. Background

2.1. Outflow channels

2.1.1. Description

Outflow channels are long (up to ∼2000 km) and wide (up to ∼100 km) valleys that were sculpted by large-scale debris-laden water flows (Baker, 1982; Baker et al., 1992; Carr, 1996). The most prominent martian outflow channels are located in the circum-Chryse area and debouch in the Chryse Planitia itself (Carr, 1996; Ivanov and Head, 2001).

Several processes have been suggested to have caused such outburst floods (Kreslavsky and Head, 2002). It is likely that the water that was released during these events come from subsurface aquifers (Clifford, 1993; Clifford and Parker, 2001). In this scenario, the temperature of the extracted subsurface water is controlled by the geothermal gradient and thus would depend on its initial depth of origin. During the Late Hesperian, when outflow channel events largely occured, this gradient could have been locally higher (Baker, 2001), because the circum-Chryse area is close to the volcanically active Tharsis region (Cassanelli et al., 2015). Therefore, the discharged water could have reached the surface at a maximum temperature of tens of degrees above the freezing point (Kreslavsky and Head, 2002). We note that the run-away decomposition of CO_2 clathrate hydrate (Milton, 1974; Baker et al., 1991; Hoffman, 2000; Komatsu et al., 2000), proposed as a possible mechanism for the origin of the outflow water, cannot produce water temperature greater than 10K above the freezing point. To a first approximation, and from a climatic point of view, the only difference between these two processes of liquid water discharge is the temperature of the water. Thus, we considered in this paper various cases ranging from 280 K to 320 K (see Section 6.1.1).

Whatever the physical process operating, large amounts of water released at very high rates are needed at the origin of the water flow in order to explain the erosion of the circum-Chryse outflow channels. The quantity of water estimated to erode all the Chryse basin channels is $\sim 6 \times 10^6$ km^3 assuming 40% by volume of sediment (Carr, 1996) but could possibly be much more if one assume lower sediment loads (Kleinhans, 2005; Andrews-Hanna and Phillips, 2007), which is, for example the case on Earth (∼0.1% of sediment by volume).

The different estimates of outflow channel single-event volumes, discharge rates and durations lead to a wide range of results, but two endmember scenarios can be defined and explored. On the one hand, some researchers estimated that only a limited number of very intense (volume up to 3×10^6 km^3, discharge rates up to 10^9 m^3 s^{-1}) outflow channel formation events actually occured (Rotto and Tanaka, 1992; Baker et al., 1991; Komatsu and Baker, 1997).

On the other hand, more recently, other researchers argued that outflow channels were formed by numerous individual small events (Andrews-Hanna and Phillips, 2007; Harrison and Grimm, 2008). This latter work implies water volumes from hundreds to thousands of km^3, discharge rates of 10^6–10^7 m^3 s^{-1} for individual events and a minimum period between successive single events of ∼20 martian years. These endmember estimates differ by several orders of magnitude, but in this paper, we explored the full range.

2.1.2. Fate of the outflow channel liquid water flow

In this section, we provide a description of the possible fate, and calculations of the possible velocities, of the outflow channel water; these will serve as input for the description of the liquid water runoff under various conditions in the GCM simulations.

The ejected liquid water flows from the circum-Chryse area all inevitably debouch into the basin of Chryse. However, Chryse Planitia is not a closed basin and if the total amount of water re-