Climate of early Mars during the late Noachian and the early Hesperian –formation of valley networks by rivers and glaciers

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The present-day Mars is cold and dry, with a low pressure of CO_2 atmosphere and little amount of surface and underground water ice. However, over the past few decades, geological observations have revealed that terrains on early Mars included widespread valley networks, which are considered to be evidence that flowing liquid water once sculpted the ancient surface of Mars during the late Noachian and the early Hesperian (3.85–3.6 Ga). Although such geological records have led many scientists to directly imagine “warm and wet” climate, several model studies have indicated a contrasting “cold and icy” climate in early Mars, in which the formation of large-scale ice sheets on southern low to middle latitudes would provide a vast reservoir of meltwater to create valleys.

In this study, to explore the best climate scenario of early Mars, we performed several series of climate simulation of early Mars for long timescale over 10^5 Mars years by a combination of global climate model (PMGCM), global river model (CRIS), and global glacier model (ALICE). We assumed a CO_2/H_2O/H_2 atmosphere (surface pressures of between 1 bar and 2 bar, and H_2 mixing ratios of between 0% and 6%), obliquity of 40˚, and geothermal heat flux of 55 mW/m^2. We defined the existence of a northern ocean and lakes in our model with the amount of corresponding to 500 m global equivalent layer (GEL) at the initial state, and implemented a pre-True Polar Wander topography to investigate the global water cycle of early Mars before late Tharsis formation. We iterated the runs of the ALICE and PMGCM–CRIS coupled model several times over the course of 10^5 Mars years to obtain the long–term equilibrium states for each condition of surface pressure and H_2 mixing ratio.

We revealed that climate on early Mars is classified into 3 types. First, when surface pressure and H_2 mixing ratio were both high, climate on early Mars would be “warm and semi–arid”, which means that global mean temperature was above 273 K, and prolonged rainfall–fed river systems carved valleys on southern highlands where the majority of valley networks are observed. These valleys were formed within a relatively short geological timescale (~10^4 Mars years), which agrees with previous geological studies of valley network formation timescale (10^4–10^6 Mars years). Second, when surface pressure and H_2 mixing ratio were both middle, climate on early Mars would be “cool and wet”, which means that global mean temperature was slightly below 273 K, but temperate–based glaciers became widespread. Subglacial meltwater–fed river systems carved valleys on southern highlands within a relatively long geological timescale (~10^5 Mars years) than “warm and semi–arid” case. Finally, when surface pressure and H_2 mixing ratio were both low, climate on early Mars would be “cold and icy”, which means that global mean temperature was much below 273 K, and cold–based glaciers became widespread, preventing glacier from melting. In both cases of “warm and semi–arid” and “cool and wet” scenarios, our river model CRIS produced valleys whose distributions agreed with more than half of the observed ones. Many river systems in the Noachian highlands are likely to have originated from either rainfall or subglacial meltwater. However, in case of “cold and icy” scenario, there was almost no apparent surface liquid water activity, which is contradictory to observations.

From our calculations and geological constraints for coexistence of fluvial and subglacial runoff systems, we conclude that early Martian climate could have experienced both “warm and semi–arid” and “cool

and wet" situations depending on atmospheric amount of H_2. However, some parts of modelled runoffs are discrepant with observed valley networks such as Margaritifer Terra. There is still a possibility that several valleys were produced by short-lived climatic warming, possibly through an increase in atmospheric greenhouse gas resulting from volcanism and meteorite events.

Keywords: Mars, early Mars, climate, valley networks, river, glacier

