LONG TERM EVOLUTION OF EARLY MARTIAN CLIMATE – VALLEY NETWORK FORMATION BY WARM OR COOL CLIMATE CONDITIONS

A. Kamada[1] *(ari_kmd@pat.gp.tohoku.ac.jp)*, **T. Kuroda**[1,2], **T. Kodama**[3], **Y. Kasaba**[4], **and N. Terada**[1]
[1]*Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan.* [2]*Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai, Japan.* [3]*Komaba Institute for Science, Graduate School of Arts and Science, University of Tokyo, Tokyo, Japan.* [4]*Planetary Plasma and Atmospheric Research Center, Tohoku University, Sendai, Japan.*

Introduction:
Although present-day Mars is cold and dry with a low pressure of CO_2 atmosphere and little amount of surface and subsurface H_2O ice, decades of geochemical and geological observations have revealed that the atmospheric environment on early Mars was quite different from that of Mars today. Early Martian terrains were carved by numerous networks of valleys, indicating evidence that prolonged liquid water activity sculpted the ancient surface of Mars during the late Noachian and the early Hesperian (3.85–3.6 Ga). However, controversy remains over the source of liquid water, that is, rainfall [1-4] and snow/ice melting [5-9]. Depending on which scenario of the water source is chosen, the climate condition of early Mars would be quite different.

Method:
To explore the best climate scenario of early Mars, we performed several series of climate simulation of early Mars for long timescale by a combination of global climate model (PMGCM, Paleo-Mars Global Climate Model), global river model (CRIS, Catchment-based RIver Simulator) [10,11], and global ice sheet model (ALICE, Accumulation and ablation of Large-scale ICE-sheets with dynamics and thermodynamics) (see **Figure 1**). We assumed a $CO_2/H_2O/H_2$ atmosphere with surface pressures of between 1 bar and 2 bar, H_2 mixing ratios of between 0% and 6%, and obliquity of 40°. Geothermal heat flux was set to 55 mW m^{-2}, which are representative of the late Noachian and the early Hesperian [12,13]. We defined the existence of a northern ocean and lakes in our model with the amount of corresponding to about 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 [14] (see **Figure 2**). 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.

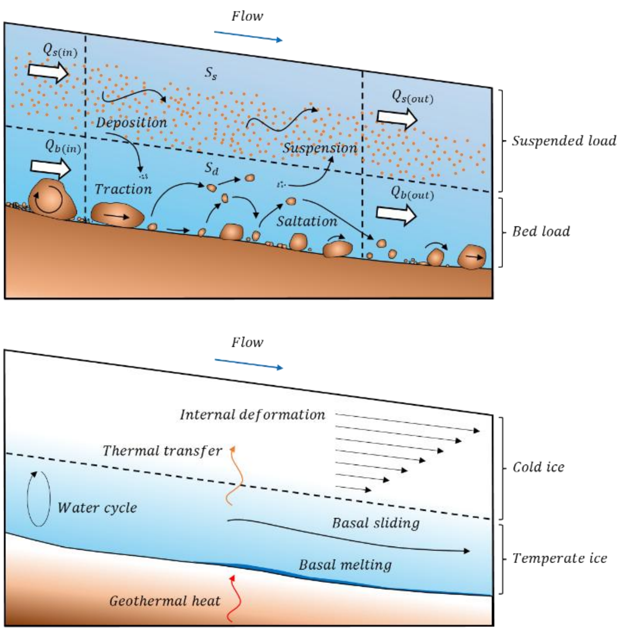

Figure 1. Schematic diagram of global river model CRIS [11] (top), and global ice sheet model ALICE (bottom).

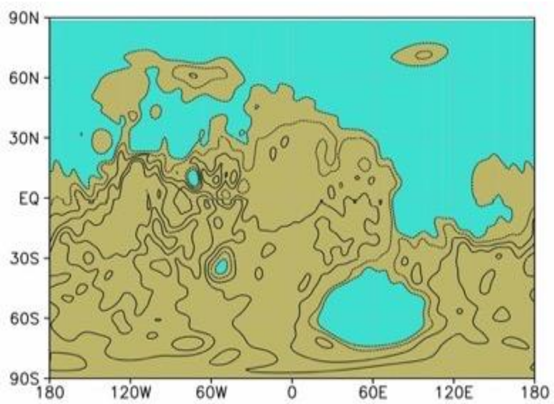

Figure 2. Pre-True Polar Wander topography and the initial distribution of ocean/lakes (in aqua) assumed in this study [11].

Results:
We showed that climate on early Mars is classified

into three conditions. First, when surface pressure and H_2 mixing ratio were both high, climate on early Mars would be “warm and semi–arid”, meaning that global averaged temperature was above 273 K, and prolonged rainfall–fed river systems carved valleys on southern low to middle latitudes where the majority of valley networks are observed (see **Figure 3**). These valleys were formed within a relatively short geological timescale (~10^4 Mars years), which agrees with previous geological studies of valley network formation timescales (10^4–10^6 Mars years) [15-17]. Second, when surface pressure and H_2 mixing ratio were both middle, climate on early Mars would be “cool and wet”, meaning that global averaged temperature was slightly below 273 K, but temperate–based ice sheets became widespread (see **Figure 4**). Subglacial meltwater–fed river systems carved valleys on southern low to middle latitudes 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”, meaning that global averaged temperature was much below 273 K, and cold–based ice sheets became widespread. In both cases of “warm and semi–arid” and “cool and wet”, 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 just case of “cold and icy” scenario, there was almost no apparent surface liquid water activity, which is contradictory to observations.

Conclusions:
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.

Acknowledgements:
This work is supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers JP19H00707 and JP21K13975, and the Astrobiology Center Program of National Institutes of Natural Sciences (Grant Numbers AB312005 and AB031014). The model runs have been performed with FUJITSU PRIMERGY CX 2550/2560 M4 (ITO) system at the Research Institute for Information Technology, Kyushu University.

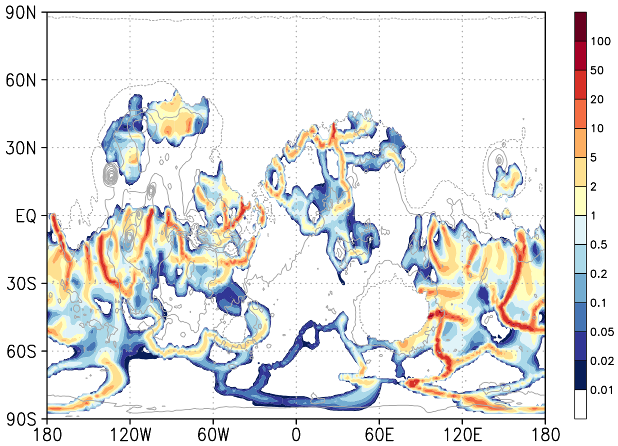

Figure 3. Annual averaged runoff (mm sol^{-1}) with a H_2 mixing ratio of 6% and surface pressure of 2 bar. Gray contours denote the topography, remapped to the present Martian topography with sea level of -2.54 km.

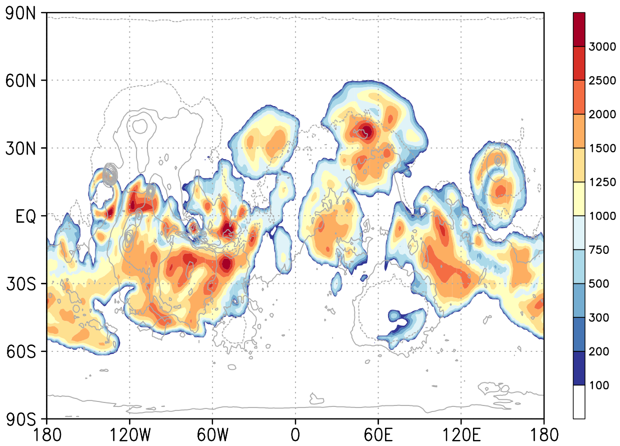

Figure 4. Simulated global distributions of glacial thickness (m) in the equilibrium state with a H_2 mixing ratio of 3% and surface pressure of 2 bar. Gray contours denote the topography, remapped to the present Martian topography with sea level of -2.54 km.

References:
[1] Craddock, R. A., Howard, A. D., 2002, The case for rainfall on a warm, wet early Mars. J. Geophys. Res., Planets, 107(E11), 5111. https://doi.org/10.1029/ 2001JE001505

[2] Irwin, R. P., Howard, A. D., Craddock, R. A.,

Moore, J. M., 2005, An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development. J. Geophys. Res., Planets, 110, E12S15. https://doi.org/10.1029/2005JE002460

[3] Hynek, B. M., Beach, M., Hoke, M. R. T., 2010, Updated global map of Martian valley networks and implications for climate and hydrologic processes. J. Geophys. Res., Planets, 115, E09008. https://doi.org/10.1029/2009JE003548

[4] Craddock, R. A., Howard, A. D., Irwin, R. P., Tooth, S., Williams, R. M. E., Chu, P.-S., 2012, Drainage network development in the Keanakāko'i tephra, Kīlauea Volcano, Hawai'i: Implications for fluvial erosion and valley network formation on early Mars. J. Geophys. Res., 117, E08009. https://doi.org/10.1029/2012JE004074

[5] Wordsworth, R. D., Foget, F., Millour, E., Head, J. W., Madeleine, J. -B., Charnay, B., 2013, Global modelling of the early martian climate under a denser CO_2 atmosphere: Water cycle and ice evolution. Icarus, 222, 1-19. https://doi.org/10.1016/j.icarus.2012.09.036

[6] Head, J. W., Marchant., D. R., 2014, The climate history of early Mars: insights from the Antarctic McMurdo Dry Valleys hydrologic system. Antarct. Sci., 26, 774-800. http://dx.doi.org/10.1017/S0954102014000686

[7] Bouquety, A., Sejourné, A., Costard, F., Mercier, D., Bouley, S., 2019, Morphometric evidence of 3.6 Ga glacial valleys and glacial cirques in martian highlands: South of Terra Sabaea. Geomorphology, 350, 91-111. https://doi.org/10.1016/j.geomorph.2019.02.022

[8] Bouquety, A., Sejourné, A., Costard, F., Bouley, S., Leyguarda, E., 2020, Glacial landscape and paleoglaciation in Terra Sabaea: Evidence for a 3.6 Ga polythermal plateau ice cap. Geomorphology, 350, 106858. https://doi.org/10.1016/j.geomorph.2019.106858

[9] Galofre, A. G., Jellinek, A. M., Osinski, G.R., 2020, Valley formation on early Mars by subglacial and fluvial erosion. Nat. Geosci., 13, 663-668. https://doi.org/10.1038/s41561-020-0618-x

[10] Kamada, A., Kuroda, T., Kasaba, Y., Terada, N., Nakagawa, H., Toriumi, K., 2020, A coupled atmosphere-hydrosphere global climate model of early Mars: A 'cool and wet' scenario for the formation of water channels. Icarus, 338, 113567. https://doi.org/10.1016/j.icarus.2019.113567

[11] Kamada, A., T. Kuroda, Y. Kasaba, N. Terada, and H. Nakagawa, 2021, Global climate and river transport simulations of early Mars around the Noachian and Hesperian boundary. Icarus, 368, 114618. https://doi.org/10.1016/j.icarus.2021.114618

[12] Solomon, S. C., Aharonson, O., Aurnou, J. M., Banerdt, W. B., Carr, M. H., Dombard, A. J., Frey, H. V., Golombek, M. P., Hauck, S. A., Head, J. W., Jakosky, B. M., Johnson, C. L., McGovern, P. J., Neumann, G. A., Phillips, R. J., Smith, D. E., Zuber, M. T., 2005. New perspectives on ancient Mars. Science, 307, 1214-1220. https://doi.org/10.1126/science.1101812

[13] Clifford, S. M., Lasue, J., Heggy, E., Boisson, J., McGovern, P., Max, M. D., 2010, Depth of the Martian cryosphere: Revised estimates and implications for the existence and detection of subpermafrost groundwater. J. Geophys. Res., Planets, 115, E07001. https://doi.org/10.1029/2009JE003462

[14] Bouley, S., Baratoux, D., Matsuyama, I., Forget, F., S.journ., A., Turbet, M., Costard, F., 2016, Late Tharsis formation and implications for early Mars. Nature, 531, 344-347. https://doi.org/10.1038/nature17171

[15] Moore, J. M., Howard, A. D., Dietrich, W. E., Schenk, P. M., 2003, Martian layered fluvial deposits: Implications for Noachian climate scenarios, J. Geophys. Res. Lett., 30(24), 2292. https://doi.org/10.1029/2003GL019002

[16] Moore, J. M., Howard, A. D., 2005, Large alluvial fans on Mars, J. Geophys. Res., 110, E04005. https://doi.org/10.1029/2004JE002352

[17] Bhattacharya, J. P., Payenberg, T. H. D., Lang, S. D., Bourke, M., 2005, Dynamic river channels suggest a long- lived Noachian crater lake on Mars, J. Geophys. Res. Lett., 32, L10201. https://doi.org/10.1029/2005GL022747