CIRCUMPOLAR OCEAN STABILITY ON MARS 3 GY AGO

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Summary: Was the nature of the Late Hesperian climate “Warm and wet” or “cold and dry?” Constructed in this manner the question leads to a paradox since both options seem implausible [1]. A “Warm and Wet” climate would have generated extensive fluvial erosion but not many valley networks have been observed in late Hesperian epoch. A cold climate would keep a northern ocean frozen most of the time. A moderate cold climate would have transferred the water from the ocean to the land in the form of snow and ice, especially to the Tharsis region and southern highlands. But this would in turn prevent tsunami formation, as some evidence suggests. We provide a novel view from numerical climate simulations in agreement with surface observations to show that the Martian climate could have been both cold and wet. We use an advanced General Circulation Model (GCM) to demonstrate that an ocean can be stable, even if the mean surface temperature of Mars is lower than 0°C. Rainfall appears moderate near the shorelines and in the ocean. Ice covers much of the southern plateau where the mean temperature is below 0°C and a glacier return flow back to the ocean exists. This scenario is accomplished with a 1 bar CO_2 dominated atmosphere with 10% H_2. At 3 Ga, the geologic evidence of a shoreline and tsunami deposits along the ocean/land dichotomy are compatible with ice sheets drained by valley glaciers in the southern highlands.

Introduction: The possibility of a Martian ocean is a topic of debate with strong implications on the habitability of the Red Planet. Geomorphological arguments in favor and against an ocean have been recently reviewed [2]. There is evidence of Martian paleo-shorelines [3] in Deuteronilus (sometimes noted contact no 2) in a geometry close to the current equipotential height [4]. Deuteronilus shoreline seems to be the latest in the last stage of Tharsis induced true polar wander [5]. Recent interpretation of tsunami deposits near the paleo-shorelines [6,7] has provided new evidence to the debate. In addition, the potential impact crater at the origin of the tsunami wave may have been identified [8]. Our investigations suggest a long-term stable water body 3 Gy ago in the Northern lowland of Mars.

Various scenarios have been investigated to maintain an ocean [1]. If the climate is cold, the ocean should have been entirely frozen shortly after its formation. It’s higher albedo helping to assist in keeping the climate cool. If warm, the ice-free ocean should have produced intense fluvial erosion of Hesperian terrains. But there is a lack of observation of such extensive valley network [1]. In addition, water should have accumulated in the southern highlands in form of ice and thus removed from the ocean. A cold and wet Mars scenario has been theoretically proposed [9] but the long-term stability of an ocean in such a scenario has never been achieved in a 3D-GCM.

Model: We utilize a fully coupled ocean/atmosphere 3-D General Circulation Model simulations called ROCKE-3D [10], which is based upon a parent Earth Climate Model known as ModelE2 [11]. This model allows one to estimate the interaction between atmosphere/ocean circulation but also encompasses a sophisticated surface hydrological scheme. We also included a glacier return flow to the ocean.

We assume the solar luminosity to be ~79% of its current value ($1360.67 W.m^{-2}$) [12], hence at 3 Gy, the flux at Mars would be $452.8 W.m^{-2}$. The ocean shoreline is set to –3900 meters in all runs. This gives an ocean surface fraction of ~16% which is small in comparison to Earth at ~71%. The ocean is also shallower than the mean depth for Earth. For this reason, the time to bring our ancient Mars model with its fully coupled ocean and atmosphere into equilibrium is much shorter (~100s of years) than would be the case for an Earth like ocean (~1000s of years). We assume this equilibrium has been reached when the net radiative balance (the difference between incoming and outgoing fluxes) is less than $0.2 W.m^{-2}$.

H_2 provides a powerful greenhouse component with CO_2 as a background gas. Other gas combinations with CH_4 or H_2S may have an equivalent radiative effect, but little motivates their use. We run simulation with 10% and 20% H_2 in a CO_2 dominated atmosphere with 0°, 20°, 40°, 60° obliquity, since the latter had large excursions in the past [13, 14].

Results: Figures 1 and 2 show the simulated effect of an ocean circulation on the surface temperature field averaged over 10 Martian years for H_2=10% and CO_2 =90% and total pressure of 1 bar. Despite a global mean surface temperature below 0°C, the ocean is stable due to its low altitude, low albedo and circulation. Thanks to the ocean gyre, the net heat is toward the pole and appears to keep the circumpolar ocean warmer than a slab ocean up to 4.5°C.

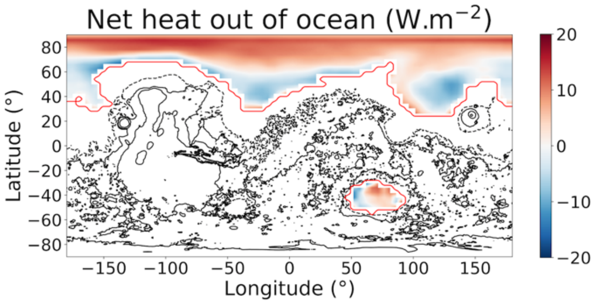

Figure 1: Net outward heat flux transported by the ocean for 60° obliquity and H_2=10%. The positive value (up to 15 W.m^{-2}) near the North pole indicates that heat goes toward the atmosphere due to ocean circulation. For a non-circulating slab ocean, this flux is null. Black contour lines represent surface elevation level and the red contour line is the paleo-shoreline.

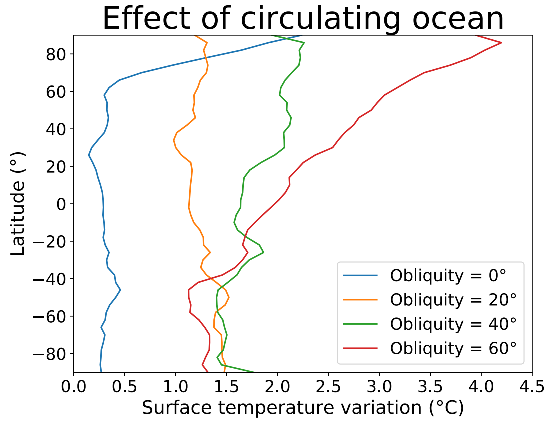

Figure 2: Latitudinal profile of the temperature increase ($T_{circulating} - T_{slab}$) due to the circulating ocean, as a function of obliquity.

On land, there is a clear boundary at the 0°C isotherm which corresponds approximately to the Martian dichotomy. In the high altitude domain, commonly referred to as the "icy highlands", the surface is mostly frozen and snow precipitation is dominant. The extensive accumulation of snow in the highlands can lead to the formation of significant ice sheets that may flow down to the Northern and Hellas basin oceans. Our model is not able to simulate glacier flow details, but only a global mass flux from land to the ocean. In the lowest altitudes, called the "wet lowlands", rain, evaporation and surface runoff are balanced.

Figure 3 represents a scheme with the climatic regions superposed with the geological evidences. Valleys network are present mainly near the shoreline. Glacial valleys are present from the icy highland domain to the ocean, as predicted by the GCM.

Discussion and conclusion: Our results [15] demonstrate that a cold and wet climate could have been stable 3Ga and is consistent with geomorphological evidence thanks to glacier return flow. Using fully coupled atmosphere / dynamic ocean modeling, we show that the ocean's circulation regionally warms the surface up to 4.5°C. In these conditions the ocean is stable even for a global mean planetary temperature below 0°C. This Martian climate may be similar to ancient Earth's with an active water cycle around the time of the early stages of life's appearance. Future work should encompass careful analysis of this stable ocean domain and its application to the past Martian climate, especially in the Noachian epoch.

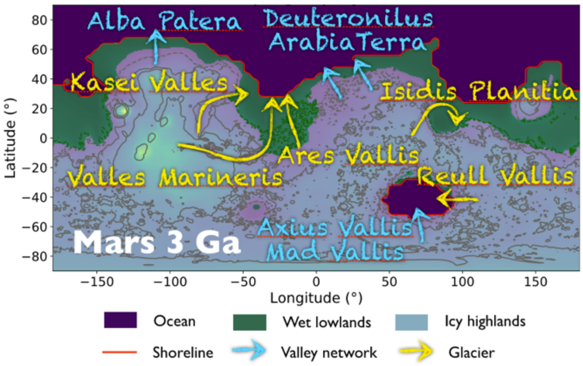

Figure 3: Proposed scenario of a cold and wet climate at the Hesperian age (3 Ga).

References: [1] M. Turbet et al., Sci. Rep., 9(1), apr 2019. [2] Z. I Dickeson et al., Ast. & Geo., 61(3):311–317, jun 2020. [3] T. J. Parker, et al., J. Geo. Res, 98(E6):11061, 1993. [4] J. W. Head et al., Science, 286 (5447):2134–2137, 1999 [5] R. I. Citron, et al,, Nature, mar 2018. [6] A. P. Rodriguez, et al., Sci. Rep., 6:25106–, May2016. [7] F. Costard, et al., J. Geo. Res 122(3):633–649, mar2017. [8] F. Costard, et al., J. Geo. Res, jul 2019. [9] A. G. Fairen, Icarus, 208(1):165–175, July 2010 [10] Way et al., Astro. Jour. Sup. Series, 231:12, July 2017 [11] G. A. Schmidt et al., J. Adv. Model. Earth Sys., 6(1):141–184, 2014 [12] D. O. Gough et al., SolarPhysics, 74(1):21–34, November 1981, [13] J. Laskar, et al.,.Icarus, 170:343–364, August 2004. [14] J. C. Armstrong, et al., Icarus, 171(2):255–271, October 2004. [15] F. Schmidt et al., PNAS, 119, 4, e2112930118, Jan. 2022, doi: 10.1073/pnas.2112930118.