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An analytical climate model to reproduce first order, yearly-averaged, climatology on early Mars: implications for the ancient lakes in Gale crater

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Abstract

We provide an analytical "toy" model to reproduce the first order, yearly-averaged, latitudinal distribution of surface temperatures for Mars under different surface pressure, luminosity, eccentricity and obliquity. The model is intended to be used as a complementary tool to include the effect of meridional heat transport for one dimensional radiative studies (i.e. investing greenhouse warming for early Mars).

1. Introduction

Sedimentary deposits characterized by the Mars Science Laboratory *Curiosity* rover provide evidence that Gale crater, Mars intermittently hosted a fluvio-lacustrine environment during the Hesperian (∼3.8Gya). [1] However, no theory has been able to provide a robust and self-consistent way to maintain global mean temperature above the freezing point due to the low solar energy input available at that time (e.g. warming by CO_2 clouds [2], water ice clouds [3], dust [4], impacts [5], volcanism [6], reduced atmospheres [7]; [8], carbonate-silicate cycles [9]). While it has been challenging to raise the *global mean* temperature above the freezing point [10], it is possible that *equatorial* temperatures could have reached 273K. We address this possibility using an analytical, latitudinally-resolved climate model.

2. Model

We adapt one of the earlier methods originally developed to study the Earth climate [11] and use the analytical formulations for the annual mean insolation provided by [12]. We show that the yearly-averaged surface temperature is:

$$\overline{T_s}(x) = \frac{\varphi_0}{4\sqrt{1-e^2}}\left(\frac{Sa_0}{B}\right) - \frac{A}{B} + \frac{\varphi_0}{4\sqrt{1-e^2}}\left(\frac{Sa_2\, p_2(x)}{6D+B} + \frac{Sa_4\, p_4(x)}{20D+B}\right) \qquad (1)$$

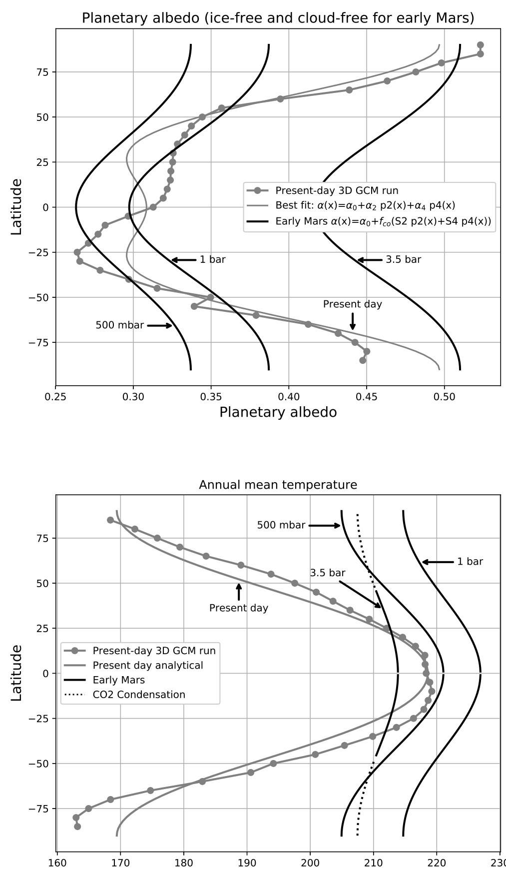

Figure 1: (Top) Zonally-averaged planetary albedo from the GCM (grey markers), best fit for present day Mars (grey line) and albedo distribution used for the early Mars predictions (black lines). (Bottom) Comparison of the mean annual temperature predicted by the NASA-Ames GCM (grey markers) with the analytical model calculation for present-day Mars (grey line), and analytical predictions for early Mars for different surface pressures (black lines).

with x the sine of the latitude, φ_0 the solar constant at Mars (e.g. $\frac{1370}{1.52^2}$ $W.m^{-2}$ for present day), e the eccentricity, D the diffusivity of the atmosphere in unit of $[W/m^2/K]$, A and B the outgoing longwave radiation (OLR) parameters such as $OLR = A + B\ T$. $p_n(x)$ are the Legendre polynomes and Sa_n the net solar insolation parameters, defined as:

$$\begin{cases} p_2(x) = \left(3x^2 - 1\right)/2 \\ p_4(x) = \left(35x^4 - 30x^2 + 3\right)/8 \\ S_{a0} = \frac{1}{5}S_2\alpha_2 + \frac{1}{9}S_4\alpha_4 + \alpha_0 \\ S_{a2} = S_2\alpha_0 + \frac{2}{7}S_2\alpha_2 + \frac{2}{7}S_2a4 + \frac{2}{7}S_4\alpha_2 + \frac{100}{693}S_4\alpha_4 + \alpha_2 \\ S_{a4} = \frac{18}{35}S_2\alpha_2 + \frac{20}{77}S_2\alpha_4 + S_4\alpha_0 + \frac{20}{77}S_4\alpha_2 + \frac{162}{1001}S_4\alpha_4 + \alpha_4 \\ S_2 = -\frac{5}{8}p_2(cos(\beta)) \\ S_4 = -\frac{9}{64}p_4(cos(\beta)) \end{cases} \tag{2}$$

where β is the obliquity, S_n the annually-averaged direct solar insolation parameters and α_n the coefficients used to parametrize the annually-averaged co-albedo as

$$\overline{\alpha}(x) = \alpha_0 + \alpha_2\ p_2(x) + \alpha_4\ p_4(x) \tag{3}$$

For present-day Mars we provide a direct fit to the NASA Ames General Circulation model (GCM) for the co-albedo: α_0=0.67, α_2=-0.095, α_4=-0.072. For early Mars, we propose to use $\alpha_0 = 1 - a_0$, $\alpha_2 = -f_a \times S_2$ and $\alpha_4 = -f_a \times S_4$ with a_0 a global mean value for the planetary albedo and f_a a parameter used to simulate the dependence of the albedo on the solar zenith angle. The albedo a_0, as well as the parameters f_a, A, and B are estimated using the NASA Ames radiative transfer code for a pure CO_2 atmosphere. Suggested values for these coefficients for present-day Mars and for 500mbar, 1 bar and 3.5bar ancient atmospheres are given in Table 1

3. Results

Figure 1 (bottom) shows that, given its simplicity, the analytical climate model (grey line) reproduces reasonably well the annually-averaged surface temperature from the GCM for present-day Mars (grey markers). For the 500 mbar atmosphere and for the 1 bar atmosphere, greenhouse warming and rather low values for the planetary albedo (see Figure 1 (top)) lead to surface temperatures warmer than present-day, despites a reduced solar luminosity (black lines in Figure 1 (bottom)). However, further increasing the surface pressure to 3.5 bar ultimately results in lower surface temperatures due to the increase in atmospheric scattering. The 3.5 bar case drops bellow the condensation temperature of CO_2 at high latitudes (dotted lines in Figure 1 (bottom)) so this solution is not stable against atmospheric collapse.

Pressure [mbar]	D	OLR=$A + B\ T$		Albedo	
		A	B	a_0	f_a
7	0.02	-212	1.54	(see text)	
500	0.46	-134	0.99	0.29	-0.111
1000	0.70	-72	0.66	0.33	-0.135
3500	1.28	13	0.23	0.45	-0.142

Table 1: Estimates for the diffusivity, outgoing longwave radiation at the top of the atmosphere, and planetary albedo as a function of the surface pressure

4. Summary and conclusions

The simple analytical climate model demonstrates that there is no obvious combination of orbital parameters nor greenhouse scenarios that would lead to annually-averaged surface temperature above 273K at the equator. This raises the possibility that the lacustrine environment at Gale crater may have subsisted during the Hesperian in the form of ice-covered lakes.

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