

ATMOSPHERIC METHANE AND MARTIAN CLIMATE. P. D. Archer Jr., A. A. Pavlov, and P. H. Smith, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 85721, darcher@lpl.arizona.edu.

Introduction: It is generally accepted from geomorphologic and geochemical evidence that Mars has had a relatively wet past. How warm Mars must have been in order to produce the fluvial features found on ancient, cratered terrain is still a subject of debate. It is generally agreed upon that, if water created the fluvial features, the global average surface temperature must have been significantly closer to the melting point of water than the current value of ~ 211 K. Also, that the surface pressure needed to be higher than the current value of ~ 7 mbar, which puts the Martian surface very close to the triple point of water. Increased atmospheric CO_2 was generally assumed to be the solution to both of these problems and that a few bars of CO_2 could raise the average surface temperature above the melting point of water [1-4]

What these models neglected, which was pointed out by Kasting in 1991 [5], is that CO_2 is condensable under Martian conditions. Kasting concluded that due to the condensable nature of carbon dioxide in the Martian atmosphere, the prior conclusions were not correct. The faint young sun paradox, which remains an open question in Earth science, was applicable to Mars as well. The paradox being the apparent geomorphologic evidence of warmer times dating to around 3.8 Ga when the sun is thought to have been only about 75% as luminous as it is today [6]. Consequently, there must have been another greenhouse agent in the Martian atmosphere to warm the planet.

Two different mechanisms have been proposed to circumvent this problem: first, another greenhouse gas, such as NH_3 or CH_4 could have been present at high enough levels in the early atmosphere to prevent CO_2 condensation and maintain a high average surface temperature [7, 8]; second, clouds of CO_2 could have been acting as IR scatterers which would also have warmed the surface [9]. The CO_2 cloud theory could work but relies on details that are very complicated and somewhat unproven [10]. The first theory was not pursued in depth because it was found that NH_3 photodissociates quickly to H_2 and N_2 and would therefore not have played a large role in long-term climate stability [5]. Furthermore, methane has a relatively short (~ 400 year [11]) lifetime in the Martian atmosphere and was also discounted as a potential warming candidate.

However, within the past few years three separate groups have reported detecting methane in the Martian atmosphere at the 10 parts per billion (ppb) level as a global average [11-13]. Formisano and Mumma have reported observing regions of enhanced methane, the

highest value being around 250 ppb. Though these numbers need to be confirmed, this again raises the possibility of methane as a potential player in Martian climate. This work seeks to take a first step towards quantifying the possible impact of atmospheric methane on Martian climate, both past and present.

Model: The radiative transfer code used in this model is a 1-dimensional radiative-convective model developed by Pavlov et al. [14]. The model uses a δ two-stream approximation with convective adjustments to the radiative transfer results. Convective adjustments are energy conserving and the lapse rate is forced to the Martian tropospheric adiabatic lapse rate of 4.5 K/km. A 1-D model, which neglects dynamical methods of heat transport, is instructive as a first step as it produces a best-case scenario for warming.

A current gap in the understanding of different Martian climate regimes is the behavior of atmospheric water vapor. Water vapor is an incredibly important greenhouse gas because of its large absorption cross-section in the IR where Mars reradiates most of its incident flux. For Earth climate models, it is generally assumed that the water vapor pressure is close to saturation. However, the amount of water in the Martian atmosphere is set by the temperature of the polar caps and the response of the polar caps to climate forcings is not currently well understood. For past Mars, the amount of H_2O in communication with the atmosphere is even more poorly constrained. In both cases, the water vapor behavior is beyond the scope of a 1-dimensional climate model. Therefore, water vapor was either held at a partial pressure equivalent to its observed mixing ratio of 150 ppm in the troposphere and 2.5 ppm in the stratosphere [15] or it was simply set to zero.

This is justifiable in that this work primarily attempts to quantify the effects of methane on Martian climate and water vapor feedback could easily wash out a small methane signal. CO_2 is also included as a greenhouse gas, but the code does not couple warming due to methane and carbon dioxide pressure for the same reason. It is readily acknowledged that feedback between CH_4 , H_2O , and CO_2 will occur and a complete and self-consistent climate model must include these effects. The purpose of this work is to make a first attempt to better understand the climatic effects of CH_4 in the martian atmosphere.

Two Physical Cases. To investigate the warming effects of methane under current and past conditions both high (up to 1 bar) and low (~ 5 mbar) pressure

regimes were modeled. For both pressure regimes, both high (~290 K) and low (~210 K) temperature cases were considered. This is useful because it not only tests the effects of methane during two different Martian climate epochs, but also quantifies the degree to which this warming depends on both temperature and pressure. Raising temperature or pressure causes an increase of the absorption cross-section, which should cause increased warming.

Unlike water and carbon dioxide, methane also absorbs in the visible and near-visible. This is important because absorbing incoming visible radiation decreases planetary albedo (increasing the amount of solar energy absorbed). However, how it affects surface temperature depends on where CH_4 becomes optically thick. If most of the absorption takes place in the troposphere, the warming will reach the surface and may also increase the saturation vapor pressure of water, serving to amplify the forcing. If absorption takes place in the stratosphere, it would decrease overall albedo but will also decrease the solar flux incident on the surface, thus decreasing the surface temperature.

Important notes. The code is run for a given total pressure to obtain a surface temperature. To keep the column mass of methane fixed as total pressure changes, partial pressure, not mixing ratio, is varied from 2.58×10^{-13} mbar (equivalent to 0.1 ppb in a 7 mbar atmosphere) up to 2.58×10^{-6} mbar (or 1000 ppm in a 7 mbar atmosphere). Throughout the runs, water vapor is also held constant for the same reason. For context, the highest observed methane mixing ratio of 250 ppb is equivalent to $\sim 6.4 \times 10^{-10}$ mbar of CH_4 .

For the low pressure, present-day case, total surface pressure was varied by changing the amount of CO_2 in the atmosphere and keeping the other gases present at the same partial pressure. The range of 5 to 20 mbar was chosen as this represents a conservative estimate of Mars pressure range during the past 10 Ma. For each total pressure case, $p\text{CH}_4$ is varied.

For the high pressure case, in order to disentangle the warming impact of methane from that of CO_2 , N_2 partial pressure was increased from its present value of 0.12 mbar up to 0.1 bar, then to 1.0 bar. Nitrogen was chosen as it demonstrates both the pressure-broadening of methane's absorption lines and the increased planetary albedo due to increased Rayleigh scattering at higher pressures without causing any warming itself. In the high pressure case and as before, CH_4 partial pressure (not mixing ratio) is varied, and the H_2O partial pressure is fixed.

Results:

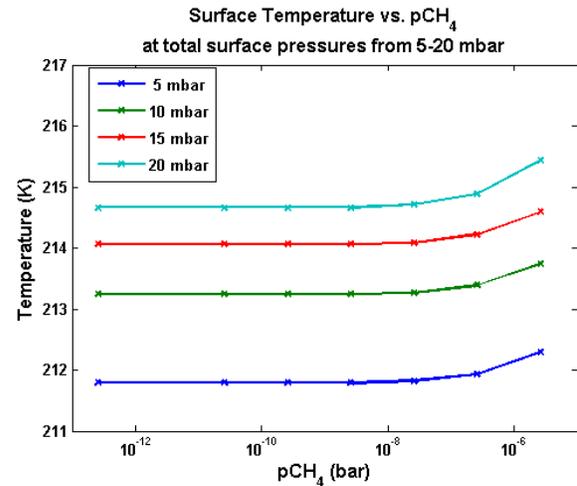


Figure 1. Mars mean global surface temperature vs. methane partial pressure at 4 different values of total surface pressure.

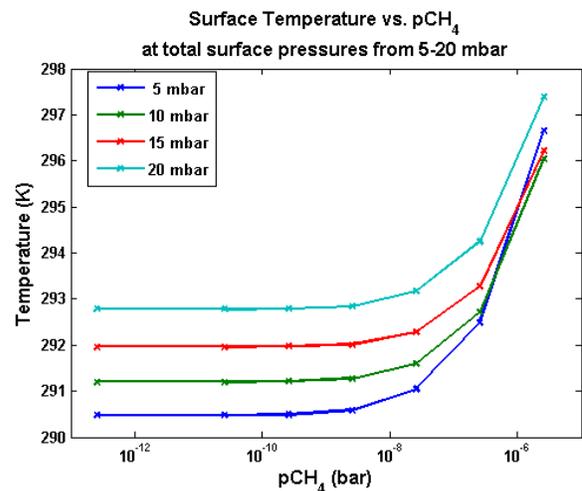


Figure 2. Mars maximum daily surface temperature vs. methane partial pressure. Why the lowest curve has the most warming is not understood. There could be a physical reason why that is happening or it could also be a problem with absorption coefficients at that pressure.

As expected, methane does not appear to be an important greenhouse gas under current Martian conditions. Under low temperature conditions, even CH_4 levels much higher than those currently observed produce very little warming. By comparison, this sort of climate variability can also be seen due to decadal albedo variations [16]. This shows that the impact of methane during the current martian climate regime is very low.

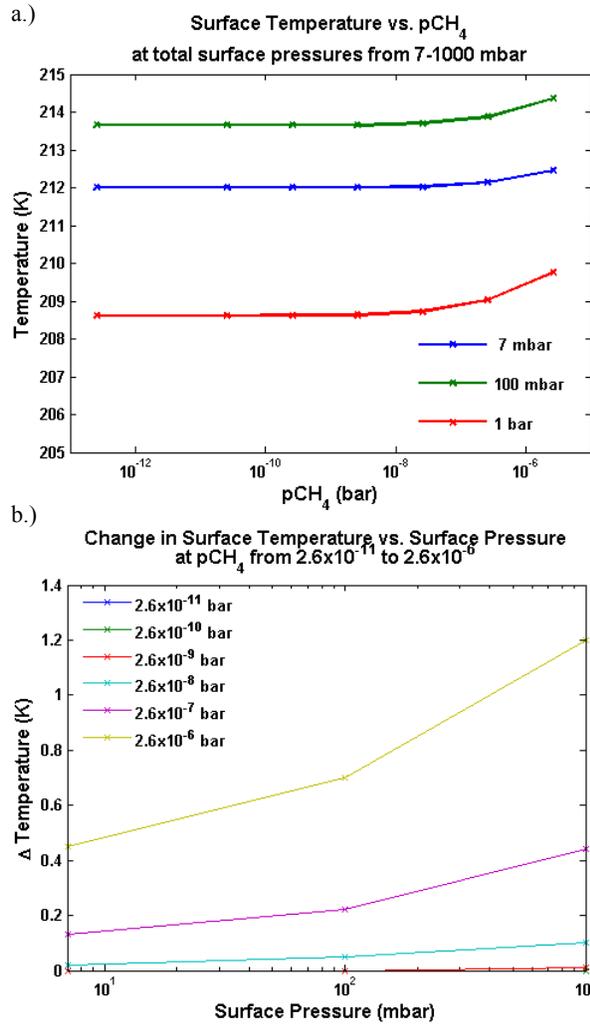


Figure 3. a.) Average surface temperature vs. CH_4 partial pressure at different levels of total surface pressure (done by increasing N_2). Note that the 1 bar case plots lower than the 7 and 100 mbar cases. This is due to the increased planetary albedo caused by increased Rayleigh scattering of the incoming light. b.) Change in surface temperature (temperature with methane minus temperature with methane zeroed out) vs. total surface pressure. Methane partial pressure is constant along a curve. (The lowest two values of methane partial pressure both plot on the x axis.)

The low temperature, high pressure case results are again as expected. High pressure alone does not cause a great amount of warming and, even at very high concentrations, does not make up for the drop in surface temperature due to the albedo increase. Plot 3b shows that the surface temperature increase is a function of total pressure and behaves as expected. The same plot done for high pressure *and* high temperature is substantially different and hence difficult to understand.

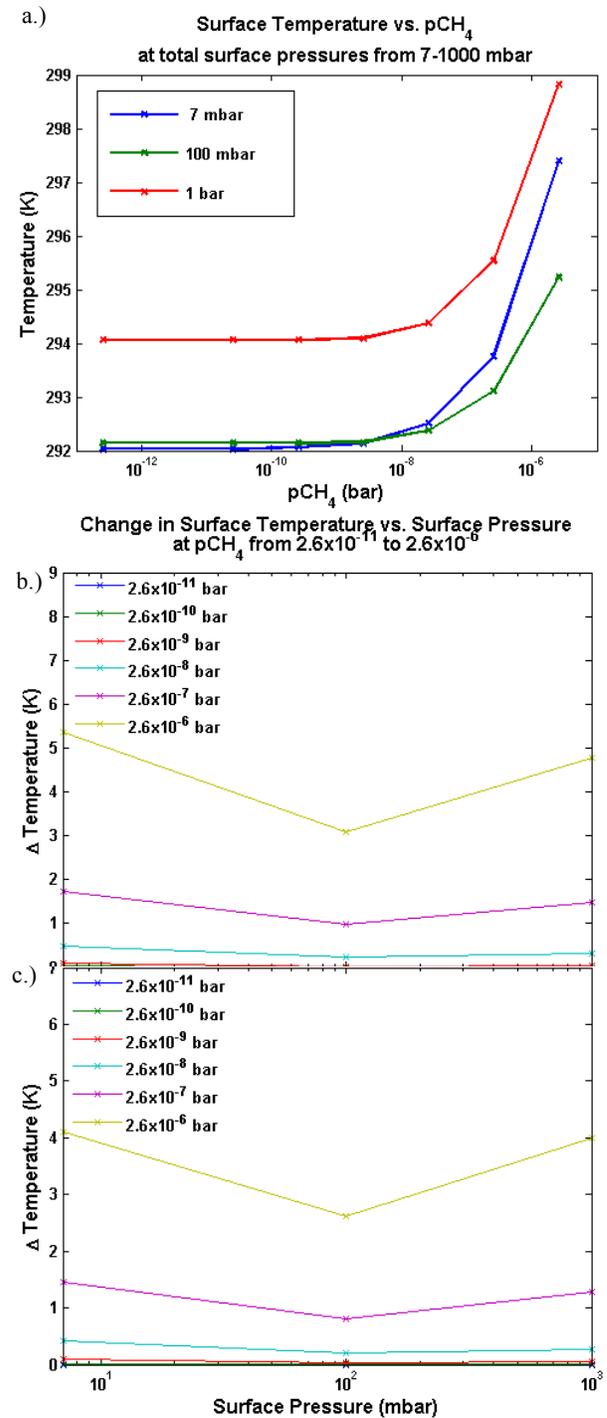


Figure 4. a.) Average surface temperature vs. CH_4 partial pressure for the high temperature case. Note that the 7 mbar run starts at a lower temperature than the 100 mbar case but that it ends at a higher temperature. This is also demonstrated by the dip at the middle point in plots b and c. b.) and c.) Change in surface temperature vs. total surface pressure, methane partial pressure is constant along a curve. c.) is a run where methane absorption in the visible is removed. Notice the lower values of ΔT in plot c (5.3 vs. 4.1 at 7 mbar and 4.8 vs. 4 at 1 bar)

The high pressure, high temperature regime is promising for two reasons. First of all, since methane partial pressure is kept constant throughout all the runs, the mixing ratio of 2.58×10^{-6} bar of CH_4 in a 1 bar atmosphere is only ~ 7 ppm. This relatively small amount gives you almost 6 degrees of warming which may be large enough to prevent CO_2 condensation, allowing for a warm early Mars. Furthermore, removing methane absorption in the visible from the code results in a decrease in surface pressure. As mentioned earlier, this implies that methane absorption is primarily a tropospheric phenomenon. This could have a big impact on the saturation vapor pressure of water and carbon dioxide. And again, water vapor and CO_2 feedback can greatly amplify a CH_4 forcing. So these results are encouraging.

The drop in ΔT at intermediate pressure is not understood at the moment. Whether this is a physical phenomenon or results from problems with our absorption coefficients has yet to be determined. If it is a real feature, it is a very interesting saddle point that would make a methane-sustained warm Mars somewhat unstable since if pressure drops for whatever reason, methane warming will decrease, which is a positive and therefore unstable feedback loop. Conversely, if Martian pressure is low and something causes pressure to increase (volcanic outgassing, an impact), methane will amplify the warming effect and the system will head to a warmer equilibrium point.

Conclusions: Current concentrations of methane, coupled with the low atmospheric pressure and low mean global surface temperature, have little to no effect on Mars climate in the present epoch. However, if Mars was warmer and had a higher atmospheric pressure in the past, methane could have played a critical role in maintaining a climate consistent with the geochemical and geomorphologic evidence.

Mars certainly had a higher atmospheric pressure at some point in the past based simply on atmospheric loss rates. This higher pressure would, due to pressure broadening of CO_2 and H_2O absorption bands, have caused more warming and a higher surface temperature. Whether or not this temperature increase would have been enough to activate a methane-water vapor-carbon dioxide feedback loop is still an open question.

As this work shows, CH_4 in and of itself will not raise Mars mean surface temperature up near the freezing point of water (without invoking a huge source of methane). However, it seems possible from these results that CH_4 could keep the atmosphere warm enough to prevent CO_2 condensation and raise the saturation vapor pressure of water to the point that the resulting greenhouse warming counteracts the effects of a faint early sun and allows for a wet, warm Mars.

References: [1] Pollack J. B. (1979) *Icarus*, 37, 479-553. [2] Cess R. D. et al. (1980) *Icarus*, 41, 159-165. [3] Hoffert M. I. et al. (1981) *Icarus*, 47, 112-129. [4] Pollack J. B. et al. (1987) *Icarus*, 71, 203-24. [5] Kasting J. F. (1991) *Icarus*, 94, 1-13. [6] Gough D. O. (1981) *Solar Physics*, 74, 21-34. [7] Sagan C. and Mullen G. (1972) *Science*, 177, 52. [8] Sagan C. and Chyba C. (1997) *Science*, 276, 1217-21. [9] Forget F. and Pierrehumbert R. T. (1997) *Science*, 278, 1273-1276. [10] Kasting J. F. (1997) *Science*, 278, 1273-6. [11] Krasnopolsky V. A. et al. (2004) *Icarus*, 172, 537-547. [12] Mumma M. J. et al. (2003) *DPS* 35, 14.18. [13] Formisano V. et al. (2004) *Science*, 306, 1758-1761. [14] Pavlov A. A. et al. (2000) *JGR*, 105, 11981-90. [15] Rodin A. V. et al. (1997) *Icarus*, 125, 212-229. [16] Fenton L. K. et al. (2007) *Nature*, 446, 646-649.