Radiative Transfer in the Early Atmospheres of Mars and Earth

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Introduction: The early climates of Earth and Mars appear to have been relatively warm, despite the existence of a less luminous young Sun [1]. Most attempts at reconciling these apparently contradicting observations rely on atmospheres that are richer in greenhouse gases (GHGs) than the present atmospheres of either planet [2]. The major contribution to most plausible greenhouses is from CO_2 and H_2O vapor. However, paleo-pCO_2 reconstructions from Proterozoic paleosols [3, 4] fall several to several hundred times short of the amount of CO_2 required for sustained habitability over Earth's history [5], whereas on Mars CO_2 condensation complicates matters by decreasing the tropospheric lapse rate and forming CO_2 clouds that scatter solar radiation [6]. While these clouds also scatter IR radiation [7], the sign and magnitude of the forcing they provide remain under debate [8, 9]. Other infrared absorbers have been suggested, such as SO_2 [10, 11] and CH_4 [12], each with their associated difficulties.

The fundamental question, whether a CO_2-H_2O greenhouse can account for the observations or whether other absorbers are necessary, is compounded by uncertainty in radiative transfer through CO_2-rich atmospheres. Using a line-by-line (LBL) radiative transfer model, we show that small differences in the formulation of absorption by CO_2 result in very large differences in radiative forcing when applied to atmospheres containing 0.1 to 5 bars of CO_2. Because band models and the more sophisticated three dimensional models in which they are embedded depend on the results of LBL calculations, this uncertainty pervades any attempt at modeling the early climate of Mars and Earth.

Absorption in Line-by-Line Models: The absorption coefficient, κ, of a single GHG at a frequency ν can be expressed as follows:

$$\kappa(\nu,p,T) = \sum_{|\nu-\nu_i|\le d} \Big[S_i(T)\cdot\chi(\Delta\nu_i,T)\cdot f\big(\Delta\nu_i,\gamma_i(p,T)\big)\Big] + C(\nu,p,T)$$

where p and T are the pressure and temperature. The sum on the right hand side is over all absorption lines within a certain cutoff distance d (in cm^{-1}) from ν. ν_i, $S_i(p)$ and $\gamma_i(p,T)$ are the frequency and strength at line center and the line half-width, which are tabulated in spectroscopic databases. The line shape function, $f\big(\nu,\nu_i,\gamma(p,T)\big)$, describes the way in which absorption decays with distance from the line center. The χ-factor, $\chi(\nu,\nu_i,T)$, accounts for sub or super-Lorentzian absorption in the far wings of the lines [13, 14]. The continuum, $C(\nu,p,T)$, accounts for observed absorption that cannot be explained by contribution from nearby lines.

The least well constrained parameters are the χ-factor, the continuum and the related line cutoff distance. These parameters can be tuned to reproduce experimental data or observed planetary spectra (e.g. modern Earth or Venus). The problem for modeling the climate of early Earth and Mars is that observational spectra obviously do not exist and experimental data are rare and have not been revisited since 1971 [13, 15].

A Line-by-Line Radiative Transfer Model: We constructed a line-by-line radiative transfer model, briefly described below. On a spectral grid of variable resolution and at every $p-T$ level in the model atmosphere, we calculate a composite optical depth, τ, including the effects of both absorption and scattering. We then solve the two-stream equations of diffuse radiative transfer:

$$\frac{dI_+}{d\tau} = \beta_2 I_- - \beta_1 I_+ + \beta_B \pi B(T(\tau)) + \beta_+ L_\odot e^{-\frac{\tau_\infty-\tau}{\cos\zeta}}$$

$$\frac{dI_-}{d\tau} = \beta_1 I_- - \beta_2 I_+ - \beta_B \pi B(T(\tau)) - \beta_- L_\odot e^{-\frac{\tau_\infty-\tau}{\cos\zeta}}$$

where I_+ and I_- are the upwelling and downwelling diffuse radiation fluxes, $B\big(T(\tau)\big)$ is Planck's function, $L_\odot$ is the solar constant and ζ is the zenith angle. The β_js are coefficients describing the attenuation of radiation due to scattering and absorption. The boundary conditions specify that there is no diffuse downelling flux at the top of the atmosphere and that the upwelling flux from the surface is comprised of blackbody emission and reflected diffuse and direct downwelling fluxes.

We compared three parameterizations of CO_2 absorption. The "MTCKD" parameterization is fashioned after the approach of [16]. The "GBKM" parameterization follows the approach of [17] and references therein. The complete absorption or "CA" parameterization is modeled after the approach of [18]. To allow comparison of the chosen formulations of CO_2 absorption, and despite uncertainty in absorption by H_2O vapor in CO_2-rich atmospheres, we kept the parameterization of absorption by H_2O vapor fixed in all three cases [16]. For $pCO_2 \le 0.1$ bar in an atmosphere with pN_2 of 0.8 bar and a relative humidity of 80%, the outgoing longwave radiation (OLR) calculated with all three parameterizations is within $\pm 0.87\%$ of the OLR calculated using the NCAR Community Climate Model.

Results and Discussion: The calculated OLR differs significantly between the three parameterizations; the difference in OLR between the least and most opaque parameterizations (CA and GBKM, respectively) increases with pCO_2 (Fig. 1). The parameterizations are also variably sensitive to addition of other GHGs, with the CA and GBKM parameterizations being the most and least sensitive, respectively (Fig. 2). When added to a pure

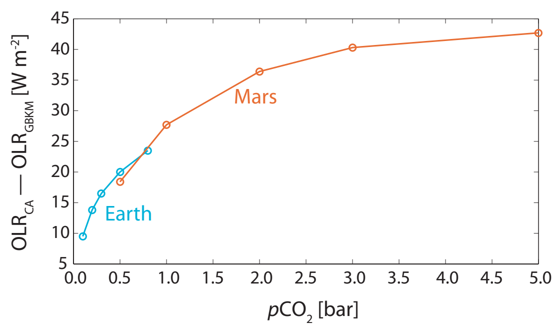

Figure 1: The difference in OLR between the CA and GBKM parameterizations, for a dry Earth atmosphere with $pN_2 = 0.8$ bar and $pCO_2 = 0.1$–0.8 bar and a dry Martian atmosphere with $pCO_2 = 0.5$–5 bar.

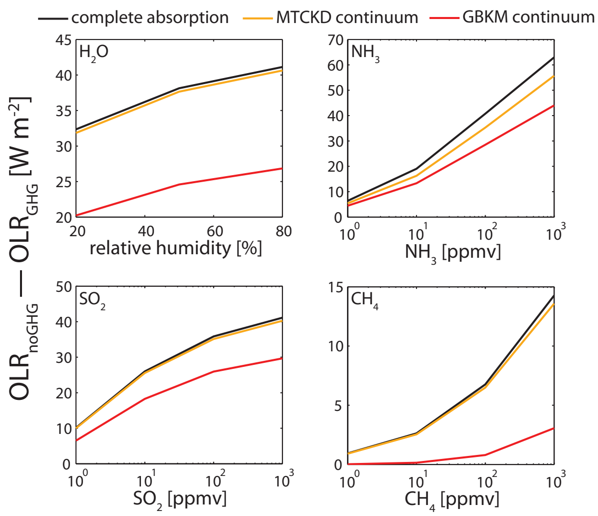

Figure 2: The difference in OLR between a dry, 1 bar CO_2 atmosphere and one containing an additional GHG.

CO_2 atmosphere, the strongest GHG (per mole) is NH_3 and the weakest is CH_4 (out of a list including also N_2O and H_2S - not shown). However, with a relative humidity of 80%, SO_2 and NH_3 are equivalent, with an advantage for SO_2 at concentrations below $\sim$30 ppmv.

The differences between the three parameterizations arise primarily from differences in the absorption coefficient calculated in the CO_2 window regions, at frequencies below 500 cm^{-1} and between 1200 and 1800 cm^{-1} (Fig. 3). In these regions the absorption coefficient calculated with the GBKM parameterization is as much as five orders of magnitude higher than that calculated with the CA parameterization. While this makes for the most effective CO_2-H_2O greenhouse under the GBKM parameterization, it also results in lower sensitivity to other infrared absorbers because there is less of a gap in absorption for the additional GHGs to fill.

It is unclear which of these parameterizations most adequately represents absorption by CO_2 under the conditions relevant to early Earth and Mars. While this uncertainty will have to be resolved by experiments over

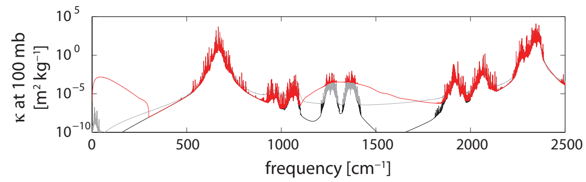

Figure 3: The absorption coefficient (m^2 kg^{-1}) at the 100 mb level of a dry, 1 bar CO_2 Martian atmosphere.

the relevant range of p, T and ν, a few implications arise: First, we show that a parameterization similar to the one used to demonstrate that a CO_2-H_2O greenhouse cannot account for an early super-freezing Martian surface [6] is currently the most opaque. If an optically thicker atmosphere was responsible for the relative warmth, then this implies that other infrared absorbers were probably required. The abundant nonbiological source of SO_2 on early Mars, as well as its effectiveness when added to a CO_2-rich atmosphere make it a likely candidate. Second, considering the uncertainties in paleo-pCO_2 reconstructions and in radiative transfer through CO_2-rich media, it is not clear that the Earth ever required GHGs other than CO_2 and H_2O to remain habitable. While other GHGs were undoubtedly present in the atmosphere and contributed to the radiative forcing, it seems likely that a CO_2-H_2O greenhouse would have sufficed.

Finally, uncertainty in the value of the surface albedo during early planetary evolution, especially during episodes of global glaciation on the Earth, translates to differences in solar input that are of a magnitude comparable to or greater than the difference in OLR between the three parameterizations for absorption by CO_2. In combination, this means that the results of any study of deep-time planetary paleoclimate involving radiative transfer or climate models are highly uncertain.

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