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MODELLING THE POTENTIAL OF ARTIFICIAL GREENHOUSE GASES TO INCREASE MARTIAN SURFACE TEMPERATURES

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The increases of temperature and pressure on Mars are considered to be the two main requirements for making Mars more suitable for life. Among the several methods reported to achieve such a change, the release of artificial greenhouse gases to increase temperatures by about 20 degrees at the Mars poles in order to trigger the evaporation of CO_2 ice is considered as being one of the more feasible approaches. This study assesses the warming potential of four fluorine based greenhouse gases (GHGs), namely CF_4, C_2F_6, C_3F_8 and SF_6, in the Martian atmosphere using for the first time a state-of-the-art three dimensional martian global circulation model. The temperature increase due to these GHGs will be assessed using the most effective mixture of these gases as determined by published laboratory experiments. The paper discusses the details of the methodology employed and the preliminary results.

I. INTRODUCTION

Over the last decades the quality and accuracy of numerical climate models increased significantly. The high variety of models with different dimensions and resolutions increased accordingly and has allowed new insights into the climate of Mars in a way that has not been possible before.[9] Especially highly sophisticated global circulation models (GCM) which are also used for simulating Earth's climate supported this new view on our neighbour planet. These GCMs, which are continuously improved, allow the assessment of past, current and future climates on Mars in more detail than ever before. Furthermore, they enable the assessment of hypothetical changes in the climate which might be triggered by, for instance, the release of greenhouse gasses in the atmosphere, i.e. planetary engineering.

Up until recent times scientific assessment of proposals to actively change the climate of other planets such as Mars to make them more suitable for life (sometimes referred to as "terraforming") have been scarce. The tools to perform such assessments in a scientifically rigorous way are maturing enough to be used also for such research questions. This paper reports on the method and first results obtained in modelling the effects of greenhouse gas releases into the Martian atmosphere.

Several measures have been proposed in the literature to increase Martian temperatures.[2]-[6] Among these proposals the release of artificial

Table 1: *Temperature increase due to greenhouse gases on present Mars ($P(CO_2)$ = 6 mbar. Cases which resulted in a surface temperature over 260K were discarded. Table adapted from [1])*

	10^{-6} mbar	10^{-5} mbar	10^{-4} mbar	10^{-3} mbar	10^{-2} mbar	10^{-1}
CF_4	0.019 K	0.143 K	0.497 K	1.817 K	5.160 K	10.100 K
C_2F_6	0.052 K	0.348 K	1.530 K	5.410 K	13.600 K	31.000 K
C_3F_8	0.065 K	0.562 K	2.910 K	10.100 K	33.500 K	-
SF_8	0.112 K	0.506 K	1.920 K	5.010 K	9.800 K	19.700 K
Best combination	0.112 K	0.677 K	3.330 K	12.300 K	37.500 K	-

greenhouse gases can be considered as being one of the more feasible ones based on current best estimates for potential technical capabilities achievable within the next decades[6]. In order to understand the orders of magnitudes underpinning any such efforts, the interactions of such gases in the Martian atmosphere need to be modelled. First assessments of the release of GHG into the Martian atmosphere have been made in one dimension using radiative-convective models. Marinova et al. [1] for instance assessed the warming potential of artificial greenhouse gases (GHGs) in the Martian atmosphere by applying a one-dimensional radiative-convective model. Based on new laboratory measurements of the absorption data of four fluorine-based (chlorine free) GHGs, Marinova et al. computed the warming caused by different mixtures of these four greenhouse gases. The best individual gas and the optimal mix of gases with the highest warming potential were determined. Their results show that for current Mars, a few tenths of a Pascal of C_3F_8 would result in sufficient warming of Mars to increase the surface temperature by approximately 20K and thus cause the evaporation of polar CO_2 ice on Mars [3]. The optimal mixture of the four fluorine-based greenhouse gases was found to be almost twice as effective than pure C_3F_8, the most effective individual GHG among the four. This effect is caused by the fact that the absorption bands of the four gases overlap but cover together a larger portion of the frequency spectrum. Absorption calculations were based on measured data in the range from 2.5 to 25 μm.[1]

In the here presented study the influence of the four fluorine-based gases used by Marinova et al. on the Martian climate is assessed by inserting the effects of these gases for the first time into a three-dimensional GCM. The study used the model developed at the *Laboratoire Météorologie Dynamique* (LMD).[7][8] This experiment will provide new insights into the reaction of the Martian climate system to artificially introduced gases in the atmosphere. In contrast with the study of Marinova et al., the present study will not only give information about the global temperature in the new balanced climate state, but also monitors the progress and typical timescales of the climate adjustment. The main aim of this paper is to give an overview of the applied method, the approach and discuss the preliminary results obtained during the continuing work on this project.

The paper is structured as follows: Section 2 summarizes the model that is used. Section 3 gives a detailed description of the changes to the radiative scheme of the model to account for the greenhouse warming of the injected gases, section 4 describes the first simulations that were performed in this study and the preliminary results. An outlook to future work on this ongoing project and other work in this area is given in chapter 5.

II. THE MODEL

The present study uses the LMD GCM described by A. Spiga and F. Forget in 2009.[8] This model is a relatively recent simulator of the Martian atmosphere and environment at horizontal scales ranging from hundreds of kilometers to tens of meters. The model combines a fully compressible non-hydrostatic dynamical core, with a comprehensive set of physical parameterizations for the Martian dust, CO_2, water, and photochemistry cycles. The model has been checked against measured data (e.g. from Viking and Pathfinder missions, from the Miniature Thermal Emission Spectrometer (Mini-TES)) and is reported to represent well a number of observed phenomena in the Martian atmosphere (wind patterns, regional / daily temperature patterns, dynamic phenomena such as convective motions, overlying gravity waves, and dust devil–like vortices).[8]

II.1. Model structure

The model calculates the temporal evolution of atmospheric and surface temperature, surface pressure, wind and tracer concentrations (e.g. variables that control or describe the Martian meteorology and climate) on a 3D grid.[12] The model parameterizes the dependencies and interactions between the different variables based on physical phenomena and integrates them over time $t+\delta t$ starting from an initial value.

The model operates in two parts:

- a 'dynamical part' contains the numerical solution of the general equations for atmospheric circulation. This part is very similar to GCMs that model Earths climate.
- a 'physical part' that is specific for Mars and calculates the tendencies due to radiative transfer, condensation and subgrid dynamics.

The calculations for the dynamical part are made on a 3D grid with horizontal exchanges between the grid boxes, whereas the physical part can be seen as a juxtaposition of atmosphere "columns" that do not interact with each other. [12]

II.2. Radiative Transfer

The radiative scheme is embedded in the physical part of the model. The radiative scheme of the LMD GCM is a classical molecular band model in which the infrared spectrum is divided into four spectral intervals:

The strong CO_2 15 μm band, extending from 11.5 to 20 μm, is divided into two wide bands representing the central strongly absorbing part (14.2-15.7 μm) and the wings. The rest of the spectrum is divided into the CO_2 9 μm band (5-11.5 μm) and a far infrared band (20-200 μm). Upward and downward heat fluxes are calculated and the radiative cooling rates of the vertical layers are derived from the flux divergence. For each spectral interval, the upward and downward fluxes (both oriented upward) are computed by

$$F^{\uparrow}_{\Delta\nu}(z) = F^{\uparrow}_{\Delta\nu}(s)\tau_{\Delta\nu}(0,z) + \pi\int_0^z B_{\Delta\nu}(T_{z'})\frac{\partial\tau_{\Delta\nu}(z',z)}{\partial z}dz' \tag{1}$$

and

$$F^{\downarrow}_{\Delta\nu}(z) = \pi\int_z^{\infty} B_{\Delta\nu}(T_{z'})\frac{\partial\tau_{\Delta\nu}(z,z')}{\partial z}dz' \tag{2}$$

where $B_{\Delta\nu}$ is the spectral-band-averaged Planck function, $\tau_{\Delta\nu}$ is the spectral-band-averaged transmission function, T_z is the temperature at level z, and $F_{\Delta\nu}(s)$ is the flux emitted or reflected by the surface.

The transmission $\tau_{\Delta\nu}$ is a function of the absorber amount, evaluated with the Padé approximant.[10][13]

The absorber amount is computed (at each time step and point on the grid) by integrating the density over the depth of the considered layer. In the original model, pressure and Doppler broadening of spectral lines is taken into account for CO_2., following Rodgers and Walshaw. [10][14]

III. ADJUSTING THE RADIATIVE TRANSFER

In the original LMD GCM the radiative transfer through the Martian atmosphere can be affected by the presence of CO_2 gas, mineral dust, water vapour, water ice particles and CO_2 ice particles [7]. For the purpose of this study the absorption coefficients of the four fluorine based GHGs CF_4, C_2F_6, C_3F_8 and SF_6, are introduced into the radiative scheme of the model. The absorption of these gases is a function of wavelength (see figure 1).

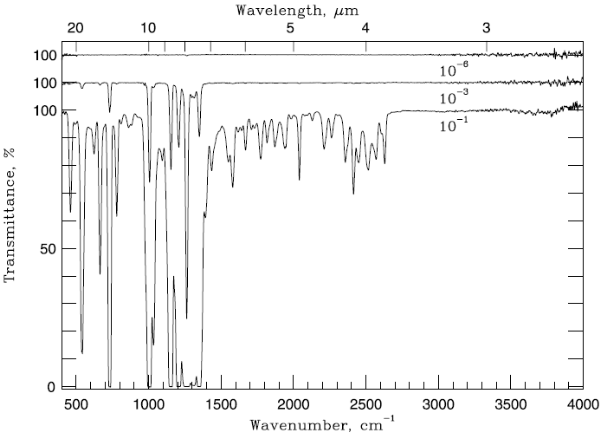

Figure 1: *Transmission spectra for C_3F_8 at concentrations of 10^{-6}, 10^{-3} and 10^{-1}. [1]*

To implement the absorption of the four artificial GHGs, the transmission function of the atmosphere is adjusted. The new atmospheric transmission value is computed by following the approach of Marinova et al. who identified different absorption bands for each gas and fitted the band-averaged transmission data (based on laboratory measurements) to a sum of exponential functions of the column density N of the absorbing gas (in molecules per m^2) [1]:

$$\mathrm{T}_{nb} = \sum_{i=1}^{n} a_i e^{-k_i N} \quad , \tag{3}$$

where T is the transmission averaged over the spectral interval, a_i is a weighing factor, k_i is the absorption coefficient (in m^2 per molecule) and n varies between 1 and 3, depending on what order exponential fit is needed to produce a good fit. N is a measure for the absorber amounts of the absorbing gas, expressed in column density (molecules m^2). In the present study these fits for 68 different absorption bands are used to compute the new opacity of the atmosphere. In the model N is derived from the partial pressure, which is computed by taking a specified percentage of the total atmospheric pressure.

After computing the transmission of the 68 narrow bands, these numbers are translated into the new wideband-averaged transmission ($\tau_{\Delta\nu}$ in equations (1) and (1)). $\tau_{\Delta\nu}$ is derived from the spectrally averaged results of the narrow band transmission (T_{nb} in equation (4)) weighted by the Planck function and the width of the narrow spectral bands[10]:

$$\tau_{\Delta\nu} = \frac{\sum_{i=1}^{n} B_{\Delta\nu}(T)\mathrm{T}_{nb}\Delta\nu}{\sum_{i=1}^{n} B_{\Delta\nu}(T)\Delta\nu}, \tag{4}$$

where n is the number of narrow bands that make up the considered wide spectral band. In this approach, the Doppler and Lorentz broadenings are not taken into account.

Table 2: *Proportional contributions of four GHGs for producing the best combination of various total gas amounts (adapted from [1])*

	10^{-6} mbar	10^{-5} mbar	10^{-4} mbar	10^{-3} mbar	10^{-2} mbar
CF_4	0.0%	0.0%	0.0%	0.0%	0.0%
C_2F_6	0.0%	5.0%	10.0%	15.0%	7.5%
C_3F_8	0.0%	60.0%	67.5%	62.5%	82.5%
SF_8	100.0%	35.0%	22.5%	22.5%	10.0%

IV. SIMULATIONS

In order to test the adjustments in the radiative scheme and to gain confidence in the functioning of the adapted model, a preliminary short-duration simulation is performed in which the climate evolution is modelled over 4 years. In this simulation the greenhouse gasses are introduced at concentrations of 0.2% (CF_4), 0.2% (C_2F_6), 0.4% (C_3F_8) and 0.2% (SF_4) of the total atmospheric pressure (so that in total these gases sum up to 1% of the atmospheric pressure). These partial pressures are taken constant in time.

IV.2 Computation details

The simulation was performed on a standard PC with a type Intel Xeon x5355 2.6 GHz 8 processor with 8 GB RAM. The simulation of the evolution of 4 martian years days takes about 2 days of calculation time. The code has not yet been optimised for speed and further improvements in the simulation speed can therefore be expected.

V. DISCUSSION AND CONCLUSIONS

V.1 Discussion of results

The typical Martian surface temperature profile as used by the model is shown in Figure 2. Temperatures vary between 150K at the poles and 280K at some locations at the equator.

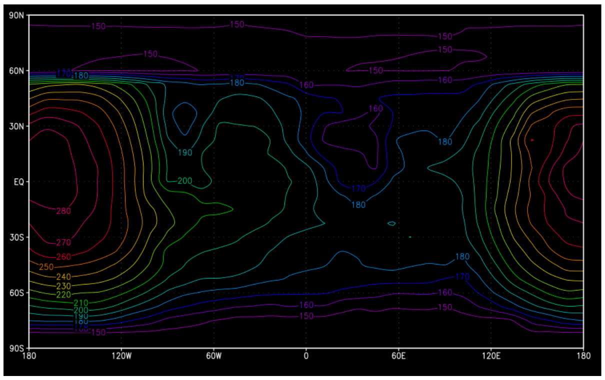

Figure 2: *Typical Martian surface temperatures profile. (values in K, isothermal line intervals in 10K)*

Due to the proportionally very small amount of GHG inserted into the Martian atmosphere, substantial effects on the surface temperatures are expected to take place only after decades and centuries. The currently employed computational setup does not yet allow the efficient and practical simulation of such time spans. It is therefore not surprising that the simulation of only a few years of effect of these gases does not alter the pattern of the Martian surface temperatures. **Figure 2** shows therefore the typical surface temperature pattern for both, with and without the additional greenhouse gases.

However, when plotting the difference between the evolution with and without the additional GHG, very small regional changes in the order of 0.01 up to 0.6 K are already detectable after only a few years. These are furthermore appearing regionally grouped and concentrated around the poles as would be expected. **Figure 3** and **Figure 4** show these differences after respectively 1 and 3 martian years.

As expected, there is yet no clear trend visible after such a short time of simulation, and regional differences exist with areas showing a slight warming and others with a slight regional cooling with respect to the unperturbed model.

The present work demonstrates the adaptation of the state of the art LMD GCM to simulate the warming effects of the introduction of artificial greenhouse gases into the martian atmosphere.

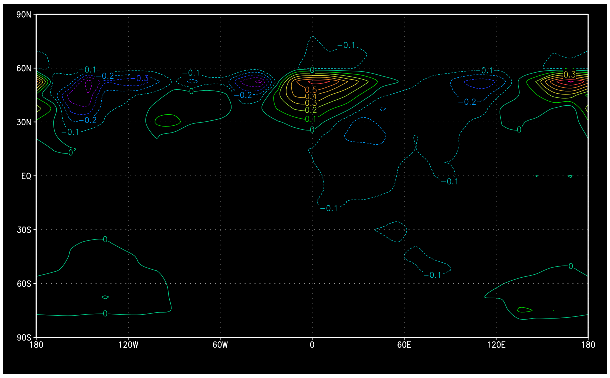

Figure 3: *Difference in the Martian surface temperatures between the model simulations with and without the introduction of the four artificial greenhouse gases after one martian year. (values in K, isothermal line intervals: 0.1 K)*

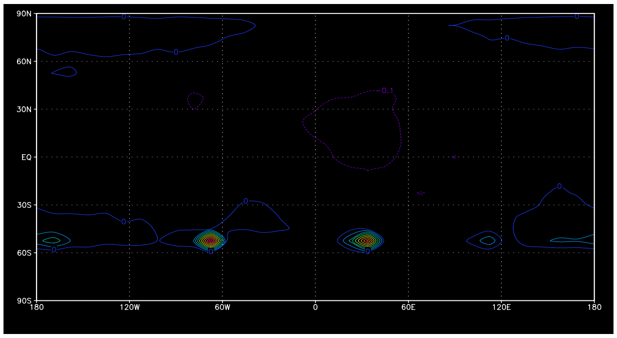

Figure 4: *Difference in the Martian surface temperatures between the model simulations with and without the introduction of the four artificial greenhouse gases after 3 martian years. (values in K, isothermal line intervals: 0.1 K)*

V.2 Summary and Concluding remarks

Short-term simulations have been performed to validate the modifications of the model and obtain confidence in the functioning of the adapted model. These simulations show small temperature changes (in the order of 0.01 to 0.6 K) after a few martian years following their introduction into the martian atmosphere. So far, the magnitudes and the spatial distribution of the temperature differences agree with our expectations, which might indicate that the adjusted model is behaving well. To get more insight into the trends and evolution of the Martian climate it is necessary to perform longer-term simulations of at least a century.

VI. ONGOING PROJECT AND NEXT STEPS

The subsequent step is to perform long-term simulations in which the Martian climate is able to converge towards a new equilibrium. When a new balance is reached, the warming potentials of the different GHGs can be determined and compared with and validated against the results obtained with the one-dimensional model by Marinova et al. To be able to perform longer simulations (at least at a temporal scale of about 100 years), one of the first priorities is to optimise the model for speed.

Once the model is optimised for speed, long-term simulations will be performed. The atmospheric concentrations will first be oriented at those published by Marinova et al. and will then be supplemented by concentrations to find the optimal warming for the LMD GCM (Table 1). The simulation approach is to first assess the temperature increase caused by one GHG at a time. Both, the global temperature increase and the spatial pattern of the changes need to be considered. These are then leading to the assessment of mixtures of GHGs (e.g. such as those reported in Table 2).

Following these phases, the proposed next logical step is the inclusion of atmospheric chemistry and the lifetimes of the chemicals in the model simulations.

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