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Using Martian Climate Models to assess the Potential of Artificial Greenhouse Gases to increase Martian Surface Temperatures

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Abstract

The study of planetary atmospheres such as the one of Mars offers valuable insights into the evolution and dynamics of atmospheres. The absence of oceans and a biosphere on Mars allows the development of simpler climate models compared to Earth's complex general circulation models. Recent improvements of Martian global climate models combined with new data obtained from Mars exploration missions allow for a better understanding of climate systems and their internal feedbacks effects. Martian climate models also provide a platform to explore theoretical options for active climate modifications such as ecopoiesis, defined as the fabrication of an un-contained biosphere on the surface of a sterile planet.

Ecopoiesis on Mars would require several environmental modifications, such as changes in its atmospheric content and the increase of its surface temperature. Specifically, models have shown that a relatively modest temperature increase of 20 K might trigger a runaway release of CO_2 gas sequestered in the polar caps or trapped in the Martian regolith. Among the several methods reported to achieve such a change, the release of artificial greenhouse gases in the Martian atmosphere is considered as one possible approach. Based on previous preliminary research, this paper assesses the warming potential of four artificial greenhouse gases (CF_4, C_2F_6, C_3F_8 and SF_6) in a Martian Global Climate Model. A critical discussion of the warming effect of the released gases is hereby presented.

Keywords:

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1. INTRODUCTION

The study of planetary atmospheres such as the one of Mars offers valuable insights into the evolution and dynamics of atmospheres. The absence of oceans and biosphere and their associated feedback effects simplifies the climate modelling compared with Earth's complex Global circulation models (GCMs). Recent improvements of Martian global climate models combined with new data obtained from Mars exploration missions allow for a better understanding of the Martian atmosphere and climate and their internal feedbacks effects. It also provides a simple platform for exploring theoretical options for active climate modifications such as ecopoiesis, defined as the fabrication of an un-contained biosphere on the surface of a sterile planet.

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 have been scarce. However, the tools to perform such assessments are maturing enough to be used also for such research questions. Especially highly sophisticated GCMs, which are also used for simulating Earth's climate, provide insight of past, current and future climates on Mars in more detail than before. Furthermore, they enable the assessment of hypothetical changes in the climate which might be triggered by artificial forcing, i.e. planetary engineering.

1.1. The Evolution of the Martian Atmosphere

It is believed that long ago Mars was a warmer and wetter planet, conditions conductive to the origin and evolution of complex life [1]. However changing geochemical forces impacted the energy flow so it became impossible for complex life to dwell upon the surface or to continue to evolve. In contrast to Earth, Mars presumably never harboured complex life. Although there is substantial debate about the possibility of microbial life, if existant, they are not in sufficient numbers to significantly alter or to maintain the atmosphere [1]. Whatever atmosphere the planet had was lost after the initial outgassing from its crust. The high atmospheric loss was most likely caused by the comparably smaller mass of the planet and the missing magnetic field that would have protected the Martian atmosphere from powerful solar winds and the impact of loss processes through, for instance, sputtering and ion pickup at the top of the atmosphere [2]. The remaining thin atmosphere, the resulting low greenhouse warming on Mars and the absence of shielding against high energetic ionising radiation are conditions that most likely inhibit the evolution of life on

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the planet's surface. Therefore, it is highly unlikely that, unlike Earth, Mars has ever developed a biologically engineered atmosphere. Martian geological history remains however subject to substantial speculation and large uncertainties due to the limited amount of data available.

1.2. *The Concept of* Terraforming

In 1971, a publication by Sagan triggered a still ongoing discussion about the deliberate alteration of the Martian climate with the aim to make the planet habitable. Sagan published the theory of the Long Winter Model (LWM), suggesting that the Martian climate alters between an icy state in which most atmospheric components are stored frozen on the surface and a state where the atmosphere is thick and sufficient to allow a warm and wet surface [3]. Even though today this hypothesis is contested, it was the beginning of the discussion about what is usually referred to as *terraforming*, a term first coined in science fiction literature, and inspired a variety of subsequent implementation proposals.

Amongst the first ones, Burns and Harwit proposed to modify the planet's precession cycle in order to provoke the transition between the cold state of the Martian climate to the warm summer state. First proposed implementation options include changing the orbit of the Martian moon Phobos and introducing material from the asteroid belt into the Martian system [4]. With further insight, such a Burns-Harwit manoeuvre is widely considered as ineffective, especially since the Long Winter Model no longer seems to be an accurate description of the Martian climate system.

Sagan suggested a less drastic modification of the Martian climate: changing the polar cap albedo to warm its surface and thus triggering the release of CO_2 into the atmosphere leading to a runaway greenhouse effect [5]. Even though Mars would not be fully habitable after this process the planet would possess a denser CO_2 atmosphere, which could provide enough greenhouse warming to heat the Martian surface to the point where liquid water could exist, fulfilling the prerequisites for ecopoiesis, i.e. the fabrication of an uncontained, anaerobic biosphere on the surface of a sterile planet [6].

However, modern observational data show that the amount of CO_2 stored in the Martian polar caps will unlikely be sufficient to trigger the necessary runaway greenhouse effect. Even if the polar caps did contain a sufficient amount of CO_2, a sufficient change of the polar cap albedo seems currently out of reach: calculations show that the amount of material with the albedo of black carbon necessary to change the albedo sufficiently would be $\sim$ 108 tonnes. The transport of such masses from Earth to Mars does not seem feasible in any foreseeable future. Alternative suggestions are therefore to use Martian soil or plants or material from asteroids. Even if such processes were feasible, ensuring a long-enough change in the albedo might prove difficult due to weathering and the harsh Martian climatic conditions [6].

Following these first proposals a variety of other partially even more ambitious concepts to terraform Mars were published. They include:

1. changing the orbital eccentricity of Mars orbit around the Sun,
2. changing the obliquity of Mars's spin,
3. channelling of volatile-roch cometary nuclei into the Martian atmosphere,
4. seeding of Martian atmosphere with heat-absorbing, cloud-forming particles,
5. heating the polar caps using large space-borne mirrors,
6. de-volatising of the carbon within the Martian crust,
7. inducing large-scale drainages of potential Martian aquifers,
8. the introduction of microbes, bioengineered to survive the harsh environment on the Martian surface,
9. the addition of bioengineered plants to lower the surface albedo and
10. the introduction of super-greenhouse gases (GHGs)

An overview of many of these methods has recently been published by Beech [7].

The entire concept of active interference in the planet of another planet raises also a series of ethical, philosophical, economic and legal questions [8, 9]. These issues are not addressed in the present paper. The authors are fully aware that especially concepts related to the deliberate introduction of terrestrial life forms would raise currently insurmountable difficulties related to planetary protection requirements [10]. The reader is referred to the Planetary Protection Policy of the Committee on Space Research (COSPAR) as well as recent publications in the field [11–16].

For the purpose of this paper, the term Martian *climate engineering* is preferred to *terraforming*.

1.3. Feasibility of Martian Climate Engineering Concepts

While some of the aforementioned proposals seem completely out of reach for foreseeable futures considering contemporary technological capabilities, their assessment and especially the potential effects on Mars and its atmosphere are often scientifically interesting, such as e.g. if the alteration of the Martian orbit as proposed by Burns and Harwit would introduce a substantial perturbation of the equilibrium of the solar system [7]. The deliberate introduction of bioengineered plants and microbes as well as space borne mirrors to sublimate the ice caps seem to be also out of reach at this stage of technological development. Proposals dealing with the devolatization of the Martian crust or the drainage of aquifers are problematic as they require a sufficient abundance of the respective material in order to introduce enough greenhouse warming to allow ecopoiesis. Considering the lack of evidence about their existence from recent measurements by Mars missions such as ESA's Mars Express and NASA's Mars Odyssey, it is not clear whether these proposals could ever be realised [17].

One of the proposals considered as potentially feasible in a far but foreseeable future is the introduction of GHGs into the Martian atmosphere as suggested by Lovelock and Allaby [18]. They originally suggested injecting chlorofluorocarbons

(CFCs) into the Martian atmosphere to increase the planet's greenhouse effect. However, the use of CFCs as GHGs to warm Mars would be limited due to the lack of shielding to protect the lower Martian atmosphere from high energetic radiation. The lower atmosphere of Earth, i.e. the troposphere, is protected via the ozone layer, which reaches from ~ 15 km to 40 km. On Mars such a layer is missing hence CFCs are photolysed at a high rate, making it it necessary to produce them continuously. Furthermore, CFCs dissolve to produce ozone-depleting species, e.g. highly reactive chlorine, which prevent the production of an effective shield against ionizing radiation similar to the one on Earth [6]. A possible way to prevent the release of O_3 depleting gases was presented in the study by Marinova et al. in 2005 who analysed a set of four fluorine-based GHGs in regards to their warming potential in the Martian atmosphere by introducing these into a one-dimensional radiative convective model of the Martian atmosphere [19]. This assessment is of special interest as it shows the ability of these gases to warm the Martian surface significantly without releasing ozone-depleting products that would prevent the development of an UV-radiation shield.

Even though some bacteria and higher life forms are known to be able to withstand high radiation levels, shielding from excessive natural radiation would likely be one key question to support the introduction of life forms like bacteria that can pursue the transformation of the Martian climate.

1.4. The Assessment of Martian Climate Engineering Proposals using Numerical Climate Models

The assessment of Martian climate engineering proposals in regards to their warming potential relies on numerical descriptions of the Martian climate system. Over the last decades the quality and accuracy of these numerical climate models has increased significantly. Especially highly sophisticated global circulation models (GCMs), which are also used for simulating Earths climate, provide better insights into past, present and future climates on Mars in more detail than before [20].

First assessments of the release of GHG into the Martian atmosphere have been made in one dimension using radiative-convective models. In particular Marinova et al. assessed the warming potential of artificial greenhouse gases (GHGs) in the Martian atmosphere by applying an one-dimensional radiative-convective model. Because of their long lifetimes, strong greenhouse effects, availability of the elements on the Martian surface and their ozone-friendly character, the authors focused on the four different greenhouse gases CF_4, C_2F_6, C_3F_8 and SF_6. Based on spectroscopic measurements of four fluorine-based 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 showed 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 20 K and thus cause the evaporation of polar CO_2 ice on Mars [19]. The optimal mixture of the four fluorine-based greenhouse gases was found to be almost twice as effective as pure C_3F_8, the most effective individual GHG among the four due to an optimal coverage of the thermal infrared spectrum.

2. MARS CLIMATE MODEL

The present study uses the LMD MARS GCM [21] which is a simulator of the Martian atmosphere and environment at horizontal scales ranging from tens to hundreds of kilometres. It combines a finite difference dynamical core, with a comprehensive set of physical parametrisations for the Martian dust [22], CO_2 [23], water [24, 25], and photochemistry cycles [26, 27]. The model has been validated against most available remote sensing and in-situ data. It is also been used to simulate climate changes on Mars due to the variations of its orbital and rotation parameters and explain the formation of various kind of surface ice reservoir in the recent past of Mars [28, 29].

2.1. Model structure

The model calculates the temporal evolution of atmospheric and surface temperature, surface pressure, wind and tracer concentrations (i.e. variables that control or describe the Martian meteorology and climate) on a 3D grid. The model performs a parameterization of each physical phenomenon and calculates the tendencies arising from such phenomenon. Then at every time step δ_t the model integrates the difference variables in time to obtain the variable evolution e.g. the temperature at one point in the atmosphere at a given time t. The model operates in two parts:

- A dynamical part containing the numerical solution of the general equations for atmospheric circulation. This part is very similar to GCMs that model Earth's 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 atmospheric columns that do not interact with each other.

2.2. Radiative Transfer

Embedded in the physical part of the model, the radiative scheme of the LMD GCM at thermal wavelengths is based on a wide-band model approach from Dufresne et al. where wide-band transmissivities are fitted as Padé approximants (i.e. ratios of two polynomials) as a function of integrated absorber amounts. In addition a simple scheme is included to account for variation of pressure and temperature within a given atmospheric layer [30].

The radiative transfer scheme is based on the net exchange formulation where the quantity under interest is directly the net energy exchange between two atmospheric layers. It is equal to the product of an optical exchange factor and the difference in the Planck function between the two layers. One immediate advantage of this approach is the possibility to use different computation frequencies for the optical quantities and for the Planck function. The Plank function, depending strongly on temperature, requires a frequent computation. For the expensive computation of the optical properties, a smaller computation frequency is sufficient as they are less sensitive to temperature. Other advantages are the easy implementation of the energy conservation principle, the reciprocity principle and the second thermodynamic principle.

The radiative heating rates $\chi_{i,j}$ are obtained from the net exchange rates $\psi_{i,j}$ for a given pair of atmospheric layers i, j:

$$\chi_{i,j} = \frac{g}{Cp}\frac{1}{\delta t}\frac{\psi_{i,j}}{\delta p_i}, \tag{1}$$

where g is the Martian gravity, Cp is the gas mass heat capacity, δt is the length of the Martian day ($\delta t = 88775$ s) and δp_i is the layer pressure thickness.The total heating rate of a layer i is:

$$\chi_i = \sum_j \chi_{i,j}. \tag{2}$$

The CO_2 wide-band model has two spectral bands chosen empirically. Band 1 extends from 635 cm to 705 cm^{-1} and from 705 to 865 cm^{-1}, corresponding to the central part of the CO_2 band. Band 2 extends from 500 to 635 cm^{-1} to represent the band wings. The rest of the NIR (near infrared) spectrum is divided into the 9 μm band (5-11.5 μm) and a far infrared band (20-200 μm). Finally absorber amounts are computed by integrating the gas density over the depth of the considered layer at each time step and point on the grid.

2.3. Adjusting the Radiative Transfer

To model the warming effects of the four fluorine-based greenhouse gases CF_4, C_2F_6, C_3F_8 and SF_6, the absorption coefficients of the elements were introduced into the radiative scheme of the model. The new atmospheric transmissivities are computed following the approach of Marinova et al. 2005 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 [19]:

$$T_{nb}(N) = \sum_{i=1}^{n} a_i \exp(-k_i N), \tag{3}$$

where T_{nb} is the averaged transmission per narrow 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 the number of terms required to accurately represent the spectroscopic data. In the absence of absorbing molecules, the transmission is naturally taken equal to one. In bands where more than one gas contributes to the total absorption, the global transmission is calculated as the product of the transmission of the individual gases. The transmission T_{nb} within a given narrow band is assumed to be constant as a function of wavelength (the narrow bands are assumed to be rectangular); the authors acknowledge that theoretically the absorption within a given narrow band can exhibit sharp fluctuations at higher resolution and consider this approach as a first approximation. In the present study these fits for 68 different absorption bands are used to compute the new opacity matrix of the atmosphere. The column density N is derived from the partial pressure of a given gas, which is computed as a percentage of the CO_2 layer pressure thickness $dp_{jl,jkl}$ for every atmospheric column jl and atmospheric layer jkl:

$$N_{jl,jkl} = N_{jl,jkl+1} + \frac{C dp_{jl,jkl}}{gm\cos\theta}, \tag{4}$$

where $g = 3.72\,N/kg$ is the gravity on Mars, C is the greenhouse gas pressure relative to the CO_2 pressure, m is the mass of one gas molecule in kilograms and θ is the mean solar angle. After computing the transmission of the 68 narrow bands, these numbers are averaged in wider bands to match the definition of the NIR spectral bands. We note here that the spectral band opacities are approximated as additive in a preliminary implementation in the radiative transfer code to estimate the impact of the greenhouse gases. This approach will therefore result in inaccuracies in case of overlapping absorption bands since the individual absorption lines highly determine how the different gases combine. Best accuracies, on the other hand, will be found in situations in which the different gases absorb in separate bands, i.e. there are no overlap between each gas spectrum. It is here assumed that the model represents a first-order approximation with a likelihood of underestimating the real warming potentials. A more accurate representation of the global transmissivities will follow at a later stage. In the meantime the greenhouse gas transmissivities $\tau_{\Delta\nu}$ are computed as:

$$\tau_{\Delta\nu}(N) = \frac{\sum_{i=1}^{n} B_{\Delta\nu_i}(T) T_{nb}(N) \Delta\nu_i}{\sum_{i=1}^{n} B_{\Delta\nu_i}(T) \Delta\nu_i}, \tag{5}$$

i.e. derived from the narrow band transmissivities T_{nb} weighted by the Planck function $B_{\Delta\nu_i}(T)$ and the width $\Delta\nu_i$ of the narrow spectral bands. In this approach, the Doppler and Lorentz broadenings are not taken into account. Once the global wide-band transmissivities $\tau_{\Delta\nu}$ are obtained in each NIR band the global exchange coefficients between each pair of atmospheric layers i, j are calculated following the net exchange formulation of the original model.

3. SIMULATIONS

Preliminary simulations were performed at different concentrations and combinations of the four greenhouse gases (GHG) consisting of the optimum mixture for a given partial pressure of GHG as determined by Marinova et al.. A grid resolution of 32x24x25 was used (Longitude x Latitude x Vertical Layers). The dynamical tendencies were computed 480 times a day and the tendencies arising from physical phenomenon were computed 12 times a day. The nonlocal thermal equilibrium scheme was not used in the radiative transfer model.

3.1. Results

A preliminary one-year simulation of the altered Martian climate was performed according to simulation parameters described above. The evolution of the global surface temperature

Table 1: Simulated GHG concentrations (ppm) for various pressures

Gas	10^{-3} Pa	10^{-2} Pa	10^{-1} Pa	1 Pa
CF_4	0.00	0.00	0.00	0.00
C_2F_6	0.083 [a]	1.667	25.0	125
C_3F_8	1.0	11.25	104.167	1375
SF_4	0.583	3.75	37.5	167

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[a] Calculated as $x\,Pa/600\,Pa\,CO_2 * 10^6$

Table 2: Temperature increase due to a mixture of greenhouse gases

	10^{-3} Pa	10^{-2} Pa	10^{-1} Pa	1 Pa
This paper	0.2 K	1.7 K	7.4 K	26.1 K
Marinova et al.	0.7 K	3.3 K	12.3 K	37.5 K

is plotted in figure 1; an instantaneous effect of the greenhouse gases can be seen. This is due to the fact that the radiative transfer model assumes a well-mixed, prescribed distribution of greenhouse gases whereas any practical attempt to inject a mixture of greenhouse gases will likely be a function of wind speed patterns and atmospheric circulation. Table 2 summarizes the mean temperature increase for each partial pressure value.

As shown in Table 2, the present study systematically underestimates the warming effect of the greenhouse gases compared to the work of Marinova et al.. This is due to the wide-band model and the underlying approximation that the gas opacities are additive while in theory they would combine in a nonlinear fashion and increase substantially the resulting transmissivities. Future key improvements of the radiative transfer model such as keeping the 68 narrow absorption bands will likely improve these figures.

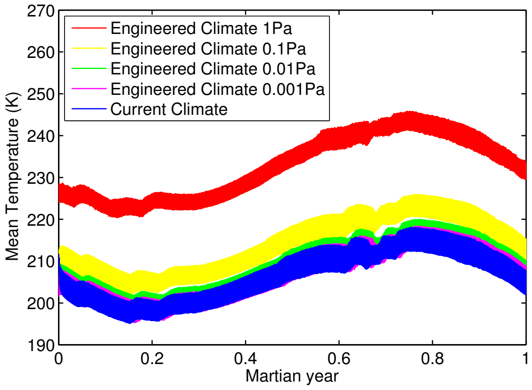

Figure 1: Mean surface temperature evolution over a Martian year (669 Martian days) for the current climate (non engineered case) and an engineered climate with an added mixture of fluorine-based greenhouse gases at various pressures (1 Pa (red curve), 0.1 Pa (yellow curve), 0.01 Pa (green curve), and 0.001 Pa (pink curve)).

Following this preliminary model validation further simulations were performed with a gradual increase in greenhouse gas concentration up to 1 Pa in 5 years. Figure 2 illustrates the mean surface temperature evolution for the current climate (nonengineered case) and an engineered climate with a gradual mixture of fluorine-based greenhouse gases. As expected the same trend as in Fig. 1 can be seen.

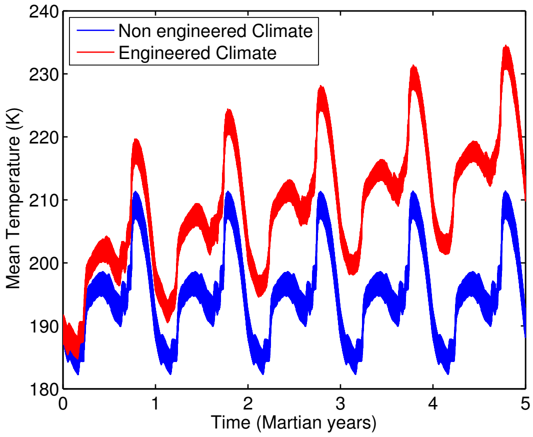

Figure 2: Mean surface temperature evolution for the current climate (non engineered case) and an engineered climate with a gradual mixture of fluorine-based greenhouse gases (up to 1 Pa in 5 years).

The spatial variations of the temperatures increase averaged over the 5th year are shown in Fig. 3. The temperature changes seem to follow the latitudinal variation and to correlate with the topography of the Martian surface. The biggest changes in surface temperature were found around the equator, with values between 20 and 35 degrees increase between 40 North and 40 South. The extreme value of 40 degrees increase was located in the center of the Hellas Planitia 9.5 km-deep impact crater. This distribution of the surface temperature changes is opposite to the effects of climate change on Earth, where the largest changes in temperature are found at the poles REF TO ADD.

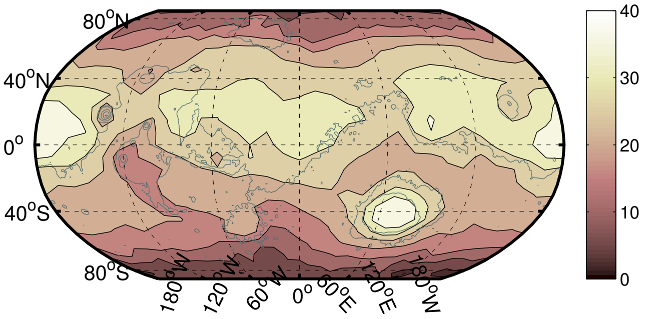

Figure 3: Surface temperatures averaged over the 5th Martian year (669 Martian days) for an added mixture of fluorine-based greenhouse gases with gradual increase in pressure up to 1 Pa in 5 years.

4. DISCUSSION

The simulations presented in this paper indicate that 1 Pa of fluorine-based greenhouse gases would achieve a global temperature rise of 20+ degrees, which could be enough to trigger the sublimation of polar CO_2 ice and cause a runaway greenhouse effect. Such positive feed-back mechanism was not modelled in the simulations as it would require a better understanding of the CO_2 polar ice reservoir and regolith in terms of its physical variables. For instance recent radar soundings of the Martian south pole revealed a perennial CO_2 ice deposit that is substantially larger than previously believed, amounting to ~ 5 mbar of volatile material [**?**].

Considering Mars's gravity and radius, 1 Pa of fluorine-based greenhouse gases corresponds to $3.91 \cdot 10^{13}$ kg, or 39 100 Mt of greenhouse gases made of 13% carbon, 5% sulphur and 82% fluorine. Converted into fluorine mass this amounts to 31 549 Mt, or ~ 8000 times the current annual world production of fluorine on Earth, or ~ 300 times the estimated world mineral reserve [31]. On Mars the bulk composition of its crust may be richer in fluorine than that of Earth [32] however it unknown whether it could be found in sufficient quantities to inject 1 Pa of fluorine-based greenhouse gases. Lower GHG concentrations options such as 0.01 Pa would seem more feasible at this point.

This study does not take into account the particle lifetime on Mars, which might be different from that on Earth due to the difference in UV radiation levels reaching the planet's surface. Lower sunlight intensities are reaching the planet (~ 43 % that of Earth), however UV radiation can penetrate much better the Mars atmosphere due to a lack of a protective ozone layer. Typical replenishment rates for the greenhouse gases considering Earth's values for the particle lifetimes [33] are here estimated to 1–12 Mt/year.

5. CONCLUSIONS

Preliminary short-term simulations have been performed to characterize the impact of adding greenhouse gases in the Martian climate. We could confirm that adding 1 Pa of fluorine-based greenhouse gases would achieve a global temperature rise of 20 degrees and could thus cause the evaporation of polar CO_2 ice on Mars. Considering Mars's gravity and radius, the fluorine mass that would be required to achieve such a change amounts to ~ 300 times its Earth's estimated reserve. In addition the temperature changes seem to follow the latitudes and to correlate with the topography of the Martian surface. The biggest changes in surface temperature were found around the equator, with values between 20 and 35 degrees increase between 40 North and 40 South. The extreme value of 40 degrees increase was located in the center of the Hellas Planitia 9.5 km-deep impact crater. Future work include a better representation of the radiative properties of the greenhouse gases and water ice clouds and the study of the evolution of the CO_2 ice cover .

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