Type of activity: Standard study (25 k€)

Study Description:
Assessment of the Impact of the Release of Greenhouse Gases into the Martian Atmosphere using Numerical Evaluations Derived from Martian GCMs

1 Background and Motivation

1.1 Introduction

With the rise of highly sophisticated technology and the increasing knowledge about Earth and its neighbouring planet Mars in the last century, the discussion about the feasibility and the ethic of planetary engineering arose. Planetary engineering denotes the "*application of technology for the purpose of influencing the global properties of a planet*" [1].
The idea of actively engineering the climate of Earth, i.e. geoengineering, started with the intention to influence local weather conditions e.g. the amount of precipitation in a specific region in the middle of the 20th century. Initially, the prospect of changing the climate on a global scale was regarded as unscientific and was thus dismissed by the scientific community. However, as the effect of global climate change became increasingly evident by the end of the 20th century, the scientific discussion about the ethics and feasibility of geoengineering was revived. This debate was mainly triggered by the Nobel price winner P. J. Crutzen who suggested counteracting global warming by injecting aerosol particle into the atmosphere [2]. With his proposal the acceptance of geoengineering as a serious field of research started to gain an ever-increasing acceptance. This acceptance reached its first peak with the report of the British Royal Society that assessed the current state of knowledge on the effect of the deliberate change of Earth's climate concluding that the research that has been done up until this point is by far not sufficient and further studies are inevitable [3].
Other than geoengineering, using engineering approaches to influence the climate of other planets (sometimes referred to as "terraforming" since the aim usually is to create conditions more similar to Earth conditions), is still considered as science-fiction and serious research in this direction is scarce. First small research steps have however been taken in this direction and the increasing understanding of climates of other planets allow for a scientific analysis of such options.

1.2 Planetary Climate Engineering Proposals

The driver for the first proposals to "terraform" Mars was the Long Winter Model (LWM) by C. Sagan [4].
In this hypothesis Sagan suggested that the Martian climate underlies two states, its contemporary state of low temperatures and one of comparably high temperatures. The increase in temperature in this hypothesis would derive from the vaporisation of gases that are currently stored in the polar caps, which would increase the greenhouse effect and thus reduce the thermal loss of the planet's surface. Sagan indicated that such a transition to a warmer climate could happen twice each equinoctial precession.
Based on the LWM J. Burns and M. Harwit proposed one of the first terraforming proposals in May 1973. In order to provoke the vaporisation of ice from the northern polar caps and with this the conversion to a warmer climate on Mars, their proposal intended to change the planet's precession cycle through either the modification of the orbit of the Martian moon Phobos or the introduction of material from the asteroid belt into the Martian system [5].
Only two months later Sagan himself published a paper in which he suggested to melt the polar ice caps through the change of the polar albedo via spreading black carbon on the ice. This, Sagan suggested, would trigger the release of the stored CO_2 and start a feedback loop that increases the greenhouse effect producing a warm climate that allows liquid water on the surface of Mars. His estimations showed however that the amount of material with the reflective properties of black carbon necessary to change the albedo sufficiently would be

approx. 10^8 tonnes [6]. The transport of this material from Earth to Mars is therefore neither desirable nor feasible. To overcome this problem it was suggested to use Martian soil. Though this would be an alternative to the costly transport of material from Earth it would be difficult to secure the layer against weathering. Yet another alternate approach is the use of plants to darken the polar caps. But also this suggestion seems unlikely, as according to current knowledge the climatic conditions on Mars do not allow either plant growth nor their survival [1].

These first proposals seem rather unlikely based on current knowledge since the hypothesis of the LWM is dismissed and the amount of volatiles stored in the Martian polar caps is assumed to be too small to allow the feedback mechanism that is needed for both proposals in order to increase the Martian greenhouse effect to the necessary extent. To overcome the limitation of insufficient abundance of volatiles recent studies focus on the assessment of artificial greenhouse gases (GHGs) produced on the surface of Mars [7][8]. The first ones to propose this Earth inspired greenhouse warming were M. Allaby and J. E. Lovelock in 1984 [7]. With the knowledge derived from the phenomenon of global warming on Earth and the acknowledgment of high global warming potential of chlorofluorocarbons (CFC), Allaby and Lovelock suggested to inject CFCs into the Martian atmosphere to increase the planets greenhouse effect.

McKay et al. assessed this proposal in regards to the increase of temperature using a one-dimensional radiative-convective model [8]. They found that a grey absorber, i.e. a mixture of GHGs absorbing over the entire infrared spectrum, has the potential to increase the global surface temperature over the freezing point of water. A cocktail of GHGs absorbing only in certain windows of the infrared most likely will not be able to warm the Martian climate sufficiently for the intended purposes [8].

The limitations of the use of CFCs as GHGs to warm Mars are based on the lack of a shield to protect the lower Martian atmosphere from high energetic radiation. The lower atmosphere of Earth, i.e. the troposphere, is protected through the ozone layer, which reaches from approx. 15 km to 40 km. On Mars such a layer is missing hence the CFCs are photolyzed at a high rate, which makes it necessary to produce them continuously. Furthermore the dissolving of CFCs produces ozone-depleting species, e.g. highly reactive chlorine, which therefore prevent the production of a radiative shield as on Earth [1].

In 2005 Marinova et al. took a similar approach as McKay et al. did in 1991 [9]. However, other than McKay et al., Marinova et al. considered only fluorine-based species that do not affect the atmospheric ozone concentration nor its evolution directly. For their paper the research group around Marinova implemented new laboratory measurements of the thermal infrared absorption spectra of CF_4, C_2F_6, C_3F_8 and SF_6 into a radiative-convective multilayer model and determined the temperature increase caused by the respective gas and various mixes of them. They conclude that, other than on Earth, the warming potential of C_3F_8 exceeds that of SF_6 and only a comparably small amount of C_3F_8 would increase the surface temperature on Mars sufficiently to outgas the stored CO_2.

1.3 Radiative-Convective Model by Marinova et al. (2005)

For their study of the effect of artificial GHGs on the Martian atmosphere Marinova et al. developed a mulitlayer nongray radiative-convective transfer computer model [9]. This model determined the temperature profile from an initial profile taking into account the thermal absorption of CO_2 and the implemented fluorine-based species, CF_4, C_2F_6, C_3F_8 and SF_6, via the horizontal mean two-stream approximation assuming a radiative-convective equilibrium [10][11]. The temperature in the lower atmosphere is determined through a convective adjustment using the dry adiabatic lapse rate[1].

The model divides the atmosphere into 30 layer equally spaced over pressure and extended to an altitude equivalent to 10^{-11} mbar. Input and boundary conditions use yearly or globally averaged values. For the calculation of the radiative flux, for instance, the inter-annually variation of the solar flux is neglected. Instead the yearly average is applied. The albedo was implemented as a global average which made it necessary to set its value to 0.209 in order to reproduce a surface temperature of 212.9 K.

[1] The application of only the dry adiabatic lapse rate allows neglecting the saturation vapour pressure. However, this makes it necessary that temperatures are lower than 260 K at all times

In order to allow the calculation of the opacity in each wavelength interval of one layer through consideration of the absorption coefficient of that wavelength and the pressure difference across the layer only, the injected GHGs are assumed to be uniformly mixed. Thus the model neglects zonal and meridional transport from a localized source for the greenhouse gases.
Applying the model to a Martian atmosphere of 6 mbar and injecting amounts of 10^{-6} mbar up to 10^{-2} mbar lead to a warming of up to 33.5 K (Table 1). The assessment of different mixtures of the gases at various total gas amounts showed that the highest temperature increase was reached when the mix did not include any CF_4 and was dominated by C_3F_8, with the exception of an amount of 10^{6} mbar where pure SF_6 gives the best results (Table 2).

	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	-

Table 1 – Temperature Increase Due to Greenhouse Gases on Present Mars (P_{CO_2} = 6 mbar. Cases which resulted in a surface temperature over 260 K were dicareded); adapted from [9]

	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%

Table 2 – Gas percentage amount for producing the best combination or various total gas amounts; adampted from [9]

2 Research and Study Objectives

The results of Marinova et al. [9] were derived from a radiative-convective model neglecting meridional and zonal transport, atmospheric chemistry as well as spatial and temporal variations of initial and boundary conditions. These restrictions which were necessary due to the kind of model which was developed for that study, can be overcome by applying a sophisticated 3-dim Global Circulation Model (GCM) with included photochemistry, like for instance the GCM developed at the Laboratoire de Météorologie Dynamique (LMD). The resolution in three dimensions allows a definition of atmospheric parameters and processes in more detail and thus gives more realistic results. The aim of this project is to **derive scientifically sound parameters for the alteration of the Martian climate yielded by state of the art 3-dimensional GCMs.**
Following the pioneering Marinova et al. (2005) based on a simple radiative-convective model, this study intends to take advantage of the substantial progress made in climate modelling and understanding of Martial climates.
For this purpose, it is proposed to use two different Mars GCMs in parallel (e.g. LMD GCM by ASPEN, NASA Ames Mars GCM) to derive at least partially independent data points and be able to compare the results.

The proposals should contain and outline of the model structure and key parameterizations as well as its functions relevant to this study.

The following four-step approach is proposed (universities are free to argue for a different approach in their proposal if considered more appropriate):

1. The first step is the **implementation of the four GHGs** (as a minimum) used by Marinova et al. (2005), i.e. CF_4, C_2F_6, C_3F_8 and SF_8, into the GCM taking into account

their infrared absorption, their influence on the other chemical species in the Martian atmosphere and other processes determining their atmospheric lifetime. It is proposed to restrict the sources of the GHGs to their emission on the surface. Universities are encouraged to suggest additional chemical species that might be of interest for injection into the Martian atmosphere.

2. The implementation is followed by the **assessment of the warming potential** of the gases when used alone and the finding of the optimal mix of GHGs to yield the desired warming, as well as their optimal choice of emission locations on the planet's surface. For this assessment the initial values of all parameter have to match those of the contemporary Martian atmosphere and all input parameters and boundary conditions must be chosen accordingly.

3. After the determination of the optimal warming constellation for the respective GCM, the **results of the two GCMs will be compared**. This will be done through the application of the values generated by the GCM of the other research group on the own model and comparison of the achieved increase in temperature as well as the changes in the general circulation and atmospheric chemistry. This comparison should focus on the comparison of the following parameters:

    - temperature: global average of atmospheric profile, surface temperature maps
    - atmospheric pressure: global average of atmospheric profile, surface pressure maps
    - total amount of GHGs needed for optimal warming of surface temperature
    - necessary emission rates to obtain a surface temperature over the freezing point of water

4. In case the models differ substantially, the two **GCMs will be examined in order to determine the sources of the aberration** (e.g. differences in key parameterisations between the two models). This step should include a detailed analysis of the processes causing the differences but is not intended to harmonise the results.

It is proposed to conduct the study in parallel by two research groups (one being the ACT) relatively independently for steps 1 and 2, and in close cooperation for steps 3 and 4.

Once the analysis of the two GCMs is completed, their results can be compared to those of Marinova et al. (2005). This will not only allow an assessment of the differences between one and three-dimensional models but also show changes in the atmospheric photochemistry and dynamics caused by the implementation of artificial GHGs into the Martian atmosphere.
As an outcome of to the research, a list of recommended measurement data should be derived, that could be included in future planetary missions.

2.1 Collaboration with the Advanced Concepts Team and the ESA Harwell site

This study is mainly addressed to researcher groups with a background in the field of three-dimensional atmospheric modelling with focus on Mars. The project will be conducted in close cooperation with ACT-researchers and with experts at the ESA Harwell site. Besides scientific discussions, ESA researchers are planning to use the LMD GCM for steps 1 and 2. Applying universities are therefore encouraged to propose a different climate model.

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