Non condensable gas enrichment and depletion in the Martian polar regions.

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Introduction

As much as 30% of the Martian atmosphere condenses every year to form polar caps in both hemisphere, inducing large surface pressure variations all over the planet. However, while carbon dioxide condenses onto the surface to form CO_2 ice, the 5% of non-condensible gases that form the martian atmosphere (mostly N2, Ar and O2, or CO) is left in the atmosphere. This process is well observed by the Gamma Ray Spectrometer (GRS) [1,2] aboard Mars Oddyssey, but has also been detected by monitoring CO using the imaging spectrometer OMEGA on Mars Express [3]. Sprague et al. [1, 2] showed that the mean Argon mixing ratio in the south polar region is enhanced by as much as a factor of 6 during winter and depleted by a factor of 2 to 3 during spring. That means that the air composition strongly vary with location and season and that non-condensible gases makes up to 30% of the bulk southern polar atmosphere around winter solstice (and probably much more locally) compare to about 5% on average.

At the previous "Mars atmosphere modelling and observations" workshop in Spain in 2006, we reported on the development of a parameterisation of the non-condensible gases enrichment suitable for 3D atmospheric models using terrain-following vertical coordinates (i.e. "sigma" or "hybrid" coordinate). It was completed with a modified convection sheme able to simulate the convection forced by the enrichment of lighter gas near the surface (these parametrisations, not yet published, are described a the end of the present abstract). However, we showed that the LMD General Circulation Model [4], using these schemes, was unable to simulate the intensity of the non-condensible gas enrichment as measured by GRS. As explained then, this was due to a major weakness of the LMD GCM at the time: the over-estimation of the atmospheric temperature in the southern polar night (compared to radio occultation or thermal IR sounding data). This overestimation weakened the polar vortex, leading to unrealistic mixing between the southern polar region and lower latitude in winter.

We have recently been able to solve this problem by improving the way the atmospheric mass was numerically updated at each timestep in our atmospheric "dynamical core". This improved model now simulates cold temperatures and CO_2 condensation in the winter high
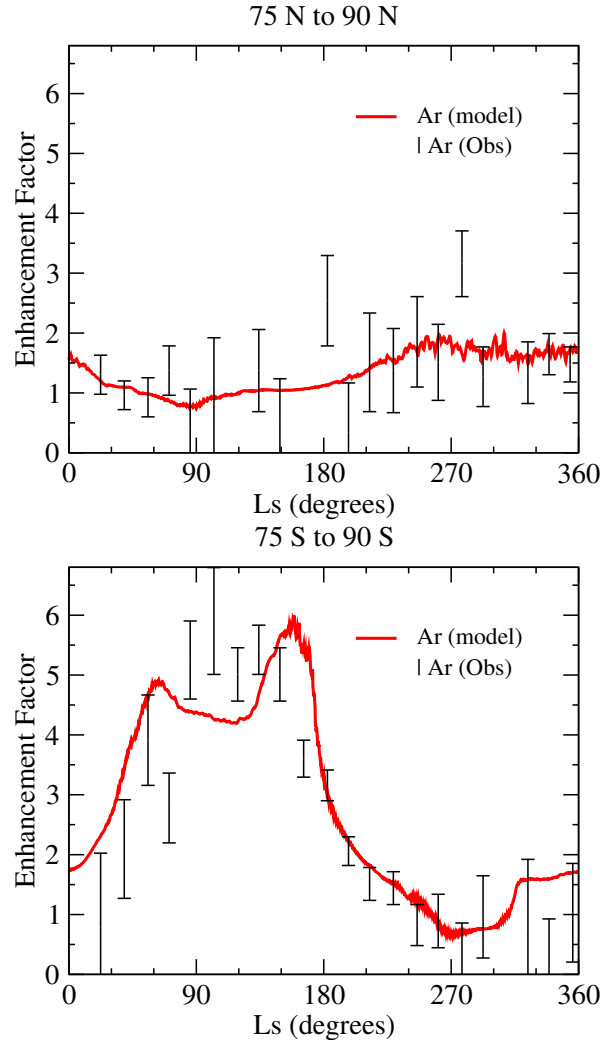

Figure 1: Seasonal evolution of the mean argon column abundance in both polar regions (from 75 latitude to the pole) compared to the Argon abundance measured by the Gamma Ray Spectrometer (GRS) aboard Mars Oddyssey from June 2002 to March 2004 (Sprague et al. 2004, 2007). The abundance are normalized and shown as a enhancement factor over what is expected from an homogeneously mixed atmosphere (see Sprague et al. 2007).

latitudes (see figure 2 in Forget et al., this issue).

We have performed new simulations of the non-condensible gas enrichment with this new model. As expected, the enrichment is much stronger than before, and can be compared to the observations.

Some results

Our simulations (figures 1 and 2) predict a polar night atmosphere where non-condensable gas such as argon are highly enriched near the surface. This occurs in spite of the various mixing mechanism that are taken into account.

In the **north polar region**, the simulation seems to be realistic, with a very limited enrichment around Ls=270° The seasonal evolution is in acceptable agreement with the Argon observation [1,2]

In the **south polar region**, our preliminary results seems to match the GRS observations from Sprague et al. (2004, 2007) poleward of 75°S. Interestingly The double peaked seasonal evolution (two maxima around Ls=80° and Ls=170°) predicted by the model is not seen in the observations. However, it is not observed in all our simulations. In Williamsburg we will discuss further comparisons with the GRS data.

## Other effects of the non-condensible gas enrichment

The local depletion of CO_2 in the polar night strongly reduces the partial pressure of CO_2, decreasing the CO_2 frost point temperature by several kelvins, and the surface thermal infrared cooling decreased by more than 5%. This can be simulated in the model. An analysis of this effect will be detailed in Williamsburg.

In addition, the winter winter martian atmosphere is characterized by a significant latitudinal gradient of molecular weight through a deep layer at the edge of the polar vortex. Meteorologists have never needed to consider such gradients, and a closer analog would be a gradient of salinity in oceanography. In practice, the enrichment observed around winter solstice would have an effect on the circulation as large as a 13 K temperature horizontal gradient (as used in the traditional thermal wind equation, for instance). The gradient should tend to reduce the intensity of the polar vortex, and favor the transport of non-condensible gas outside the polar region, acting as a negative feedback. This effect, however, will be quite difficult to simulate in a GCM.
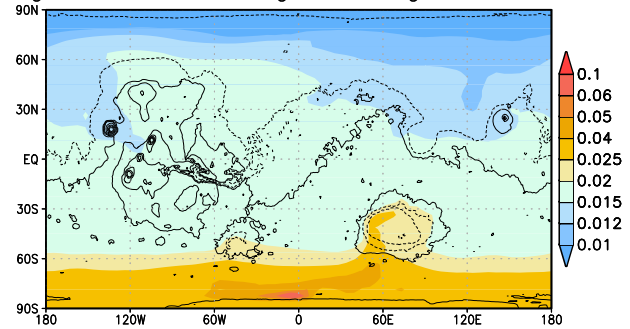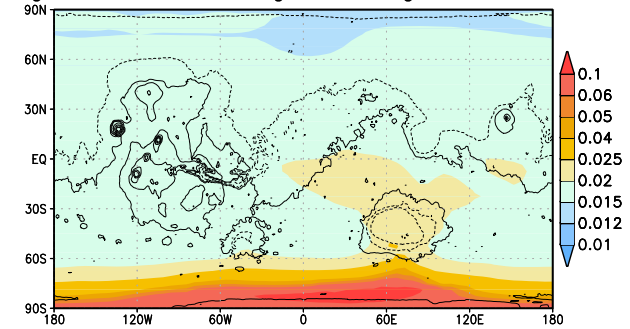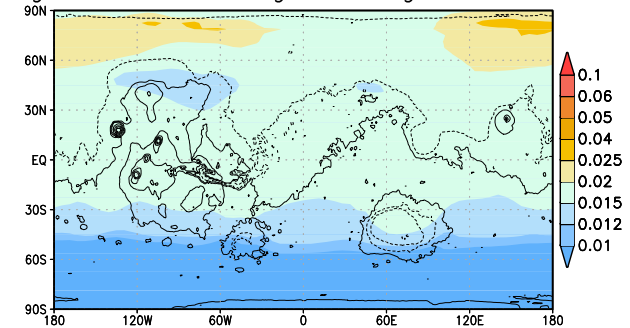

Figure 2: Map of the column averaged volume mixing ratio of argon at various season, simulated by the LMD Mars general Circulation Model.

How the model works : A GCM parameterisation of Non-condensable Gas Enrichment, depletion, and induced convection

Here we describe the detailed parametrisation developped to simulate this non-condensible enrichment and depletion process in the LMD General Circulation Model. Our objective is to estimate the variation of the mass mixing ratio q (kg/kg) of a non-condensible gas (e.g. argon) when CO_2 condenses on the surface and in the atmosphere. For this we can adapt the CO_2 conden-

sation scheme described in Forget et al. (1998) [5].

The model atmosphere consist of N layers. The loss of atmospheric mass due to condensation (or conversely the gain due to sublimation) is taken into account by modifying the surface pressure p_0 at each timestep by :

$$\delta p_0 = -\frac{g}{A}\sum_{k=0}^{N}\delta m_k \qquad (1)$$

With δm_k is the mass of ice that has condensed in the layer k (>0 when condensing ; δm_0 is the surface ice). A is the area of the grid mesh (m^2) and g the gravity (m/s^2.

In most atmospheric models, GCMs in particular, one difficulty is that the model layers are defined in vertical coordinate $\sigma = p/p_0$ (what is presented below is also valid for hybrid coordinate). The changes in p_0 due to the CO_2 condensation-sublimation induce "artificial" movements of the σ levels in the atmosphere that must be reflected in the variation of q.

A model layer l can be defined by its boundaries $\sigma_{l-\frac{1}{2}}$ and $\sigma_{l+\frac{1}{2}}$. At each timestep, its mass $M_l = \frac{A}{g}(\sigma_{l-\frac{1}{2}} - \sigma_{l+\frac{1}{2}})p_0$ varies because of the global variation of p_0. Such a variation is associated with transfers of mass between the layers (on which one must add the sink corresponding to the local condensation $-\delta m_l$). The local mass balance may be written :

$$\delta M_l = \frac{A}{g}(\sigma_{l-\frac{1}{2}} - \sigma_{l+\frac{1}{2}})\delta p_0 = W_{l-\frac{1}{2}} - W_{l+\frac{1}{2}} - \delta m_l \qquad (2)$$

where $W_{l-\frac{1}{2}}$ is the air mass (kg) "transfered" through the level $\sigma_{l-\frac{1}{2}}$ (> 0 when up) during the timestep. Equations 1 and 2 may be combined to yield a recursive formula on W :

$$W_{l+\frac{1}{2}} = W_{l-\frac{1}{2}} - \delta m_l + (\sigma_{l-\frac{1}{2}} - \sigma_{l+\frac{1}{2}})\sum_{k=0}^{N}\delta m_k \quad (3)$$

with:
$$W_{\frac{1}{2}} = -\delta m_0 \qquad (4)$$

The knowledge of W can then be used to compute the exchange of the condensable gase (mass mixing ratio q_l in layer l) between the layers:

$$\delta(M_l q_l) = W_{l-\frac{1}{2}}\overline{q}_{l-\frac{1}{2}} - W_{l+\frac{1}{2}}\overline{q}_{l+\frac{1}{2}} - \delta m_l\, q_{ice} \quad (5)$$

with $\overline{q}_{l-\frac{1}{2}}$ the mean mixing ratio transported through the $\sigma_{l-\frac{1}{2}}$ interface. Various operators have been suggested in the litterature to calculate $\overline{q}_{l-\frac{1}{2}}$. Indeed, this

process is similar to a classical transport process. We used the "Van-Leer I" finite volume transport scheme (Van-Leer 1977, Hourdin and Armengaud 1997).

Separately, one can also write :

$$\delta(M_l q_l) = (M_l + \delta M_l)\delta q_l + q_l\delta M_l \qquad (6)$$

with δq_l a correction to be applied at every timestep in each layer after the CO_2 condensation or sublimation. Eqs 5 and 6 may be combined to obtain δq_l.

In the lower layer:

$$\delta q_1 = \frac{1}{M_1 + \delta M_1}[-\delta m_0(q_{ice}-q_1)-W_{1+\frac{1}{2}}(\overline{q}_{1+\frac{1}{2}}-q_1)-\delta m_1(q_{ice}-q_1)] \qquad (7)$$

The term $\delta m_0(q_{ice} - q_1)$ corresponds to the condensation-sublimation flux from the ground with :

$q_{ice} = 1$ for CO_2

$q_{ice} = 0$ for non-condensable gas.

In the layers above :

$$\delta q_l = \frac{1}{M_l+\delta M_l}[W_{l-\frac{1}{2}}(\overline{q}_{l-\frac{1}{2}} - q_l) \\ -W_{l+\frac{1}{2}}(\overline{q}_{l+\frac{1}{2}} - q_l) - \delta m_l(q_{ice} - q_l)] \qquad (8)$$

The first two terms, with $W_{l-\frac{1}{2}}$ and $W_{l+\frac{1}{2}}$, correspond to the transport of gas over the entire column due to the pressure variations in σ coordinates.

This may look complex, but it is the only way to compute non-condensable gas enrichment and depletion in a 3D Mars atmospheric model !

Convection induced by lighter gas enrichment. Since the mean molecular weigtht of the non-condensible gaz is only 32.3 g mol^{-1} compared to 44 g mol^{-1} for CO_2, the enrichment near the surface where most of the CO_2 condense induces deep static instability and vertical mixing that were considered by Seymour Hess 25 years ago [6] but that have always been neglected in atmospheric models. However, one can demonstrate that the air density variations can easily be taken into account in the convective adjustment scheme that are usually use to simulate convective when the potential temperature lapse rate is negative: $(\partial\theta/\partial z < 0)$. When the air molecular mass m varies, unstability occur if $\partial\theta m/\partial z < 0$. Thus the usual GCM convection scheme can be used with θm instead of θ.

Reference

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