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 hemispheres, inducing large surface pressure variations all over the planet. However, while carbon dioxide condenses onto the surface to form CO_2 ice, the non-condensable gases that constitute 5% of the martian atmosphere (mostly N_2, Ar and O_2) remain suspended. This process is now well observed by the Gamma Ray Spectrometer (GRS) aboard Mars Odyssey. Sprague et al. (2004) 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. This in turns means that the air composition varies strongly with the location and season and that non-condensable gases constitute up to 30% of the bulk southern polar atmosphere around winter solstice (and probably much more locally), compared to about 5% on average. Here we describe a detailed parameterisation of this phenomenon, which has been developed to simulate this process in the LMD Mars General Circulation Model.

A GCM parameterisation of non-condensable gas enrichment and depletion

Our objective is to estimate the variation of the mass mixing ratio q (kg/kg) of a non-condensable gas (e.g. Argon) when CO_2 condenses on the surface and in the atmosphere. For this, we can adapt the CO_2 condensation scheme described in Forget et al. (1998).

The model atmosphere consists 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 :

$$\delta p_0 = -\frac{g}{A}\sum_{k=0}^{N}\delta m_k, \tag{1}$$

where 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 is 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 coordinates). 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 transfer of mass between the layers (to which one must add the sink corresponding to the local condensation $-\delta m_l$). The local mass balance may be written :

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

where $W_{l-\frac{1}{2}}$ is the air mass (kg) which is "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 :

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

with:

$$W_{\frac{1}{2}} = -\delta m_0. \tag{4}$$

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

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

with $\overline{q}_{l-\frac{1}{2}}$ being the mean mixing ratio transported through the $\sigma_{l-\frac{1}{2}}$ interface. Various operators have been suggested in the literature 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 :

$$\delta(M_l q_l) = (M_l + \delta M_l)\delta q_l + q_l \delta M_l, \tag{6}$$

where δq_l is 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:

$$\begin{aligned}\delta q_1 = \; & \frac{1}{M_1+\delta M_1}[-\delta m_0(q_{ice} - q_1) \\ & -W_{1+\frac{1}{2}}(\overline{q}_{1+\frac{1}{2}} - q_1) - \delta m_1(q_{ice} - q_1)].\end{aligned} \tag{7}$$

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

$$\begin{cases} q_{ice} = 1 & \text{for } CO_2 \\ q_{ice} = 0 & \text{for non-condensable gas.}\end{cases}$$

In the layers above :

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

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 weight of the non-condensable gas is only 32.3 $\mathrm{g \cdot mol^{-1}}$ compared to 44 $\mathrm{g \cdot mol^{-1}}$ for CO_2, the enrichment near the surface, where most of the CO_2 condenses out, induces deep static instability and vertical mixing that were studied by Seymour Hess 25 years ago (Hess, 1979), 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 is usually adopted to simulate convection when the potential temperature lapse rate is negative ($\partial\theta/\partial z < 0$). When the air molecular mass m varies, unstability occurs if $\partial\theta m/\partial z < 0$. Therefore the usual GCM convection scheme can be used with θm replacing θ.

Other effects of non-condensable gas enrichment

The local depletion of CO_2 in the polar night should strongly reduce the partial pressure of CO_2, decreasing the CO_2 frost point temperature by several degrees, and the surface thermal infrared cooling by more than 5%. In addition, the 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 never needed to consider such gradients, whereas a close analogous in oceanography would be a gradient of salinity. In practice, the enrichment observed around winter solstice would have an effect on the circulation which manifests as a horizontal gradient of temperature as large as 13 K (as used in the traditional thermal wind equation, for instance). This gradient should tend to reduce the intensity of the polar vortex, and to favour the transport of non-condensable gas outside the polar region, acting as a negative feedback.

Results of the LMD GCM simulations

Our simulations (figures 1 to 5) predict a polar night atmosphere where non-condensable gases such as Argon are highly enriched near the surface. This occurs in spite of the various mixing mechanisms that are taken into account.

In the **north polar region**, the simulation seems to be realistic, with a 3 fold enrichment around Ls=270^o, but significantly less otherwise, north of 75^{o}N. The seasonal evolution is in close agreement with the Argon observations (check the abstract by Sprague et al., this issue).

In the **south polar region**, our results do not match the GRS observations from Sprague et al. (2004). The predicted Argon enrichment south of 75^{o}S is much lower than observed. After investigation, we believe that this discrepancy is due to a main weakness of the LMD GCM: the overestimation of the atmospheric temperature in the southern polar night (compared to radio occultaion or thermal IR sounding data; see, for instance, our abstract on the LMD GCM presented at the first Granada workshop in 2003). This overestimation weakens the polar vortex, leading to unrealistic mixing between the southern polar region and the lower latitudes in winter. Work is in progress to undestand and correct this weakness in the model.

References

1. Sprague et al. Science, Volume 306, Issue 5700, pp. 1364-1367 (2004)
2. Forget et al. Icarus, Volume 131, Issue 2, pp. 302-316. (1998)
3. Hess, J. Geophys. Res 84, 2969 (1979)

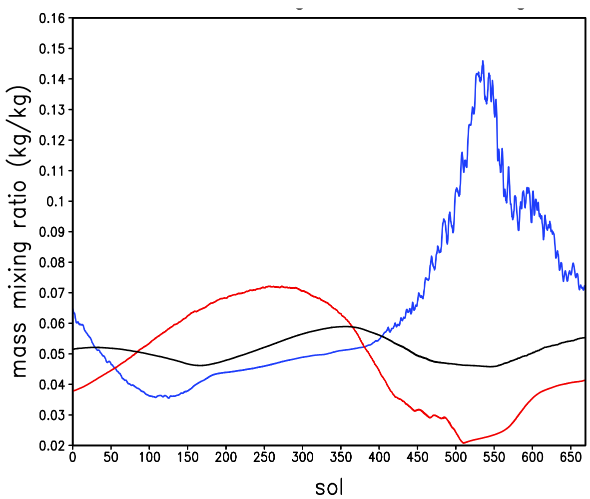

Figure 1: Seasonal evolution of the mean mixing ratio of non-condensable gases predicted by the LMD GCM. **BLACK** line: in the tropics (latitudes between 30°S and 30°N); **BLUE** line: north polar region (lat > 75°N). **RED** line: south polar region (lat < 75°S). Sols are counted starting at $L_s = 0°$.

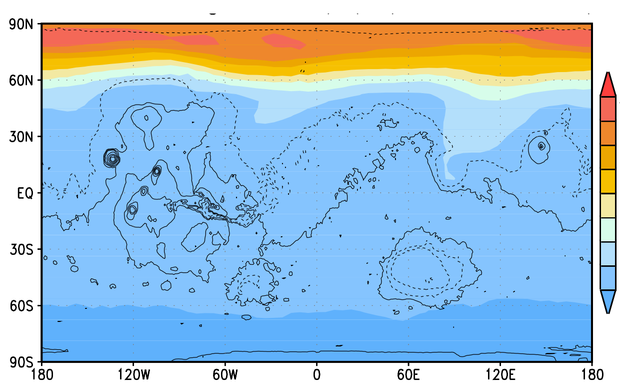

Figure 2: Map of the column averaged mass mixing ratio (% of kg/kg) of non-condensable gases during northern winter ($L_s = 270°–300°$), as simulated by the LMD Mars General Circulation Model.

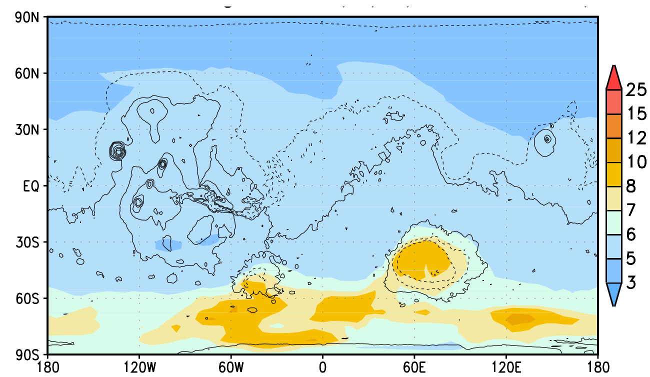

Figure 3: Map of the column averaged mass mixing ratio (% of kg/kg) of non-condensable gases during southern winter ($L_s = 90°–120°$), as simulated by the LMD Mars general Circulation Model.

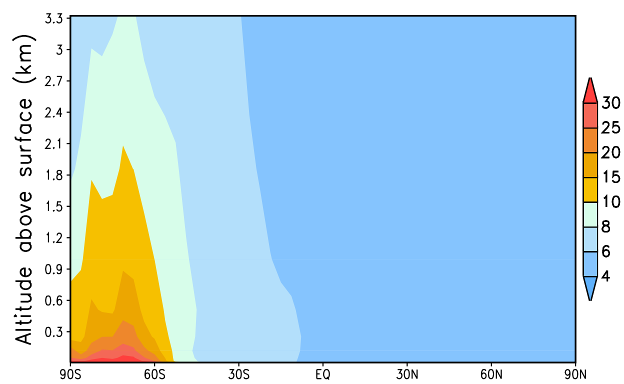

Figure 4: Zonal mean cross-section of non-condensable gas mixing ratio (%) at $L_s = 120°$, as simulated by the LMD Mars General Circulation Model.

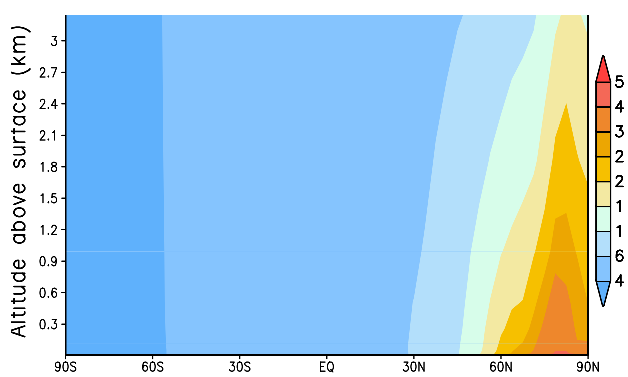

Figure 5: Zonal mean cross-section of non-condensable gas mixing ratio (%) at $L_s = 270°$, as simulated by the LMD Mars General Circulation Model.