**EXPLORING FEEDBACKS BETWEEN THE INTERIOR AND ATMOSPHERE OF VENUS: $CO_2$ AND**
**$H_2O$.** I. van Zelst[1] (iris.vanzelst@dlr.de), A.-C. Plesa[1], C. Brachmann[1], D. Breuer[1], [1]Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany.

**Introduction:** The evolution of the composition of planetary atmospheres is largely determined by the partial melting and volcanic outgassing of the planetary interior. In turn, the composition of the atmosphere dictates the surface temperature of the planet (due to processes like the greenhouse effect), which is an important boundary condition for crustal and mantle processes in the interior of a planet (Fig. 1). Venus in particular has a thick atmosphere at present with an abundance of the greenhouse gas $CO_2$ and a small amount of water vapour. Its surface conditions are harsh with a surface temperature of 737 K and a surface pressure of 93 bar. However, the surface conditions may have been much milder up to recent times [1]. The evolution of the surface evolution and therefore its convective regime is thought to be significantly affected by volcanic outgassing throughout the thermal evolution of Venus.

Here, we show the first results of coupling a grey atmosphere model (i.e., we assume that the absorption coefficients are constant and hence independent of frequency) considering only $CO_2$ and $H_2O$ as greenhouse gases to the geodynamic code Gaia [2]. We compare our results to previous studies [3, 4, 5] who employed similar coupled models to address the interaction between the interior and atmosphere of Venus.

**Model:** We briefly describe the methods we use to both calculate the atmospheric composition from the produced melt and the atmospheric model that is used to then calculate the surface temperature $T_s$. These methods have previously been described in [5, 6, 7]. In short, we calculate the fraction of outgassed $CO_2$ and $H_2O$ from the melt and then use the resulting partial pressures to calculate the surface temperature, which we use as the top boundary condition for mantle convection.

We use the geodynamic code Gaia [2] to model mantle convection and to calculate the amount of melt produced. We then calculate the abundance of $CO_2$ in the melt for each cell $j$ according to [6]

$$X_{\text{liq},j}^{CO_2} = \frac{b X_{\text{liq},j}^{CO_3^{2-}}}{1 + (b-1) X_{\text{liq},j}^{CO_3^{2-}}}, \tag{1}$$

where $b$ is a constant and the concentration of carbonate $X_{\text{liq},j}^{CO_3^{2-}}$ in each cell $j$ is calculated as

$$X_{\text{liq},j}^{CO_3^{2-}} = \frac{K_{II} K_I f_{O_2,j}}{1 + K_{II} K_I f_{O_2,j}}, \tag{2}$$
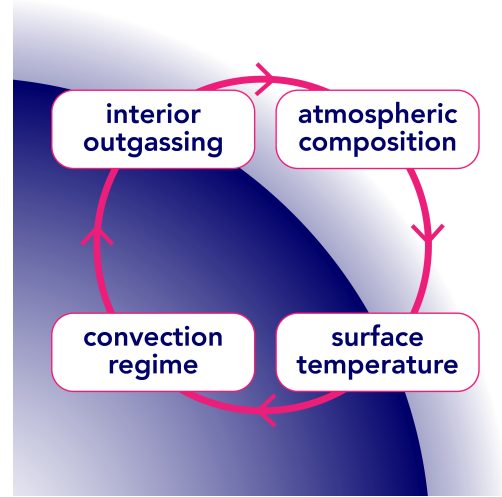


Figure 1: Schematic illustration of the feedback loop between the interior of the planet and its atmosphere.

where $K_{II}$ and $K_I$ are constants [6] and $f_{O_2,j}$ is the calculated oxygen fugacity in cell $j$ [8].

The amount of $H_2O$ in the melt for each cell $j$ is calculated as

$$X_{\text{liq},j}^{H2O} = \frac{X_m}{\phi_j} \Big(1 - (1 - \phi_j)^{1/\delta}\Big), \tag{3}$$

where $X_m$ is the bulk mantle concentration, $\phi_j$ is the local melt fraction in a given cell, and $\delta$ is an appropriate partition coefficient [6].

We calculate the total extracted mass from the mantle for both species by summing over all cells $j$ according to

$$M^i = \rho_{\text{crust}} \sum_j \phi_j V_j X_{\text{liq},j}^i, \tag{4}$$

where $\rho_{\text{crust}}$ is the density of the crust, $V_j$ is the volume of a given cell $j$, and the superscript $i$ denotes different chemical species, i.e., either $CO_2$ or $H_2O$. Using this total extracted mass for each species, we compare with saturation curves to determine how much of the species is actually outgassed to the atmosphere and how much is enriched in the crust. We also adjust the total mass of outgassed species according to the ratio between intrusive and extrusive volcanism [7]. Then, knowing the total mass of $CO_2$ and $H_2O$ in the atmosphere, we calculate the partial pressures $P_{CO_2}$ and $P_{H_2O}$.

We use these partial pressures to calculate the optimal depth of the atmosphere in the infrared $\tau$ according

to [5]

$$\tau = \sum_i \tau_i = \sum_i \frac{3 K_i' P_i}{2g}, \tag{5}$$

where $g$ is the gravitational acceleration at the surface of Venus, $P_i$ is the partial pressure of a given atmospheric species $i$, and $K_i'$ is the absorption coefficient corresponding to this pressure calculated according to

$$K_i' = \sqrt{\frac{K_{0,i} g}{3 P_0}}, \tag{6}$$

where $K_{0,i}$ is the absorption coefficient for the chemical species $H_2O$ or $CO_2$, and $P_0$ is the standard atmospheric pressure. Note that the so-called 'grey' atmosphere model we use here stems from the assumption of taking $K_{0,H20}$ and $K_{0,CO2}$ as constants.

The equilibrium temperature $T_e$ is defined as

$$T_e = \sqrt[4]{\frac{(1-A) S_\odot}{4\sigma}}, \tag{7}$$

where $A$ is the planetary albedo, $S_\odot$ is the incident insolation at the top of the atmosphere, and $\sigma$ is the Stefan Boltzmann constant.

Combining $\tau$ and $T_e$ allows us to calculate the surface temperature resulting from the atmospheric composition according to

$$T_s = \sqrt[4]{T_e^4 \left(1 + \frac{3\tau}{4}\right)}. \tag{8}$$

After each velocity and temperature solve and calculation of the resulting produced melt, we calculate the new atmospheric composition and the corresponding surface temperature and apply that temperature as the uniform top boundary temperature condition in the model which serves as input for the next solve of the energy equation. Hence, we have a coupled model of interior-atmosphere evolution.

**Conclusion:** We study the feedbacks between the interior and atmosphere on Venus through a geodynamic model of mantle convection that incorporates an atmospheric model to constrain the top boundary condition according to the (outgassed) atmospheric composition. In this study, we particularly focus on the effect of the ratio between intrusive and extrusive volcanism on the evolution of Venus by conducting a parameter study, although other parameters such as the planetary albedo are also interesting research avenues for future work.

In future work, we aim to consider the entire $C$-$O$-$H$ system, i.e., $CO_2$, $H_2O$, $H_2$, $O_2$, $CO$, and $CH_4$, to shed light on the coupled evolution of the interior and atmosphere of Venus.

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