CIDGA - Coupling of Interior Dynamic models with Global Atmosphere models

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1) Introduction

The atmospheric and climatic evolution of a planet is mainly controlled by the solar flux and the amount of greenhouse gases in the atmosphere. The latter can change significantly with time due to the release of greenhouse gases from the planetary interior as a consequence of partial melting and the associated volcanic degassing. In fact, a positive feedback process can operate by the release of greenhouse gases to the atmosphere via mantle melting, leading to an increase in the surface temperature which on the other hand may result in an increase of the mantle temperature and then in an increase of the partial-melting rate [1]. The coupling between the interior and the atmosphere, however, is not well understood and here we present a preliminary study of a coupled atmosphere-interior evolution for Venus with a 2D convection model and a gray radiative-convective atmospheric model.

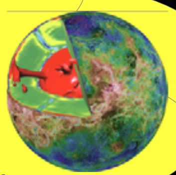
2) 2D Mantle Convection Model

For the interior of Venus, we use the 2D/3D spherical simulation code *GAIA* [2], which solves the standard conservation equations of

mass $\nabla \cdot u = 0$

momentum $\nabla \cdot \left[\eta\left(\nabla u + (\nabla u)^T\right)\right] + RaT\,e_r - \nabla p = 0$

energy $\frac{\partial T}{\partial t} + u\nabla T + Di(T+T_0)u_r = \nabla^2 T + \frac{Ra_Q}{Ra} + \frac{Di}{2Ra}\eta\left(\nabla u + \nabla u^T\right)^2$



for Rayleigh number *Ra*, internal Rayleigh number *RaQ*, dissipation number *Di*, and viscosity η, which is calculated with the Newtonian Arrhenius law.

3) Partial Melt and Outgassing

We calculate the melt fraction [3] with

$$F_{melt} := \max\left\{\frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} - 0.05\ ,\ 0\right\}.$$

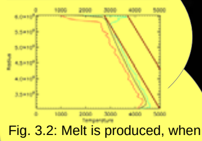


Fig. 3.2: Melt is produced, when the temperature exceeds the solidus.

We assume, that all volatiles are enriched in the melt and are released into the atmosphere by extrusive volcanism (10% of the melt).

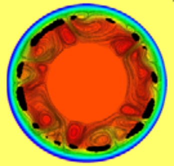
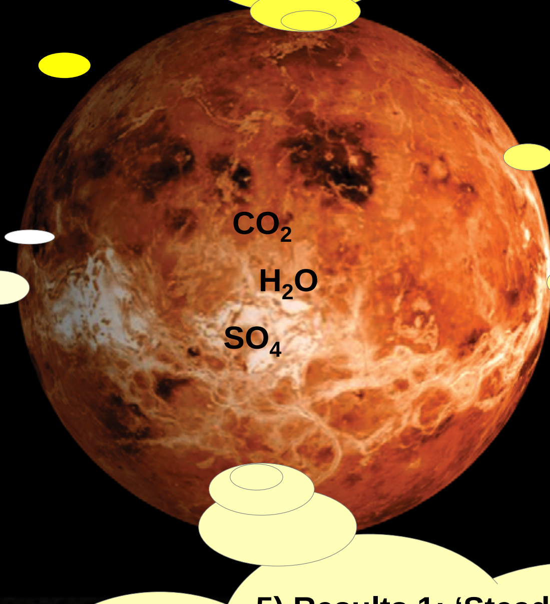


Fig. 3.1: Temperature profile for Venus-size planet. Melt regions are coloured in black.

Only the greenhouse gas H_2O is released, whereas the concentration of CO_2 in the atmosphere is constant assuming the present-day value. In the mantle, an initial concentration of C_{H2O} = 50 ppm is assumed.



4) 1D Gray Atmosphere Model

Radiative Layer

The temperature profile depends on the partial pressures of the gases, which define the optical thickness τ for the effective temperature T_e:

$$T_r(z) = \left(1 + \frac{3}{4}\tau(z)\right)^{1/4} T_e.$$

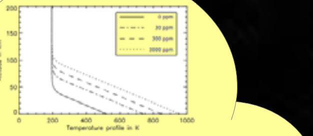


Fig. 4.2: The surface temperature strongly depends on the amount of water in the atmosphere, changing the partial pressure of H_2O.

Convective Layer

The temperature increases with altitude *z* along a dry adiabatic lapse rate Γ_d:

$$\frac{dT_c(z)}{dz} = -\Gamma_d.$$

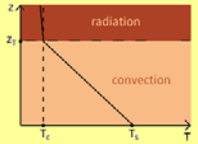


Fig. 4.1: Two-layer atmosphere structure for Venus. At the tropopause Z_T, the temperatures as well as their gradients must match.

Surface pressure	P_0	95 * 10^5 Pa
Effective temperature	T_e	227 K
Adiabatic lapse rate	Γ_d	7.5 K/km
Scale height	H	6.5 km
Albedo	α	0.77
Exospheric loss rate	τ_{H2O}	95 Myr

Tab. 3.1: Atmosphere parameters.

The concentration of water changes due to outgassing and exospheric erosion processes.

7) Conclusions

This simple model shows, that the young surface of Venus could thus be explained solely with a strong variation in surface temperature. High degassing rates lead to a mobile surface (not plate tectonics, which would need a cold and stiff crust) and thus new material at the surface. This resurfacing event appears (and disappears) self-consistently when modelling the thermal evolution of Venus with an atmosphere model.

6) Results 2: Thermal Evolution

In the thermal evolution model, the heat sources in the mantle decay, the core cools down, and the mantle is depleted as volatiles are outgassed.

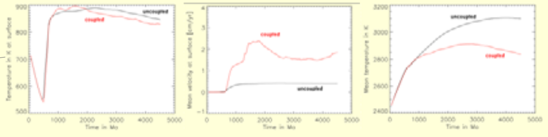


Fig. 6.1: Again, the increase in surface temperature leads to a mobilization of the surface. In the first billion years, the surface temperature increases like for the steady state model. But since the mantle is depleted and the radioactive heat sources decay with time, the flux of volatiles to the surface is strongly reduced. This leads to smaller surface temperatures, which roughly reach a nowadays value after 4.5 Ga.

Planetary radius	r_p	6050 km
Core radius	r_c	3025 km
Reference surface temperature	T_0	737 K
Core temperature, 4.5 Ga ago	T_c	4000 K
Reference viscosity (100km depth, 1600 K)	η_{ref}	10^{22} Pa s
Activation energy	E^*	100 kJ/mol
Activation volume	V^*	2.5 cm^3/mol
Mantle density	ρ	3300 kg/m^3
Surface acceleration	g	8.87 m/s^2
Initial amount of heat sources	H_0	7.59 * 10^{-8} W/m^3
Decay rate of heat sources	λ	0.339 1/Ga

Tab. 6.1: Parameters for the thermal evolution of Venus.

During the thermal evolution of Venus, the surface temperature reaches a critical value (800 – 900K), where the lid is locally mobilized, leading to a resurfacing of the lid. The efficient mantle cooling due to local resurfacing, the depletion of volatiles, and the decay of heat sources lead to a decrease of degassing rate and hence smaller surface temperatures - the surface material stagnates.

5) Results 1: 'Steady State'

For the steady state simulation, the amount of heat sources is taken to be constant, as well as the amount of volatiles in the mantle. The influence of the surface temperature is investigated in the coupled model, in the uncoupled model the surface temperature is constant.

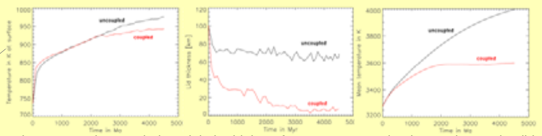


Fig. 5.1: For the coupled model, the high surface temperature leads to a decreasing lid and local resurfacing, such that the missing isolating lid leads to fast cooling of the mantle. The amount of partial melt decreases, in the atmosphere are less volatiles, and thus the surface temperature is smaller compared to the uncoupled model.

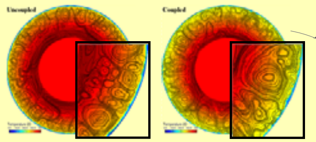


Fig. 5.2: After 4.5 Ga, the coupled model shows a much cooler interior than the uncoupled model due to local resurfacing. In the steady state model, the mantle is not depleted, and during the whole evolution the surface temperature increases.

References

[1] R.J. Phillips, M.A. Bullock, and S.A. Hauck, II (2001), GRL.
[2] C. Hüttig and K. Stemmer (2008), PEPI.
[3] A.-C. Plesa (2010), Poster, EGU2010-6351.

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