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Temporal variations in the convective style of planetary mantles

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Abstract

Investigations of mantle convection with temperature- and strain-rate-dependent viscosity have shown the existence of fundamentally different convective styles: By varying e.g. the Rayleigh number, the viscosity contrast or the strain-rate dependency of viscosity, the planform of convection in the asymptotic stationary state changes from the so-called stagnant lid regime to an episodic behaviour and further to a state characterised by a permanently mobilised surface. Our studies suggest that this transition may not only be induced by a change of parameters but also occurs temporally for fixed parameters. We have in fact observed convective systems in the stagnant lid regime that show isolated events of surface mobilisation occurring out of a thermally equilibrated state. We use a 3D numerical mantle convection model to investigate mantle convection and surface dynamics as a coupled fluid dynamical system. Our studies focus on the existence of a transitional regime in which temporal variations between the stagnant lid and the episodic regime occur. We were able to deduce a mobilisation criterion that describes the stability of the stagnant surface, thus allowing for a quantitative analysis of the transition to a (temporarily) mobilised surface. This criterion is also suitable to predict the occurrence of surface mobilisation events.

Keywords: mantle convection; convective regimes; episodic regime; stagnant lid; transitional behaviour

1. Introduction

Thermal convection is an important mechanism for heat transport in terrestrial planets, with the actual convective style and the thermal evolution differing strongly among the planets. Mars, Mercury and the Moon, for example, are today characterised by an immobile and rigid surface (stagnant lid) under which the convection is confined [1,2]. This behaviour is in contrast to the plate-tectonics style of convection observed on Earth. Here, the rigid surface is actively participating in the convective process, i.e. large surface pieces move from the mid-ocean ridges, where they are newly created by rising material, to subduction zones, where they are pulled into the Earth's interior. While the mobilisation of the surface on Earth is continuous, an occasional mobilisation is found on Venus. Events of resurfacing appear between phases of stagnant lid convection [3–6]. Early episodes of surface mobilisation have also been speculated for Mars but are assumed to have died off today [7–9].

Due to the specific type of surface expression the thermal structure in the planets differ. A thick, conductive lid significantly constrains the heat flux through the surface compared to a mobilised plate that

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effectively cools the interior by its sinking. Consequently the interior of planets characterised by the stagnant lid mode of convection is initially heated up [10].

The thermal evolution of terrestrial planets has been widely investigated [e.g. [6,11–15]]. This is commonly done by applying a scaling relationship which comprises a parameterisation of the heat flux in terms of the Rayleigh number. Separate parameterisations have been discussed for different convective regimes by Solomatov [16]. A transition from one convective style to another is thus mimicked by prescribing different scaling laws appropriate for each regime [17].

Several studies using a fully dynamical model have shown that the combination of rheological aspects and mantle convection processes leads to different convective regimes by varying parameters such as the Rayleigh number or rheological parameters [18–20]. For a strongly temperature-dependent viscosity and an increasing strain-rate dependency, these regimes are the stagnant lid regime, the episodic regime and the mobile lid regime.

The stagnant lid regime is dominated by the strong temperature dependence of the viscosity. As such the cold surface material is highly viscous and becomes immobile. Similar to the so-called ‘one-plate’ planets [21] the stagnant lid covers the hot, convecting mantle material.

If the strain-rate dependence of the viscosity also influences the system, the supercritical stresses in the material lead to a reduction of the effective viscosity. As a consequence the surface is weakened and able to move. The sinking of cold surface material and the rising of hot mantle material is comparable to the subduction and accretion of plates on Earth. In the mobile lid regime the surface mobilisation is continuous, while in the episodic regime the convective recycling of the surface material appears repeatedly. In between the stagnant lid recovers almost completely. But due to the fast sequences of mobilisation no thermal equilibrium for the phases of stagnant lid formation is observed.

A further interesting feature occasionally observed, is the temporal variation in the convective styles [18,20]. This has not yet been intensively discussed, though, for example, the change from a previous plate-tectonics style of convection to the stagnant lid mode of convection is of great potential importance for Mars. A further change more relevant for Venus could be the stagnant lid mode of convection interrupted by several, single episodes of surface mobilisation.

The topic of this paper is thus the closer investigation of the transitional behaviour, i.e. the temporal change from the stagnant lid behaviour to (episodic) mobilisation of the surface. A fluid dynamical approach has been applied for this purpose.

2. The model

2.1. The numerical model

We consider thermally driven convection of an incompressible Boussinesq medium with infinite Prandtl number. The governing equations describing the conservation of mass, momentum and energy, respectively, are as follows:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$-\nabla p + \nabla \sigma + Ra\ T\hat{z} = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + \nabla(\mathbf{u}T) - \nabla^2 T = Q \tag{3}$$

Here, $\mathbf{u}$ is the velocity vector, p the dynamic pressure (i.e. the pressure without the hydrostatic component) and σ the stress tensor with $\sigma = \eta\,[(\nabla\mathbf{u}) + (\nabla\mathbf{u})^t]$. T is the temperature and $\hat{z}$ the vertical unit vector. The rate of internal heat production Q is assumed to be constant in space and time. All variables have been non-dimensionalised by using a common scaling based on thermal diffusion time and vertical temperature difference. The Rayleigh number resulting from this scaling (defined at the surface) reads:

$$Ra = \frac{\alpha \rho g \Delta T d^3}{\kappa \eta_0} \tag{4}$$

where α denotes the (constant) thermal expansivity, ρ the density, g the gravitational acceleration, ΔT the vertical temperature difference, d the height of the model volume and κ the (constant) coefficient of thermal conductivity. η_0 is the reference viscosity defined at the surface of the box.

These equations are solved using a numerical method presented by Trompert and Hansen [22]: A finite volume approach is applied for spatial discretisation and an implicit Crank–Nicholson scheme for discretisation in the time domain. The algebraic equations are solved iteratively employing a multigrid technique with SIMPLER as smoother. The experiments were carried out in a Cartesian box with stress-free, impermeable boundaries. The box was heated from below and cooled from above with constant temperatures of $T_{\text{top}} = 0$ and $T_{\text{bot}} = 1$. Reflecting conditions were employed at the sides.

2.2. The rheological model

In order to investigate systems that show variations in the convective style, we employ a viscosity depending on temperature T and strain-rate E. This combination