



How does small-scale convection manifest in surface heat flux?

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ABSTRACT

Small-scale convection in the suboceanic mantle, if present, is commonly thought to manifest in surface heat flux, and the steady-state scaling of sublithospheric convection has often been used to interpret heat flow data from old ocean basins. Relations among small-scale convection, surface heat flux, and the steady-state scaling, however, have been vague. A series of transient cooling modeling are conducted here to quantify such relations. Given the strong temperature-dependency of mantle viscosity, results suggest that small-scale convection could take place without noticeably disturbing surface heat flux, and that the use of steady-state scaling may not be warranted for the present-day suboceanic mantle.

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1. Introduction

The ocean floor represents the surface of the top boundary layer in mantle convection, and as the seafloor ages, the boundary layer (or oceanic lithosphere) gradually thickens by thermal diffusion (Turcotte and Schubert, 1982). The thickness of oceanic lithosphere may not increase indefinitely, however, because it could become dynamically unstable (Parsons and McKenzie, 1978; Davaille and Jaupart, 1994; Korenaga and Jordan, 2003). The existence of small-scale convection that prevents the growth of oceanic lithosphere has long been speculated from various kinds of observations including topography, heat flow, and seismic structure (e.g., Parsons and McKenzie, 1978; Lister et al., 1990; Montagner, 2002; Ritzwoller et al. 2004) and the focus of this article is on the relation between small-scale convection and heat flow.

Because small-scale convection modifies the thermal structure of lithosphere, its operation is expected to be reflected in surface heat flux. Earlier numerical and laboratory studies indicate that surface heat flux would divert considerably from that expected for simple half-space cooling, as soon as convection occurs (Davies, 1988; Davaille and Jaupart, 1994). A more recent analysis, however, suggests that the influence of small-scale convection on surface heat flux may be limited if the strong temperature-dependency of mantle viscosity is considered (Korenaga and Jordan, 2002), and one of the purposes of this paper is to quantify the effect of temperature-dependent viscosity on the timing of surface manifestation.

Also, small-scale convection has commonly been thought to achieve a quasi-steady-state shortly after its onset, and the scaling of stagnant-

lid convection, which is valid for (statistically) steady state, has been used to interpret the heat flow data of old (> 100 Ma) ocean basins (e.g., Davaille and Jaupart, 1994; Solomatov and Moresi, 2000). Even when small-scale convection is taking place, however, it is not obvious whether it should follow the steady-state scaling. A relation between transient cooling and steady-state scaling was previously investigated (Daly, 1980; Choblet and Sotin, 2000), but as explained later, it is yet to be understood when small-scale convection could achieve a quasi-steady-state in case of strongly temperature-dependent viscosity.

To address these timing issues, the transient cooling of a uniformly hot fluid is investigated for a range of Rayleigh numbers and the temperature-dependency of viscosity. A model setup will be explained next, followed by numerical results. The implications for the dynamics of suboceanic mantle will be discussed briefly at the end.

2. Model formulation and results

Numerical formulation follows closely that of Korenaga and Jordan (2003); a uniformly hot fluid with temperature-dependent viscosity is subject to instantaneous cooling and no internal heating at $t^* = 0$ (asterisk indicates a nondimensionalized variable and time is normalized by the diffusion time scale of D^2/κ , where D is the system depth and κ is thermal diffusivity). The nondimensionalized governing equations for thermal convection in an incompressible fluid are solved by the 2-D finite element code of Korenaga and Jordan (2003). The top and bottom boundaries are free slip. Temperature is normalized by ΔT , which is the difference between the surface temperature and the initial internal temperature. The top temperature is fixed to 0, and the bottom boundary is insulating. A reflecting boundary condition (i.e., free slip and insulating) is applied to the side boundaries. Internal temperature is set to 1 at $t^* = 0$. The aspect ratio

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of a model is four to eliminate wall effects, and the model is discretized by 256×64 uniform quadrilateral elements. The amplitude of random perturbation in the initial temperature field is 10^{-5} , and the following linear–exponential viscosity is employed:

$$\mu^*(T^*) = \exp[\theta(1 - T^*)], \quad (1)$$

where θ is the Frank–Kamenetskii parameter. Viscosity is normalized by reference viscosity μ_0 , which corresponds to viscosity at $T^* = 1$.

The convection system is characterized by two nondimensional parameters, the above Frank–Kamenetskii parameter and the Rayleigh number defined as

$$Ra = \frac{\alpha \rho_0 g \Delta T D^3}{\kappa \mu_0}, \quad (2)$$

where α is thermal expansivity and ρ_0 is reference density. All combinations of five Rayleigh numbers (10^7 , 3×10^7 , 10^8 , 3×10^8 , and 10^9), and five Frank–Kamenetskii parameters (9, 12, 15, 18, and 21) are considered. An ‘effective’ activation energy for the temperature-dependency of upper mantle viscosity is likely to be $\sim 300 \text{ kJ mol}^{-1}$ regardless of creep mechanisms (Korenaga, 2006; Korenaga and Karato, 2008), which is equivalent to θ of ~ 18.5 (assuming the temperature scale of 1350 K). As far as the physics of small-scale convection is concerned, it is immaterial whether linear–exponential or Arrhenius viscosity is used. Both types of temperature-dependent viscosity result in similar dynamics (Reese et al., 1999; Korenaga and Jordan, 2003). My choice here is to facilitate direct comparison with the scaling law of stagnant-lid convection (Solomatov and Moresi, 2000), which is built on numerical simulation with linear–exponential viscosity.

Numerical modeling here is limited to 2-D, but it is sufficient to capture relevant physics for the following reasons. First, whether 2-D or 3-D does not matter for the onset of convection in a horizontally infinite layer (Chandrasekhar, 1981). More critical is the restriction of modes by wall effects (Davis, 1967; Korenaga and Jordan, 2001), which should be minimized by the use of the large aspect ratio. Three-dimensionality becomes important for finite-amplitude convection, in particular regarding its spatial configuration. The planform of small-scale convection beneath oceanic plate has long been thought to be influenced by vertical shear associated with plate motion (e.g., Richter, 1973). To minimize the interference with such background flow, convection cells tend to align in parallel to plate motion, and the dynamics of small-scale convection becomes 2-D, being decoupled from vertical shear (Jeffreys, 1928; Ingersoll, 1966; Richter and Parsons, 1975). The temporal evolution of sublithospheric convection can thus be well captured by 2-D models if such models are interpreted as the cross section of suboceanic mantle perpendicular to plate motion (e.g., Buck and Parmentier, 1986; Korenaga and Jordan, 2004). Finally, the scaling law of stagnant-lid convection adopted here is also built on 2-D models (Solomatov and Moresi, 2000). More important, the scaling of stagnant-lid convection can be derived by the local stability analysis of thermal boundary layer (Solomatov, 1995), indicating that 2-D treatment is sufficient as for the onset of convection.

The onset time of convection, t_c^* , is defined as the time when the kinetic energy of the system exceeds its initial value by more than three orders of magnitude (Fig. 1a and b). After the onset, the surface heat flux, q^* , starts to deviate from what is expected for half-space cooling (i.e., $1/\sqrt{\pi t^*}$), and the time when the deviation exceeds 5% of the half-space prediction is marked as t_s^* . The internal temperature, T_i^* , is calculated by averaging the temperature field beneath the thermal boundary layer (Fig. 1c). Steady-state heat flux, q_s^* , is then calculated from the following scaling law for stagnant-lid convection (Solomatov and Moresi, 2000):

$$q_s^* \left[1 - 2 \left(1 - 2.4 \theta_i^{-1} \right) / q_s^* \right]^{1/2} = 0.53 \theta_i^{-4/3} Ra_i^{1/3}, \quad (3)$$

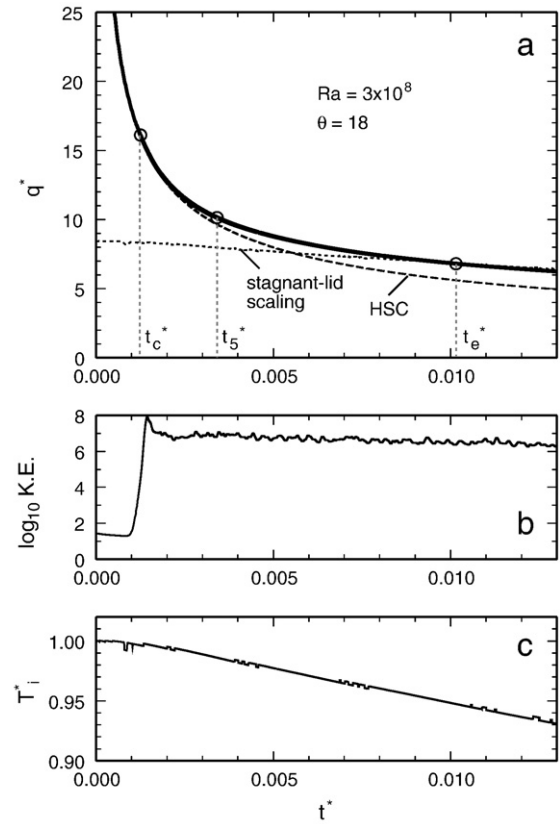


Fig. 1. Example of numerical solutions in case of Ra of 3×10^8 and θ of 18. (a) Surface heat flux as a function of diffusion time t^* . Numerical solution (solid) is compared with the half-space cooling prediction (dashed) and the stagnant-lid scaling (dotted). (b) Kinetic energy. (c) Internal temperature.

where Ra_i and θ_i are redefined Rayleigh number and Frank–Kamenetskii parameter, respectively, as $Ra_i = Ra \exp[-\theta(1 - T_i^*)]$ and $\theta_i = \theta T_i^*$. The time when surface heat flux matches the steady-state prediction is denoted as t_e^* (Fig. 1a).

The use of the term ‘steady-state’ here may require some clarification because it does not refer to time-independent convection. When the Rayleigh number is sufficiently high, convection is usually chaotic and highly time-dependent, but it is still possible to define a statistically steady state at which time-averaged quantities converge. The scaling law of Eq. (3) is based on such steady-state solutions. This steady-state heat flux is a function of Ra_i and θ_i , both of which depend on the internal temperature T_i^* . Because T_i^* slowly decreases in a system cooled from above (Fig. 1c), heat flow predicted by the steady-state scaling also changes with time (Fig. 1a). Thus, it should be understood as the amount of heat flow expected when small-scale convection is in a statistically steady state with given Ra_i and θ_i .

As Fig. 2a shows, the ratio t_s^*/t_c^* increases almost linearly as θ increases, and for $\theta \sim 20$, it takes three times longer to have a noticeable heat flow anomaly than just to have the onset of convection. This tendency of delayed surface manifestation may already be recognized in Fig. 2 of Korenaga and Jordan (2002), but Fig. 2a here demonstrates that there is a simple linear relation independent of the Rayleigh number. The scaling law for the onset of convection (Korenaga and Jordan, 2003) suggests that the onset times for different model runs should collapse onto a single curve if they are normalized by the local boundary layer time scale t_r^* of $Ra^{-2/3}$, which is indeed the case (Fig. 2b). Similar data collapse is also achieved for the equilibration time t_e^* , but data are more scattered for greater θ because the steady-state prediction and the measured heat flux tend to cross at smaller angles. As for t_s^* , t_e^*/t_c^* increases for larger θ . This behavior may be

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