SPURIOUS TRANSITIONS IN CONVECTIVE REGIME DUE TO VISCOSITY CLIPPING: RAMIFICATIONS FOR MODELING PLANETARY SECULAR COOLING.

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Introduction: The thermal evolution of rocky planets and icy-moons depends on (or has in their past depended on) convective heat transfer across a silicate-mantle or ice-1 shell [e.g.,1]. The rate of heat loss is determined by the convective regime and hence the viscosity variation across the mantle or ice shell layer [2,3]. As the core cools due to secular cooling, the temperature at the base of the mantle changes. Consequently, the evolving viscosity at the base of the mantle and the associated change in viscosity contrast across the mantle depth may instigate a convective regime shift.

In the Arrhenius equation for describing effective viscosity in systems where flow occurs by diffusion creep, the sensitivity of viscosity to temperature is determined by the activation energy, E, (a property of the deforming material). For typical mantle temperature contrasts, ΔT, and silicate composition layers (e.g., E $\geq$ 300 kJ/mol and $\Delta T \geq 1500$ K) a viscosity contrast, $\Delta\eta_T$, between the planetary surface and core mantle boundary exceeds 10^{40} [4,5]. However, such a literal application of the viscosity variation is not appropriate for fluid models.

In numerical models, viscosity contrast reduction methods are often employed to obtain tractable problems [6,7]. For example, it is common to employ thermal viscosity contrasts that simply exceed the threshold required for stagnant-lid convection, in order to obtain a desired behavior while by-passing the difficulties entailed by modelling the full magnitude of $\Delta\eta_T$ in a planet [8]. In this work, we investigate the effect of specifying a maximum (clipping) viscosity in the system at a value below the surface viscosity magnitude and determine its effect on thermal evolution. Periods of secular cooling comparable to the lifetime of the solar system are modeled. Biases resulting from implementing reduced viscosity contrasts are discussed and we demonstrate a method for modeling large viscosity contrasts using a much lower viscosity contrast model.

Methods: Thermally driven convection in a Boussinesq fluid with infinite Prandtl number is modeled in two-dimensional spherical annulus and three-dimensional spherical shell geometries. A hybrid finite-difference/finite-volume code, StagYY, solves the governing equations, using a parallelized multigrid method [9,10]. Secular cooling is emulated for a planet with a 1700 km outer radius. The surface and core-mantle boundary are modeled as free-slip in each calculation and are isothermally fixed to $T = T_{\mathrm{surf}}$ and $T = T_{cmb}(t)$. The core-mantle boundary temperature is evolved by adjusting the change in energy of the core given the basal heat flow into the mantle.

Our initial condition emulates a well mixed post-magma ocean mantle characterized by a conducting lid overlying an interior with a temperature profile specified by the solidus curve of peridotite. Employing a core radius to outer shell radius ratio of 0.5 (implying a mantle thickness of 850 km), and initial reference Rayleigh number, $Ra = 10^{10}$, corresponding to a superadiabatic temperature difference of $\Delta T = 1700$ K across the mantle, we investigate the influence of three distinct concentrations of decaying internal heating rates, *H,* on convective regime transitions.

An Arrhenius rheology law is implemented, with an activation energy of 230 kJ/mol and a reference viscosity of 1.8×10^{16} Pa.s at a temperature of 2077 K. We first consider calculations with an evolving viscosity contrast $\Delta\eta_{var} = \eta(T_{clip})/\eta(T_{cmb})$ where any material colder than T_{clip} is assigned the maximum viscosity $\eta(T_{clip})$. The viscosity contrast is $10^{5.5}$ initially and decreases over time as the core-mantle boundary cools. Subsequently, we consider calculations with a constant viscosity contrast ($\Delta\eta_{const}$) of $10^{5.5}$ where the maximum viscosity evolves according to $\eta(T_{clip}) = 10^{5.5}\,\eta(T_{cmb}(t))$.

Results: We first consider calculations that differ only by their heating modes. The thermal-dependence of the viscosity does not change in time. Each system is heated by core heat loss and some cases also include internal heating that decays with a half-life of 3.0 Gyr. The contribution of internal heating to system energy starts at time $t = 0$.

Figure 1 shows the effect of a varying viscosity contrast on planetary secular cooling. Depending on the initial internal heating rate, rapid cooling sets in as a result of a convective regime change from stagnant-lid to mobile-lid convection, followed by gradual cooling to a weakly convecting and eventually nearly conductive state.

In order to illustrate the influence of the clipping viscosity on convective regime changes, we present the results of a series of calculations that feature a changing value in the temperature corresponding to the threshold at which the maximum viscosity is obtained.

Figure 2 shows the effect of a constant viscosity contrast on the planetary secular cooling with no internal heating. In this case, stagnant-lid convection is the only convective regime observed. Convection with an initially large viscosity contrast (10^{10}) is also shown and we find strong agreement in the thermal evolution when compared with the dynamic clipping model.

Our findings show that convective regime changes due to secular cooling can occur due to permiting a variable viscosity contrast that becomes sub-critical with respect to obtaining a stagnant-lid. To avoid spurious convective regime changes, the specification of a dynamic clipping viscosity can be used to emulate much higher viscosity contrasts.

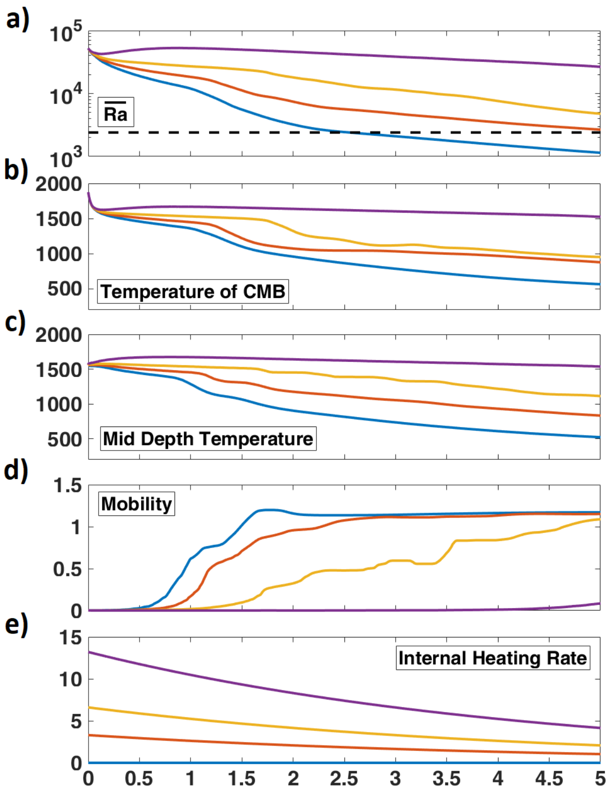

Figure 1. *Time series of averaged Rayleigh number Ra (a), temperature of the core-mantle boundary (b), mid-depth temperature (c), Mobility (surface normalized by system Vrms) (d), and internal heating rate (e) for four heating conditions. Heating modes are indicated by color: purely basally heated (blue), basally and internally heated convection with nondimensional H initially 3.3 (red), 6.6 (yellow), or 13.2 (violet). Temperature is indicated in Kelvins and time is indicated on the horizontal axis in units of billions of years. The dashed horizontal line indicates the critical Rayleigh number (Ra_{crit} = 2405) for the onset of convection in an isoviscous spherical shell with a core-to-surface radii ratio of 0.5.*

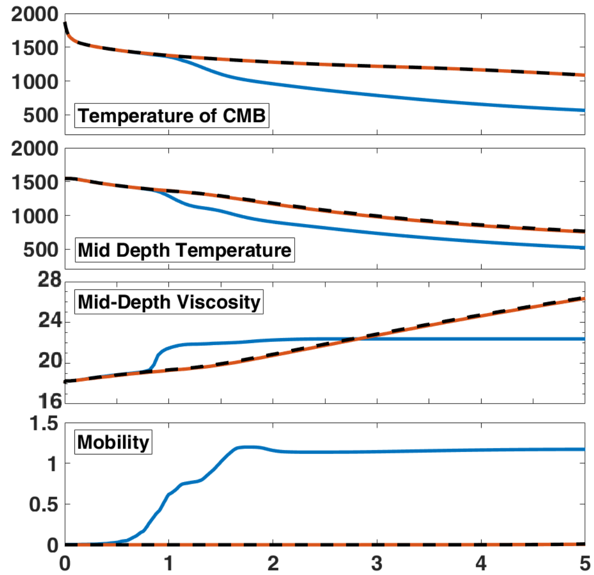

Figure 2. *For the case with no internal heating, shown (from top to bottom) are temperature of the core-mantle boundary (top), mid-depth temperature (second), mid-depth viscosity (third), and Mobility (bottom). Comparisons of evolution between models with $\Delta\eta_{var}$ (blue) and $\Delta\eta_{const}$ (red) viscosity are illustrated. The black dashed curve corresponds to a case where $\Delta\eta_{var}$ is initially 10^{10}. Temperature is indicated in Kelvins and time is indicated on the horizontal axis in units of billions of years.*

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