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An analytic model for thermal convection with plates and the implications for plate-mantle coupling and the thermal evolution of the Earth

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We present an analytic model for thermal convection with a finite-strength plate and depth-dependent viscosity. The formulation of the model uses a simplified 2D flow structure that depends on the dynamics. The energy balance equations for the lithosphere and convective cell are distinct and the model predicts the plate velocity, plate thickness and heat flow, as well as the laterally averaged horizontal flow profile for a convective cell. The model reproduces the classic scaling laws when the plate is weak and the mantle isoviscous. We find that the introduction of a strong plate has a significant impact on the behavior of the system. Solutions predicted by our model exhibit several convective regimes: the mobile-lid, sluggish-lid and near stagnant-lid regimes. In some cases, the model predicts multiple solutions, each with different behavior and heat flow, for the same set of model parameters. The distinct solutions are physical and emerge from the energetics of the model as different balances between competing terms in the energy balance equations.

With appropriate conditions, such as those expected in the early evolution of the Earth, a branch of solutions predicts a sluggish plate that can move slowly above a rapidly convecting mantle. A simple relationship between the model parameters and the heat flow, interior convective rate, and plate velocity is derived. The plate velocity and heat flow are shown to depend only on the local properties of the lithosphere and are independent of the mantle viscosity. The model results have been compared with numerical calculations of convection with depth and temperature dependent viscosity and strong plates. Model results predict the numerical results well, and clarify the transitions between the different convection regimes.

These results have important implications for planetary evolution and plate tectonics over time. The predicted effect of this behavior on the thermal history and Urey ratio of the Earth will be discussed.