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Effects of Thermodynamic Properties on the Geometrical Evolution of Subducting Slabs

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In this study, we perform a series of numerical experiments to investigate the effects of thermodynamic properties on the geometrical evolution of subducting slabs. We calculate density, thermal expansivity, and heat capacity of mantle mineral assemblages of a lherzolite composition over a range of pressure and temperature (PT) conditions applicable to the Earth's mantle, using the thermodynamic database of Stixrude and Lithgow-Bertelloni (2011) and the thermodynamic calculation code Perple_X (Connolly, 2009). Following Nakagawa et al. (2009), we assume that thermal diffusivity follows a theoretical power-law relationship with density and derive thermal conductivity from the calculated density, expansivity, and diffusivity. The calculations show that density, expansivity, and conductivity varies significantly with depth; for example, the ranges of their values for a typical mantle geotherm are 3300-5100 km/m^3, 1.5-3.5 10^{-5}/K, and 3-18 W/m K, respectively. The change in heat capacity is relatively small ($<$ 5%). We incorporate the effects of these thermodynamic properties into a 2-D finite element code with compressible convection formulations under the anelastic liquid approximation (Lee and King, 2009) and develop a thermodynamically consistent dynamic subduction model with kinematic boundary conditions. In the model, we use a composite mantle rheology that accounts for both diffusion and dislocation creep for the upper mantle with rheological parameterization for wet olivine (Hirth and Kohlstedt, 2003). For the lower mantle, following Billen and Hirth (2007) and Lee and King (2011), we adjust the rheological parameter values for wet olivine diffusion creep to test the effects of viscosity contrast between the upper and lower mantle on slab evolution. In models with PT-dependent density, lithostatic pressure in the lower mantle at a given depth is higher than a case with a constant density (by ~800 kg/m^3 at the core-mantle boundary). The higher pressure leads to stronger mantle due to the pressure dependence of the mantle viscosity, leading to a different viscosity structure from the case with a constant density. This change in the viscosity structure due to PT-dependent density alone can have a significant effect on the simulation of slab evolution; for example, for a given set of rheological parameters, a model with PT-dependent density predicts buckling of the slab in the lower mantle while a model with constant density shows no buckling. To focus on the effects of thermodynamic properties, we remove this rheological effect of density variation by adjusting the rheological parameters for the lower mantle to maintain a similar viscosity structure for each set of experiments. When no viscosity contrast is imposed between the upper and the lower mantle, the model predicts that the slab sinks vertically into the lower mantle without experiencing much resistance regardless of the effects of thermodynamic properties. When viscosity contrast of~10-100 is imposed, the model with constant thermodynamic properties predicts the buckling of the slab immediately below the transition zone. In contrast, the thermodynamically consistent model with the same viscosity structure predicts that the slab sinks sub-vertically into the lower mantle, and slab buckling tends to occur in the bottom half of the lower mantle. When large viscosity contrast ($>$100) is imposed, however, slab buckling occurs immediately below the transition zone even in a thermodynamically consistent model. These modeling results indicate that in numerical simulations, particularly those with viscosity contrast of $<$~100, noticeably different slab geometry can evolve, depending on the treatment of thermodynamic properties.

Keywords: Dynamic slab model, Thermodynamic properties, Mantle viscosity, Slab geometry, Slab buckling