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An improved formulation for the incompressible Navier-Stokes equations with variable viscosity

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We present a new formulation of the incompressible Navier-Stokes equations with variable viscosity. By utilizing the incompressibility constraint to remove the trace from the deviatoric stress tensor, we eliminate second-order cross-derivatives of the velocity field, simplifying and improving the accuracy of co-located discretization techniques on both structured- and unstructured grids. This formulation improves the performance of SIMPLE-type algorithms that use sequential mass-momentum iterations to enforce incompressibility. A trace-free stress tensor also removes a typical source of net-rotation for simulations employing free-slip boundary conditions in spherical geometry. We implement the new scheme as a modification of an existing Boussinesq convection code, which we benchmark against analytical solutions of the Stokes problem in a spherical shell with both constant and radially dependent viscosity, and time-dependent thermal convection at infinite Prandtl number with large viscosity contrasts.