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A Benchmark Study for the Stokes Flow and Thermal and Thermochemical Convection for 3-D Spherical Shell Models

S. J. Zhong (1), A. K. McNamara (2), E. Tan (3), L. N. Moresi (4), and M. Gurnis (5)

(1) Department of Physics, University of Colorado, Boulder, Colorado, USA (szhong@colorado.edu), (2) School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, USA (Allen.McNamara@asu.edu), (3) Computational Infrastructure for Geodynamics, Pasadena, California, USA (tan2@geodynamics.org), (4) School of Mathematical Sciences, Monash University, Victoria 3800, Australia (louis.moresi@sci.monash.edu), (5) Seismological Lab, Caltech, Pasadena, California, USA (gurnis@gps.caltech.edu)

In the last ten years, a number of numerical codes for 3-D spherical mantle convection with parallel computing capability have been developed. Vigorous benchmarks for 3-D spherical convection codes become important. In this study, we present numerical benchmark results for the Stokes flow, thermal convection and thermochemical convection from CitcomS. CitcomS is a 3-D spherical finite element code for mantle convection problems. CitcomS is currently maintained by and publically available from the US-NSF funded center of Computational Infrastructure for Geodynamics (CIG). A limited number of benchmark calculations for the Stokes' flow and thermal convection problems using CitcomS have been published previously for simple models [Zhong et al., 2000]. However, the current study significantly expands the model parameter space. We present 25 thermal convection calculations with different Rayleigh number, activation energies (i.e., for temperature- dependent viscosity) and resolution, and 5 thermochemical convection calculations. For thermal convection cases, viscosity variations from its temperature-dependence (the Frank- Kamenetski viscosity formulation) range from 1 to 1e7, thus covering all the three regimes of convection from mobile-lid, sluggish, stagnant-lid. The outputs of the benchmark calculations include not only global quantities such as the Nussult number, RMS velocity, and bulk temperature, but also local quantities including maximum and minimum velocity and temperature and spectral distribution at the mid-mantle depth. For thermo-chemical convection calculations, we also quantify entrainment rate. For convection problems, since no analytical solutions are available, the results are compared with previously published ones, whenever available (mostly for mobile-lid thermal convection). We also present systematic benchmark comparisons with analytical solutions for the Stokes' flow for dynamic topography and geoid for the Earth with and without self-gravitation. This benchmark study may form a basis for future benchmark studies with more complicated physics and different codes.