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Effects of small-scale buoyancy in geodynamo simulations

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Flow and magnetic fields in the Earth's outer core are expected to have a vast range of length scale from the size of the outer core to the thickness of the boundary layers. Limited spatial resolution in geodynamo simulations prohibits solutions with the full range of scales. Consequently, subgrid scale (SGS) models are required to account for the effects of the unresolved fields on the large scale solution. Each nonlinear term in the geodynamo problem requires a SGS model; this includes the SGS heat flux, Reynolds stress, SGS Maxwell stress, and SGS magnetic induction. We perform large-eddy simulations (LES) of a dynamo in a rotating spherical shell using the dynamic scale-similarity model. However, LES result underestimates the large-scale magnetic energy by nearly 0.5 times with that from a fully resolved simulation on a finer grid.

We seek to identify the energy pathway in LES for geodynamo problems to identify the problem of the underestimation of the large scale magnetic energy in the present LES. In LES, energy is transferred between the large scales and small scales by the nonlinear terms in the governing equations. On the other hand, buoyancy forces are thought to be responsible for driving vigorous convection in the Earth's liquid core, but there is no direct energy transfer between scales by buoyancy because the buoyancy force is linear in temperature, which ensures that large-scale temperature anomalies drive large-scale flow and small-scale temperature anomalies drive small-scale flow. We investigate the effects of the small-scale buoyancy on the large scale magnetic field generation in the dynamo simulations.

To evaluate effects of the small-scale buoyancy in a dynamo simulation, we perform a fully resolved simulation using spatially filter to the buoyancy force at each time step to remove small-scale contributions. We find that the small-scale buoyancy is a likely explanation for the low magnetic energy in the LES because we obtain very similar results to the LES solution in this resolved simulation with filtered buoyancy.

A clue to the energy pathway is found in our SGS model for the Reynolds stress, which shows a positive (upscale) transfer to kinetic energy to the large scales in a region around the tangential cylinder, consistent with the results inferred from a fully resolved calculation. We assume that some of SGS buoyancy flux is transferred to the large scale kinetic energy through the Reynolds stress. By increasing the amplitude of the Reynolds stress by a factor of four, we obtain substantial improvements in the simulation over the standard LES.

We discuss a parameterization of the Reynolds stress which relies on a local estimate of SGS buoyancy flux in the dynamo simulations. The local SGS buoyancy flux can be approximated using the SGS heat flux, which is routinely calculated in the standard LES, so the modified parameterization requires few additional computations.

Keywords: Geodynamo simulation, Sub-grid scale modeling