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Large eddy simulation of a convection-driven dynamo using a dynamic scale-similarity sub-grid scale model

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The Sub-grid scale modeling is required for the geodynamo simulations because the fluid motion and the magnetic field in the Earth's outer core have small scale components which cannot be resolved in numerical simulations. We have previously modeled the influence of sub-grid scale motion for the momentum and heat flux, the Lorentz force, and the induction term using the nonlinear gradient model by Leonard (1974), which is a form of the scale similarity model. The result suggests that the nonlinear gradient model can represent basic characteristics of the effects of the sub-grid scale motion, but we observe discrepancies near the boundaries, which are due to the spatial dependence of the filter function when the grid is non-equidistant (Matsui and Buffett, 2005). Ghosal and Moin (1995) point out that this error arises when the order of filtering and spatial differentiation operation is changed. In the present study, we correct the commutation error specifically for the nonlinear gradient model. We also implement a dynamic scheme to evaluate time-dependent coefficients for the SGS models as a function of vertical position. The correction term and dynamic model are used to performed a large eddy simulation (LES) of a convective dynamo in a rotating plane layer. The simulation results are compared with the resolved direct simulation (resolved DNS) on 64ˆ3 grid, unresolved direct simulation on 32ˆ3 grid (unresolved DNS), and LES using the nonlinear gradient model without the commutation error correction. We obtain the following results:

i) Time average of the kinetic energy in the simulation domain in the dynamic LES case is closest to that in the resolved DNS case. However, time averaged magnetic energy in the dynamic LES case becomes 15% larger than that in the resolved DNS case, while the magnetic energy only 1% larger than that in the resolved DNS case.

ii) Behavior of the magnetic field is characterized by the intense horizontal component which rotates slowly. The direction of the averaged horizontal magnetic field in the dynamic LES case is very similar to that in the resolved DNS case, while direction of the averaged magnetic field in the other cases is approximately 40 or 60 degree different from that in the resolved DNS case after rotating approximately 180 degree in the resolved DNS case.

iii) The convection and magnetic field patterns tends to be parallel with respect to the direction of the averaged horizontal magnetic field. The results obtained in the LES using the dynamic model are in much better agreement with the convection pattern in the resolved DNS case.

iv) Comparison of the one-dimensional spectra of the kinetic and magnetic energies in the dynamic LES is much closer to the resolved direct simulation than that given by the unresolved DNS. The magnetic energy was damped too strongly at high wave numbers in the both LES case. However, the magnetic energy spectrum is improved when the dynamic model is used, although it still lies below the energy spectrum for the resolved DNS at high wave number.