Force balance in numerical geodynamo simulations: a systematic study

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Dynamo action in the Earth's outer core is expected to be controlled by a balance between pressure, Coriolis, buoyancy and Lorentz forces, with marginal contributions from inertia and viscous forces. Current numerical simulations of the geodynamo, however, operate at much larger inertia and viscosity because of computational limitations. This casts some doubt on the physical relevance of these models.

Our work aims at finding dynamo models in a moderate computational regime which reproduce the leading-order force balance of the Earth. By performing a systematic parameter space survey with Ekman numbers in the range $10^{-6} \leq E \leq 10^{-4}$, we study the variations of the force balance when changing the forcing (Rayleigh number, Ra) and the ratio between viscous and magnetic diffusivities (magnetic Prandtl number, Pm). For dipole-dominated dynamos, we observe that the force balance is structurally robust throughout the investigated parameter space, exhibiting a quasi-geostrophic (QG) balance (balance between Coriolis and pressure forces) at zeroth order, followed by a first-order MAC balance between the ageostrophic Coriolis, buoyancy and Lorentz forces. At second order this balance is disturbed by contributions from inertia and viscous forces. Dynamos with a different sequence of the forces, where inertia and/or viscosity replace the Lorentz force in the first-order force balance, can only be found close to the onset of dynamo action and in the multipolar regime. Our study illustrates that most classical numerical dynamos are controlled by a QG-MAC balance, while cases where viscosity and inertia play a dominant role are the exception rather than the norm.