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Rapidly rotating plane layer convection with zonal flow

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We study the onset of convection in a rapidly rotating layer in which a zonal flow in the form of a thermal wind is present and the effects of diffusion are included. The main motivation is from convection in planetary interiors including the Earth's core, where thermal winds are expected to be generated due to temperature variations on the core-mantle boundary. The system we consider admits both a convective instability and a baroclinic instability. We find a smooth transition between the two types of modes, and investigate where the transition region between the two types of instability occurs in parameter space by varying the Ekman, Prandtl, Reynolds and Rayleigh numbers.

The thermal wind helps to destabilise the well-studied convective modes of plane layer convection. With a large enough flow strength a baroclinic instability can occur when the applied vertical temperature gradient is stable, in which case the Rayleigh number is then negative. In this scenario long wavelength modes are the first to become unstable and the Reynolds number becomes the onset parameter. An asymptotic analysis is possible for the transition region and also for long wavelength instabilities, and the results agree well with our numerical solutions. We also investigate how the instabilities in this system relate to the classical baroclinic instability in the Eady problem. We conclude by noting that baroclinic instabilities in the Earth's core arising from heterogeneity in the lower mantle could possibly drive a dynamo even if the Earth's core were stably stratified and so not convecting.