Origin of Irreversibility in Vorticity Transport and its Role in Zonal Flow Generation

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Zonal flow generation is often linked to the well-known inverse cascade in quasi-2D turbulent fluids. This conventional wisdom, however, is simplistic since zonal flow can be and are driven by Reynolds stresses, which result from vorticity (or potential vorticity) mixing. Such small scale mixing processes depend more upon the forward scattering of fluctuation enstrophy than they do on the inverse cascade. In pragmatic terms, understanding vorticity mixing requires determination of the cross phase in the vorticity flux. Thus, the origin of irreversibility in vorticity transport is fundamental to zonal flow formation. In this work, we consider the general structure of the vorticity flux for the Hasegawa-Mima (HM) and Hasegawa-Wakatani (HW) models, each of which has different driving gradients and mixing processes. Each of these models presents an interesting challenge, in that: i) the advecting velocity field is closely related to the advected vorticity field (HM and HW). ii) the particle flux is strongly tied to the vorticity flux (HW), and Pr≠1 is possible. For the HM model, a modulational calculation of the vorticity flux reveals both a negative turbulent viscosity and a positive turbulent hyper-viscosity, which act in tandem. Both are enabled by forward enstrophy cascade. These tend to pump zonal flow energy from small to large scales, and together link the zonal flow scale to the turbulence integral scale by the stationarity condition of zero vorticity flux. For the HW model, with Pr=1, an elegant solution is to calculate the total PV flux by standard quasi-linear theory, and then subtract off the particle flux, which is set by the parallel electron dissipation. This reveals both a diffusive and 'residual stress' (i.e. ∇<n>driven) component in the vorticity flux, and implies that collisional drift waves generate zonal flows by converting ∇<n> free energy to flow energy. The Pr≠1 case will be addressed by standard quasi-linear theory. Other ongoing work is concerned with turbulent magnetic field effects on inhibiting PV mixing.