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Emergence and equilibration of jets in planetary turbulence

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Spatially and temporally coherent large scale jets that are not forced directly at the jet scale are prominent feature of rotating turbulence. A familiar example is the midlatitude jet in the Earth's atmosphere and the banded winds of the giants planets. These jets arise and are supported by the systematic organisation of the turbulent Reynolds stresses. Understanding the mechanism producing the required eddy momentum flux convergence, and how the jets and associated eddy field mutually adjust to maintain a steady jet structure at finite amplitude, constitute fundamental theoretical problems.

Stochastic Structural Stability Theory (SSST) gives an explanation for jet formation that is fundamentally based on the interaction between jets and their associated field of turbulent eddies. SSST combines the full dynamics of the zonal mean flow with the second order statistics of the turbulent field obtained from a stochastic turbulence model (STM). The quasi-linear (QL) approximation to the full nonlinear dynamics (NL) results when the perturbation-perturbation interactions are parameterized in the perturbation equations, while interaction between the perturbations and the zonal mean flow is retained in the zonal mean equation. SSST consists of an infinite ensemble of perturbations evolving under QL. Therefore, SSST provides a set of dynamical equations for the mean flow and the second order statistics of the second cummulant of the perturbation vorticity field, which are autonomous and fluctuation free and can facilitate analytic study of turbulent equilibria and their stability as a function of parameters. Thus, jet formation in homogeneous beta-turbulence can be identified with an SSST structural instability of a homogeneous (mean flow free) SSTT equilibrium. We investigate the emergence and equilibration of jets from homogeneous barotropic beta-plane turbulence in the absence of coherent external forcing. SSST predicts that infinitesimal perturbations with zonal jet form organise homogeneous turbulence to produce systematic upgradient fluxes, giving rise to exponential jet growth and eventually to the establishment of finite amplitude equilibrium jets.

We compare these predictions with simulations of the NL equations and their QL approximation in order to examine further the mechanism of emergence and equilibration of jets from turbulence. We concentrate on the effects of perturbation-perturbation nonlinearity on jet bifurcation and equilibration, and on the influence of perturbations in exciting the manifold of SSST modes with jet structure. We find that the bifurcation structure predicted by SSST for the emergence of zonal jets from a homogeneous turbulent state is confirmed by both QL and NL simulations. Moreover, we show that the finite amplitude equilibrium jets found in NL and QL simulations are as predicted by the fixed point solutions of SSST. Obtaining this agreement between NL and both SSST and QL simulations required in some cases that the modification of the turbulent spectrum caused by the perturbation-perturbation nonlinearity in NL be accounted for in the specification of the stochastic forcing in QL and SSST. These results confirm that jet emergence in barotropic beta-plane turbulence can be traced to the cooperative mean flow/perturbation instability that is captured by SSST.