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On the origin of jets and vortices in turbulent planetary atmospheres.

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Stratified rotating fluids tend to form large scale coherent structures. These structures are present in many different geophysical fluids, for example jet streams in the Earth's atmosphere, the famous and conspicuous jets in the Jovian atmosphere, and oceanic jets like the latent jets and the well-known main currents including the Gulf stream and Kuroshio. Observations, numerical models, and laboratory experiments have sought to explain their origins and their evolutions.

To investigate the coexistence, evolution and vertical structure of jets and vortices in turbulent planetary atmospheres, we make use of the widely studied two-layer quasi-geostrophic shallow water model on the β-plane. Numerical simulations at ultra-high resolution are carried out with the Combined Lagrangian Advection Method [1]. Following Panetta 1988 [2], to characterise the pole to equator heating variation on a planet, a vertical shear is imposed and maintained by thermal damping. To crudely represent convection from the bottom layer to the top layer, hetons are constantly added to the flow. Many numerical simulations covering a large range of parameters have been run. The thermal damping and vertical shear dependence has been widely studied and analysed.

The baroclinicity of the flow is clearly evident in all cases studied. Moreover, the flow is strongly dependent on thermal damping. There is a competition between baroclinic instabilities trying to reduce the imposed vertical shear and thermal damping trying to maintain the vertical shear. Without any thermal damping, the imposed vertical shear quickly erodes. On the other hand if the thermal damping is very high, the flow is mainly dominated by incoherent, small-scale turbulence. For weaker thermal damping, the competition between baroclinic instability and thermal damping may lead to oscillations between stable and turbulent phases. However, thermal damping does not have a significant impact on the number of homogeneous regions and jets. By contrast, vertical shear has a strong impact.

The Rhines scale, $L_{\mathsf{Rh}} = \sqrt{U/\beta}$, appears to be relevant in deducing the number of jets in each layer. Moreover, the number of jets can change with time, and for a range of parameters, the flow may oscillate (irregularly) between stable and turbulent phases. After a turbulent phase, the flow can adopt different 'meta-stable' configurations consisting of different numbers of jets. Notably, none of the many simulations conducted exhibited long-lived vortices (lasting more than 100 'days'). Evidently, vertical shear and thermal damping alone are not capable of producing long-lived vortices.

[1] D.G. Dritschel and J. Fontane. The combined Lagrangian advection method. *J. Comp. Phys.*, 229:5408-5417, 2010.

[2] R. L. Panetta and I. K. Held. Baroclinic eddy fluxes in a one-dimensional model of quasi-geostrophic turbulence. *J. Atmos. Sci.*, 45(22):3354-3365, 1988.