Rossby waves in the Stratosphere: The effect of mean flow on the accuracy of quasi-geostrophic solutions

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Quasi-Geostrophic (QG) theory forms the underpinnings of our understanding of stratospheric dynamics and stratosphere-troposphere coupling. However, in the presence of mean flow the application of planetary wave theory to the stratosphere can violate two of the basic QG assumptions: $\beta L \ll f_0$ (where L is the meridional length scale), and L not too larger compared to the Rossby radius of deformation. Here, we develop a Shallow Water Equations (SWE) setup on the β-plane for Rossby waves in order to quantify the biases introduced by QG theory in the presence of a uniform mean zonal flow that is in geostrophic balance with the mean height field. Comparing the QG results with those of the exact solution of the SWE we find that when the radius of deformation is of the order of the zonal flow's meridional extent the QG theory accurately describes the propagation speed of Rossby waves but errs in describing their associated meridional structure. This error of the QG theory increases with the mean flow's speed. When the radius of deformation is smaller than the zonal flow's meridional extent the QG theory fails to predict both the phase speeds of Rossby waves and their meridional structure (which is trapped near the equatorward boundary rather than oscillatory). Unlike QG theories in which the speed of the mean flow is unrestricted, in the SWE, where the mean speed is balanced by the gradient of the layer's height, the requirement that the total height of the layer be positive bounds the maximal allowed mean speed. The formulation of the SWE developed here can be applied to zonal mean flows that are not uniform.

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