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Study on the Ekman Pumping corrected by nonlinear terms

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Ekman (1905) proposed a physical theory of the planetary boundary layer (PBL) dynamics, which predicts the existence of the vertical velocity at the top of the PBL due to the action of the vorticity in the free atmosphere (so called the Ekman pumping). It is well known that the Ekman pumping is proportional to the relative vorticity in the FA. In his model, the nonlinear terms in the governing equations, which are important for phenomena of geophysical fluids, are completely ignored. The magnitude of the Ekman pumping in the Ekman theory is independent of the sign of voticity in the FA. In contrast, it has been pointed out that the magnitude of the Ekman pumping induced by the nonlinear governing equations is increased (decreased) in anticyclonic (cyclonic) shear compared with that in the Ekman theory (*e.g.*, Bannon, 1998; Tan, 2001). However, little has been investigated the detail mechanisms of such characteristic phenomena. Therefore the objective of this study is to understand the effects of the nonlinearity of the governing equations on the Ekman pumping theoretically and numerically.
Here, we follow the study of Benton *et al.* (1964) using the vorticity and divergence equations derived from the primitive momentum equations. From numerical computations and the perturbation analysis by expansion for the Rossby number, we conclude the following results: the most effective nonlinearity on the Ekman pumping comes from the coupling between the vertical component of vorticity and the horizontal divergence appeared in the vorticity equation. The Ekman pumping derived by approximated governing equations that are constructed by the exact vorticity equation and the linear divergence equation aggres well with that derived by the exact nonlinear governing equations.

Keywords: Planetary Boundary Layer; Ekman pumping

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