Geophysical Research Abstracts
Vol. 21, EGU2019-11683, 2019
EGU General Assembly 2019

Nonlinear and time-dependent equivalent-barotropic flows with topography

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Some oceanic and atmospheric flows may be modelled as equivalent-barotropic systems, in which the horizontal fluid velocity varies in magnitude at different vertical levels while keeping the same direction. The governing equations at a specific level are identical to those of a homogeneous flow over an equivalent depth, determined by a pre-defined vertical structure. Most oceanic studies using the equivalent-barotropic approach are focused on steady, linear formulations. In this work, the nonlinear, time-dependent model with variable topography is examined. To include nonlinear terms, we assume suitable approximations and evaluate the associated error in the dynamical vorticity equation. The model is solved numerically to investigate the equivalent-barotropic dynamics in comparison with a purely barotropic flow. We consider two problems in which the behaviour of homogeneous flows has been well-established either experimentally or analytically in past studies. First, the nonlinear evolution of cyclonic vortices around a topographic seamount is examined. It is found that the vortex drift induced by the mountain is modified according to the vertical structure of the flow. When the vertical structure is abrupt, the model effectively isolates the surface flow from both inviscid and viscous topographic effects (due to the shape of the solid bottom and Ekman friction, respectively). Second, the wind-driven flow in a closed basin with variable topography is studied (for a flat bottom this is the so-called Stommel problem). For a zonally uniform, negative wind-stress curl in the homogeneous case, a large-scale, anticyclonic gyre is formed and displaced southward due to topographic effects at the western slope of the basin. The flow reaches a steady state due to the balance between topographic, β, wind-stress and bottom friction effects. However, in the equivalent-barotropic simulations with an abrupt vertical structure, such an equilibrium cannot be reached because the forcing effects at the surface are enhanced, while bottom friction effects are reduced. As a result, the unsteady flow is decomposed as a set of planetary waves.