Geophysical Research Abstracts
Vol. 14, EGU2012-2736-5, 2012
EGU General Assembly 2012


# Integral constraints in zonal flows with parameterized potential vorticity fluxes

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Green (1970) and Welander (1973) developed a diffusive parameterization for eddy fluxes of potential vorticity (PV), which introduces eddy coefficients $k$ as free parameters. Both observations and numerical models indicate that eddies can not only weaken mean flow, but also concentrate mean momentum in jets ("negative viscosity"). Upgradient eddy momentum fluxes effects can be reproduced with a diffusive parameterization of PV using spatially varying $k$-coefficients (Ivchenko et al., 1997). In this study we investigate integral constraints on the choice of $k$ arising from momentum conservation (Marshall, 1981, Ivchenko et al., 1997) for flows in a zonal channel. The integral constraint for a two-layer quasi-geostrophic model can be written as:

$$\int_0^L (H_1 \overline{v_1' q_1'} + H_2 \overline{v_2' q_2'}) dy = f_0 \int_0^L \overline{v_2 \, b} dy. \quad (1)$$

Here $v_i$ are the meridional components of horizontal velocity; subscripts 1 and 2 mark the upper and lower layers whose mean thicknesses $H_i$ are constant. $q_i$ is the quasi-geostrophic potential vorticity, $f_0$ is the reference value of the Coriolis parameter; $b$ is the bottom relief measured relative to the unperturbed constant depth of the lower layer $H_2$. The overbar and prime denote the zonal average and eddy component (deviation from the zonal mean), respectively. $y = 0$ is the southern boundary and $L$ is the channel width. For the flat bottom case the rhs of eq.(1) becomes zero implying larger $k$-coefficients in the lower layer (Marshall, 1981).

We investigate restrictions on coefficients introduced by equation (1) for bottom topography varying sinusoidally in both the zonal and meridional directions. We find the solution to be the product of a zonally averaged solution and a zonally dependent solution. The former is found by asymptotically expanding in terms of a small parameter (Rossby radius divided by channel width). The latter is prescribed as a Fourier series. Substituting the solution into the integral constraints (1) substantially alters the restrictions on the values of the $k$-coefficients, compared with the flat bottomed case. Coefficients in the lower layer can be smaller than coefficients in the upper layer, depending on external parameters such as: the amplitude of bottom topography, wind stress, geometry of the zonal channel, the Rossby radius of deformation, bottom viscosity, the Coriolis parameter and its meridional variation ($\beta$). Numerical experiments with a two-layer quasi-geostrophic eddy-resolving channel model (Ivchenko et al., 1997) were made to verify the solution and tune parameters.