Geophysical Research Abstracts
Vol. 14, EGU2012-4997, 2012
EGU General Assembly 2012

3D Analytical solution for the tidally induced Lagrangian residual current in a narrow bay

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In a weakly nonlinear tidal system, the three-dimensional equations for the first-order Lagrangian residual velocity (LRV) are deduced systematically. The ratio between the tidal amplitude and the water depth is used as a small parameter in perturbation procedure. The equations are split into several sets based on the different order of that small parameter. The zeroth-order equations describe the linear tidal movements. The first order equations are processed to get the LRV equations with taking into consideration of the zeroth-order equations. Additional terms which are compromised of the zeroth-order values are introduced into the LRV equations, which are named as the tidal body force to represent driving mechanism of the tidal current to the residual current.

For the case of a narrow bay, the equations are solved analytically and the results for a specific bottom profile are discussed in detail. The narrow bay is set to 1.5 wave-length and the topography varies only across the bay with a deep trench in the middle of the bay and two stairs at either shore of the bay. The bay's topography has a line of symmetry through the center of the bay.

For the surface layer the residual current flows in at the deep part of the bay till the head of the bay. Then it turns back to the position where 1 wave-length away from the head of the bay and turns towards the deep part of the bay. Then the residual current joins the return flow of the semi-gyre coming in from the open boundary and flows out of the bay. The middle layer exhibits similar pattern but the two semi-gyres near the open boundary are pushed further out by the gyre inside the bay. In the deep trench the residual current split apart at 0.75 wave-length with the current flowing in at the inner part and flowing out at the outer part. The corresponding vertical residual velocity is also obtained.

The 3D LRV is sensitive to the eddy coefficient. When it becomes smaller the LRV increases and the structure changes accordingly. The residual flux can be obtained by integrating the horizontal residual current. The results are compared with those obtained from the depth-integrated 2D equations in the present authors' earlier paper. It is found that the two gyres at the head of the bay in depth-integrated 2D equations case disappears in 3D case. This shows that the 3D nature of the Lagrangian residual current.

The analytical solution of LRV can help to understand the dynamics to the shallow circulation and can be used in studies of the mass transport in water exchange related applications.