Mixing in rotating and non-rotating lock release gravity currents down canyons

by

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Extended Abstract

The flow of dense water from the marginal seas down the continental slopes and into the deep ocean is crucial for the large scale ocean circulation. Overflows and dense water plumes are observed in many areas, e.g. the Greenland-Scotland ridge overflows [Girton and Sanford, 2003, Mauritzen et al., 2005, Hansen and Østerhus, 2007, Fer et al., 2010], and the Antarctic overflows [Foldvik et al., 2004, Ilicak et al., 2011, Baines and Condie, 1998].

Overflow regions are generally considered as regions with intense mixing. The fraction η of the viscous dissipation that is used to irreversibly mix the ocean is often refereed to as the mixing efficiency [Wunsch and Ferrari, 2004] and $\eta \sim 0.2$ is a value that is considered to be necessary to maintain the general stratification and circulation. In controlled exchange flows, η may be estimated and Prastowo et al. [2008] and Prastowo et al. [2009] report values of $\eta \sim 0.11 \pm 0.01$ from experiments in non-rotating systems. This value indicates that exchange flows play a minor role in the overall energy puzzle.

In a rotating system, a secondary transverse circulation induced by the frictional Ekman transport in the bottom boundary layer will be superimposed on the primary flow of the dense plume. Such a circulation is present when the gravity current is flowing in a channel [Johnson and Sanford, 1992, Davies et al., 2006] or if the plume is steered down slope by canyons [Wåhlin, 2002] or ridges [Darelius and Wåhlin, 2007].

The focus in the present presentation is on mixing and mixing efficiencies in rotating and non-rotating gravity flows. Two sets of high resolution numerical experiments with a non-hydrostatic model are performed. First it is shown that the model reproduces the main features of a laboratory scale gravity current in a canyon. Next, a sequence of lock release experiments is performed to investigate the sensitivity of the mixing efficiency to rotation, viscosity, the initial volume, V, of dense fluid released, and non-hydrostatic effects.

In a rotating system, the transverse flows may transport lighter fluid parcels underneath the heavier core of the dense plumes. This will create instabilities and enhanced mixing. On the other hand, the speed of the down-flowing water will decrease in a geostrophically balanced flow. This will reduce the vertical shear and thereby the mixing. The results from the numerical experiments show that these effects counteract and may even balance.

The mixing efficiencies increase substantially as the initial volume of released fluid is reduced. If the lock release experiments are initiated with small values of V, the mixing efficiencies may

become substantially larger than the commonly assumed value of approximately 0.2. The scaling $\eta \sim V^{-1/3}$ is suggested. However, the shape of the body of fluid also plays a role and stretching of the body, e.g. forced by rotational effects, increase the surface area in contact with the ambient. The bodies of heavy fluid are shaped by topographic features such as canyons, ridges, troughs, bends and constrictions in addition to smaller scale topography superimposed on the larger scale features. The breaking up of a plume into eddies or domes as observed for instance in the Faroe Bank Channel overflow [Geyer et al., 2006] also reshape the body of dense water. In addition, topography directly affect drag and mixing, see for instance MacCready and Pawlak [2001], MacCready and Rhines [2001], Edwards et al. [2004], McCabe et al. [2006]. However, in most larger scale ocean model studies, the detailed topography that shapes for instance gravity plumes are not resolved. Topographical effects must hence be parameterised.

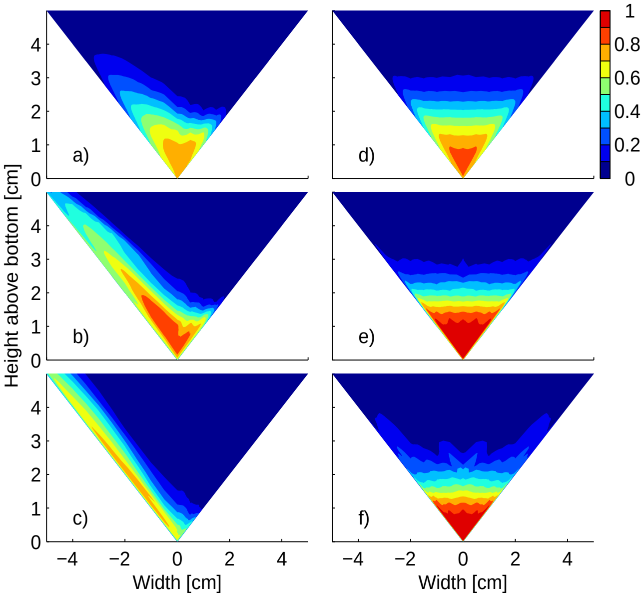

Figure 1: Vertical cross-sections of the density perturbations in kg m^{-3} in the middle of the canyon. Results for the rotational cases are given in the left panel and results for the non-rotational cases are given in the right panel. Results for $\nu = 10^{-5}$ m^2 s^{-1} are given in the top panel, for $\nu = 10^{-6}$ m^2 s^{-1} in the middle panel, and for $\nu = 10^{-7}$ m^2 s^{-1} in the bottom panel. (ν is the viscosity.)

Many ocean model studies are today performed with hydrostatic models. Non-hydrostatic pressure gradients tend to counteract nonlinear steepening [Boegman et al., 2005]. When neglecting the non-hydrostatic terms, mixing efficiencies may accordingly become larger due to a stronger flow of energy towards the grid scale. This effect is most clear in the non-rotational case. With rotation, a geostrophic balance is soon established and this balance is only slightly adjusted by the non-hydrostatic effects.

There is a growing literature on entrainment and mixing parameterisations [Kantha and Clayson, 2000, Cenedese and Adduce, 2010, Bates et al., 2012]. These parameterisations are typically based on *Fr*, *Re*, and *Ri* numbers. However, they do not directly capture subgridscale topographic effects. There are attempts to model the large scale topographic effects on the flow, see e.g. Holloway [1992] who applied statistical mechanics to derive a model that may capture the effects of topographic stresses. Topography, included subgridscale topography, will steer the flow and affect

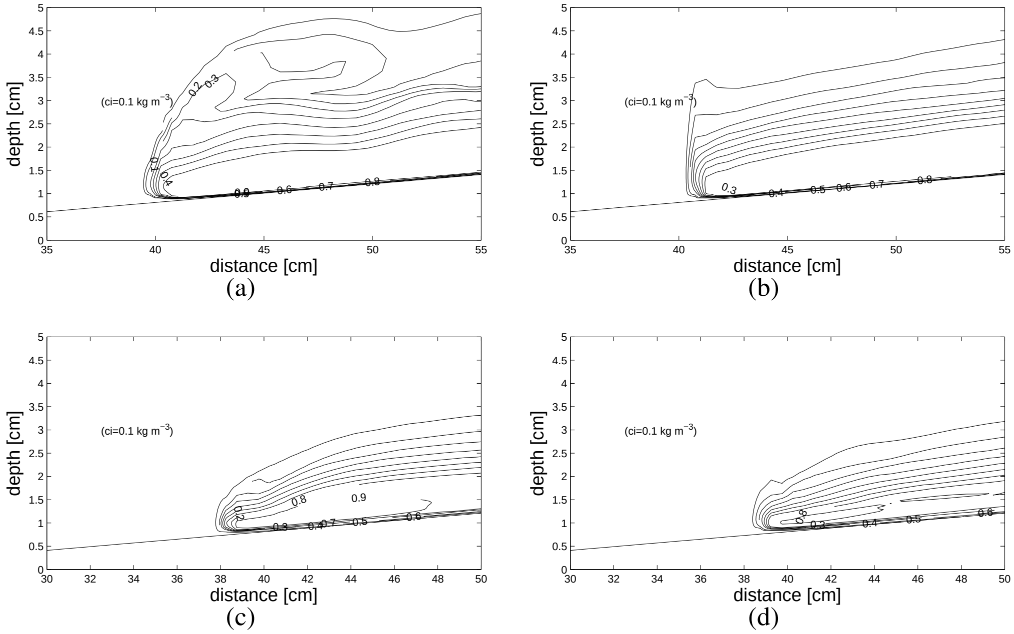

Figure 2: Along canyon vertical sections of the density perturbation. Results for the non-rotational case are given in the top panel and results for the rotational case are given in the bottom panel. The non-hydrostatic solutions are given to the left and the hydrostatic results to the right.

mixing and entrainment. To capture and correctly include these effects in large-scale numerical model we first need to improve our understanding of them. Only then, can we take the next step and, e.g. use statistical mechanics and/or statistical representations of the subgridscale topography to parameterise the effects on larger scale flows.

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References

Peter G. Baines and Scott Condie. Observations and modelling of Antarctic downslope flows: A review. In Stanley S. Jacobs and Raymond F. Weiss, editors, *Ocean, Ice, and Atmosphere - Interaction at the Antarctic Continental Margin*, volume 75. AGU, Washington D.C., 1998.

M.L. Bates, S.M. Griffies, and M.H. England. A dynamic, embedded Lagrangian model for ocean climate models, Part II: Idealised overflow tests. *Ocean Modelling of Fluid Mechanics*, 59-60: 60–76, 2012.

L. Boegman, G.N. Ivey, and J. Imberger. The degeneration of internal waves in lakes with sloping topography. *Limnology and Oceanography*, 50:1620–1637, 2005.

C. Cenedese and C. Adduce. A New Parameterization for Entrainment in Overflows. *Journal of Physical Oceanography*, 40:1835–1850, 2010.

E. Darelius and A. Wåhlin. Downward flow of dense water leaning on a submarine ridge. *Deep-Sea Research Part I-Oceanographic Research Papers*, 54(7):1173–1188, 2007.

P.A. Davies, A.K. Wåhlin, and Y. Guo. Laboratory and analytical model studies of the Faroe Bank Channel deep-water outflow. *Journal of Physical Oceanography*, 36(7):1348–1364, 2006.

K.A. Edwards, P. MacCready, J.N. Moum, G. Pawlak, J.M. Klymak, and A. Perlin. Form Drag and Mixing Due to Tidal Flow past a Sharp Point. *Journal of Physical Oceanography*, 34: 1297–1312, 2004.

I. Fer, G. Voet, K.S. Seim, B. Rudels, and K. Latarius. Intense mixing of the Faroe Bank Channel overflow. *Geophysical Research Letters*, 37:doi: L02604, 10.1029/2009GL041924, 2010.

A. Foldvik, T. Gammelsrød, S. Østerhus, E. Fahrbach, G. Rohardt, M. Schröder, K.W. Nicholls, L. Padman, and R.A. Woodgate. Ice shelf water overflow and bottom water formation in the southern Weddel Sea. *Journal of Geophysical Research*, 109, 2004. C02015, doi:10.1029/2003JC002008.

F. Geyer, S. Østerhus, B. Hansen, and D. Quadfasel. Observations of highly regular oscillations in the overflow plume downstream of the Faroe Bank Channel. *Journal of Geophysical Research: Oceans*, 111:doi=10.1029/2006JC003693, 2006. doi: 10.1029/2006JC003693.

J.B. Girton and T.B. Sanford. Descent and Modification of the Overflow Plume in the Denmark Strait. *Journal of Physical Oceanography*, 33:1351–1364, 2003.

B. Hansen and S. Østerhus. Faroe Bank Channel overflow 1995-2005. *Progress In Oceanography*, 75(4):817–856, 2007.

G. Holloway. Representing topographic stress for large-scale ocean models. *Journal of Physical Oceanography*, 22:1033–1046, 1992.

M. Ilicak, S. Legg, A. Adcroft, and R. Hallberg. Dynamics of a dense gravity current flowing over a corrugation. *Ocean Modelling*, 38:71–84, 2011.

G.C. Johnson and T.B. Sanford. Secondary Circulation in the Faroe Bank Channel Outflow. *Journal of Physcical Oceanography*, 22(8):927–933, 1992.

L.H. Kantha and C.A. Clayson. *Small scale processes in geophysical fluid flows*. International Geophysics Series Volume 67. Academic Press, 2000.

F. Lott and M.J. Miller. A new subgrid-scale orographic drag parametrization: Its formulation and testing. *Quarterly Journal of the Royal Meterorological Society*, 123:101–127, 1997.

P. MacCready and G. Pawlak. Stratified flow along a corrugated slope: Separation drag and wave drag. *Journal of Physical Oceanography*, 31:2824–2838, 2001.

P. MacCready and P.B. Rhines. Meridonal Transport across a Zonal Channel: Topographic Localization. *Journal of Physical Oceanography*, 31:1427–1439, 2001.

C. Mauritzen, J. Price, T. Sanford, and D. Torres. Circulation and mixing in the Faroese Channels. *Deep-Sea Research I*, 52(6):883–913, 2005.

R.M. McCabe, P. MacCready, and G. Pawlak. Form Drag due to Flow Separation at a Headland. *Journal of Physical Oceanography*, 36:2136–2152, 2006.

T. Prastowo, R.W. Griffiths, G.O. Hughes, and A.M. Hogg. Mixing efficiency in controlled exchange flows . *Journal of Fluid Mechanics*, 600:235–244, 2008.

T. Prastowo, R.W. Griffiths, G.O. Hughes, and A.M. Hogg. Effects of topography on the cumulative mixing efficiency in exchange flows . *Journal of Geophysical Research*, 114(C08008), 2009. doi: 10.1029/2008JC005152.

A.K. Wåhlin. Topographic steering of dense currents with application to submarine canyons. *Deep-Sea Research I*, 49:305–320, 2002.

C. Wunsch and R. Ferrari. Vertical Mixing, Energy, and the General Circulation of the Oceans. *Annual Review of Fluid Mechanics*, 36:281–314, 2004.