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3D numerical simulations of dense water cascading in an idealised laboratory setting

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The sinking of dense waters flowing from shelf seas down the continental slope “cascading” contributes to ocean ventilation and water mass formation (notably in the Antarctic) and hence ocean circulation. It is also deemed to affect carbon cycling by providing an efficient mechanism of export of carbon-rich surface waters to a greater depth thus contributing to the “carbon pump”. Cascading occurs where dense water - formed by cooling, evaporation or ice-formation with brine rejection over the shallow continental shelf - spills over the shelf edge and descends the continental slope as a near-bottom gravity current. During its descent, the plume is modified by mixing and entrainment, and detaches off the slope when reaching its neutral buoyancy level.

Cascading over steep bottom topography is studied here in numerical experiments using POLCOMS, a 3D ocean circulation model which utilizes a terrain-following s-coordinate system (Wobus et al, 2011). The model setup is based on a previously conducted (Shapiro and Zatsepin, 1997) laboratory experiment of a continuous dense water flow from a central source on a conical slope in a rotating tank. The governing parameters of the experiments are the density difference between plume and ambient water, the flow rate, the speed of rotation and (in the model) diffusivity and viscosity. The descent of the dense flow as characterised by the length of the plume as a function of time is studied for a range of physical and model parameters.

Very good agreement between the model and the laboratory results is shown in dimensional and non-dimensional variables. It is confirmed that a hydrostatic model is capable of reproducing the essential physics of cascading on a very steep slope if the model correctly resolves velocity veering in the bottom boundary layer. Experiments changing the height of the bottom Ekman layer (by changing viscosity) and modifying the plume from a 2-layer system to a stratified regime (by enhancing diapycnal diffusion) confirm previous theories, demonstrate their limitations and offer new insights into the dynamics of cascading outside of the controlled laboratory conditions.

Our results show that the correct resolution of bottom boundary layer physics is critical to successfully model cascading, while non-hydrostaticity is not required to capture the descending plume. The traditional square drag law fails to capture the Ekman veering at the bottom boundary and is shown to insufficiently represent bottom friction, while our model with a no-slip bottom boundary condition and increased vertical resolution near the bottom was successfully validated against laboratory experiments. The required resolution to fully resolve the BBL is currently impractical for large ocean and climate models, and we therefore call for the development of an improved parameterization for bottom friction, which includes the Coriolis force and thus captures velocity veering.

References

Shapiro, G.I. and A. G. Zatsepin. 1997. Gravity current down a steeply inclined slope in a rotating fluid. Ann. Geophys., 15(3), 366–374.

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