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Interaction of a round turbulent jet with a thermocline

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Vertical turbulent jets serve as the models of numerous flows both in nature and industry including convective cloud flows in the atmosphere, effluents from submerged wastewater outfall systems in the ocean, pollutant discharge from industrial chimneys, subglacial discharge. We investigate the dynamics of an axisymmetric vertical turbulent jet in a stratified fluid with two layers of different temperature separated by a thermocline. This configuration is a typical model of the upper thermocline layer of lakes and pycnocline in oceans as well as thermal inversions in the atmosphere.
In general, turbulent jets in nature and industry originate from the mixed sources of buoyancy and momentum. However, when the source is located far enough from the pycnocline, the jet mixes effectively with the surrounding fluid and the density of the flow at the pycnocline entrance tends to the density of the lower layer of stratification. Dynamics of such a flow in the pycnocline can be modelled employing a neutrally buoyant turbulent jet with the positive vertical momentum.
We study the behaviour of a vertical round turbulent jet in an unconfined stratified environment by means of well-resolved large eddy simulation. We consider two cases: when the thermocline width is small and of the same order with the jet diameter at the thermocline entrance. Mean jet penetration, stratified turbulent entrainment and jet oscillations as well as the generation of internal waves are quantified.
The mean jet penetration is predicted well by a simple model based on the conservation of the jet volume, momentum and buoyancy fluxes. The entrainment coefficient for the thin thermocline is consistent with the theoretical model for a two-layer stratification with a sharp interface, while for the thick thermocline entrainment is larger at low Froude numbers. For the thick thermocline we demonstrate the presence of a secondary horizontal flow in the upper thermocline, resulting in the entrainment of fluid from the thermocline rather than from the upper stratification layer.
The spectra of the jet oscillations in the thermocline display two peaks, at the same frequency for both stratifications at fixed Froude number. For the thick thermocline, internal waves are generated only at the lower frequency. For the thin thermocline, conversely, the spectra of the internal waves show the two peaks at low Froude numbers, whereas only one peak is observed at higher Froude numbers, associated with the lower frequency of the jet oscillations. The results for the thick thermocline are consistent with available experimental data.