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Drag generation by interfacial waves at an inversion/thermocline in non-hydrostatic flow past an axisymmetric obstacle

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The drag associated with 3D trapped lee waves generated at a density interface by an axisymmetric obstacle is evaluated using a linear non-hydrostatic model. These waves propagate at temperature inversions capping the boundary layer in the atmosphere, or at the oceanic thermocline, generated by, for example, drifting ice keels. They are responsible for near-surface drag that may be misrepresented as turbulent form drag in numerical models. This drag receives contributions from a continuous wavenumber range forced by the obstacle, in contrast with 2D flow (where only discrete wave modes exist), as the waves are able to vary their angle of incidence with respect to the incoming flow to satisfy their dispersion relationship. Hence (and again in contrast with 2D linear flow), the drag is non-zero both for subcritical and supercritical flow, and attains a maximum for a value of the Froude number slightly smaller than 1. This drag maximum has lower magnitude than in the hydrostatic limit, due to the effect of wave dispersion. The drag calculated from the model is in good agreement with that obtained from experiments carried out in a laboratory water flume that use axisymmetric obstacles of different heights, especially for the lowest obstacle (as would be expected). The best agreement is achieved when the effects of both a rigid lid bounding the fluid layer further away from the obstacle, and friction (represented as a Rayleigh damping), are taken into account. The model is not as quantitatively accurate when the highest obstacle used in the experiments is considered, as this corresponds to stronger flow nonlinearity. But, even in that case, the model has a qualitatively correct behaviour, which is much more accurate than the 3D hydrostatic or 2D non-hydrostatic limits. This suggests that 3D and non-hydrostatic effects to a large extent determine the drag behaviour observed in the experiments. The wave signatures associated with this behaviour are dominated by transverse waves for relatively low Froude numbers, a dispersive 'Kelvin ship wake' for nearly critical Froude numbers, and divergent waves for high Froude numbers. The interface displacement existing directly over/beneath the lee of the obstacle has a minimum height/depth that is significantly correlated with the value of the drag. This is not surprising, given that this asymmetric displacement is associated with a lee-side pressure deficit that is ultimately responsible for the drag force in this flow configuration.