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Critical level effects on the mountain wave drag exerted by a piecewise-linear wind profile at low Ri

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This study investigates the asymmetric behaviour of the surface drag with respect to the sign of the shear when a non-rotating, hydrostatic, stratified atmosphere flows over mesoscale mountains. The theoretical model developed employs the simplest possible realistic flow with shear, including the possibility of critical levels and directional shear. The wind profile is assumed to vary linearly up to a certain height and to become constant above. In a non-hydrostatic framework, the asymmetry between flows with forward and backward shear is well known, and readily understood. However, calculations using linear theory in hydrostatic conditions for a wind profile with constant shear extending indefinitely in the vertical predict that the drag variation with the Richardson number (Ri) does not depend on the sign of the shear. For the case of a finite shear layer, which reproduces much more closely the setup of numerical simulations, this result is found not to hold for two reasons. Firstly, the gravity waves that are generated by mountains are reflected at the shear discontinuity above which the wind velocity becomes constant. Secondly, if the wind profile has critical levels, filtering of the waves as they pass through these levels before they are reflected by the shear discontinuity alters the drag behaviour. For forward unidirectional shear, there are no critical levels and the drag has an oscillating behaviour with Ri (due to reflection at the shear discontinuity), attaining values higher than predicted for a shear extending indefinitely. For backward unidirectional shear, all wavenumbers are filtered by the critical level, and the drag behaviour is relatively close to that predicted for an infinite shear layer. On the other hand, for flows with directional shear, a fraction of the wavenumbers of the internal wave spectrum are filtered by their critical levels, while another fraction is not, leading to intermediate behaviour. Nonlinear effects, particularly when conjugated with shear, are found to considerably amplify the drag.