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Trapped lee waves in layered atmospheres: an important source of low-level drag?

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Typically, orographic drag parameterization schemes consist of two components: one associated with vertically propagating internal gravity waves, which is generally based on hydrostatic, inviscid, mountain wave theory, and the other accounting for low-level flow blocking below the mountain summit level. This latter drag component, which, despite also relying on stable stratification, is not associated with wave propagation, is generally represented through a simple drag coefficient approach. In addition to this, and also acting at low levels, there is a turbulent form drag, active even in neutrally stratified flow over orography, which is included in turbulence parameterization schemes. However, drag parameterizations generally do not account for non-hydrostatic waves, in particular trapped lee waves. The momentum flux associated with these waves propagates (and dissipates) horizontally downstream of the mountains that generate them, and might well give a substantial contribution to the low level drag.

Although generic mathematical expressions for trapped lee wave drag have been obtained by Bretherton (for a rigid-lid atmosphere), and later by Smith for an unbounded atmosphere, these expressions are practically awkward to implement, and give no clear indication of the dependence of this drag on the basic flow parameters. In the present study, the drag produced by lee waves trapped within a layer near the surface (case 1, following Scorer), or at a temperature inversion (case 2, following Vosper), are calculated explicitly, either for an atmosphere with higher static stability near the surface and lower static stability aloft (in case 1), or for an atmosphere that is neutrally stratified near the surface, has an inversion capping the neutral layer, and is stably stratified above (in case 2). In both flow configurations, the drag can be split into a component associated with waves that propagate upward in the upper layer - called propagating wave drag - and a component associated with waves trapped in the lower layer (in case 1) or at the inversion (in case 2) - called trapped lee wave drag.

The propagating wave drag and the trapped lee wave drag normalized by the hydrostatic drag produced by a single-layer atmosphere depend on three parameters: in case 1, these are the dimensionless height of the interface separating the two layers, the ratio between the Scorer parameters in the two layers, and the dimensionless width of the orography, which controls the importance of non-hydrostatic effects. In case 2, the Scorer parameter ratio is replaced by the Froude number of the flow at the inversion. For the two cases, the trapped lee wave drag and the propagating wave drag are found to be of comparable magnitude, especially for intermediate values of the dimensionless mountain width, and under certain circumstances the former even exceeds the latter, being several times larger than the hydrostatic reference drag. This highlights the potential importance of including a representation of trapped lee wave drag in parameterization schemes, where its absence may currently be compensated by an overestimation of the blocking or turbulent form drag components.