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A linear analysis of resonant gravity wave drag enhancement and flow stagnation

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In the globally integrated drag force exerted by the Earth's mountains on the atmosphere, due to the generation of stationary internal gravity waves, high-drag states, where the gravity wave drag is amplified by up to one order of magnitude relative to leading order estimates, are of obvious importance. It is generally accepted that these situations are in essence nonlinear, and two influential theories exist to explain them. In one of them, drag amplification is attributed to the reflection of waves at critical levels, either environmental or self-induced. In the other, which seems to be more strongly supported by numerical simulations, the drag amplification results from hydraulic behaviour of the atmospheric flow. While strongly nonlinear flow regimes are not treatable analytically, purely linear processes occurring in mountain waves may give clues as to what triggers the behaviour observed in high drag states. For that reason, a linear model of high drag states is developed in this study, considering a unidirectional wind profile that is constant near the surface, but above a certain level decreases linearly, reaching a critical level. It is shown that, in the linear regime, the drag oscillates due to wave resonance in the lower layer, as the waves are reflected partially at the level where the shear has a discontinuity. Drag maxima are attained when there is constructive interference of the upward and downward propagating waves, and drag minima occur when there is destructive interference. The amplitude of the drag modulation increases as the Richardson number (Ri) in the shear layer decreases. At drag maxima, for Ri below 2.25, the locations where linear theory predicts flow overturning to occur first differ from those predicted for a constant wind, being displaced both laterally and vertically by an amount that increases as Ri decreases. For mountains of larger amplitude (where linear theory is no longer valid), numerical simulations show that the drag maxima and minima become more pronounced, slightly

shift their locations, and the critical level height appears to become more important than the height where the shear is discontinuous. The flow also becomes much less sensitive to the environmental Richardson number. Because of horizontal dispersion, large amplitude 2D and 3D waves lead to different resonance patterns, a fact that was already known from numerical simulations. While large amplitude 2D waves resonate with shear discontinuities vertically separated by one wavelength, that separation in 3D waves remains at half-wavelength, as in linear theory.