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Rossby-gravity wave drag produced by large-scale mountain ranges in a continuously stratified atmosphere

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Mountains and mountain ranges of various scales are known to generate waves in the atmosphere. An important fraction of these are internal gravity waves, which must be parameterized in weather and climate models. As one goes toward the largest scales, internal waves tend to become evanescent due to the effect of the Earth's rotation. However, at larger scales still, the variation of the Coriolis parameter with latitude (beta effect) supports again vertical propagation. Internal waves at such planetary scales are explicitly represented in atmospheric models, so they do not need to be parameterized. Nevertheless, the physical processes determining the associated drag force deserve detailed study. Most previous studies have focused on the drag produced by barotropic Rossby waves, where the atmosphere is represented as not continuously stratified, but rather uniform, and topped by a rigid lid or a sharp density interface. In this case, the drag in the quasi-geostrophic approximation can be determined analytically, and originates only from the wavenumber of free barotropic Rossby waves compatible with the speed of the incoming wind. In this study, we determine the drag produced by vertically propagating Rossby-gravity waves in the hydrostatic approximation, for an atmosphere with constant wind and static stability, in a beta-plane geometry. In that case, contributions to the drag come from a continuous range of wavenumbers. As for barotropic Rossby wave drag, there is considerable drag enhancement at low Rossby number, or equivalently for wide mountain ranges, with the drag values exceeding substantially the non-rotating, hydrostatic internal wave limit. For typical values of the flow parameters in mid-latitudes, the barotropic and the internal Rossby wave drags are found to be comparable in magnitude. However, their dependencies on the flow parameters controlling this problem are different. While both the model proposed here and the barotropic Rossby wave model are crude approximations to the real atmosphere, they provide complementary approaches to address Rossby wave drag, which may contribute to clarify the range of behaviour of this force.