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The Impact of Surface Friction on Boundary Layer Separation for Different Mountain Flow Regimes: An Analysis Based on Large-Eddy-Simulations

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Boundary layer separation (BLS) may occur when a strong external adverse pressure gradient force is imposed on the boundary layer flow, leading to detachment of streamlines from the surface due to a strong deceleration of the flow within the boundary layer. This process commonly occurs at the salient edge of very sharp obstacles. In stably stratified flows pressure perturbations strong enough to cause BLS can also be induced by internal gravity waves. A well-known phenomenon related to wave-induced BLS is that of atmospheric rotors that form on the lee side of mountain ranges. Rotors are boundary-layer zones characterized by strong turbulence, surface wind reversals, large values of spanwise vorticity and neutral stability. Due to the high intensity of turbulence, atmospheric rotors are known to pose a hazard for general aviation and road traffic and can significantly impact the energy yield of wind parks in mountainous terrain. Hence, the onset of BLS and formation of rotors have been extensively investigated in recent years. However, only a few systematic studies of the processes involved in the formation of rotors are available in the literature.

In this study, the CM1 model is used to explore the impact of different mountain flow regimes (from hydrostatic to non-hydrostatic and from weakly to strongly non-linear) and the surface exchange coefficient for momentum on the size and strength of rotors. In addition to that, a feedback mechanism of BLS onto the larger-scale flow is investigated. The results show that the governing flow regime has a strong impact on the strength and size of atmospheric rotors, whereas friction mainly influences the rotor interior structure. The most intense rotors, as measured by the strength of surface reversed flow, are found to occur in strongly non-linear and non-hydrostatic flows. The largest rotors instead do not necessarily occur in the strongest non-linear flow regime, in which the largest amplitudes of mountain waves are to be expected; rather we find those in moderately non-linear flows. A possible explanation for that is that for flows in the strongest non-linear regime, the BLS is associated with low-level mountain-wave breaking which leads to the formation of a lee wave train underneath a self-induced critical level and an attendant train of smaller rotors underneath the lee wave crests. It appears also that the trapped flow over this train of rotors excites an upward propagating gravity wave (similar to a terrain generated internal gravity wave) which partially passes through the critical level and changes the structure of the larger-scale flow above. The sensitivity tests for the strength of surface friction show that with increasing surface drag the rotor interior structure changes from a single coherent horizontal vortex to a more complex interior filled with sub-vortices that impact the overall shape of the rotor.