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Essential features of entrainment in the sheared atmospheric convective boundary layer as represented by first- and zero-order bulk models

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The first-order model (FOM) of the atmospheric convective boundary layer (CBL) represents the CBL as a two-layer fluid system: a mixed layer with height-constant buoyancy and momentum capped by an interfacial entrainment layer with buoyancy and momentum profiles that are linear functions of height. If the finiteness of the interfacial layer is an essential feature of the sheared CBL structure, one could expect the FOM to better predict the sheared CBL entrainment than the zero-order CBL bulk model (ZOM), in which the interfacial layer is reduced to a discontinuity interface. Integration of the FOM momentum and buoyancy balance equations over the interfacial layer yields profiles of the corresponding fluxes that are quadratic functions of height. However, quadratic terms are usually neglected in the bulk FOM energy, momentum, and buoyancy balance equations. The effect of these simplifications on the ability of the FOM to predict the entrainment rate in sheared CBLs has never been examined. In the present study, a set of complete FOM equations was derived and applied to describe the CBL evolution. The FOM predictions were compared with large eddy simulation (LES) results for entrainment in 24 CBL cases of varying shear, surface buoyancy flux, and outer stratification. The FOM predictions were found to agree reasonably well with LES results once the scaling for the dissipation of entrainment zone shear was appropriately specified. Generally, the FOM-based equations predicted simulated entrainment more accurately than their ZOM-based counterparts, but the results appear to be at least as sensitive to the dissipation scaling as to the order of the model. None of the terms in the complete FOM equations were found to be negligible in all cases, suggesting that the nonsimplified versions of the bulk equations should be used.