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# Modelling Scalar Skewness in Cloudy Boundary Layers

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Following the pioneering work of Sommeria and Deardorff (1977), statistical cloud schemes are widely used in numerical weather prediction (NWP) and climate models to parameterize the effect of shallow clouds on turbulent mixing and radiation fluxes. Statistical cloud schemes compute the cloud fraction, the amount of cloud condensate and the effect clouds on the buoyancy flux in a given atmospheric-model grid box. This is done with due regard for the sub-grid scale (SGS) fluctuations of temperature and humidity (and possibly the vertical velocity), thus providing an important coupling between cloudiness and the SGS mixing processes. The shape of the PDF of fluctuating fields is assumed, whereas the PDF moments should be provided to the cloud scheme as an input. For non-precipitation clouds, the mixing schemes are usually formulated in terms of quasi-conservative variable, e.g. the liquid (total) water potential temperature and the total water specific humidity. Then, the cloud schemes are conveniently cast in terms of the linearized saturation deficit, referred to as the "s" variable (Mellor 1977), that accounts for the combined effect of the two scalars. If a simple two-parameter single-Gaussian PDF is used, the only "turbulence" parameter to be provided to the cloud scheme is the variance of s. The single-Gaussian PDF ignores the skewed nature of SGS motions and fails to describe many important regimes, e.g. shallow cumuli. A number of more flexible skewed PDFs have been proposed to date. A three-parameter PDF, based on a double-Gaussian distribution and diagnostic relations between some PDF parameters derived from LES and observational data (Naumann et al. 2013), appears to be a good compromise between physical realism and computational economy. A crucial point is that the cloud schemes using non-Gaussian PDFs require the scalar skewness as an input.

Using rather mild non-restrictive assumptions, we develop a transport equation for the s-variable triple correlation. That equation contains three terms that require closure. A simple relaxation approximation in terms of the turbulence time (length) scale is used for the dissipation term. The third-order and the fourth-order scalar-velocity correlations are parameterized using an advanced advection-diffusion formulation and a generalized Millionschikov hypothesis (Mironov et al. 1999, Gryanik et al. 2005). These formulations satisfy both the Gaussian limit and, importantly, the limit of strong skewness. The equation for the s triple correlation is coupled to the turbulence kinetic energy (TKE) - scalar variance mixing scheme (Machulskaya and Mironov 2013), where not only the TKE but also the scalar variances and covariance are computed from the prognostic transport equations with due regard for the third-order transport. The coupled scheme is tested through single-column numerical experiments. Results compare favourably with large-eddy simulation data from well-documented shallow cloud cases. Some details of the implementation of the s-skewness formulation into NWP models are discussed.