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Stochastic modeling of transient surface scalar and momentum fluxes in turbulent boundary layers

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Turbulence is ubiquitous in atmospheric boundary layers and manifests itself by transient transport processes on a range of scales. This range easily reaches down to less than a meter, which is smaller than the typical height of the first grid cell layer adjacent to the surface in numerical models for weather and climate prediction. In these models, the bulk-surface coupling plays an important role for the evolution of the atmosphere but it is not feasible to fully resolve it in applications. Hence, the overall quality of numerical weather and climate predictions crucially depends on the modeling of subfilter-scale transport processes near the surface. A standing challenge in this regard is the robust but efficient representation of transient and non-Fickian transport such as counter-gradient fluxes that arise from stratification and rotation effects.

We address the issues mentioned above by utilizing a stochastic one-dimensional turbulence (ODT) model. For turbulent boundary layers, ODT aims to resolve the wall-normal transport processes on all relevant scales but only along a single one-dimensional domain (column) that is aligned with the vertical. Molecular diffusion and unbalanced Coriolis forces are directly resolved, whereas effects of turbulent advection and stratification are modeled by stochastically sampled sequence of mapping (eddy) events. Each of these events instantaneously modifies the flow profiles by a permutation of fluid parcels across a selected size interval. The model is of lower order but obeys fundamental conservation principles and Richardson's 1/4 law by construction.

In this study, ODT is applied as stand-alone tool in order to investigate nondimensional control parameter dependencies of the scalar and momentum transport in turbulent channel, neutral, and stably-stratified Ekman flows up to (friction) Reynolds number $Re = O(10^4)$. We demonstrate that ODT is able to capture the state-space statistics of transient surface fluxes as well as the boundary-layer structure and nondimensional control parameter dependencies of low-order flow statistics.
Very good to reasonable agreement with available reference data is obtained for various observables using fixed model set-ups. We conclude that ODT is an economical turbulence model that is able to not only capture but also predict the wall-normal transport and surface fluxes in multiphysics turbulent boundary layers.