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Direct Numerical Simulation of a Dry Shear-free Convective Boundary Layer

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Due to the thinness of the inversion layer, entrainment in the Convective Boundary Layer (CBL) is not explicitly resolved in models and is still a major source of uncertainty. Recent work using Large Eddy Simulations (LES) shows lack of convergence in the inversion layer with further grid refinement, even for a vertical resolution of 2 meters. Observational studies of entrainment in the CBL are even more problematic, whether they be field observations or their low Reynolds number analogs in the laboratory, since fine measurements of the three-dimensional flow field at the inversion layer are practically unattainable. As an alternative, we use Direct Numerical Simulations (DNS), which resolves the three-dimensional flow field down to the scale of molecular diffusion. Faithful representation of the whole range of turbulent scales would mean that attainable Reynolds numbers are orders of magnitude lower than that in the atmosphere because of limited computational resources. However, the significant increase in computing power now allows for simulations that are comparable in size to tank experiments. Furthermore, we can invoke Reynolds number similarity to justify the use of DNS to study an idealized convective boundary layer. As a first step, we consider here the dry, shear-free case with constant surface buoyancy flux B_0 working against a stable background stratification with constant buoyancy frequency N. Fixing the Prandlt number $Pr = \nu/\kappa$ to 1, where ν is the molecular kinematic viscosity and κ is the molecular diffusivity, the problem is characterized by a single non-dimensional parameter $(B_0/\kappa)/N^2$ which can be interpreted as the ratio between a reference well-mixed layer height and the diffusive layer thickness. In the atmosphere, $(B_0/\kappa)/N^2$ is at least $O(10^6)$, while for our first simulation, $(B_0/\kappa)/N^2 \sim 40$. We have done one simulation with a 1024x1024x541 grid that uses vertical grid stretching, and another that is twice as wide (2048x2048x541) for assessing statistical convergence and the effect of the computational domain size. Even with vertical grid stretching, the grid spacing is smaller than the Kolmogorov length scale. Despite the low Reynolds number, we obtain qualitatively comparable vertical structure as in LES and observations. Relative values $\langle w'w' \rangle_{max} / w_*^2 \sim 0.35 - 0.48$, $\langle b'w' \rangle_{max} / B_0 \sim 0.8 - 0.9$, and $TKE_{max}/w_*^2 \sim 0.3 - 0.38$ are within the range found in literature. The entrainment ratio $A = - \langle b'w' \rangle_{min} / B_0$ fluctuates in time but has an increasing trend from 0.08 to 0.12, smaller than the canonical value ($A = 0.2$) but close to the result from fine-resolution LES ($A \sim 0.14$). We explored different definitions of the mean inversion height z_i and chose the vertical location of the buoyancy fluctuation peak at the inversion ($\max(b_{rms})$) because it proved to be more robust. As a function of time, z_i is approximated well by a $\sqrt{t}$ curve within 10%. The corresponding Richardson number $Ri_{b_{rms}} = (\max(b_{rms}) z_i)/w_*^2$ approaches $Ri_{b_{rms}} \sim O(1)$ and is slightly increasing in time. To check for low Reynolds number effects, we do a simulation that is twice as high (2048x2048x1024), therefore increasing $(B_0/\kappa)/N^2$ to approximately 100 and the physical domain to approximately a 2-meter box. After establishing DNS as a feasible tool for studying the dry shear-free CBL, we will then use DNS data to investigate the physics of entrainment.