EXAMINATION OF NEUTRALLY STRATIFIED ATMOSPHERIC BOUNDARY LAYERS WITH THE HELP OF LARGE EDDY SIMULATION

Igor N. Esau[1]
Uppsala University, Uppsala, Sweden

Intoduction

The discussion about basic properties of LES-fluids with formally infinite Reynolds number (Re) was initiated more than 15 years ago (Mason & Callen, 1986). Nevertheless, a great majority of LES publications do not investigate possible breaks of similarity between simulated and physical flows. Instead, authors usually claim that "large-eddy simulation of an atmospheric (oceanic) boundary layer is performed ...". Having said that, they tried to explain obvious discrepancy between their LES and measured data by distinct features of their LES codes or conditions of numerical experiments.

Another strategy is followed in this paper. We do not suggest from the very beginning that the simulated flow is a computed analog of the real atmospheric flow. To the contrary, we try to look for a real flow which is resemble the simulated one.

Re-effects in LES-fluids

A low "effective" Reynolds number of LES-fluids can limit the similarity between simulated and physical high Re flows. After Muschinski (1996), *a posteriori* estimation of the "effective" viscosity reads $\nu_{LES} = l_s^{4/3}\varepsilon^{1/3}$. It is based on the shortest relevant length scale, l_s, and the actual dissipation rate, ε, in the model. Thus, the "effective" Re became $\mathrm{Re}_{LES} = |u^g|h/\nu_{LES}$. A set of LES runs with different resolutions discloses a strong dependence of turbulent statistics on Re_{LES}. This dependence is stronger in quantities involving the vertical velocity fluctuations. The simulated flow must have $\mathrm{Re}_{LES} > 20000 - 40000$ to posses turbulent properties similar to turbulent properties of physical high Re fluids. Typical Re_{LES} of modern LES are below 50000. This is less than it is expected from the atmospheric LES.

MIUU LES model

It has to be attributed not only to a coarse resolution of numerical experiments but to numerical schemes and subfilter models as well. The MIUU LES code involves a dynamic mixed subfilter model (Vreman et al, 1994). The model admits (i) energy backscatter, (ii) real values of normal components of the subfilter stress and (iii) a self-consistent estimation of the dissipative length, l_s. These features result in increasing of the perturbation energy on the smallest resolved scales. Consequently, the MIUU LES provides significantly larger Re_{LES} than LES with the Smagorinsky subfilter model calculated on the same mesh.

The MIUU LES model solves numerically the incompressible Navier-Stokes equations for the Boussinesq fluid. Comparisons showed the ability of the model to reproduce turbulent statistics and coherent structures with good accuracy.

Examination of atmospheric NBLs

Knowledge about the MIUU LES advantages and drawbacks allows to reconsider turbulent statistics of the atmospheric neutrally stratified boundary layers. The non-dimensional gradient of the mean velocity was practically equal to unity in all runs. Thus, there is no need for further improvements of the mean velocity profile. The A_0 and B_0 constants of the resistance low are well within the measured range of their natural variations. The second order statistics are in excellent agreement with the NBL data (Figure 1). However, the third order statistics are much smaller in LES than in the atmospheric NBLs. It seems that this discrepancy is due to residual convection in the atmospheric NBLs used for the comparison.

Surface roughness seems to be improperly parameterized in the high Re LES. The absence of individual roughness elements leads to underestimation of the pressure and vertical velocity fluctuations in LES. This reasoning helps to explain better agreement between LES and measurements over a smooth surface than over a rough surface.

The MIUU LES confirmed existence of powerful coherent structures at least in moderate Re boundary layers. In all runs, 33%-37% of the TKE were attributed to the first characteristic eddy shown in figure 2. At the same time, the classical picture of the roll vortices (Lilly, 1966) was not confirmed. It seems that the horseshoe vortices (Robinson, 1991) overcome the roll vortices in neutral BLs. The inflection point instability of the atmospheric NBLs can

[1]Corresponding author address: Igor N. Esau Dept. of Earth Sciences, Uppsala University, Villavägen 16, S-75236, Uppsala, Sweden
e-mail: igoresau@met.uu.se

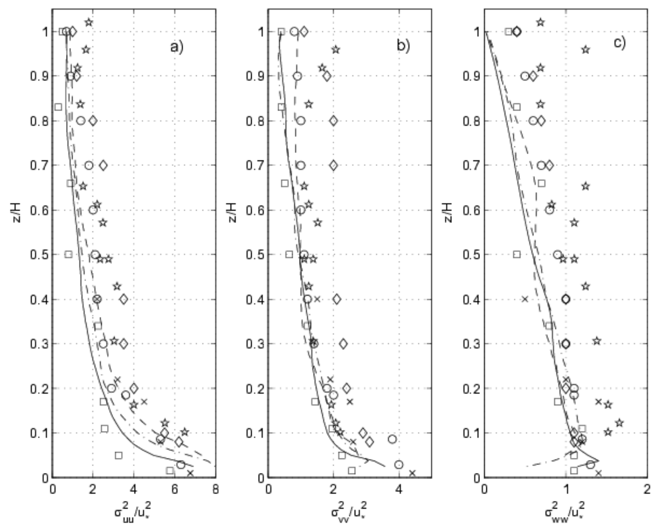

Figure 1: Normalized variances, σ^2_{uu}/u^2_* (a), σ^2_{vv}/u^2_* (b), σ^2_{ww}/u^2_* (c), of velocity components plotted agaist normalized height z/H. Symbols state for atmospheric measurements. The solid line represents a high resolution (80^3 grid points) run, the dashed line represents a low resolution (40^3 grid points) run.

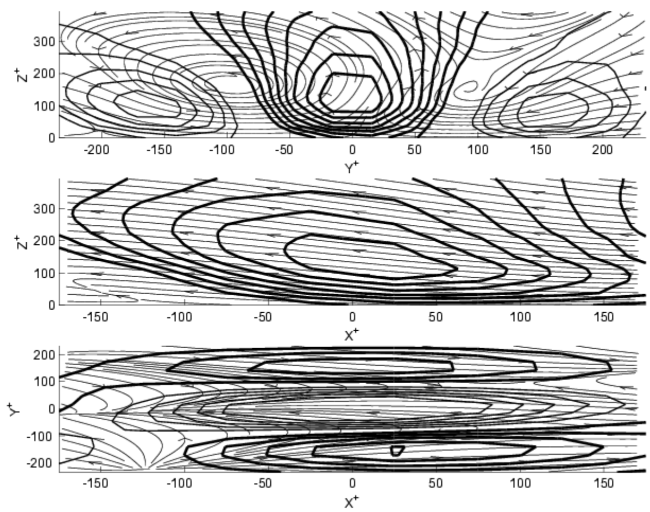

Figure 2: The first characteristic eddy in simulated atmospheric NBL. Projections on spanwise YZ plain at $X^+ = 0$ (top panel), streamwise XZ plain at $Y^+ = 0$ (middle panel) and horizontal XY plain at $Z^+ = 20$ (bottom panel). The secondary flow is presented. Bold contours show positive and thin contours show negative values of u (top and middle panel) and w (bottom panels). The coordinates are measured in "effective" wall units, e.g. $X^+ = x\nu_{LES}/u_*$.

be resolved through turning of the horseshoe vortices. The turning angle about 18° was in good agreement with analytical predictions for the roll vortices.

Conclusions

Summing up, the atmospheric neutrally stratified boundary layers can be simulated by means of finite-difference LES codes with the dynamic mixed subfilter models. The spatial resolution of $150 \times 150 \times 100$ meters is sufficient to receive accurate profiles of the mean wind and the second order statistics. The spatial resolution finer than $50 \times 50 \times 30$ meters is desirable to receive accurate higher order statistics and spectra. It is necessary to include an explicit representation of roughness elements to reproduce relevant pressure fluctuations in LES.

References

Lilly, D. K. 1966: On the instability of Ekman boundary layer, *J. Atmos. Sci.*, **2**, 481-494

Mason, P. J., Callen, N. S. 1986: On the magnitude on the subgrid scale eddy coefficient in large-eddy simulations of turbulent channel flow, *J. Fluid Mech.*, **162**, 439-462

Muschinski, A., 1996: A similarity theory of locally homogeneous and isotropic turbulence generated by a Smagorinsky-type LES, *J. Fluid Mech.*, **325**, 239-260

Robinson, S.K. 1991 Coherent motions in the turbulent boundary layer, *Annu. Rev. Fluid Mech.*, **23**, 601-639

Vreman, B, Geurts, B., Kuerten, H. 1994: On the formulation of the dynamic mixed subgrid-scale model, *Phys. Fluids*, **6**(12), 4057-4059