15.7 LES OF THE ATMOSPHERIC BOUNDARY LAYER OVER HETEROGENEOUS SURFACES USING A DYNAMIC LAGRANGIAN SGS MODEL

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1. INTRODUCTION

Similarity theory is the main practical tool used in hydrology and atmospheric sciences to obtain average fluxes over a wide range of spatial scales. One of the premises of the theory is that surface conditions are homogeneous. Nevertheless, the theory was found to be applicable over heterogeneous surfaces; this can be attributed to the blending effects of atmospheric turbulence. Similarity theory was found to yield good estimates of average values but fails to accurately predict variances and higher order moments. In addition, some field experiments suggest that similarity theory might not even yield a good approximation of average parameters in areas with large distinct and abrupt changes in land use (Parlange and Brutsaert, 1993) and in chessboard-like terrain (Asanuma and Brutsaert, 1999). Despite the wide use of the theory several question are yet to be addressed. Some of these questions include: How are internal boundary layers formed over patches blended? What is the effect of surface heterogeneity on ABL dynamics and land-atmosphere interactions? When does the similarity theory fail? How can variances and higher moments be obtained?

2. THE LAGRANGIAN DYNAMIC SGS MODEL

To answer these questions, Large Eddy Simulation (LES) of the Atmospheric Boundary Layer (ABL) will be performed. The usefulness of LES in atmospheric applications has significantly increased in the past decade due to the increase in computing power and the improvement in LES models. A major improvement in LES techniques has been the introduction of the dynamic Sub-Grid Scale (SGS) model (Germano *et al.,* 1991). Traditionally, the filtered turbulence equations used in LES are closed using a viscous model of the sub-grid scale stresses. This model requires a parameter, the Smagorinsky coefficient, that has to be prescribed in a rather ad-hoc fashion. The dynamic model uses the same closure scheme but computes the Smagorinsky coefficient from the turbulence in the resolved scales. The dynamic model as proposed by Germano continued to have some practical and theoretical deficiencies, such as: the need for homogeneous directions in the flow field (the coefficient is averaged over these directions to reduce the strong oscillations that might lead to numerical instabilities), the inability to handle complex geometries, and the assumption of scale-invariance.

The use of this model in the current application is not possible since averaging over the horizontal planes neglects a major aspect of the problem, namely surface heterogeneity. Instead, the so-called Lagrangian dynamic SGS model (Meneveau *et al.*, 1996) is well suited for strongly heterogeneous conditions. The approach is based on the dynamic model but averages are obtained over fluid pathlines rather than horizontal planes. The model is very suited for the current application since it preserves local variability, preserves Galilean invariance, and does not require homogeneous directions. Using first order interpolation in space and time and assuming the model has an exponential relaxation function, the computation of the Smagorinsky coefficient is reduced to the solution of the two relaxation-transport equations shown below.

$$\mathcal{I}_{LM}^{n+1}(\boldsymbol{x}) = \mathrm{H}\left\{\varepsilon\ [\mathrm{L}_{ij}\mathrm{M}_{ij}]^{n+1}(\boldsymbol{x}) + (1-\varepsilon)\mathcal{I}_{LM}^{n}(\boldsymbol{x}-\overline{\boldsymbol{u}}^{n}\Delta t)\right\}$$

$$\mathcal{I}_{MM}^{n+1}(\boldsymbol{x}) = \varepsilon\,[\mathrm{M}_{ij}\mathrm{M}_{ij}]^{n+1}(\boldsymbol{x}) + (1-\varepsilon)\mathcal{I}_{MM}^{n}(\boldsymbol{x}-\overline{\boldsymbol{u}}^{n}\Delta t)$$

where: $\varepsilon = \dfrac{\Delta t / \mathrm{T}^n}{1+\Delta t/\mathrm{T}^n}$

$\mathrm{T}^{\mathrm{n}} = 1.5\Delta(\mathcal{I}_{LM}^{n}\mathcal{I}_{MM}^{n})^{-1/8}$

$L_{ij} = \widehat{u_i u_j} - \hat{u}_i \hat{u}_j$

$M_{ij} = 2\Delta^2\left[\widehat{|\overline{S}|\overline{S}_{ij}} - 4|\hat{\overline{S}}|\hat{\overline{S}}_{ij}\right]$

S_{ij} = Strain rate tensor

$\boldsymbol{x}-\overline{\boldsymbol{u}}^{n}\Delta\mathrm{t}$ = particle position at previous timestep

and H = ramp function = $\begin{cases} x & \text{if } x \geq 0 \\ 0 & \text{otherwise} \end{cases}$

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The Smagorinsky coefficient c_s is given by the ratio:

$$c_s^2(\boldsymbol{x},t) = \frac{\mathcal{I}_{LM}}{\mathcal{I}_{MM}}$$

3. RESULTS

The Lagrangian dynamic sub-grid scale parameterization has been implemented in this study. Both a scale independent and a novel scale-dependent parameterizations are tested and compared with a Smagorinsky SGS model. Previous comparative studies have shown a significant improvement associated with the use of the Lagrangian model. This study is the first to perform this comparison for atmospheric LES. Results for a neutral atmospheric boundary layer flowing over a heterogeneous surface will be presented. The effects of changes in surface roughness on turbulence structures and subgrid-scale coefficients appear to be significant (Figure.1). The computed coefficient depicts a plume-like behavior due to the transport of turbulence structures from the surface. Preliminary results suggest that the blending layer height is strongly influenced by the length of the patches and the surface conditions. Figure 1 shows that, for a patch length of 1850 meters, the blending height was about 200 m. This indicates that the similarity theory might not hold well in this region.

4. REFERENCES

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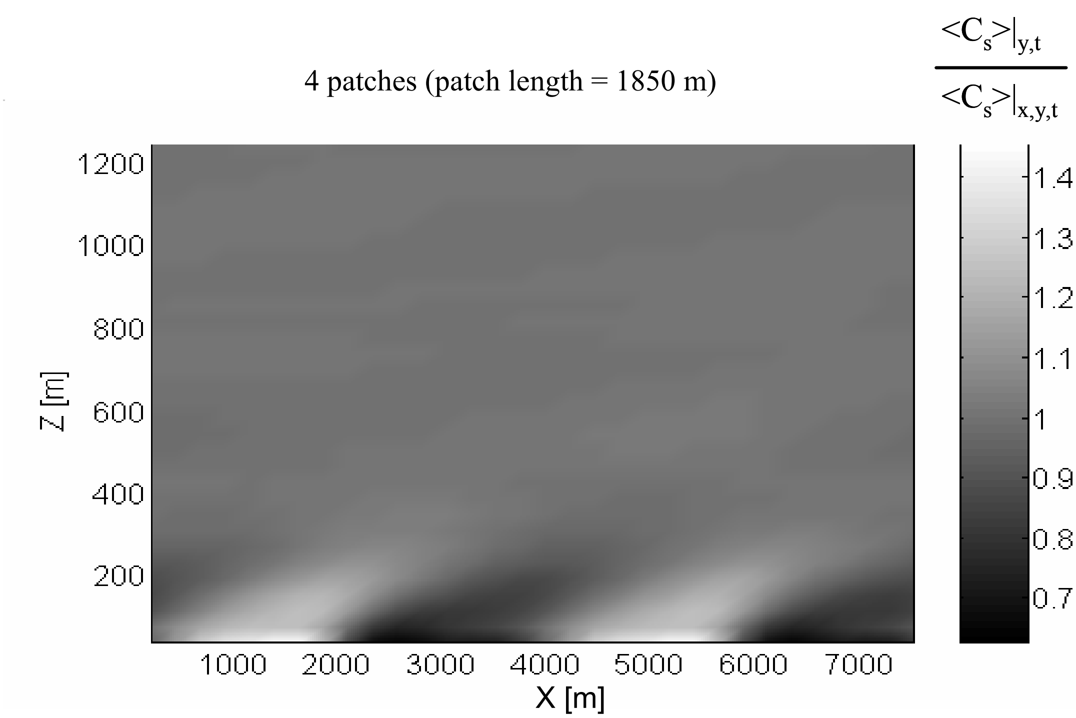

Figure 1. Smagorinsky coefficient computed by the scale-invariant Lagrangian dynamic SGS model normalized by the plane-averaged value at each height above ground