A Study of Turbulence in an Evolving Stable Atmospheric Boundary Layer Using Large-Eddy Simulation

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A STUDY OF TURBULENCE IN AN EVOLVING STABLE ATMOSPHERIC
BOUNDARY LAYER USING LARGE-EDDY SIMULATION

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ABSTRACT
A study is made of the effects of stable stratification on
the fine-scale features of the flow in an evolving stable
boundary layer (SBL). Large-eddy simulation (LES)
techniques are used so that spatially and temporally
varying and intermittent features of the turbulence can be
resolved; traditional Reynolds-averaging approaches are
not well suited to this. The LES model employs a
subgrid turbulence model that allows upscale energy
transfer (backscatter) and incorporates the effects of
buoyancy.

The afternoon, evening transition, and nighttime
periods are simulated. Highly anisotropic turbulence is
found in the developed SBL, with occasional periods of
enhanced turbulence. Energy backscatter occurs in a
fashion similar to that found in DNS, and is an important
capability in LES of the SBL. Coherent structures are
dominant in the SBL, as the damping of turbulent energy
occurs more at the smaller, less organized scales.

INTRODUCTION
The effects of stable thermal stratification on the fine-
scale features of the flow in an evolving stable
atmospheric boundary layer are examined. The
meteorological scenario begins with a developing
convective boundary layer (CBL) during the day,
followed by an evolving SBL after sunset due to surface
cooling. Large-eddy simulation techniques are used so
that spatially and temporally varying and intermittent
features of the turbulence can be resolved; traditional
Reynolds-averaging approaches are not well suited to
this. The LES model uses a dynamic, two-parameter
subgrid-scale (SGS) turbulence submodel (see Cederwall
and Street, 1997) that provides upscale (backscatter) of
turbulent energy and incorporates effects of buoyancy
through the use of a time-evolving SGS turbulent kinetic
energy (TKE) scheme. This model is an extension of the
dynamic SGS model of Zang, et al. (1993), and Salvetti

In the daytime CBL, the turbulent transport is primarily
from large, thermally-generated eddies from surface
heating. At night, however, most of the turbulence is from
small, mechanically-generated eddies from wind shear
near the ground. During the transition from day to night
when surface heating is reduced and replaced by surface
cooling, the turbulence structure in the upper part of the
CBL collapses. Compared to the too rapid collapse in
simulations using a previous SGS model (Cederwall,
1995), the new SGS submodel used here allows
backscatter and provides a more realistic simulation of the
onset and development of turbulence damping by stable
stratification. In the presence of strong stability, periods
of intermittent and enhanced turbulence are simulated.

This study addresses the turbulence structure and
energy transfer features of the SBL. Particular attention is
given to the layers near the ground where the wind shear
is strong in the presence of strong thermal stratification.

METHODOLOGY
Our LES model is based one used previously for
atmospheric studies (Wyngaard and Brost, 1984;
Nieuwstadt and Brost, 1986). The time-integration is
done by a leapfrog scheme that is 2nd-order accurate and
non-dissipative. A filter, proposed by Robert (1966) and
used further by Klemp and Wilhelmson (1978) for three-
dimensional atmospheric flows, is used to control the
computational mode. Asselin (1972) evaluated the
damping characteristics and found that the computational
modes were effectively damped with little effect on the physical modes. We have reduced the value of the damping factor from 0.1 to 0.02 to minimize further the impact on the fine-scale fields. The advection scheme is 2nd-order accurate and conserves velocity variances (Piacsek and Williams, 1970). Since there is very little numerical diffusion, we have added a fourth-order dissipation term to control non-linear instabilities.

The subgrid scale (SGS) model is a further extension of one developed by Zang, et al. (1993), and extended by Salvetti and Banerjee (1995). This SGS model is a two-parameter approach that dynamically evaluates coefficients for the eddy viscosity and modified Leonard term, and allows backscatter (upscale transfer) of energy. The SGS model has been modified for application to the PBL by replacing the Smagorinsky viscosity scheme with a time-evolving SGS turbulent kinetic energy (TKE) scheme (Deardorff, 1980) so that effects of atmospheric stability and turbulent transport of SGS TKE can be included. The model equations for shear stress are:

$$\overline{u_i u_j} - \frac{1}{3} \delta_{ij} \overline{u_i u_k} = -2C_1 \ell E^{1/2} S_{ij} + C_2 \left( L_{ij}^m - \frac{\delta}{3} L_{kk}^m \right)$$

(1)

where the length scale $\ell$ is proportional to the grid resolution, $E$ is the SGS TKE, $S_{ij}$ is the strain rate of the resolved-scale flow, and $L_{ij}^m$ is the modified Leonard term. Coefficients $C_1$ and $C_2$ are determined dynamically, based on the local character of the flow. The corresponding equations for the SGS heat fluxes are:

$$\overline{u_i \bar{\theta}} = -2C_3 \ell E^{1/2} \frac{\partial \bar{\theta}}{\partial x_k} + C_4 \left( F_{k}^{m} - \frac{\delta}{3} F_{k}^{m} \right)$$

(2)

RESULTS

Mean Quantities and Turbulence Profiles

The simulations of the afternoon CBL agree with observations and previous LES studies. The strong mixing is evident in temperature and wind speed profiles, where the vertical gradients are very small, except near the ground (see Figures 1 and 2). By the end of the simulation, a strong, surface-based temperature inversion
has developed (see Figure 1), and a strong wind shear (see Figure 2). In the CBL, the wind speed is nearly constant through the boundary layer. In contrast, a low-level jet has developed within and above the surface-based temperature inversion, as frequently observed in well-established stable boundary layers.

The profiles of velocity variance for the simulations are also typical of those observed in the CBL. The turbulence is strongest in horizontal velocity components near the ground (see Figure 3a), but more dominant in the vertical component within the middle of the boundary layer. In contrast, the velocity variance

profiles for the SBL at the end of the simulation show a much different distribution of turbulence. Most of the turbulence is close to the ground, where it is generated by wind shear. The turbulence is highly anisotropic, with most of the turbulence in the horizontal velocity components (see Figure 3b). The strong stability has damped out most of the fluctuations of vertical velocity. There is some very near the ground, and a small amount further aloft left over from the decaying CBL. The magnitude of the velocity variances in the SBL is about an order of magnitude smaller than that in the CBL; note that the horizontal axis scale in Figure 3b differs by a factor of 4 from that in Figure 3a to illustrate better the vertical distribution. In the SBL, there are large-scale patterns in the fluctuating velocity and temperature fields, that are seen also in the energy transfer. Such large-scale patterns are not seen in the CBL.

The reduction of turbulence through the boundary layer is evident in Figure 4, which shows the time history of the vertically-integrated velocity variances by component as the CBL to SBL transition occurs. The preferential reduction of turbulence in vertical velocity component is clearly illustrated as the SBL develops. The variability of turbulence in the SBL is evident, with a period of enhanced turbulence occurring at hour 10.

Energy Transfer

The transfer of energy between resolved and unresolved (subgrid) scales can be studied with the SGS model used in these simulations. The character of the energy transfer in the CBL and SBL is discussed in Cederwall and Street (1999). We found that the forward scatter dominated the backscatter terms in the CBL, leading to a relatively large net transfer from resolved to unresolved scales. In
contrast, in the SBL, the forward and backscatter terms were more balanced with a small, net transfer to unresolved scales. The vertical profiles of net transfer (dissipation) were similar to those one would obtain using an eddy viscosity approach. Here we extend that analysis to investigate the role of the different stress and heat flux components in the energy transfer in the SBL, and in particular for the periods before and during the enhanced turbulence event.

The individual component contributions to the energy transfer can be evaluated in terms of the dissipation:

\[ \varepsilon_{i,j}^{TKE} = \overline{u_i u_j S_{ij}} \quad \text{and} \quad \varepsilon_{k}^{\theta} = \overline{u_k \theta \partial \theta / \partial x_k} \]  

(3)

For the resolved\rightarrow unresolved scale transfer of TKE (see Figure 5), the 1,3 component is dominant, especially near the ground. The enhanced turbulence leads to greater forward scatter and a deeper layer of turbulence. Near the ground, the 1,3 component is a primary source for backscatter. This is consistent with analysis of DNS of turbulent channel flow by Hartel and Kleiser (1998), where they found that the correlation of the wall-normal SGS stress with the wall-normal derivative of the resolved streamwise velocity plays a key role in inverse cascade (backscatter) of TKE.

The resolved\rightarrow unresolved scale transfer of thermal energy (temperature dissipation) poses a challenge for interpretation. Thermal backscatter in atmospheric flow

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Figure 5. Vertical profiles of TKE transfer by component (1,2: dotted line; 1,3: short dashed line; 2,3: long-dashed line) for periods (a) before and (b) during enhanced turbulence; units are 0.01 m²/s².

Figure 6. Vertical profiles of thermal energy transfer by component (1: dotted line; 2: short dashed line; 3: long-dashed line) for periods (a) before and (b) during enhanced turbulence; units are 0.01 K²/s.
is a relatively new topic. As shown in Figure 6, the streamwise \((1)\) component is dominant, and becomes very active during the period of enhanced turbulence. Thermal backscatter (negative dissipation of temperature variance) has been reported for the CBL near the ground by Porte-Agel, et al. (1998). They used conditional sampling for analysis of data from an atmospheric field experiment. The thermal backscatter was associated with ejections of warm surface air due to the action of coherent structures in the unstable surface layer. These ejections occurred when there were local decreases in the streamwise velocity. Our finding of the dominance of the streamwise component suggests that coherent structures may be the mechanism for thermal backscatter in the SBL. We investigate coherent structures in the next subsection.

**Coherent Structures**

Horizontal \((x-y)\) planes of streamwise velocity and potential temperature were analyzed for coherent structures. A striking example is given in Figure 7 for a period just after the enhanced turbulence event. Large-scale structures are evident in both the velocity and temperature fields, which are highly correlated. In regions where the streamwise velocity is decreasing locally, there are cool regions in the temperature. This suggests ejections of cool surface air, analogous to the warm air ejections in the CBL. More analysis is underway, using conditional sampling, to clarify the role of coherent structures in the resolved-unresolved scale transfer of thermal energy in the SBL.

**CONCLUSIONS**

From these preliminary results, we draw the following tentative conclusions: (1) an LES model with energy backscatter provides a realistic simulation of the evolving SBL, with periods of intermittently enhanced turbulence; (2) the character of the turbulence is modified by the presence of stable stratification in the reduction both of magnitude, especially in the vertical velocity component, and of the vertical depth through which it is active; (3) energy transfer occurs in both directions between resolved and unresolved scales and can be large even when the net transfer is small; and (4) this LES approach allows component analysis of kinetic and thermal energy transfer that can give insights into the physics governing the evolution of the turbulence; in particular, we see that coherent structures appear to be dominant in the SBL near the ground and may play a decisive role in thermal energy backscatter there.

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