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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 and Banerjee (1995).

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

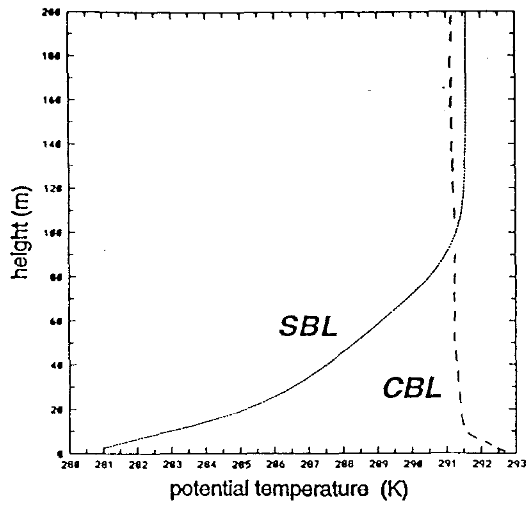


Figure 1. Vertical profiles of horizontally-averaged potential temperature for the CBL and SBL within the lower part of the model domain.

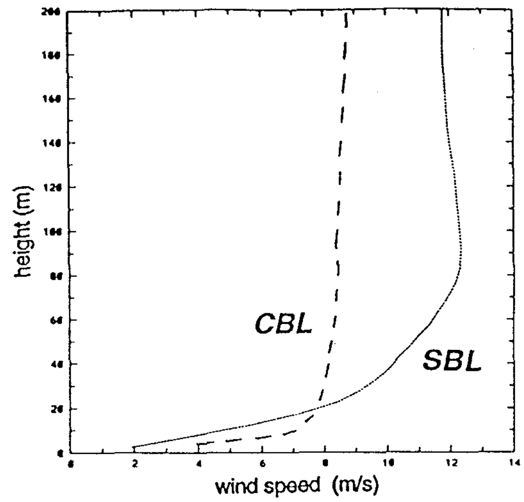


Figure 2. Vertical profiles of horizontally-averaged wind speed for the CBL and SBL within the lower part of the model domain.

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:

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

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:

$$\overline{u_k \theta} = -2C_3 \ell E^{1/2} \frac{\partial \theta}{\partial x_k} + C_4\left( F_k^m - \frac{\delta}{3} F_k^m \right) \quad (2)$$

The grid is oriented with the x, y, and z axes in the west-to-east, south-to-north, and upward directions, respectively; the u-, v-, and w-velocity components correspond to the x, y, and z axes. This equates essentially to the streamwise, spanwise, and normal components. The grid resolution is 20 m in the horizontal direction and 5 m in the vertical direction. For these preliminary, sensitivity computer runs, a small grid of 32x32x80 points is used for efficiency. The momentum forcing at the top of the model domain is a 10.4 m/s geostrophic wind. A weak temperature inversion is prescribed for the upper model levels. Periodic boundary conditions are used in the horizontal direction. Similarity is used at the bottom boundary with a specified surface roughness of 0.1 m. The simulation is initialized with a neutral boundary layer for one hour, forced with a linearly-increased surface heating for one-hour, and maintained at its maximum (75 W/m$^2$) for an additional hour as the CBL develops. Then the surface heating is gradually reduced over an hour period to surface cooling (-25 W/m$^2$) to simulate the transition around sunset. This cooling is maintained for an additional 6 hours. Several other runs were made with varied geostrophic wind speeds and strengths of surface cooling.

## 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

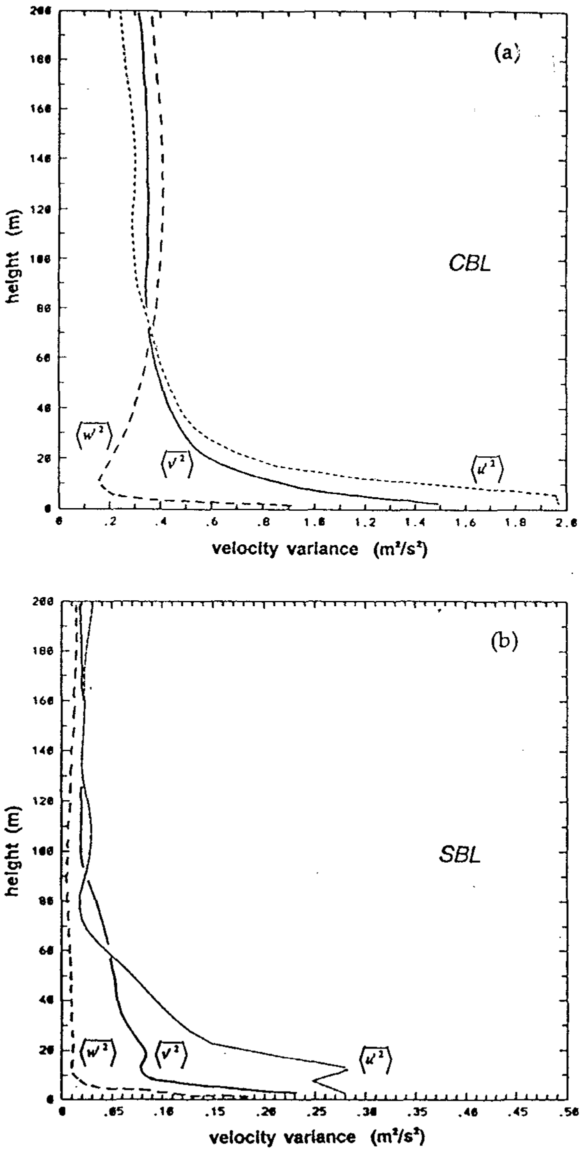


Figure 3. Vertical profiles of horizontally-based variances of the velocity components for the (a) CBL and (b) SBL; note the different horizontal axis scales.

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

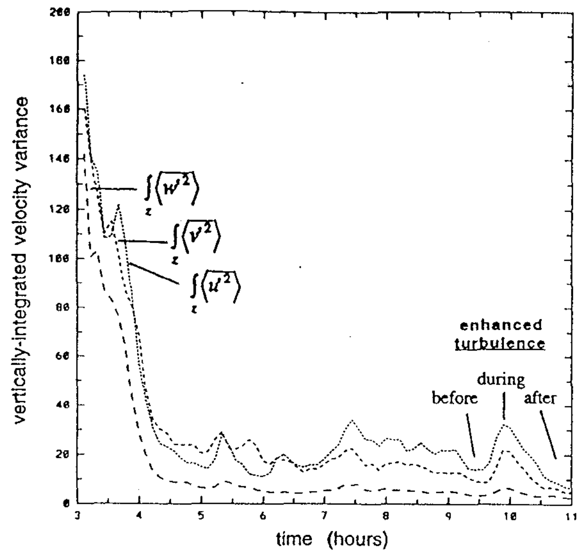


Figure 4. Time series of vertically-integrated velocity variance by component.

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 domonated the backscatter terms in the CBL, leading to a relatively large net transfer from resolved to unresolved scales. In

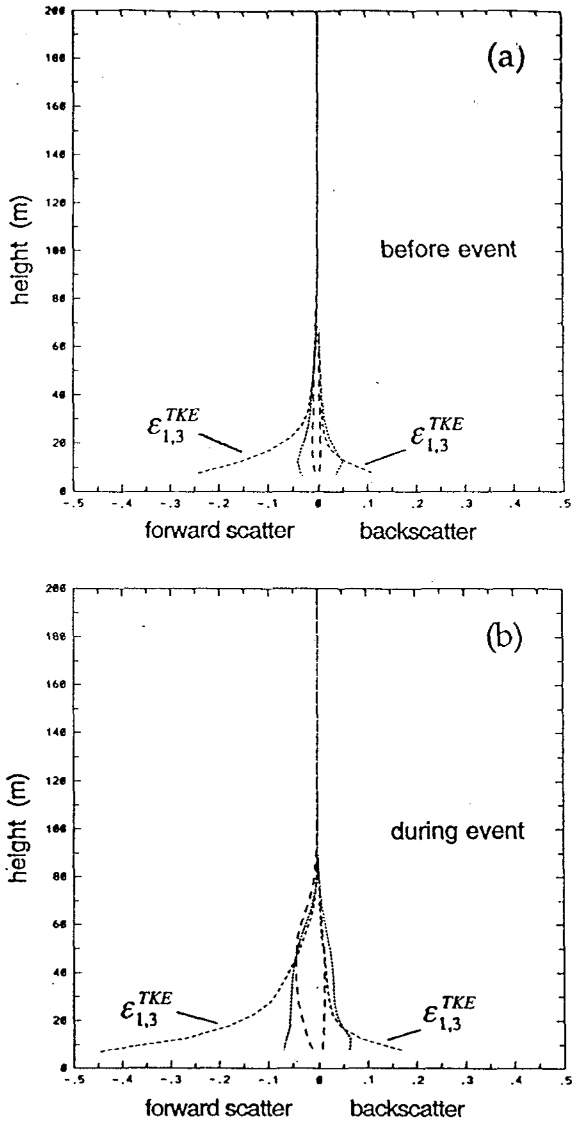


Figure 5. Vertical profiles of TKE transfer by component (1,2: dotted line; 1,3: short dashed line; 2,3: long-dashed line) for periods (a) before and (b) during enhanced turbulence; units are 0.01 $m^2/s^3$.

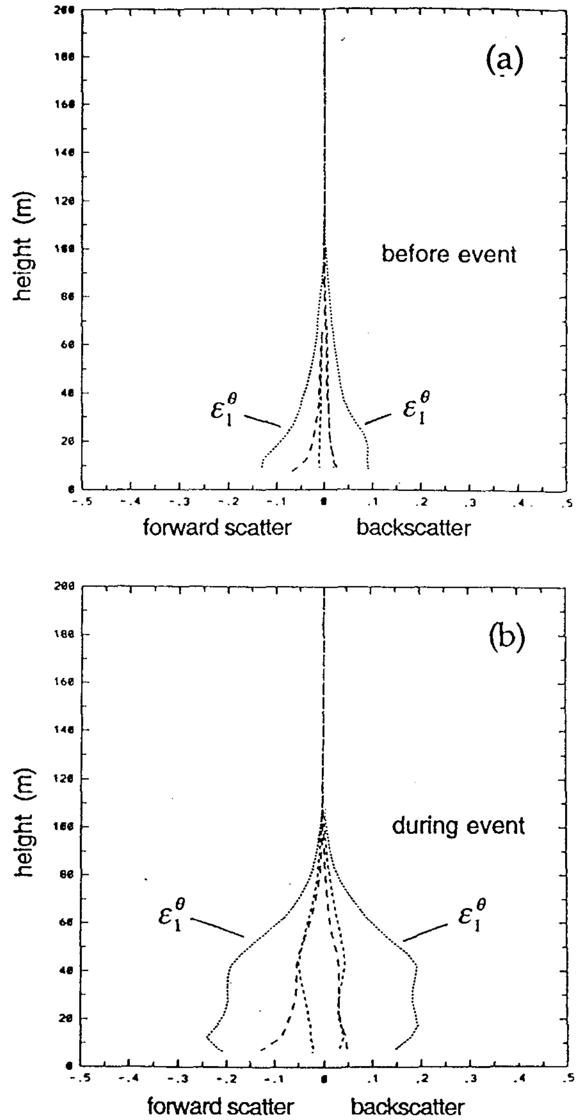


Figure 6. Vertical profiles of thermal energy transfer by component (1: dotted line; 2: short dashed line; 3: long-dashed line) for periods (a) before and (b) during enhanced turbulence; units are 0.01 $K^2/s$.

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:

$$\varepsilon_{i,j}^{TKE} = \overline{u_i u_j}\, S_{ij} \qquad \text{and} \qquad \varepsilon_k^{\theta} = \overline{u_k \theta}\, \partial\theta/\partial x_k \quad (3)$$

For the resolved<-->unresolved scale transfer of TKE (see Figure 5), the 1,3 component is dominant, especially near the ground. The enhanced turbulence leads to a 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<-->unresolved scale transfer of thermal energy (temperature dissipation) poses a challenge for interpretation. Thermal backscatter in atmospheric flows 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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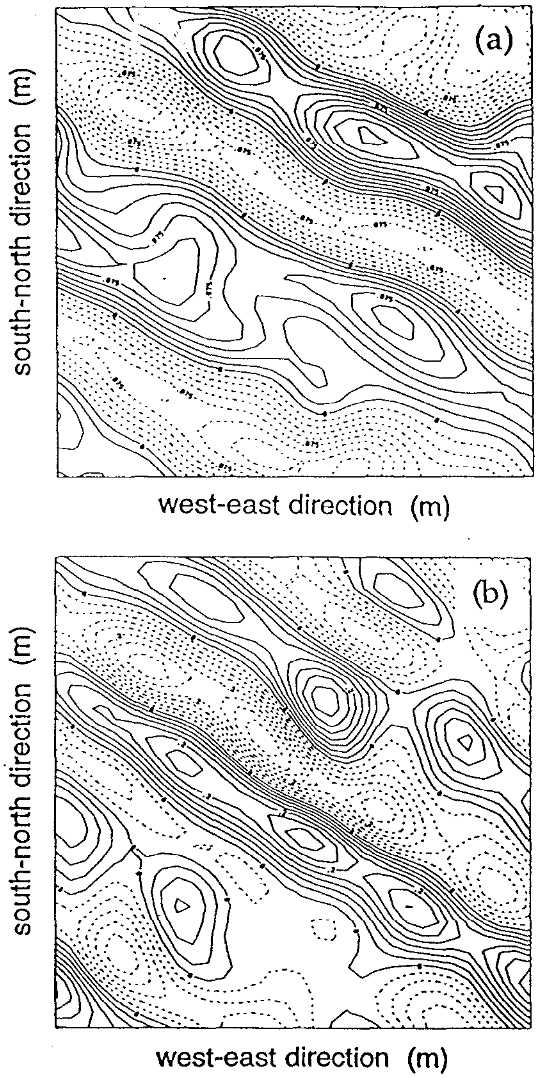


Figure 7. x-y planes at z=7.5m of fluctuating (a) u-velocity and (b) potential temperature, with mean values of 1.9 m/s and 280.8 K, respectively; contour values: 0.015 m/s and 0.04K; mean flow is left to right in these planes.

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