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Large-Eddy Simulation Of The Development Of Stably-Stratified Atmospheric Boundary Layers Over Cool Flat Surfaces

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LARGE-EDDY SIMULATION OF THE DEVELOPMENT OF STABLY-STRATIFIED ATMOSPHERIC BOUNDARY LAYERS OVER COOL FLAT SURFACES

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1. INTRODUCTION

The stable boundary layer (SBL) has received less attention in atmospheric field studies, laboratory experiments, and numerical modeling than other states of the atmospheric boundary layer . The low intensity and potential intermittency of turbulence in the SBL make it difficult to measure and characterize its structure. Large-eddy simulation (LES) offers an approach for simulating the SBL and, in particular, its evolution from the onset of surface cooling. Traditional approaches that involve Reynolds-averaged models of turbulence are not able to simulate the stochastic nature of the intermittent turbulence that is associated with the SBL. LES shows promise in this area through its explicit calculation of turbulent eddies at resolved scales.

In the LES approach, the Navier-Stokes equations governing the flow are averaged (filtered) over some small interval, such as one or more cells of the computational grid. The grid size is small enough so that large eddies, which carry most of the turbulent energy, are explicitly calculated. The turbulence associated with the subgrid-scale (SGS) eddies is modeled. In the Reynolds-averaging approach, on the other hand, the turbulence model must account for all scales of turbulence. Thus the advantage of LES is that the choice of turbulence parameterization for the SGS turbulence is not nearly as critical as in the Reynolds-averaged approach. Complications faced by turbulence models, such as anisotropy and pressure-strain correlations, are associated mainly with large, energy-containing eddies. LES offers the potential for more realistic simulations since the more complicated features of turbulence are calculated explicitly.

The ability of LES to simulate the stochastic behavior of turbulence makes this approach suitable for developing and testing stochastic models of turbulent diffusion. One of the goals of the present work is to provide stochastic datasets to be used in such studies as that described by Ermak and Nasstrom (1995). For example, LES results can be used to characterize how the probability density of vertical velocity varies with height, as done previously by Lamb (1982). LES results can also be used to develop and evaluate parameterizations for vertical velocity variance and TKE dissipation rate that are required for some stochastic models. LES for cases covering a wide range of atmospheric stabilities is desirable in order to test stochastic models over a range of expected atmospheric conditions.

2. LARGE-EDDY SIMULATION OF THE SBL

LES of the SBL is quite challenging due to the nature of the SBL. First, a large number of grid points are needed. A requirement of LES is that the numerical grid must be fine enough to resolve the energy-containing eddies. In the case of the convective boundary layer (CBL), this is not a problem since the convectively-driven eddies are quite large, and most of the turbulent transport is resolved by modest grids. In the case of the SBL, the grid must be quite fine, especially near the ground; at the same time, the modeling domain must be sufficiently large to capture the large-scale features that impact the behavior of the SBL. For LES to be successful in the SBL case, energy-containing eddies must be resolved as much as possible. Otherwise the SGS eddy model is being tasked to model too much of the turbulent motion, and the advantage of LES is lost.

Second, the SBL is non-steady for a long period during its development. The diffusion time scale for the SBL is about 30 hours, compared to about 10 minutes for the CBL (Brost and Wyngaard, 1978). Thus it takes a long time for the mean fields to respond to changes within the domain.

Finally, in strongly stable conditions, turbulence may become intermittent or episodic. Turbulent mixing, especially in the vertical, can be reduced by stable stratification to the point where vertically

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adjacent horizontal layers become decoupled. The lack of strong turbulence provides the SBL with a long "memory", so that turbulence can exist at locations far removed from the generation source; thus local conditions may not be adequate for parameterizing turbulence.

As a consequence of the above, LES of the SBL is very demanding of computer resources: (1) a large number of grid points are required to resolve the energy-containing eddies while maintaining an adequate domain size, and (2) long simulation times are needed to achieve statistically meaningful results. In order to perform LES within reasonable demands on computer resources, ways must be found to incorporate features in the subgrid-scale (SGS) turbulence model to adequately represent turbulence at small scales in the SBL.

3. LARGE-EDDY SIMULATION MODEL

The LES model used here is based on work by Brost (Wyngaard and Brost, 1984). The model is for a three-dimensional, incompressible, viscous flow, and solves governing equations for the volume-averaged velocity components, potential temperature, and SGS turbulent kinetic energy (TKE). The SGS parameterizations follow Deardorff (1980) where turbulent stresses and heat flux are related to mean field gradients by eddy diffusion coefficients. obtained from the SGS TKE and the length scale for SGS turbulence. The SGS dissipation rate is also related to the SGS length scale and SGS TKE.

The work described here extends Brost's LES model in several ways: (1) variation of the vertical grid resolution, (2) addition of energy backscatter in the SGS turbulence model, and (3) incorporation of longwave radiative cooling. The last two modifications are discussed further in Section 5.

For LES of the CBL, an equally spaced grid in the vertical is adequate since the large eddies extend throughout the well-mixed layer. For shear-driven boundary layers, both neutral and stable, the vertical extent of eddies is limited when near the ground. Since the main source of turbulence is shear near the ground, LES must resolve the small eddies there. Hence, a telescoping grid is used that gives the finest resolution near the ground. This is accomplished by a change of vertical coordinate (Ohmstede, et al., 1988), where the vertical coordinate is normalized by the scale of the turbulence; i.e.

$$d\xi = dz \; / \; \ell(z) \quad , \qquad (1)$$

where $d\xi$ is the differential of the normalized vertical coordinate, dz is the height differential, and ℓ is the scale (vertical) of the turbulence. The turbulence scale is related to the mixing length used by Appleby and Ohmstede (1964):

$$\ell(z) = \ell_o(1 - e^{-kz/\ell_o}) \quad , \qquad (2)$$

where k is the von Karman constant (0.4) and ℓ_o is proportional to u_*/f , according to similarity theory. The turbulence scale increases with height in the surface layer and is constant above that. The lowest point is chosen well within the surface layer. Similarity theory is used below the lowest grid point. Mason and Thomson (1987) used a similar change of coordinate.

The 'wall effect' may arise when the subgrid length scale exceeds the dissipation length scale, related to the wavelength of the outer edge of the inertial subrange (Ohmstede, et al., 1988). Therefore, the SGS length used in the model is proportional to the length defined by equation (2). The constant of proportionality is of order one, and is a relative measure of the filtering. Use of the modified length eliminates the need to introduce any artificial 'wall-effect' correction to the dissipation constant.

4. A PRELIMINARY CASE STUDY

In order to evaluate the capability of the LES model to simulate varying states of the PBL, a preliminary case study was run with changing stratification. A 32 x 32 x 64 grid was used, with 150 m, 75 m, and 25 m, spacing in the x, y, and z directions respectively. The associated modeling domain was 4.8 by 2.4 by 1.6 km The initial conditions were an isothermal (290K) layer below a height of 1000 m, and a capping inversion (4K/100m) above that. The run was begun by simulating a typical daytime convective layer (CBL). A surface heat flux of 100 W/m^2 was applied for about 3 hours. The heating was then removed, as was done by Nieuwstadt and Brost (1986). However, in this preliminary run, the surface heat flux was set at -5 W/m^2, rather than zero, to provide surface cooling. The cooling was applied for an additional 6 hours.

For the results presented below, the vertical profiles are based on horizontally-averaged values that are temporally averaged over a period of 750 seconds. The volume-integrated values are for the model domain from the surface up to 1000 m, and are for the same 750-second periods.

The mean wind and temperature structure for the CBL that developed in the first part of the simulation are as expected. A well-mixed layer developed above the near-surface superadiabatic layer and extended slightly up into the initial capping inversion. After the surface cooling had been applied for several hours, a well developed shear layer developed in the lower part of the former mixed layer. This shear layer was much deeper than the shallow, surface-based temperature inversion that formed; this is not the final expected state since the SBL is still evolving.

The time history of turbulence in the boundary layer is quite revealing. A time history of the vertically-integrated variance for each of the three velocity components is shown in Figure 1. The model spin-up is evident in the rapid rise and initial peak within the first 0.5 hours. After recovery, the CBL turbulence is increasingly energized by the surface heating and resulting large eddies. As the CBL develops, a slightly larger amount of turbulent energy is contained in the vertical component, than in the horizontal components. This is expected since the convective updrafts will lead to large fluctuations in the vertical velocity across a horizontal model plane. Once the surface cooling begins to have an effect, the rapid drop in turbulence is dramatic. The greatest effect is on the vertical component since the vertical velocity fluctuations are damped most by the increasing stable stratification. The rapid decrease in turbulence after the onset of cooling reflects the loss of the thermal generation for large eddies, and is consistent with CBL eddy turnover times. Although the turbulence appears to have become rather steady, the mean fields (especially temperature) are not yet steady. The continuing evolution of the SBL is slowed by the reduction in turbulence.

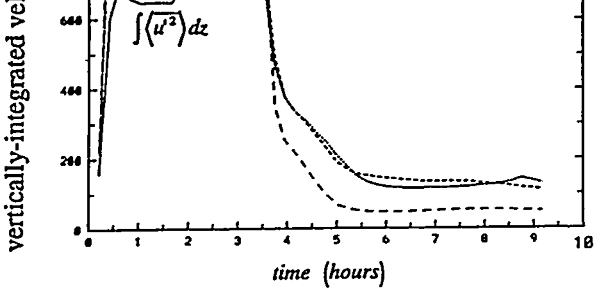

Fig. 1. Time history of the vertically-integrated velocity variances (for each over each model plane and temporally averaged over 750 seconds).

The vertical distribution of turbulence is of special importance in diffusion modeling, especially when the source height may vary. Vertical profiles of velocity variances (obtained for each horizontal model plane and temporally averaged over 750 seconds) are shown in Figure 2, representing (a) end of surface heating, (b) transition, and (c) end of surface cooling. The maximum for horizontal velocity variances, and the associated minimum for the vertical velocity, near the ground is typical for the CBL, as is the maximum for the vertical velocity at about one-third the mixed-layer top height. During the transition period after onset of surface cooling, this maximum in vertical velocity variance dies away quickly, and the overall magnitudes of all velocity variances decrease significantly. After a rather long period of surface cooling, the turbulence in the upper part of the former CBL dies away, while a low level of turbulence remains in the lower boundary layer through the same depth where there is strong shear in

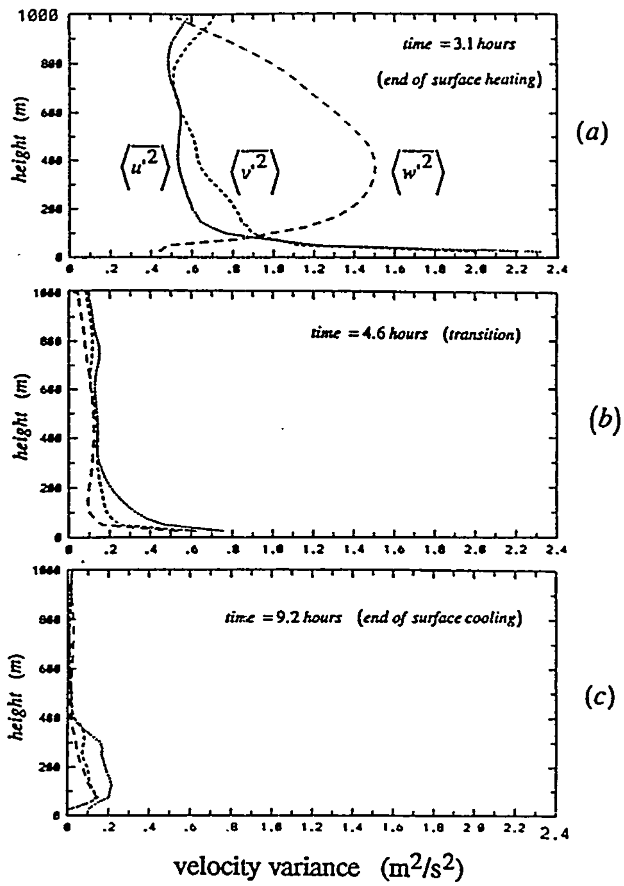

Fig. 2. Vertical profiles of velocity variances (for each horizontal model plane and temporally averaged over 750 seconds) at simulation times of (a) 3.1 hours: end of surface heating, (b) 4.1 hours: transition, and (c) 9.2 hours: end of surface cooling; the type of dashed line for each velocity component is indicated in Figure 2a.

the mean wind. The decrease in all velocity variances approaching the surface is not expected, and suggests shortcomings the SGS model that results in poor matching of resolved and SGS TKE near the ground.

5. DISCUSSION

This preliminary case study has demonstrated that the LES model can simulate the turbulence structure under conditions of varying stratification. The level of turbulence is reduced by about an order of magnitude, and the structure is highly anisotropic due to the greater damping of vertical compared to horizontal motions. The results after a long period of surface cooling highlight the need for additional improvements. Use of the telescoping vertical grid will improve resolution near the ground, which is especially important under non-convective conditions.

Most SGS models are purely dissipative. However, recent studies using direct numerical simulation (see Piomelli, et al., 1991), indicate that there is also upscale transfer (backscatter) of energy in shear flows. The incorporation of backscatter in SGS models has been shown to improve simulations, especially near the surface and under stably-stratified conditions (Mason, 1994; Brown, et al., 1994). Long simulations under conditions of strong surface cooling lead to a more laminar SBL (i.e. resolved turbulence vanishes), as found by Mason and Derbyshire (1990). With backscatter included, this does not occur as readily, allowing a better simulation of intermittency at resolved scales.

The total heat flux is composed of a turbulent component associated with resolved and SGS eddies, and a radiative component associated with longwave radiative flux. Although the turbulent component dominates, the radiative component makes important contributions to the evolution of the SBL under certain vertical distributions of temperature and moisture. Future case studies will investigate how differing moisture conditions (dry continental vs. maritime) affect the evolution of the SBL.

6. ACKNOWLEDGMENTS

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