11B.4 SIMULATION OF THE MORNING TRANSITION BOUNDARY LAYER

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1. INTRODUCTION

The atmospheric boundary layer over land often has a clear diurnal cycle forced by solar heating. The diurnal cycle consists of a neutral or convective phase by day and a stably stratified phase by night. Understanding the transitions between these phases remains an ongoing area of research. It is important for improving Numerical Weather Prediction and climate models and an important aspect of air pollution dispersion models. The subject of this paper is the morning transition using large-eddy simulation (LES). Whilst previous LES studies (Sorbjan 2007) focus on the entraining convective boundary layer (CBL) phase, little has been done on the role of the stable boundary layer.

This paper aims to perform idealised LES of *both* the SBL and CBL phases of the morning transition. One constraint that has dissuaded LES modellers from doing this is the fact that a small grid length is required for a reliable SBL LES (5m) but a large domain for the CBL (typically 3km sided cube). However, only a small domain is required for the SBL, and if a method is formulated for inserting such SBL turbulence into a coarser grained grid and bigger domain, then simulating the range from the SBL to the CBL is possible. This paper employs such a method and explores the full range from SBL to CBL. This study aims to use LESs forced by a range of geostrophic winds to better define the mixed CBL-SBL state and its sensitivity to shear.

2. METHOD

The Met Office (UK) Large-eddy model is used and configured in a similar way to Beare et al (2006) except for the following differences. The initial potential temperature is a mixed layer up to an inversion height (z_{i0}), and then an overlying stratification above:

$$
\begin{aligned}
&\theta = \theta_0 \quad z < z_{i0}\\
&\theta = \theta_0 + \Gamma(z - z_{i0}) \quad z > z_{i0}\\
&\theta_0 = 300K \; ; \quad z_{i0} = 900m\\
&\Gamma = 0.003Km^{-1}
\end{aligned}
\tag{1}
$$

where Γ is the overlying vertical temperature gradient. The Coriolis parameter (f_0) is 0.0001 s^{-1}. The initial wind is set to its geostrophic value at all levels above the surface. A random perturbation of amplitude 0.1 K is applied below 100m to initiate turbulence. Roughness lengths of 0.1m for momentum and 0.01m for heat are used, typical of a rural land surface. A typical surface flux for the early morning transtion (H_0) is defined by:

$$
\begin{aligned}
H_0 &= H_s \quad t < t_{trans}\\
H_0 &= H_s + (H_{max} - H_s) sin^2\left(\frac{\pi(t - t_{trans})}{2\tau_h}\right)\\
&\text{t} \geq t_{trans}
\end{aligned}
\tag{2}
$$

where H_s, H_{max}, t, t_{trans} and τ_h are the SBL surface heat flux, maximum surface heat flux, time, time of transition (from start of simulation), and time scale for transition respectively.

The morning transition boundary layer includes a large range of scales, from the small SBL turbulence scales in the early morning of about 20m to the convective scale in the late morning of about 1km. An LES of the SBL only requires a small domain (of order 400m), but the convective boundary layer requires a much larger domain of at least 3km. The simplest, but computationally very expensive, approach is to combine both a large domain with a small grid length. This was done for some simulations. However, to explore the sensitivity of the area averaged fields to shear, a more computationally efficient strategy was used. The method is called 'domain expansion' and exploits the fact that only a small domain is required for the SBL and a coarser grid for the CBL. The method was checked against a simulation with a larger domain but without the domain expansion.

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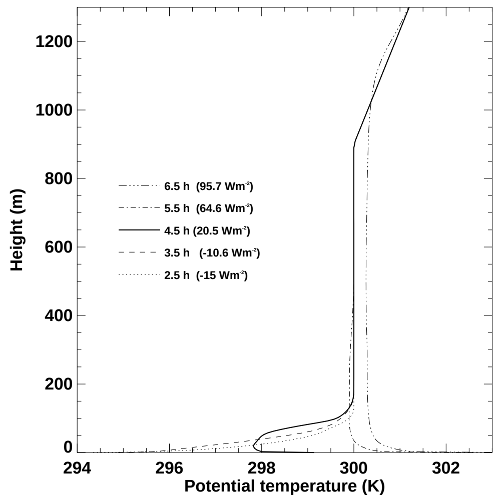

Figure 1: Vertical profiles of area averaged potential temperature from t=2.5 to 6.5h. The mixed CBL-SBL state is marked in bold.

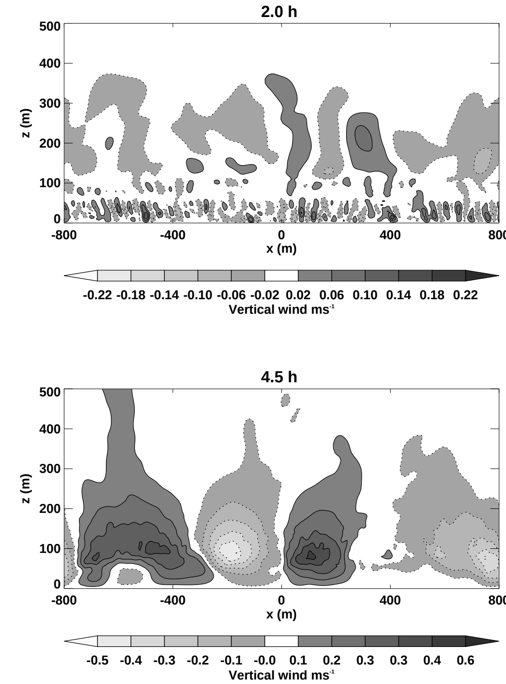

Figure 2: Vertical cross-sections of the instantaneous vertical velocity in the middle of the domain for geostrophic wind $10ms^{-1}$ at 2 (top) and 4.5 hours (bottom). Zero contour omitted for clarity and positive (negative) values shaded dark (light) grey.Note different contour intervals in each.

The first part of the domain expansion involves inserting the fine mesh resolved fields into the coarse mesh. The second involves matching the fine mesh sub-grid model to the coarse grid. The Smagorinsky model in the Met Office LES model is adjusted to ensure a close match between the domains. The mixing length used in the Smagorisky model was modified to be different in the vertical and the horizontal.

3. OVERVIEW OF RESULTS

Figure 1 shows the evolution of the area averaged potential temperature for geostrophic wind $10ms^{-1}$. At time 2.5h, a SBL is established with a depth of approximately 100m. From time 3h, the surface heat flux increases from its initial negative value of $-15Wm^{-2}$ (Eq. 2). By 4.5h, the surface sensible heat flux is positive, and there is a shallow CBL up to height 50m, but there remains a significant stably stratified layer between heights 50m and 150m. This state shall be called the mixed CBL-SBL state as it has features of both the SBL and the CBL. By 5.5 hours, the boundary layer has a depth of about 500m, as it is lifting through the residual layer. By 6.5 hours, the structure is a classic mixed layer with entrainment at the top.

Figure 2 shows vertical cross sections of the vertical velocity at the SBL stage (2h) and the mixed CBL-SBL stage (4.5h). The turbulence has much larger scale (about 200m horizontal scale) at 4.5h than at 2h and about three times the magnitude. The vertical velocity at 4.5h is maximum at about 100m, and Fig. 1 shows that this height is within the stably stratified layer. So, the turbulence structure is neither a pure SBL or a pure CBL, hence its definition as a mixed CBL-SBL state.

Figure 3 shows the turbulent kinetic energy (TKE) budget at the mixed CBL-SBL stage. It has much in common with the classic SBL, in that the dominant terms are still shear production and dissipation. However, the transport is now more significant and the buoyancy production is positive in the lower atmosphere. The classic CBL state later in the morning transition now has a much smaller shear component, except near the surface.

In order to link this study more with other observational studies, Fig. 4 casts the data in a form similar to Angevine et al. (2001), plotting the time delay between crossover (surface sensible heat flux greater than zero) and onset (when inversion above a certain height threshold) against the 10m wind speed and friction velocity. The results are qualitatively similar to Angevine et al. 2001 with the time delay

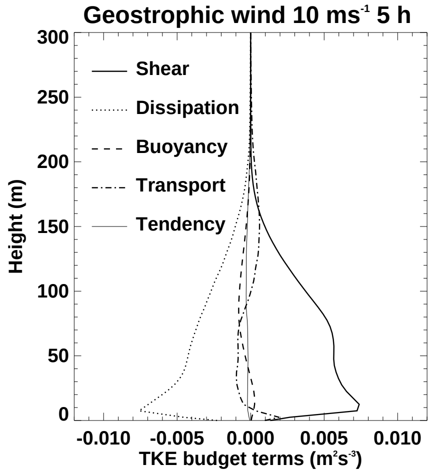

Figure 3: Turbulent kinetic energy budgets averaging between 4.5-5 hours.

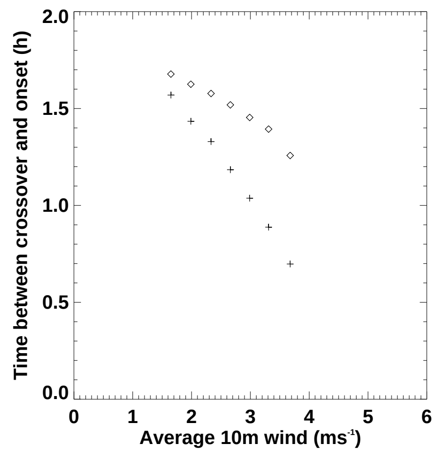

Figure 4: Time delay between crossover (surface heat flux > 0) and onset (when inversion above a certain height threshold) against the average 10m wind over this period at the SBL phase (3 hours) for thresholds of 100m (crosses) and 200m (diamonds).

decreasing with wind speed.

Figure 5 shows the heat flux profiles normalised by the surface value against height normalised by the inversion depth (z_i) over the range of geostrophic winds, for the mixed CBL-SBL state (Fig. 5). The CBL-SBL state has a negative flux which extends to about $2.5z_i$ for the geostrophic wind of $10ms^{-1}$, and the negative flux is sensitive to the geostrophic wind.

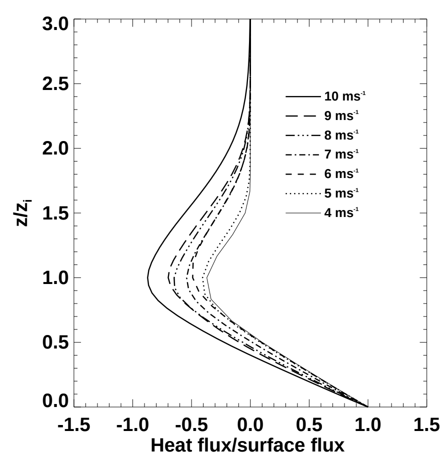

Figure 5: Scaled heat flux profiles averaged over area and times 4.5-5 hours for different geostrophic winds.

4. SUMMARY

This paper used large-eddy simulations to capture the evolution from the stable to the convective boundary layer in the morning transition. Previous studies (e.g Sorbjan, 2007) simulated just the convective boundary layer stage. By applying different geostrophic winds, it was revealed the that the morning transition was most sensitivity to shear in the early stages, the so called mixed convective-stable boundary layer state (CBL-SBL state). This state consisted of a shallow convective boundary layer capped by a significant shear driven boundary layer. Although such a state was commented on by Stull (1988), it has not been modelled in detail.

The turbulent kinetic energy budgets revealed that the CBL-SBL state was shear dominated. In contrast, the convective boundary layer at the later stage of the transition, was buoyancy driven with little sensitivity to shear. The mechanism of the sensitivity of the CBL-SBL state to shear was connected to the stable boundary layer (SBL). As the geoostrophic wind increased, the SBL depth increased, contributing to a deeper CBL-SBL state. Thus, the SBL must not be ignored in understanding the morning transition. The negative flux from the CBL-SBL extended much further beyond the minimum value than the classic convective boundary layer picture. This indicates that the combination of shear, convection and the overlying stratification are important in the mixed CBL-SBL state. The results also showed qualitative agreement with the observations of Angevine et al. 2001. A method called the domain expansion method was devised where a small domain stable boundary boundary layer LES was inserted into a domain with double the length. An appropriate modification to the Smagorinsky sub-grid model was given. The method was shown to be effective at simulating the area averaged quantities throughout the morning transition. The method may have applications beyond the morning transition for simulating other multi-scale turbulence or cloud phenomena.

There are implications from this study for parametrization of the morning transition boundary layer in climate models. The fact that the turbulent kinetic energy tendency term was small suggests that the quasi-equilibrium assumption which underpins first order closures (Lock, 2000) may still be valid, despite the rapidly evolving surface heat flux forcing. Also, boundary layer parametrization schemes often switch between a local stable boundary layer scheme and a non-local convective scheme when the surface heat flux is greater than zero. It is possible that this assumption is not sufficient to successfully model the mixed CBL-SBL state and further investigation of this issue is required.

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