MODELLING OF TRANSITION BOUNDARY LAYERS

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1. INTRODUCTION

The atmospheric boundary layer over land exhibits a strong diurnal cycle, with unstable conditions during the day, followed at sunset by a transition to stable conditions over night. This evening transition involves the growth of a shallow stable layer from the surface. Whilst equilibrium boundary layers have been widely studied and parametrizations of the boundary layer used in General Circulation Models (GCMs) are largely based on equilibrium models, transitional boundary layers have received somewhat less attention. Observational studies include that of Grimsdell and Angevine (2002) and theoretical studies include those of Nieuwstadt and Brost (1986) and Sorbjan (1997).

Current developments in Numerical Weather Prediction (NWP) place increased emphasis on short-range high-resolution forecasts and provide the motivation for a more detailed study of non-equilibrium effects in the boundary layer. The aim of this study is to guide the further development of parametrizations for GCMs using a combination of observations, large-eddy simulation (LES) and modelling in a single-column version of the the GCM (SCM). The work presented here is focused on an initial study of one particular case.

2. THE OBSERVATIONS

On the 23rd and 24th of September 2003, the UK experienced settled anticyclonic conditions and the skies remained clear over land. Surface observations were taken at 15-minute intervals at the Meteorological Resarch Unit at Cardington, together with near-surface measurements from towers. Ascents to almost 600m were made with a tethered balloon through the evening and the earlier part of the night. The observed potential temperature and wind-speed are shown in figure 1. The growth of the stable layer

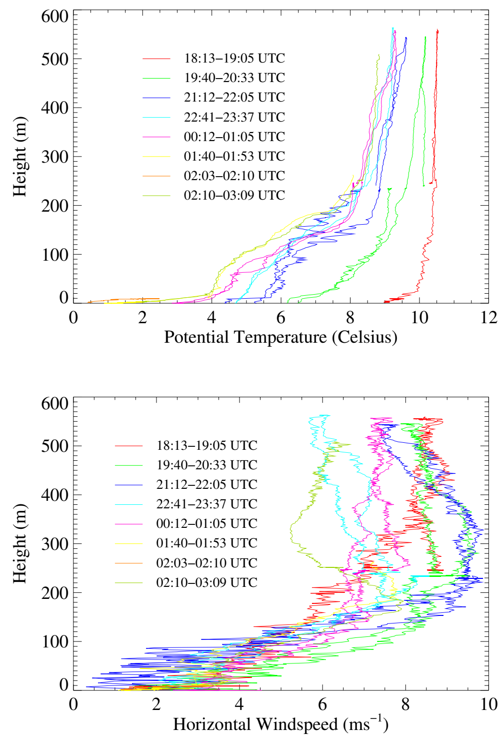

Figure 1: The observed profiles of potential temperature (upper panel) and horizontal wind-speed (lower panel) as recorded from the tethered balloon through the evening transition and the early phase of the nocturnal boundary layer taken over the periods indicated.

from the surface into the residual well-mixed layer and the formation of a nocturnal jet are clearly seen.

3. MODELLING STUDIES

Modelling studies are undertaken to assess the ability of parametrizations to reproduce the observed behaviour and to gain further insight into the physical processes operating. Different levels of sophistication in modelling are possible. Initially, we have

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concentrated on forcing models with the observed surface temperature, initializing the model with the mesoscale analysis at 12Z. Other possible approaches include prescribing the surface flux.

3.1 Large-eddy Simulation

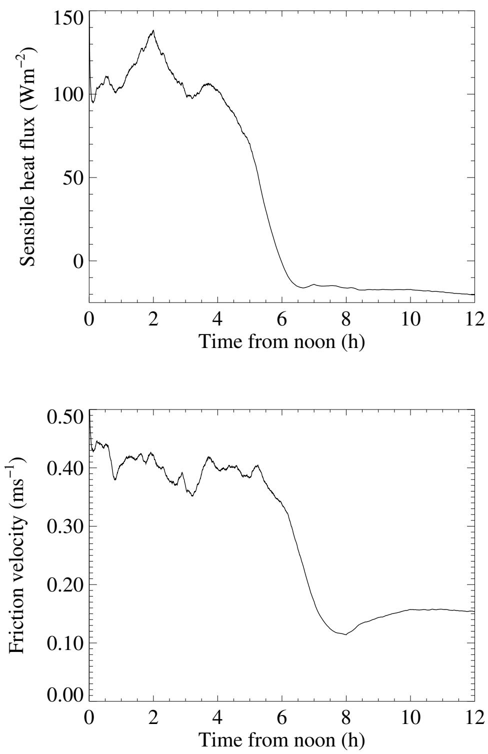

Figure 2: The sensible heat flux and the friction velocity taken from a large-eddy simulation based on the observational data.

Large-eddy simulation has been successfully used in the development of parametrizations of unstable boundary layers. The simulation of stable boundary layers presents a greater challenge because of the smaller size of turbulent eddies under stable conditions; but the recent GABLS intercomparison (Beare (2004)) shows that the current generation of large-eddy models is able to simulate weakly stable boundary layers successfully. As a consequence, it is reasonable to attempt large-eddy modelling of transitional boundary layers. Figure 2 shows the sensible heat flux and surface friction velocity from an initial large-eddy simulation based on this observational case, carried out in a domain 3km × 3km × 2km with a vertical grid-length of 10m near the surface, increasing with height. Surface temperatures are prescribed, but radiative effects are omitted. The model simulates a transition with a time-scale of about 2 hours. The transition in the friction velocity lags that in the sensible heat flux.

3.2 Single-Column Modelling

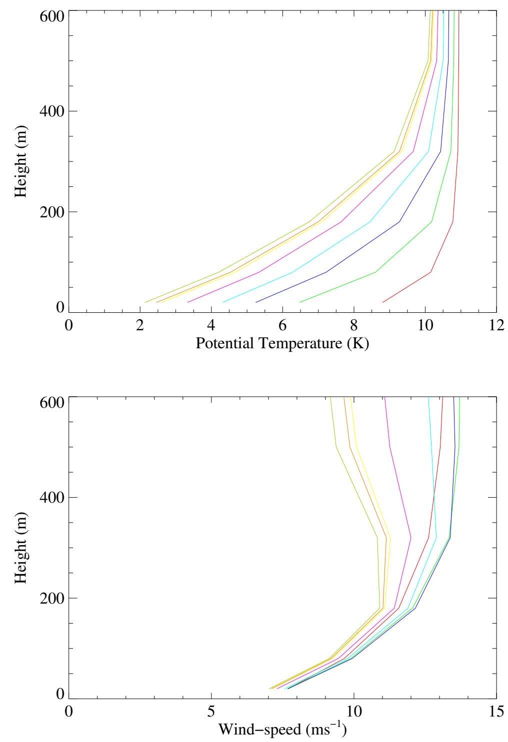

Figure 3: The profiles of potential temperature (upper panel) and horizontal wind-speed (lower panel) taken from the basic simulation in the SCM, forced with the observed surface temperature. Profiles here are instantaneous values, although the observational profiles are taken over a period. However, the colours are chosen roughly to match the times of the observed profiles.

The SCM is a useful tool for investigating sensitivities to changes in parametrizations. Figure 3 shows the evolution of the potential temperature and wind-speed from a control integration started from 12Z with prescribed surface temperatures. The colours of lines have been chosen roughly to match the times of the observed ascents. The vertical grid employed was the 38-level configuration used in the global and European models at the Met Office. "Long-tailed" stability functions were used in the stable boundary layer scheme. Since the SCM cannot include large-scale dynamics, it has been forced with an imposed geostrophic velocity based on the geopotential height field at 12Z; consequently, the nocturnal jet is rather poorly simulated and too broad. The model fails to capture the detailed structure of the potential temperature near the surface. Notice also that the observed cooling above 500m is roughly twice that calculated here, despite the inclusion of radiative effects in the model. The divergences of the sensible heat flux and of SW and LW radiation are shown in figure 4: except near the surface the divergence of the sensible heat flux is generally more important.

3.3 Sensitivity Studies

Various sensitivity studies have been carried out in an attempt to match the observed data better.

To improve on geostrophic forcing, the driving mesoscale model has been rerun to provide dynamical increments. As shown in figure 5, this improves the simulation of the jet and leads to increased cooling at around 500m in the residual layer, although the magnitude is now overestimated.

The resolution near the surface is quite coarse, with the bottom two temperature levels at 20 and 80m. The simulation has therefore been repeated with a finer grid, incorporating twice as many levels up to about 3.5 km. Qualitatively, this does not alter the structure of the profiles of potential temperature.

The role of decaying turbulence in the evening transition is of interest. In their study, Nieuwstadt and Brost (1986) considered an instantaneous change of sign in the surface flux and demonstrated a rapid decay of convective turbulence. However, Sorbjan (1997) drew attention to the fact that the surface flux changes sign over a period of a few hours and argued that this external timescale was also relevant. Ha and Mahrt (1999) included a simple representation of the decay of convective turbulence in their model of the nocturnal boundary layer. We have incorporated a similar prescription into our SCM, imposing various different timescales for the decay of convective turbulence, from the value of 300 s used by Ha and Mahrt to timescales of several hours. Whilst the direct impact of this parametrization on the turbulent diffusivities is clear, the impact on the evolution of the potential temperature is much less significant, except for implausibly long time-scales of several hours: this suggests that the decay of convective turbulence is not an important factor in this case.

The parametrization of the stable boundary layer has been the subject of much debate, particularly in

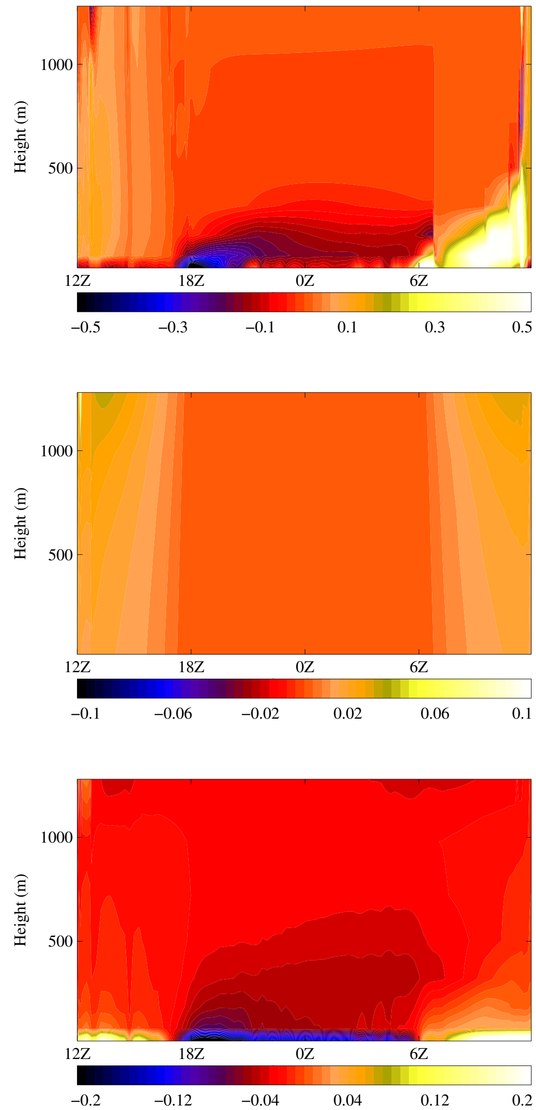

Figure 4: The divergences of the fluxes of sensible heat (upper panel), SW radiation (middle panel) and LW radiation (lower panel) (Wm-3) through the period of the simulation and the subsequent morning transition as calculated using the SCM. Note the different scale used on the colour-bar for the sensible heat flux.

the area of stability functions. Theoretical considerations imply a faster decay of the stability function with Richardson number than is given by the "long-tailed" functions generally used in operational NWP models. The introduction of the "sharpest" stability functions does yield a more realistic narrower jet, but does not lead to significant improvements in the

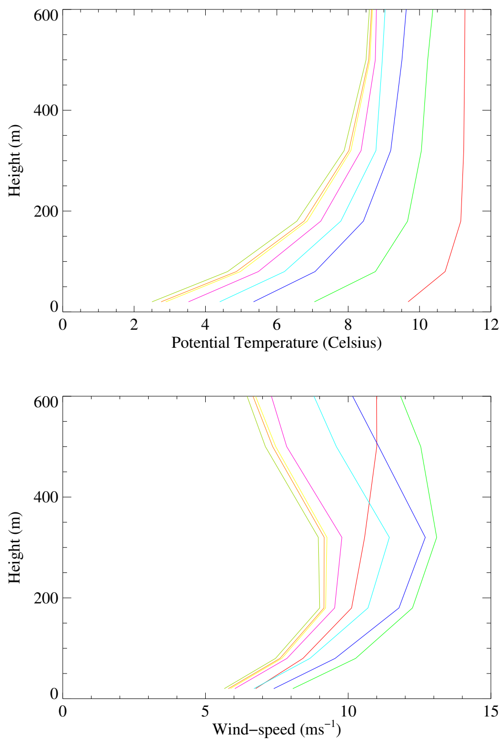

Figure 5: The profiles of potential temperature (upper panel) and horizontal wind-speed (lower panel) taken from a simulation in the SCM, forced with the observed surface temperature and with large-scale tendencies calculated from the driving mesoscale model. As in figure 3, the profiles are instantaneous values, with colours chosen roughly to match the times of the observed profiles.

representation of the potential temperature.

The treatment of radiation adopted in the previous SCM integrations is that standardly used in NWP and climate models, which has a relatively coarse spectral resolution. A simulation has also been carried out using a more elaborate version of the radiation scheme with much higher spectral resolution, but little impact was seen in the results.

4. CONCLUSION

Large-eddy and single-column simulations of a well-observed evening transition have been carried out. Although the models demonstrate the growth of the stable layer from the surface, within the range of the sensitivities considered here they fail to capture the detailed evolution of the profile of potential temperature, which is important in forecasting near-surface weather elements. Little sensitivity was found to the introduction of a decay time for convective turbulence, or to a moderate increase in the vertical resolution. (The impact of a more significant increase in the resolution is under investigation). Improvements in the overall structure of the simulated profiles on introducing large-scale increments from the driving model point to the importance of formulating the numerical set-up well when comparing with observations.

For the future, we plan further investigation of this and other transitional cases in conjunction with continued large-eddy modelling.

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