4.3 MODELLING THE EVOLUTION OF THE NOCTURNAL BOUNDARY LAYER FOR THREE DIFFERENT NIGHTS IN CASES-99

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1. INTRODUCTION

The evolution of the stable nocturnal boundary layer over land (SBL) is largely determined by three physical processes: turbulent mixing, radiative cooling and heat exchange with the underlying soil. Depending on the relative importance of each process, one of the following three SBL-archetypes may occur: fully turbulent, intermittent turbulent and non-turbulent SBL (Van de Wiel et al*.,* 2003).

The latter two are generally regarded as SBLs of the very stable type, whereas the fully turbulent night occurs under weakly stable conditions (Mahrt et al., 1998).

In the fully turbulent situation, wind shear is the dominating factor, whereas in the non-turbulent situation, surface radiative cooling and heat conduction from the soil dominate. For the intermittent SBL, periods of alternating increasing and decreasing turbulent fluxes occur, so that the relative importance of each process changes in time.

The challenge is to develop a model able to capture these three archetypes that differ dynamically.

From a practical point of view, there is a clear need for a better description of SBLs in Numerical Weather Prediction and climate modelling. Current weather prediction and climate models are not capable of simulating very stable boundary-layers and often enhanced mixing formulations are utilised (not based on observations). This may lead to unrealistic deep SBLs (Beljaars and Viterbo, 1998) with a strong sensitivity on choices of empirical parameters (Viterbo et al., 1999; Holtslag, 2003).

In this study we use a fine-scale single column model with detailed process description, and prescribed dynamical forcings. We compare model results with detailed local observations from the CASES-99 experiment, Kansas U.S.A. (Poulos et al., 2002).

In view of the discussion above, the emphasis lies on simulation of the whole "stability spectrum", i.e. simulation of both the fully turbulent, non-turbulent and intermittent turbulent situations. It will be shown that for this purpose, accurate modelling of the soil – vegetation – heat diffusion is essential.

2. MODEL SET-UP

a) Turbulence

The turbulent fluxes of momentum and heat are described by local diffusion for both the surface layer and the SBL. The eddy diffusivity *K* is given by (*x* = heat or momentum):

$$K_x = \frac{k^2 z^2}{\phi_m \phi_x}\left|\frac{\partial \vec{V}}{\partial z}\right| \qquad (1)$$

with κ the Von Karman constant, taken at 0.4. Duynkerke (1991) proposes for the stability functions:

$$\phi_x(\zeta) = \frac{kz}{X_*}\frac{\partial \overline{X}}{\partial z} = 1 + \beta_x \zeta \left(1 + \frac{\beta_x}{\alpha_x}\zeta\right)^{\alpha_x - 1} \qquad (2)$$

with $\zeta = z/\Lambda$ and Λ the local Monin-Obukhov length. For CASES-99 we found $\beta_m = \beta_h = 5$ for $\zeta < 1.5$ and $\alpha_m = \alpha_h = 0.8$; this implies a critical Richardson number of 0.29.

b) Radiation

Several studies show the relevance of radiative transport divergence on the SBL structure and development (Andre and Mahrt, 1982). We use the grey body emissivity model from Garratt and Brost (1981), taking into account the absorbing effects of H_2O, CO_2 and liquid water. Ha and Mahrt (2003) showed that a vertical resolution of about 1 m is required for reasonable modelling. With coarser resolution estimated radiative cooling near the ground is negligible small or even radiative warming is predicted. Therefore we use a stretched grid with 0.5 m grid spacing near the surface.

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c) Soil and land surface

Soil temperature evolution is calculated by the diffusion equation (using a grid length of 5 mm) and we calculate the heat flux through vegetation G by the resistance law:

$$G-(1-f_{veg})K^{\downarrow}=r_g\left(T_{veg}-T_{s0}\right) \qquad (3)$$

where $K^{\downarrow}$ is the incoming shortwave radiation and T_{veg} the vegetation surface temperature, and T_{s0} the soil temperature at z = 0 m, just below the vegetation. We assume no heat flux divergence over the vegetation layer.

Using the CASES-99 observations with f_{veg} = 0.9 we found r_g = 6.8 W m^{-2} K^{-1}. T_{veg} is computed as the residual of surface energy budget:

$$C_v\frac{\partial T_{veg}}{\partial t}=Q^*-G-H-L_vE \qquad (4)$$

with C_v the heat capacity of the surface per unit of area (C_v = 2000 J m^{-2} K, Van de Wiel et al., 2003), Q^* the net radiation, H the sensible heat flux and L_vE the latent heat flux.

d) Forcings

The model is only forced with the observed geostrophic wind estimated from 3 hourly radio soundings. During the second day an advection rate of 3.10^{-4} K s^{-1} was applied, as based on a mesoscale analysis.

e) Location

The CASES99 measurement campaign was held from October 1-31, 1999, near Leon, Kansas, USA (37.64º N, -96.73º E). The terrain is relatively homogeneous flat, prairie grass with a roughness length 0.03 m and both atmosphere and soil were very dry. See Poulos et al. (2002) for details. We selected three consecutive nights, starting 23-10-'99, 1900 UTC, of which the first night is intermittent, the second fully turbulent and the last one non-turbulent.

3. RESULTS

The estimated diurnal cycles of the net radiation Q^*, and both long wave components from the radiative transfer model are in good agreement with the observations. The simulation of friction velocity (u_*) is shown in Figure 1. The decrease of u_* during sunset of the first night is simulated quite well, but during the first night u_* is overestimated about 0.10 m s^{-1} without an explicit turbulence collapse.

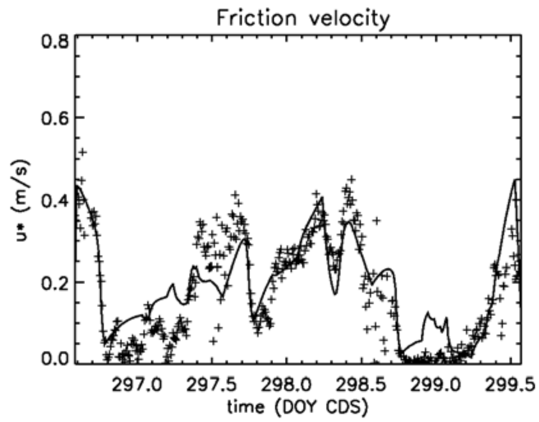

Figure 1: Simulated (line) and observed (+) u_*.

From DOY = 297.3 – 298.7 the model performs well. During the last night u_* is slightly too high up till midnight, but follows the collapse at the end of the night.

Figure 2 shows the estimated and observed sensible heat flux (H). During the first night, the average value of $H \cong$ -10 W m^{-2} is simulated well. However, the model does not simulate the intermittent character of the fluxes. We note that this intermittency was simulated for other parameter ranges. The reason for this discrepancy is still under investigation.

During the turbulent night, the predicted H follows the observations; especially during the day-night transition (DOY = 297.8), where the characteristic peak is reproduced well. Such a peak is a realistic feature, often found in observations (during 11 of the 30 nights for CASES99).

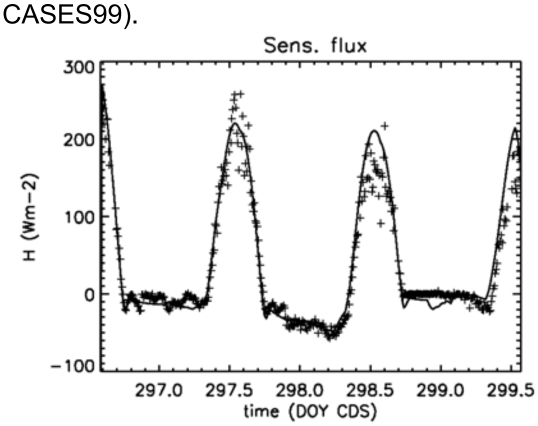

Figure 2: Estimated (line) and observed (+) H.

During the last night radiation dominates and observed H vanishes. The model slightly overestimates H, caused by an overestimation of u_*. The second half of this night, the model behaves well compared to observations.

The soil heat flux, G is shown in Figure 3. $|G|$ is largest (with a sharp peak) just after sunset and then slowly decreases during the night. For these nights G is a relative dominant term in the energy budget (about −50 W m^{-2}) and therefore requires proportional modelling effort. Obviously, the estimated G is in very good agreement with the observations. Also the sharp peak at the beginning of the night (consisting of high frequency contributions) is simulated well by virtue of the fine soil resolution. Since, as indicated above, intermittency is not simulated in the current case, no oscillations are seen in the soil heat flux either.

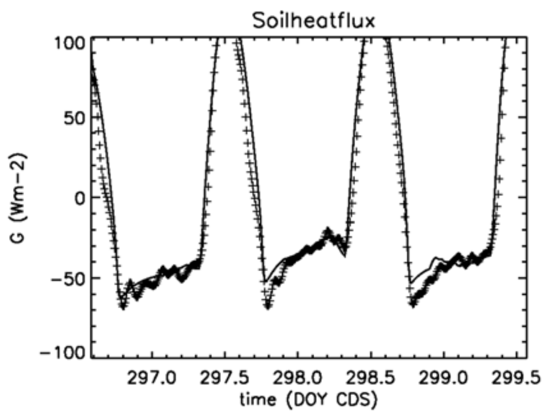

Figure 3: Simulated (line) and observed (+) G.

A common problem for large-scale models is the unsatisfactorily prediction of the vegetation temperature T_{veg}. In the introduction, it was mentioned that operational models often have troubles with simulating very stable boundary layers. Some models show decoupling (in an unrealistic sense) of the atmosphere from the surface resulting in so-called “runaway cooling” of T_{veg}. On the other hand, the enhanced mixing approach as in common practise leads to overestimation of T_{veg}.

Here, T_{veg} is simulated in good agreement with the data for both daytime and night time (Figure 4), despite the fact that a broad stability range is simulated! In case when turbulence vanishes, radiative transport and soil heat diffusion take over in a natural way. This prevents unrealistic surface cooling.

The capability of the model is further illustrated by three typical temperature and wind profiles of the nights studied above (Figure 5).

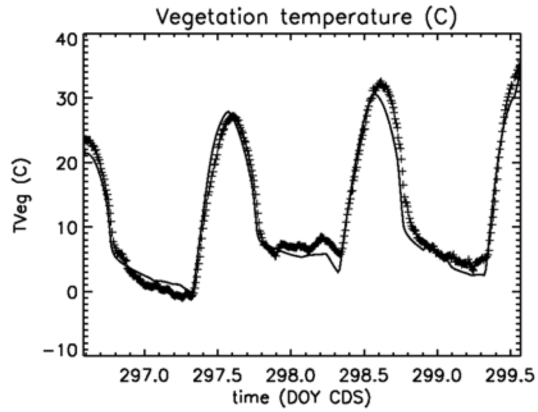

Figure 4: Simulated (line) and observed(+)T_{veg}.

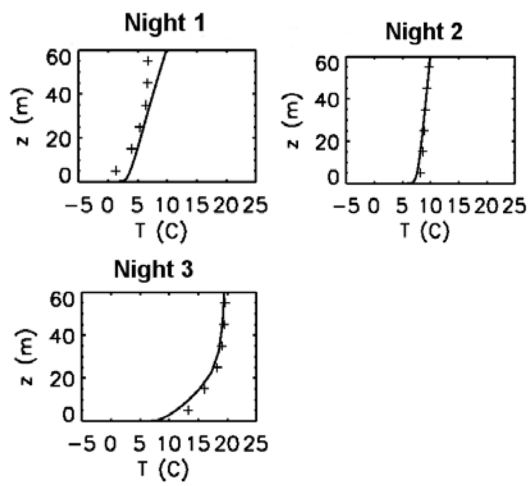

Figure 5: Simulated (line) and observed (+) Potential Temperature profiles for the three nights

4. CONCLUSIONS

This study shows that the evolution of SBLs during CASES-99 can be simulated well over a broad range of stabilities (ranging from weakly to very stable) with a state-of-the-art single column model with high vertical resolution. Besides turbulent mixing, a detailed description of radiative transport and the soil-vegetation heat transport is a prerequisite (especially in the very stable boundary-layer) to achieve realistic model behaviour.

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