4.18 STABLE BOUNDARY LAYER DECOUPLING: TOWARDS A LINEAR STABILITY ANALYSIS

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1. INTRODUCTION

During clear nights we often observe that winds become very weak near the surface. In this situation surface- and screen level temperatures reach relatively low values. Also, there is little (if any) turbulence activity close to the surface, so that the stable boundary layer (SBL) is 'detached' from the surface leading to a so-called decoupled state (Mahrt, 1999). Despite the fact that it is omnipresent, the process of decoupling is poorly understood. At present there is no theory available to predict this phenomenon.

In contrast, weakly stable boundary layers, which usually are present during nights with (relatively) strong winds, are relatively well-understood. According to Nieuwstadt (1984), the SBL tries to achieve some form of a quasi-steady state (see also: Derbyshire, 1999b). In that case, the turbulent heat flux decreases linearly with height and the shape of the temperature profiles remains unchanged in time (i.e. cooling is constant with height). A similar picture exists for momentum/wind, being slightly more complicated due to Coriolis- and inertial effects. Apparently, according to the previously mentioned observation of decoupled boundary layers, the SBL is not always able to maintain such a quasi-steady state, especially not when low dynamic forcing is present. *So, what does the SBL make to decide between a decoupled and a quasi-steady equilibrium state?*

In this perspective, an interesting approach on SBL dynamics was given by McNider et al. (1995) and by Van de Wiel et al. (2002a,b). Both studies use a highly simplified bulk model of the SBL and investigate its dynamic behaviour over a large parameter range. As a direct consequence of the non-linear character of stable boundary layer diffusion, they obtained intriguing results, showing: instability, oscillations, bifurcations and potential loss of predictability. Although, the models used are too simplified to be more than a suggestive of SBL behaviour, it does provide an alternative (or rather: extension) to the quasi-steady picture suggested by Nieuwstadt (Derbyshire, 1999; from now on D99).

In stead of using simplified bulk models, a multi-layer single column model was used by D99 to investigate the dynamic behaviour of the SBL, with special emphasis on the decoupling problem This pioneering work shows that, in essence, decoupling is a real physical phenomenon, arising from a positive feedback between turbulent transport in the SBL and the surface cooling. As such it is shown that the physical properties of the surface play an important role in decoupling of the boundary layer as a whole (see also: Van de Wiel et al. 2002a,b).

It is tempting to generalize these results by a formal linear stability analysis, so that SBL decoupling can be predicted from observable parameters. In fact, such an analysis was performed by D99. He further simplified the column model mentioned above, by defining an idealized shear flow model for linear temperature and wind profiles, assuming a constant neutral mixing length. The result of the stability analysis supported the findings from the numerical simulations, in a sense that some profiles were unstable to (a certain type) of perturbations. However, the assumption of linearity of the profiles cannot be justified in reality, especially not close to the surface (i.e. where the instability initiates!). As a consequence of the fact that, close to the surface, the neutral mixing length scales with height, profiles tend to be logarithmic rather than linear. Therefore, the aim of the present work is to extend the stability analysis of D99 to the general case, allowing realistic (Monin-Obukhov type of) profiles. Such analysis will enable us to compare analytical results with actually observed cases, enabling explicit prediction of SBL decoupling.

In the following section an observational example of the decoupling phenomenon is given from tower observations at the Cabauw. In section 3 a numerical simulation of the quasi-steady SBL and a decoupling SBL is given. In section 4 the perspectives towards an analytical stability analysis are given.

2. AN OBSERVATIONAL EXAMPLE

In Fig. 1 and 2 an example of decoupling is given, based on observations from the KNMI observational tower at Cabauw, The Netherlands. The SBL decoupling occurred in the evening of

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15 November 2002 under clear sky conditions. Fig. 1 shows that between 21-22 [hr] the turbulent heat flux rapidly decreases from small values to a level of hardly any turbulent flux. Similar behaviour was found for the friction velocity (not shown), indicating a total collapse of near-surface turbulence. Since, in such case there is no turbulent transport between the surface and the atmosphere above, the boundary layer is decoupled from the surface.

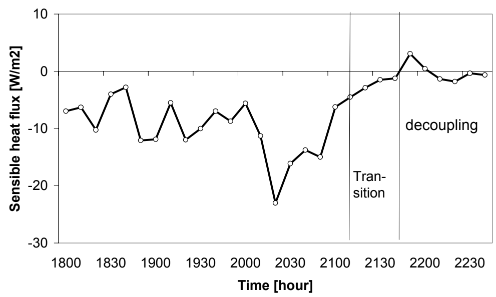

Fig 1.: Example of the turbulent heat flux prior to and during a SBL decoupling process. (Cabauw, The Netherlands Nov. 15, 2002).

In order to gain more insight on the background of this decoupling process, the temperature profiles were studied just before (thin lines) and during (thick lines) the decoupling state (Fig. 2).

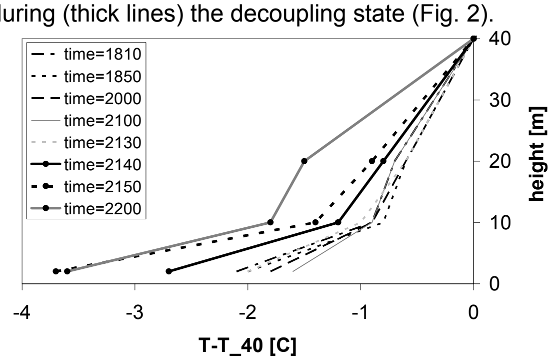

Fig. 2: temperature profiles prior (thin lines) to and during (thick lines) the decoupling event as observed at Cabauw, Nov. 15, 2002. Note that on the horizontal axis T(40m) is subtracted.

Temperature observations were done at 2m, 10m, 20m, 40m and (not shown) at three higher levels up (to 200m. In order to account for the gradual cooling of the SBL as a whole the temperature observation at 40m is subtracted from the original temperature observation. In case that the SBL reaches a quasi-steady state, the original profiles will not change their shape in time, but only shift due to the uniform cooling. In that case, subtraction of the 40m temperature at all times would result in one general temperature curve (on which all curves coincide). From Fig. 2 it is clear that this is the case for all curves before 21:30 hr (thin lines), i.e. before the turbulence collapse. After the turbulence collapse (thick lines) the profiles rapidly diverge, departing from the quasi-steady state. A rapid cooling of the near surface air reflects the lack of turbulent heat transport from above in the decoupled SBL. Apparently, due to some external disturbance the SBL is not able to maintain its quasi-steady state and it tries to find a new, colder equilibrium state.

3. NUMERICAL SIMULATION

In order to explore the background of the decoupling mechanism above, a simple nocturnal boundary layer model was developed (as in D99). Some characteristics (common notation):
-geostrophic wind speed, UG, height-independent (barotropic situation; $f_c = 10^{-4}\ [s^{-1}]$)
-a *single layer* surface model with prescribed net radiation at the surface Q_{net}.
-no long wave radiative divergence is taken into account
-no soil heat flux
-turbulent transport is modeled by using first order closure based on Ri (local equilibrium assumption in the TKE budget), e.g. the turbulent diffusivity

$$K_H = l_n^2 \left|\frac{\partial \overline{\mathbf{U}}}{\partial z}\right| f_H(Ri) \qquad \textbf{(1)}$$

and similar definition for K_m. The neutral mixing length is taken as: $\frac{1}{l_n} = \frac{1}{\kappa z} + \frac{1}{l_M}$, with l_M the asymptotic mixing length. The surface temperature equation of the single-layer surface model reads (here C_g per unit of area $[J m^{-2} K^{-1}]$, *H* the sensible heat flux $[W m^{-2}]$)

$$C_g \frac{\partial \theta_s}{\partial t} = Q_{net} - H \qquad \textbf{(2)}$$

A 20m resolution was applied in the boundary layer. A relatively small value of -15 [W/m2] is prescribed for the net radiative cooling. This small value is applied because in reality a large part of the net radiative cooling is compensated by the soil heat flux, which is not included in the presented case. Similar results were obtained for larger magnitudes of Q_{net}. A surface heat capacity of $10^4\ [Wm^{-2}K^{-1}]$ was used.

Case 1: moderately high geostrophic wind speed

The model was run, starting from a neutral boundary layer. The imposed geostrophic wind speed was 10.5 [m/s] for 30 hours (to ensure that 'transient effects' have disappeared). Between 30 and 31.5 hrs. UG is lowered from 10.5 to 9 [m/s], which is kept until the end of the simulation. Results are presented in figures 3 and 4.

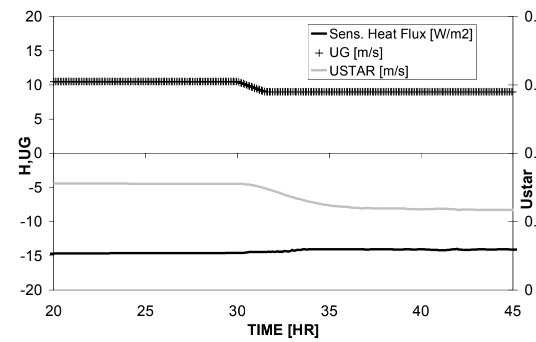

Fig. 3: The prescribed geostrophic wind speed, the simulated evolution of the sensible heat flux and the friction velocity at the surface, during the first run after 20 hrs of simulation.

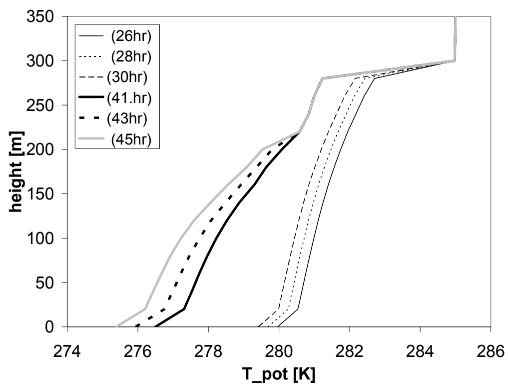

Fig. 4: Evolution of temperature profiles prior (thin lines) and after (thick)lines the change in geostrophic wind speed, corresponding to the numerical simulation presented in Fig. 3.

Figure 3 shows that the sensible heat flux changes only little (from -14.6 to -14.3 [W/m2]), and the friction velocity changes from 0.31 to 0.23 [m/s]. The profiles in Fig. 4 indicate that a new quasi-steady state is reached, with a less deep boundary layer. Again, for the 'new' steady-state only results after 41 hrs are shown to ensure that possible 'transient effects' have disappeared. The profiles behave similarly to the observed steady–state profiles (for clarity we did not subtract the 40m temperature in Fig. 4, since the difference between the curves would not be visible).

Case 2: moderately low geostrophic wind speed.

The same type of simulation is done but now by changing UG from 8.5 to 7 [m/s] after 30-31.5 hrs.

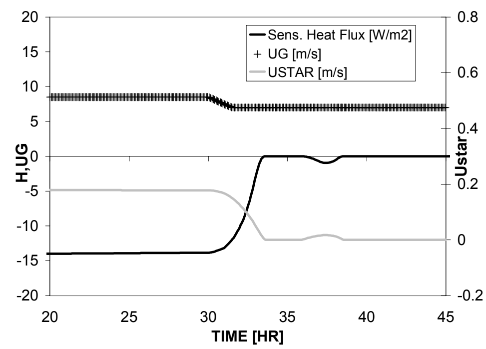

Fig. 5: As figure 3 but with a geostrophic wind changing from 8.5 to 7 [m/s]

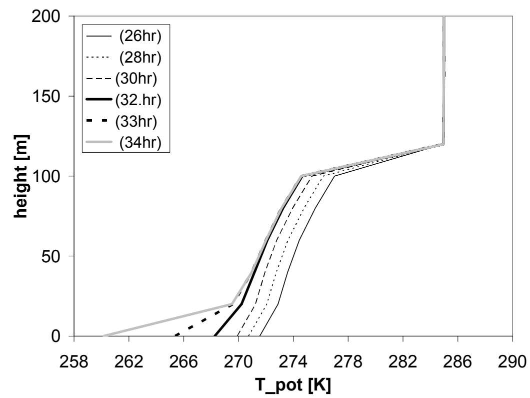

Fig. 6: As figure 4 but corresponding to the simulation presented in Fig. 5. Note that the time steps are smaller than in Fig. 4 in order to visualize the decoupling process.

Instead of a 'smooth' change as in the previous case, ***the results change dramatically***. In Fig. 5 one sees that within a few hours both the sensible heat flux and the friction velocity drop to virtually zero (apart from a short 'revival' around 37 hrs.). A similar dramatic change is found in the evolution of the temperature profiles (Fig. 6). In stead of reaching a 'new' steady state as previously, the temperature profiles exhibits so-called 'run-away' cooling, within a few hours, similar to the observational example in Fig. 2. In absence of turbulence, the SBL becomes decoupled from the surface (as inferred from the unchanged temperature profiles up from the first model level).

In the idealistic case presented above, the surface temperature may runaway to unrealistic low values. In reality negative feedbacks in the long-wave net radiation and the soil heat flux will lead to new (i.e. realistic cold) equilibrium: a balance between the net radiation and the soil heat flux in absence of turbulence near the surface.

Sensitivity of the results

The results in the previous section clearly illustrate the non-linear response of stable boundary layers to external disturbances. The results are general in a sense that similar results would have been obtained by changing the net radiative cooling at a fixed geostrophic forcing. The results are sensitive to surface properties such as the roughness length and heat capacity. For example: when a larger heat capacity is applied, more radiative cooling is needed for decoupling to occur (see also: D99). These results also confirm the findings of McNider et al. (1995) and Van de Wiel et al. (2002b) who showed that surface properties have a major influence on the dynamic behaviour of the stable boundary layer as a whole.

4. DECOUPLING: TOWARDS A LINEAR STABILITY ANALYSIS

In the following the methodology is discussed in a qualitative sense only. The details of the analysis are currently explored in ongoing research. A more detailed background on similar methodology is given in Derbyshire (1994, 1999).

As pointed out by Landau and Lifshitz (1959) (in: Drazin and Reid, 1981): "Yet not every solution of the equations of motion, even if it is exact, can actually occur in nature. The flows that occur in nature must not only obey the equations of fluid dynamics, but also be stable." In the present work this is interpreted as follows: **we hypothesize that:**

1) the quasi-steady solutions are (mathematically) stable for high geostrophic forcing, and are therefore observed in nature.
2) the quasi-steady solutions are (mathematically) unstable for low geostrophic forcing, and are therefore not observed in nature for low UG. In this second case a decoupled SBL will be observed.

In the current analysis we investigate the (mathematical) stability of quasi-steady solutions of the single column model described above to small perturbations. The shear and static stability are governed by the tendency equations:

$$\frac{\partial\left(\dfrac{\partial\theta}{\partial z}\right)}{\partial t} = -\frac{1}{\rho c_p}\frac{\partial^2 H}{\partial z^2} \qquad \textbf{(3)}$$

$$\frac{\partial\left(\dfrac{\partial\overline{\mathbf{U}}}{\partial z}\right)}{\partial t} = \frac{\partial^2 \tau}{\partial z^2} \qquad \textbf{(4)}$$

(Coriolis term was left out for simplicity). These equations are the vertical derivative of the fundamental Reynolds-averaged equations for the rate of change of mean wind and temperature in terms of flux and stress divergence. In terms of the first order closure adopted above the equations become:

$$\frac{\partial\left(\dfrac{\partial\theta}{\partial z}\right)}{\partial t} = \frac{\partial^2}{\partial z^2}\left\{ l_0^2(z)\frac{\partial\theta}{\partial z}\left|\frac{\partial\overline{\mathbf{U}}}{\partial z}\right| f_H(Ri)\right\} \textbf{(5)}$$

$$\frac{\partial\left(\dfrac{\partial\overline{\mathbf{U}}}{\partial z}\right)}{\partial t} = \frac{\partial^2}{\partial z^2}\left\{ l_0^2(z)\frac{\partial\overline{\mathbf{U}}}{\partial z}\left|\frac{\partial\overline{\mathbf{U}}}{\partial z}\right| f_m(Ri)\right\} \textbf{(6)}$$

The set of equation above is both coupled and non-linear so that a direct analytical solution cannot be found. It is, however, possible to investigate the behaviour of the equations analytically close to a certain reference state. In our case this reference state corresponds to the quasi-steady state. The quasi-steady equilibrium solution can actually be found from equations **(5)** and **(6)**, by putting the l.h.s. of the equations to zero. The resulting equilibrium solution is denoted as: $\partial\theta/\partial z|_{eq}, \partial\overline{\mathbf{U}}/\partial z|_{eq}$ or, alternatively as θ_{eq} and $\overline{\mathbf{U}}|_{eq}$.

Close to the surface these equilibrium solutions follow M-O similarity profiles.

Next, from Eqs. **(5)** and **(6)** the linearized tendency equations for infinitesimal perturbations $\partial\theta/\partial z|_p = \partial\theta/\partial z - \partial\theta/\partial z|_{eq}$ and $\partial\overline{\mathbf{U}}/\partial z|_p = \partial\overline{\mathbf{U}}/\partial z - \partial\overline{\mathbf{U}}/\partial z|_{eq}$ are constructed trough Taylor expansion of the r.h.s. of **(5)** and **(6)** (see: D99)**.** The resulting equations for the temporal evolution of the perturbation are not only coupled but in the present case also height dependent (contrary to D99), but *linear* in the perturbations $\partial\theta/\partial z|_p$ and $\partial\overline{\mathbf{U}}/\partial z|_p$.

This enables an analytical investigation of the solutions close to the quasi-steady reference state. We will investigate the temporal behaviour of perturbations that obey the linearized set of equations and also fulfill the boundary conditions at $z = z_{0m} = z_{0H}$:

$\overline{\mathbf{U}}_P = 0$ (no slip).

And $\left(\dfrac{\partial\theta_p}{\partial t}\right)_{Soil} = \left(\dfrac{\partial\theta_p}{\partial t}\right)_{atml}$ or

$$\left.\frac{H_p}{C_g}\right|_{Z_0} = -\frac{1}{\rho c_p}\left.\frac{\partial H}{\partial z}\right|_{Z0}$$

We restrict ourselves by investigating one-dimensional perturbations of the following type:

$\overline{\mathbf{U}}_P(z,t) = \hat{\mathbf{u}}(z)e^{\sigma t}$ and

$\theta_P(z,t) = \hat{\theta}(z)e^{\sigma t}$.

Perturbations of this type can only exist if they fulfill both the perturbation equations and the boundary conditions. This puts a restriction on σ : each set of external forcing parameters corresponds to a certain growth rate σ. Alternatively, in an equilibrium situation, this is also true for each set of $u_*, H, z_0, C_g, ..$,which are ultimately determined by the external forcings.

Let us assume that a perturbation of the exponential type (no matter how small) is actually present, then the sign of σ will determine what will happen to this disturbance. If $\sigma < 0$, the disturbance will vanish in time, and the reference state is said to be stable to this disturbance. On the other hand, if $\sigma > 0$ the disturbance has the tendency to grow exponentially in time. As a result the reference state is (linearly) unstable to this type of disturbances.

In practice it will be helpful to calculate the so-called 'marginal' curve (i.e. the $\sigma = 0$ curve) as a function of the external forcing parameters. This critical curve separates the (mathematically) stable cases from the unstable cases (compare e.g. Van de Wiel et al, 2002b).
The restriction to the analysis above is that only 1-D perturbations that grow *exponentially* in time are investigated. The rationale behind this is that, once they are unstable, they are likely to become dominant over other, slower growing solutions. However, this limits the generality of the results and comparison with observations (and numerical solutions of the non-linear system) is essential before definite conclusions can be drawn

We note that the analysis outlined above is more complicated (both from a physical and mathematical point of view) than the analysis discussed by Derbyshire by the fact that our equilibrium profiles are height dependent. As before, this mainly results from our assumption that the mixing length is proportional to z rather than constant, at least close to the surface. This makes the analysis more realistic so that it can be compared more easily with observational material. In ongoing research the mathematical and physical consequences of this extension are investigated.

CONCLUSIONS

Based on observational evidence and numerical simulations it is hypothesized that the process of stable boundary layer decoupling is caused by an (linear) instability of the quasi-steady stable boundary layer. A mathematical analysis of realistic profiles (shape according to MO-similarity) is proposed, based on stability analysis on 1-D perturbations, and is currently under investigation.

ACKNOWLEDGEMENT

We wish to thank Dr. Fred Bosveld (KNMI) for providing the Cabauw data.

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