J4.8 INSTABILITY OF THE STABLE BOUNDARY LAYER?

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1. INTRODUCTION

During clear nights it is often observed that, winds become very weak near the surface. In this situation there is little turbulence activity and near the surface temperatures reach relatively low values. The boundary layer is strongly stratified and it is sometimes referred to as the very stable boundary layer (VSBL) (Mahrt, 1999).

Alternatively we may also refer to this boundary layer as a so-called **decoupled boundary layer**. This is because the boundary layer is more or less 'detached' from the underlying surface due to a lack of significant turbulent transport. It is also known that, after a certain amount of time the decoupled boundary layer may re-couple again during a short period of enhanced turbulence leading to so-called intermittent turbulence. In the present work we will only focus on the initial state of the decoupling process, because it is hypothesized that this process marks the transition between the weakly stable boundary layer and the very stable boundary layer (see below).
Despite the fact that decoupled boundary layers seem to be omnipresent, the cause of the decoupling process itself is poorly understood: at present there is no theory available to predict this phenomenon or to predict the occurrence of VSBL's (Nieuwstadt, 2005).

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 a quasi-steady state (also: Derbyshire, 1999). In that case, the turbulent heat flux decreases linearly with height and the shape of the temperature profiles remains unchanged in time. Note that we use the term 'quasi'-steady (and not steady) because of the fact that the boundary layer cools. A similar picture exists for momentum, 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 later by the present authors (Van de Wiel et al., 2002a,b) from now on VdW2002a,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, they may 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 showed that, in essence, decoupling is a real physical phenomenon, arising from a positive feedback between turbulent transport in the SBL and the surface.

D99 attempted to generalize these results by performing a linear stability analysis on the system equilibria. With such a generalization, SBL decoupling could be predicted from observable parameters. To this end D99 simplified the column model mentioned above, by defining an idealized shear flow model *for linear temperature and wind profiles* (assuming a constant neutral mixing

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length). The result of the stability analysis supported the findings from the numerical simulations to a certain extent, in a sense that some profiles were unstable to perturbations at large *Ri*.

Although the assumption of linear profiles is mathematically attractive and maybe justified above the surface layer, it is *physically unrealistic* close to the surface. This is important because the instability of the flow is initiated close to the surface by the interaction between the atmosphere and the underlying surface (e.g. no-slip boundary condition; D99, VdW2002). It is commonly known that close to the surface profiles tend to be logarithmic rather than linear as a direct consequence of the fact that in this region the size of the dominant turbulent eddies scales with height. Thus, despite of fact that the theory of D99 is promising, no definite predictions of SBL behaviour can be made from this theory.

The aim of the present work is to apply stability analysis to the (more complicated) general case using realistic profiles. Such analysis will enable us to compare analytical results with actually observed cases, so that explicit predictions of SBL decoupling can be made in future applications.

2. AN OBSERVATIONAL EXAMPLE

Figures 1 and 2 show an example of decoupling based on CABAUW observations. The SBL decoupling occurred in the evening of 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 higher up, the boundary layer is decoupled from the surface.

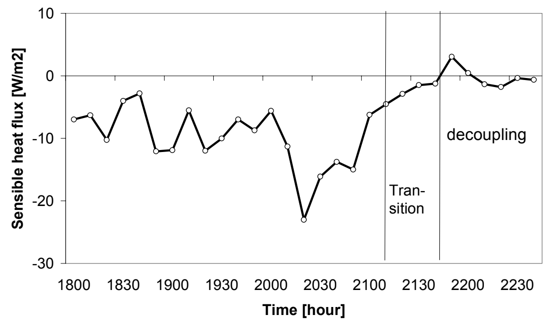

Fig 1: example of the turbulent heat flux prior to and during a SBL decoupling process. (Cabauw, Netherlands Nov. 15, 2002).

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 process (Fig. 2). Temperature observations were done at 2m, 10m, 20m, 40m. 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.

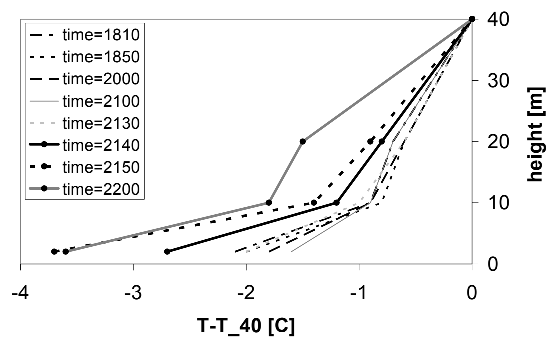

Fig. 2: temperature profiles prior to and during the decoupling event as observed at Cabauw, Nov. 15, 2002. Note that on the horizontal axis T(z =40m) is subtracted.

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 a single temperature curve (steady state). 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 collapses. After the turbulence collapses (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. A COUETTE FLOW AS A SURFACE LAYER ANALOGY

In order to explore the background of the decoupling mechanism above a relatively simple Couette type of flow was studied both numerically and analytically.
The model set up is such that in its stationary state the temperature and wind profiles follow Monin-Obukhov similarity. Such a model may serve as an analogy of the real atmospheric surface layer.
Some characteristics of the model are (Fig: 3, common notation):
-Both the wind speed and the temperature at the top of the model are prescribed: U_{TOP}, T_{TOP}.
-At the surface the heat flux H_0 is prescribed and via the introduction of the roughness length a no slip condition for wind is applied.
-Coriolis effects are ignored: 1-D flow.
-long wave radiative divergence is neglected.
-turbulent transport is modeled by using first order closure based on *Ri* (local equilibrium assumption in the TKE budget), e.g. the turbulent diffusivity is given by:
$K_{H,m} = l_n^2 (\partial U/\partial z) f(Ri)$; with
$l_n = \kappa z$ and

$$f(Ri) = (1 - \frac{Ri}{Rc})^2 \; ; \quad Rc = 0.2$$

The latter formulation is asymptotically (in a constant flux layer) in agreement with the MO-relations according to Businger (1971) (VdWa,b).
In summary: our governing equations read:

$$\frac{\partial U}{\partial t} = \frac{\partial \tau/\rho}{\partial z} \quad \text{and} \quad \frac{\partial T}{\partial t} = -\frac{\partial H/\rho c_p}{\partial z}$$

The log-linear character of the wind and temperature profiles requires a very fine numerical discretization near the surface in order to obtain accurate results. The results need to be accurate in order to be comparable with the analytical analysis. Therefore, we use a grid spacing Δz of 0.2 [m] near the surface with a stretch factor of 5 % upwards. With 40 layers the resulting model domain δ becomes 23.6 [m], comparable with typical values of the atmospheric surface layer under stable conditions (see: section 5).

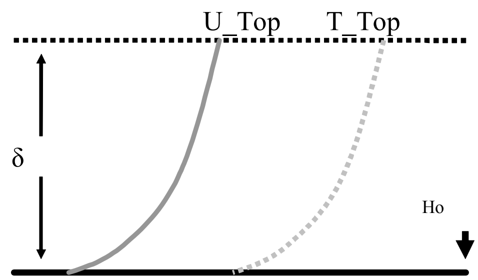

Fig. 3: Schematic picture of the Couette system.

Results

As a first exercise the response of the system to increased cooling is examined. To this end the wind speed at the top is fixed at 4 [m/s] and four different simulations were done for different fixed heat flux values H_0. Alternatively we could have varied U_{TOP} between the cases and keep a single value for H_0, which would lead to similar results. The four simulations start from a neutral state, so that, according to our set up the simulation have the same friction velocity at *t* = 0. In figure 4 the time evolution of the friction velocity for the cases is shown as an indication of the evolution of turbulence intensity in response to different cooling rates.

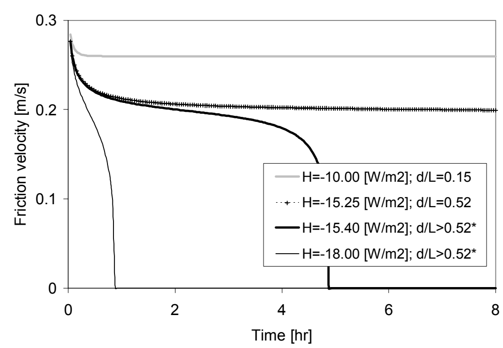

*Fig. 4: Time evolution of the friction velocity for four different cooling rates. *The equilibrium values for δ/L are given except for the collapsed cases where no turbulent equilibrium is reached.*

We observe that a stationary situation is reached for heat flux values of -10 and -15.25 [W/m2], the latter being the limiting case of the stationary solutions for this U_{TOP} of 4 [m/s]. The limiting case correspond to a δ/L of 0.52. It immediately occurs that the model's response to a slightly larger cooling rate of -15.40 [W/m2] is not smooth as might be expected. Instead a **dramatic change** of the results is observed, with the friction velocity rapidly going to zero. Apparently the Couette model cannot support more than 15.25 [W/m2] of flux with this given wind speed at the top.

In order to get more insight in the model results we look into more detail at the limiting continuous turbulent case H_0=-15.25 [W/m2] and at the collapse (decoupled) case H_0=-15.40. [W/m2]

The continuous turbulent case

In Figure 5 and 6 the evolution of the wind and temperature profiles for the continuous case are given. It is observed that both the wind and the temperature profiles evolve from the initial neutral situation towards a limiting situation (steady state) that is stably stratified. This limiting situation agrees well with the analytical equilibrium (see: next section) for the given values of the external parameters U_{TOP} and H_0. Because in a true steady state both the momentum and the heat flux are constant with height (not shown), the analytical solution is exactly represented by the classical MO profiles mentioned in section 2.

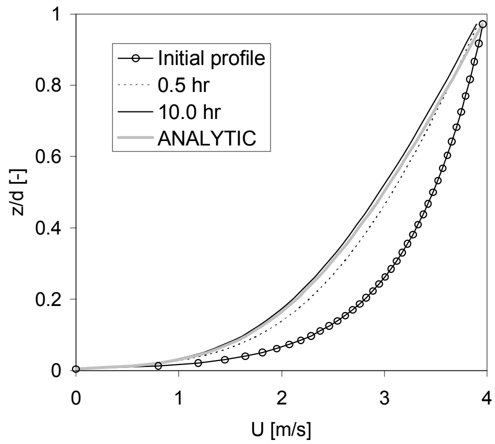

Figure 5: evolution of the wind profile for the 'continuous turbulent' case. Also the analytical solution for the steady state is given (see: text).

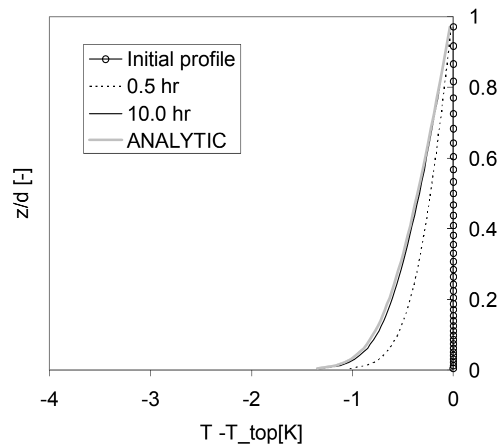

Figure 6: as Figure 5 but now for the temperature profile.

The decoupled case (collapse)

In the period after 4.5 hours the turbulent stress profile rapidly decreases over the whole layer (not shown), which causes a strong divergence of the turbulent heat flux profile (not shown)

In Figure 7 and 8 the evolution of the wind and temperature profiles for the decoupled case are given. Figure 7 shows that the wind profile changes from a logarithmic shape (in the initial neutral state) to a more log-linear shape at large stability. Consequently, during the decoupling process, the wind close to the surface becomes weaker than initially, during the neutral conditions. *The effect of the decoupling process is also evident in Figure 8. After a gradual initial cooling of2 K* *in about 4.5 hours, the boundary layer starts to cool very rapidly (over 1 K in 20 minutes). Obviously, this effect is strongly connected with the collapse of turbulence indicated by the results of Fig. 4.*

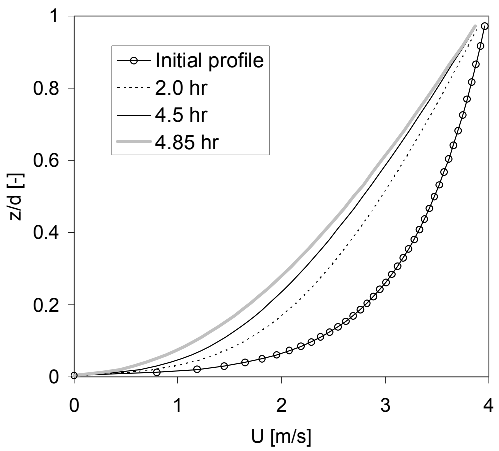

Figure 7: evolution of the wind profile for the 'decoupled' case.

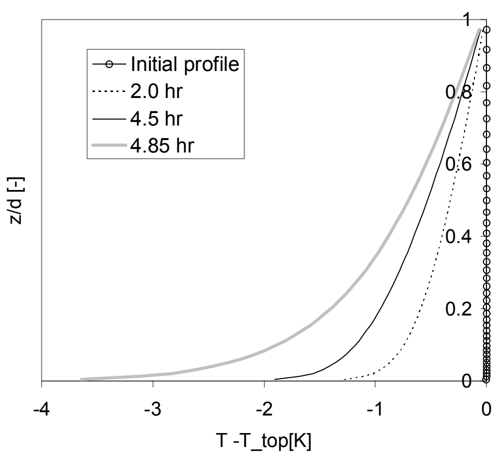

Figure 8: as Figure 7 but now for the temperature profile.

The process in Figure 8 is sometimes referred to as 'runaway-cooling'. In numerical modelling this may lead to continuation problems, and often this process is suppressed by an artificial modification of the observationally based stability functions (e.g. Louis, 1979).
According to the authors, however, this 'runaway' cooling is a realistic physical feature of the SBL! Nevertheless, normally, the 'runaway' cooling of the surface 'stops' after a certain amount of cooling (say O(5-10 K)), because of strong negative feedbacks in the net longwave radiation and in the soil heat flux that eventually enable a temperature equilibrium even in absence of a turbulent heat flux (VdWa,b2002).
Finally, it is noted that, although a detailed comparison with observations is beyond the scope of this text, figure 6,8 and 2 look rather similar, at least in a qualitative sense.

4 PREDICTING DECOUPLING

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 must also be stable."

In the present work this is interpreted as follows: **we hypothesize that:**
1) the continuous turbulent solutions of the SBL are (mathematically) stable for high mechanical forcing, and are therefore observed in nature.
2) the continuous turbulent solutions of the SBL are (mathematically) unstable for low mechanical forcing, and are therefore not observed in nature. In this second case a decoupled SBL (with very low turbulence levels) will be observed.

Recently, the Couette system was analyzed analytically. Expressions for the equilibrium solution(s) were found. A (preliminary) result is given in Figs. 5 and 6. It is shown that the numerical solutions indeed evolve towards these solutions.
Moreover, the (mathematical) *stability* of the equilibria was investigated, because this is essential according to the philosophy indicated above. The stability of the system could be predicted a priori from the forcing parameters and results agreed with the numerical simulations. That is, both (mathematically) stable equilibria with continuous turbulence and unstable equilibria with a decoupled SBL are predicted under exactly the same conditions as with the numerical simulations.

Because the results were obtained only recently, a detailed treatment is beyond the scope of the present text.

Both the numerical and analytical results will be presented at the conference, together with a discussion on the atmospheric implications.

SUMMARY

In the present work investigated the physics behind the decoupling phenomenon (collapse of turbulence). To this end a simplified Couette flow was studied both numerically and analytically. It was shown that decoupling arises from a natural physical instability. The resulting framework enables future prediction of this phenomenon in meteorological application.

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