The collapse of turbulence in the atmospheric boundary layer

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Abstract. A well-known phenomenon in the atmospheric boundary layer is the fact that winds may become very weak in the evening after a clear sunny day. In these quiet conditions usually hardly any turbulence is present. Consequently this type of boundary layer is referred to as the quasi-laminar boundary layer. In spite of its relevance, the appearance of laminar boundary layers is poorly understood and forms a long standing problem in meteorological research. Here we investigate an analogue problem in the form of a stably stratified channel flow. The flow is studied with a simplified atmospheric model as well as with Direct Numerical Simulations. Both models show remarkably similar behaviour with respect to the mean variables such as temperature and wind speed. The similarity between both models opens new way for understanding and predicting the laminarization process. Mathematical analysis on the simplified model shows that relaminarization can be understood from the existence of a definite limit in the maximum sustainable heat flux under stably stratified conditions. This fascinating aspect will be elaborated in future work.

1. General introduction

For many purposes related to meteorology and climate a proper understanding of the boundary layer processes in stably stratified conditions is essential, see: Fernando & Weil (2010). In spite of its importance, a true general framework of the stable boundary layer (SBL) is still lacking. In absence of a framework, it appears useful to classify stable boundary layers into two major prototypes (Mahrt et al., 1998): the Weakly Stable Boundary Layer (WSBL) and the Very Stable Boundary Layer (VSBL). Weakly stable boundary layers are characterized by the presence of continuous turbulence and tend to occur in windy and/or cloudy conditions. This type of boundary layer is generally rather well-understood and both fluxes and profiles more or less obey the local similarity scaling as formulated by Nieuwstadt (1984). Therefore, for most practical modeling applications our representations of the WSBL are acceptable to some degree (e.g. Sorbjan (2006); Steeneveld et al. (2006)).

In contrast the very stable boundary layer is poorly understood. This type of boundary layer is characterized by the occurrence of turbulence that is discontinuous in time and usually rather weak or virtually absent. In the latter case we may speak of a so-called radiative SBL, due to the fact that, in the absence of turbulent heat transport, radiation and soil heat conduction are the...
dominant thermodynamic processes (van de wiel et al., 2003). Even though a complete picture of the VSBL does not exist, considerable effort has been made in recent years to characterize important features of the SBL under strongly stratified conditions. Especially, extensive field campaigns such as CASES99 (Poulos & Blumen, 2002) facilitated detailed characterization of e.g.: drainage flow, (Mahrt & Vickers, 2001), low-level jet formation (Banta, 2007), intermittent turbulent events and flow instabilities (Sun et al., 2003; Newsome & Banta (2003)), longwave radiative divergence (Sun & Lenschow, 2004) and soil heat transport (van de wiel et al., 2003). Although the aforementioned classification into WSBL and VSBL is useful as a concept, a formal well-established criterion for existence of different SBL regimes does not exist. It is not clear why and when turbulence in the WSBL 'gives up' and loses its continuous character. The current work aims to improve our understanding of the transition mechanism by studying the dynamics of a stratified channel flow, with a simple eddy viscosity model based on local similarity closure. Based on this model it will be shown that the collapse of turbulence can be understood from a limitation in the heat that can be transported downward by turbulence, i.e. under stably stratified conditions: the so-called maximum sustainable heat flux (see below). As the eddy viscosity model is based on simplified physics it is necessary to provide some kind of validation of the assumed turbulence closure for this type of flows. Therefore, in the next sections, we will first compare the simulations with the simplified model with those from direct numerical simulations (DNS).

2. Set up of the numerical experiment

Our set up follows the set up by Nieuwstadt (2005), summarized here. An aerodynamic smooth channel flow is simulated for which $Re_\infty = \frac{u_\infty h}{\nu} = 360$, with $u_\infty = \sqrt{-\frac{1}{\rho} \left( \frac{\partial P}{\partial x} \right) h}$ and channel depth $h$. At the lower boundary, the extracted heat $H_0$ is prescribed by fixing the external parameter $h/L_\infty \equiv \frac{\kappa g h H_0}{\rho c_p u_\infty^3}$. A schematic view of the flow set-up is given in Figure 1. Note that the heat extraction is initiated after a neutral spin-up period of $25t_\ast$ with $25t_\ast = h/u_\infty$.

![Pressure force](image)

**Figure 1.** Schematic picture of the channel flow. Decreasing temperature is reflected by increasing grey-scale.

3. Model characteristics

The DNS numerically solves the conservation equations for momentum (basically, the Navier-Stokes equations under the Boussinesq assumptions) and heat. Some characteristics of the model are given below. Here, we opted for a limited number of grid cells ($200^3$; tests on finer grid sizes where performed showing that this resolution is sufficient for the Reynolds number considered) in order to be fully consistent with the original simulations of Nieuwstadt (2005), which will be
used for future comparison. For more details on the model characteristics, we refer to Moene (2003). The model utilizes periodic boundary conditions in the \(x\) and \(y\) direction. In the \(z\)-direction temperature is fixed at the channel top and the heat flux at the surface is prescribed. For velocity a no slip at the bottom and a free slip condition at the top is applied. The flow is driven by a horizontal pressure gradient.

In the atmospheric model parameterized versions of the aforementioned momentum and heat equations are solved. In particular first order closure (K-theory) is adopted to relate the local stress and local heat flux to the local gradients of mean wind and temperature, e.g. for momentum (see: van de wiel et al. (2007)):

\[
\frac{\tau}{\rho} = K_{TOT,M} \frac{\partial U}{\partial z}.
\] (1)

The total diffusivity is taken to be the sum of molecular and turbulent contributions:

\[
K_{TOT,M} = \nu + K_M,
\] (2)

\[
K_{M,H} = l^2 \frac{\partial U}{\partial z} f(Ri) \text{ with } l = \kappa z \text{ and the gradient Richardson number defined as:}
\]

\[
Ri \equiv \frac{g}{T} \frac{\partial T/\partial z}{(\partial U/\partial z)^2},
\] (3)

where \(f(Ri)\) is an exchange function based on vast atmospheric observations (local similarity scaling). Note that, as atmospheric conditions are in the high Reynolds number regime (typically \(O(10^8)\)), it is not a priori obvious that this gradient transfer approach would lead to a reasonable model in the relatively low Re regime studied here. Below it will be argued that such simplified approach has potential relevance.

4. Model comparison

With the DNS-model the numerical experiment is carried out for two different cooling rates (again, following Nieuwstadt (2005)). By altering the surface heat flux, a regime transition from a continuous SBL to a non-turbulent SBL is observed, resembling typical behavior observed in the atmosphere. Figure 2 shows the turbulent kinetic energy (TKE) as a function of time. For moderate cooling, \(h/L_{ext} = 0.4\), the TKE approaches a steady state as in the continuous turbulent atmospheric boundary layer. For \(h/L_{ext} = 2.0\), however, the TKE rapidly decreases reflecting a case with ceasing turbulence. Apparently, the system’s response is highly non-linear (not ‘smooth’) for increased cooling.

As an innovative aspect the cases presented in figure 2 were also simulated with the simplified atmospheric model. The simulated profiles of the mean variables (wind and temperature) and fluxes were compared with the outcome from the DNS. For brevity reasons only temperature profiles are shown here (Figures 3 and 4). For the moderate cooling rate \((h/L_{ext} = 0.4); \text{ Fig. 3}\) the similarity between the time evolution of the profiles found by the models is remarkable. Note that a similar kind of agreement was found for the velocity profiles (not shown). For the strongly cooled case \((h/L_{ext} = 2.0)\) again both model seem to agree reasonably well (Figure 4). On the other hand it is realized that the simplified model is at best a surrogate of the direct numerical simulation model with respect to the mean and the flux profiles: in general, subtle dynamical effects, particularly those that occur around the critical transitions will not be captured by a one-dimensional gradient-transfer model.
Figure 2. Evolution of the normalized turbulent kinetic energy in a stably stratified channel flow. The cases represent moderate cooling (black line) and strong cooling (grey line).

Figure 3. Temporal evolution of the mean temperature profile as calculated by the present work Direct Numerical Simulation (left) and for the atmospheric model (right). Turbulent case.

5. The maximum sustainable heat flux

Encouraged by the results above, we propose to use the atmospheric gradient-transfer model as a surrogate model for the DNS in order to understand the underlying collapse mechanism. Then, by simple gradient-transfer thinking, one can anticipate that the turbulent heat flux must have some definite maximum: obviously, a small mean temperature gradient results in a small turbulent heat flux. At the other extreme, when the temperature gradient is very large, vertical mixing is strongly suppressed, which again allows only a limited turbulent heat exchange. As a result the turbulent heat flux reaches a certain maximum at some intermediate (optimal) temperature gradient. Clearly, when the surface cooling exceeds this maximum, the system is
not able to reach a steady turbulent state. By using this gradient-transfer analogy, (van de wiel et al., 2007) quantified this turbulent heat flux maximum for a stably stratified Couette flow configuration. Additionally, linear stability analysis was used to show that flow transitions coincided with the exceedance of this maximum. In Figure 5 a bifurcation diagram for this flow is given, showing the (normalized) equilibrium friction velocity of the flow, as a function of the normalized surface cooling. For cooling rates beyond the maximum, the system cannot reach a turbulent equilibrium state and will end up in a laminarized end state.

6. Conclusion and outlook

The present work suggests a strong similarity between the simplified atmospheric model and the DNS. As such, it is concluded that the simplified model is a useful alternative tool for
theoretical work on the mechanisms behind the collapse phenomenon. It remains a challenge to extend the concept of the maximum sustainable heat flux, as recently developed for Couette flows, to pressure driven flow configurations in future work. Such extension would facilitate a more direct comparison with real cases of ceasing turbulence observed in the atmosphere.

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