THE MAXIMUM SUSTAINABLE HEAT FLUX IN THE ATMOSPHERIC NOCTURNAL BOUNDARY LAYER

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Abstract Here, the mechanism behind the collapse of turbulence in the evening as a precursor to the onset of the very stable boundary layer, is investigated. To this end a cooled, pressure-driven flow is investigated by means of a local similarity model. This local similarity model is effectively a gradient-diffusion/eddy viscosity model, which was validated against atmospheric observational data and Direct Numerical Simulations in a previous study. Current simulations reveal a temporary collapse of turbulence whenever the surface heat extraction, expressed in its non-dimensional form h/L, exceeds a critical value. As any temporary reduction of turbulent friction is followed by flow acceleration, the long-term state is unconditionally turbulent. In contrast, the temporary cessation of turbulence, which may actually last for several hours in the nocturnal boundary layer, can be understood from the fact that the time scale for boundary layer diffusion is much smaller than the time-scale for flow acceleration. This limits the available momentum that can be used for downward heat transport. In case the surface heat extraction exceeds the so-called maximum sustainable heat flux (MSHF), the near-surface inversion rapidly increases. Finally, turbulent activity is largely suppressed by the intense density stratification which supports the emergence of a different, calmer boundary layer regime

FLOW SET UP

In the present work we follow the setup of Nieuwstadt (2005) [1] and Flores and Riley (2011) [2]. A pressure driven non-stratified flow is suddenly cooled from below. A schematic picture of the configuration is given in Figure 1 below.

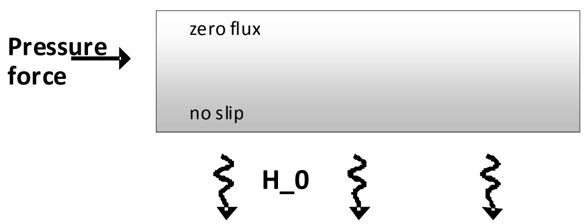

Figure 1. schematic picture of the channel flow configuration with the pressure gradient force and prescribed surface heat extraction as external parameters. Decreasing temperature is indicated by increasing grey-scale.

RESULTS

In Figure 2 the evolution of the normalized surface stress is given as a function of time for different rates of surface cooling. Observe that a temporary collapse of turbulence occurs for cooling rates above 1.14. In the long-term the flow re-establishes its turbulent state due to flow acceleration which re-establishes shear generated turbulence (Figure 3).

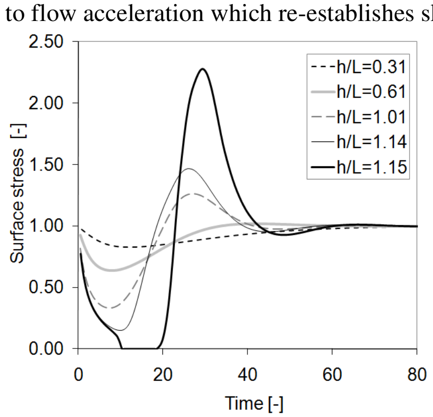

Figure 2. Normalized surface stress as a function of dimensionless time for different surface cooling rates, represented by the dimensionless parameter h/L.

Goal of the present study is to predict whether turbulence is able to survive or not during the transient period (~say for t< 10). To this end an analytical model was developed that uses a so-called *pseudo-steady state* (PS) concept [3,4]: due to the fact that the time scale for boundary layer diffusion is much smaller than the time-scale for flow acceleration, the system temporarily reaches a (near) equilibrium with the new boundary condition by redistribution of its available initial momentum in the layer adjacent to the surface (this occurs around t~10 in Figure 2). A typical velocity profile during this pseudo-equilibrium state is given by the blue dashed line in figure 3 below; the analytical approximation for the pseudo-steady state solution is given by the thick blue line. For comparison also the simulated and predicted long-term steady state solutions are given in red. Note that the pseudo-steady state (to which the system is attracted initially) differs considerably from the true steady state to which the system is attracted eventually on the long term (after acceleration).

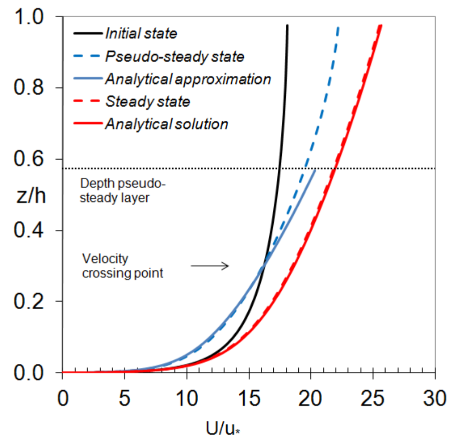

Figure 3. Simulated evolution of the velocity profile. Note also that, as turbulent diffusion is limited in the long-term, stratified case in comparison with the neutral initial state, higher shears are needed to oppose the pressure gradient.

Next we evaluate for which external condition such pseudo-steady state solution can be obtained (Figure 4). This reveals that there is a maximum surface heat flux h/L for which turbulence can survive on the short term. In view of the approximations done (predictions where made for a transient situation which is only pseudo-steady, assuming separation of diffusion and acceleration time scales), the predicted critical value h/L~1.29 seems to be in acceptable agreement with the critical value of h/L~1.14, which appears from the numerical simulations (Fig. 2).

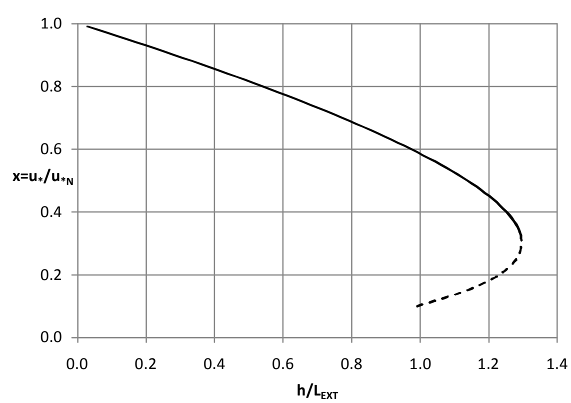

Figure 4. pseudo-steady solution-space: normalized friction velocity as function of normalized cooling h/L_ext. The maximum heat flux that can be sustained by the flow for those initial conditions is predicted to be at h/L_ext=1.29.

References

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