The maximum sustainable heat flux in stably stratified channel flows

Donda Judith[1], Van Hooijdonk Ivo[1], Moene Arnold[2],
Van Heijst GertJan[1], Clercx Herman[1], Van de Wiel Bas[1]
[1]*Fluid Dynamics Laboratory, Eindhoven Univ. Techn., Netherlands*
[2]*Dept. Meteorology, Wageningen Univ., Netherlands*

Abstract In analogy to the nocturnal atmospheric boundary layer a flux-driven, cooled channel flow is studied using Direct Numerical Simulations (DNS). Here, in particular, the mechanism behind the collapse of turbulence at large cooling rates is analyzed. In agreement with earlier studies, the flow laminarizes at large cooling rates. The mechanism for the cessation of turbulence is understood from a Maximum Sustainable Heat Flux hypothesis, which is here tested against simulations. In stratified flow the maximum heat flux that can be transported downward by turbulence at the onset of cooling is limited to a maximum, which, in turn, is limited by the initial momentum of the flow. If the heat extraction at the surface exceeds this maximum, near-surface stability will rapidly increase, which further hampers efficient vertical heat transport. This positive feedback eventually causes turbulence to be fully suppressed by the intensive density stratification. It is shown that the collapse in the DNS-simulations is successfully predicted by the MSHF-theory. Apart from formal analysis, also a simplified methodology is presented, which is more useful in practice for prediction of regime-transitions in atmospheric field observations.

Introduction

The state of the nocturnal atmosphere is influenced by two competing factors: longwave radiative cooling, which acts to create a pool of cold dense air near the surface, and turbulence driven by wind shear, which acts to mix this air with warmer air aloft [1, 2]. On a synoptic scale those aspects are generally related to the amount and type of cloud coverage and the strength of the synoptic wind field. Depending on the relative importance of the aforementioned factors boundary layers with different flow characteristics may occur. Based on observational analysis, a widely accepted vision is the separation in a so-called weakly stable boundary layer and the very stable boundary layer [3]. Weakly stable boundary layers are characterized by continuous turbulence and tend to occur in cloudy and/or windy conditions. In contrast, very stable boundary layers commonly occur under clear skies with weak winds. In this case turbulence is weak or, in extreme cases, almost absent (quasi-laminar flow).

A stably stratified channel flow

The regime transition is studied using Direct Numerical Simulations following the configuration by [4]. A homogeneous channel flow is simulated forced by a horizontal pressure gradient and cooled by a fixed amount of cooling at the surface denoted by the dimensionless parameter h/L_{EXT} (Figure 1).

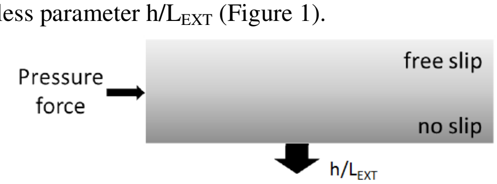

Figure 1. Schematic view of the configuration. Decreasing temperature is indicated by increasing grey-scale.

In agreement with earlier studies (e.g. [4]) the flow shows a collapse of turbulence when the nondimensional cooling parameter h/L_{EXT} exceeds a value of 0.5 (Figure 2a).

Hypothesis

In this work the aforementioned occurrence of turbulent/laminar regimes is explained from the so-called Maximum Sustainable Heat Flux hypothesis (MSHF). It uses the fact that in stratified flow the downward turbulent heat flux is limited to a maximum, which occurs at moderate stability. In turn, this is understood from the fact the heat flux becomes small in the neutral limit (no stratification) and in the very stable limit (weak mixing; Figure 2b). When the extracted heat at the surface exceeds the maximum heat flux that can be sustained by the flow, the near-surface stratification rapidly intensifies. Mixing is strongly suppressed so that vertical heat transport decreases further. Turbulent length scales decrease and finally this positive feedback ends in a total suppression of turbulence.

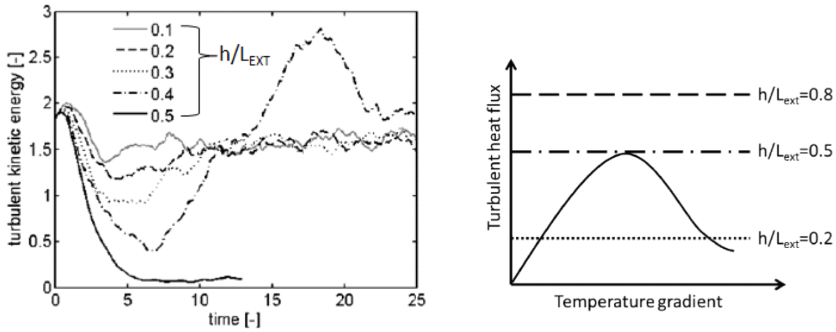

Figure 2.a) Temporal evolution of the scaled turbulent kinetic energy. Cases represent different cooling rates. b). Idealized sketch of the downward turbulent heat flux as a function of the temperature gradient (based on typical observational statistics). Different cases of surface cooling are indicated by the horizontal lines: weak surface cooling (dotted line), 'critical cooling' (dashed-dotted) and strong cooling (dashed). Note that the heat transport maximum depends on the available momentum of the flow at the onset of cooling.

In order to predict the regime transition in the DNS a simple turbulence closure based on an eddy viscosity concept was adopted. The height-dependent eddy viscosity depends on both wind shear and temperature gradient and is based on atmospheric observational data. The predicted mean profile of wind and temperature agree well with the simulated profiles. With this 'calibrated' model the full theoretical solution curve can be given, similar to Figure 2b. For three different values of the closure model parameter, the non-dimensional solution space is depicted in Figure 3. The curves indicate that when $h/L^{-1/3}$ drops below a critical value (i.e. when h/L exceeds a critical value) no turbulent state is allowed in the short term after the onset of cooling. Note that the specific choice of plotting is chosen for the purpose of further physical interpretation in terms of a new velocity scale Umin (not discussed here). Besides theoretical curves also results of the numerical simulations are given. It appears that the model is able to mimic the solutions space obtained by the simulations. This qualitative agreement suggests that the proposed mechanism (the Maximum Sustainable Heat Flux mechanism) indeed is responsible for the flow transition observed in the numerical simulations. In future work, there is a need to extend the present framework to configurations which are more realistic from an atmospheric perspective. This allows for inclusion of for example Coriolis effects and more realistic surface boundary conditions.

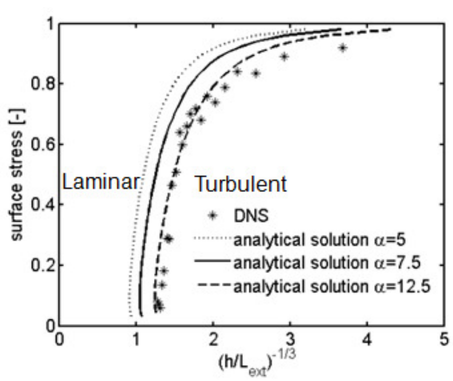

Figure 3. Minimum surface stress after onset of cooling for different cases with different cooling rates represented by the black star symbols (cooling increases to the left). Predictions by the MSHF-hypothesis are given by the solid, dashed and dotted line (for three different values of the turbulent closure parameter).

References

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