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Laboratory and Numerical Modeling of a Stably Stratified Wind Flow over a Water Surface

D. A. Sergeev[a,b,*], O. A. Druzhinin[a,b,], Yu. I. Troitskaya[a,b,***], W. T. Tsai[c], M. I. Vdovin[a,b], and A. A. Kandaurov[a,b]**

[a] *Institute of Applied Physics, Russian Academy of Sciences, Nizhniy Novgorod, 603155 Russia*
[b] *Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603022 Russia*
[c] *National Taiwan University, Taipei, 10617 Taiwan*
**e-mail: daniil@hydro.appl-sci-nnov.ru,*
***e-mail: druzhinin@hydro.appl.sci-nnov.ru,*
****e-mail: yuliya@hydro.appl.sci-nnov.ru*

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Abstract—The objective of this paper was to perform laboratory modeling and direct numerical simulation of a turbulent wind flow over a water surface under stable stratification conditions of the air boundary layer. Laboratory and numerical experiments were carried out with the same bulk Reynolds (Re) and Richardson (Ri) numbers, which first allowed direct comparison between measurements and calculations. A wind flow with an air–water temperature difference of up to 20°C and a relatively low wind speed (up to 3 m/s) were obtained in laboratory experiments in the wind–wave flume of the large thermostratified tank at the Institute of Applied Physics of the Russian Academy of Sciences. This allowed a sufficiently strong stable stratification with a bulk Richardson number of up to 0.04. The air velocity is obtained using both contact (a Pitot tube) and particle image velocimetry methods. At the same time, the air temperature profile is also measured by a set of contact probes. Analogous bulk Richardson and Reynolds numbers are prescribed in the direct numerical simulation, where the turbulent Couette flow is considered as a model of the near water constant-stress atmospheric boundary layer. The mean velocity and temperature profiles obtained in our laboratory and numerical experiments agree well; they are also predicted well by the Monin–Obukhov similarity theory. The experimental results state that sufficiently strong stratification, although it allows a statistically stationary turbulent regime, leads to a sharp decrease in momentum and heat fluxes. For this regime it is demonstrated that the turbulent Reynolds number for the boundary layer (based on the Obukhov length-scale and friction velocity) satisfies the known criterion that characterize stationary strongly stratified turbulence.

Keywords: boundary layer, wind, waves, stratification, numerical simulation, laboratory experiment.

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INTRODUCTION

In large-scale predictive weather and climate models, it is important to know the detailed parameters of the small-scale processes in the near water atmospheric boundary layer to correctly parameterize the turbulent exchange that occurs there. Under the conditions of a relatively small air–water temperature difference (a few grades) and a sufficiently strong wind (from a few meters per second), the near-water boundary layer flow may be considered turbulent and weakly stratified and its parameters are well predicted by the Monin–Obukhov similarity theory [1]. The subcritical regime of sufficiently strong stable stratification is of special interest in which the wind is statistically stationary and turbulent, although the momentum and heat fluxes can abruptly decrease in comparison with the case of a weakly stratified flow. In practice, the subcritical regime occurs, for instance, under advection of the relatively warm continental wind into the domain of a colder sea or lake water surface in the spring season, when the water–air temperature difference can be rather considerable (more than 10°C) enough to make the stratification effects more pronounced under sufficiently low winds (3 m/s or lower) [2, 3]. The known field data and laboratory experiments show that strong stable stratification effectively weakens turbulent exchange of momentum and heat in the boundary layer, compared with the case of a weakly stratified turbulent boundary layer, where the Monin–Obukhov similarity theory can be applied [4]. The detailed experimental measurements of velocity profiles and temperature of the stably stratified boundary layer (from the case of weak stratification to the case of strong stratification) were carried out in [5]. In this laboratory experiment the airflow over a cold solid bottom was studied in a thermostratified wind channel. The bulk velocity of the flow U_0 was from 0.8 m/s to 3 m/s, the temperature difference between the air and the solid bottom ΔT varied from 46 to 57°C, the bulk Reynolds and Richardson numbers were $\mathrm{Re} = O(10^4–10^5)$ and $\mathrm{Re} = O(0.1–1)$. The results show that under the stable stratification the wind velocity in the boundary layer normalized by the bulk velocity decreases compared with the case of weak stratified flow. The results also demonstrate a decrease in the turbulent momentum flow when the stratification increases. However, in this paper there were no comparisons between the experimental results obtained under the strong stratification conditions and the prediction of the Monin–Obukhov similarity theory.

In our previous works we studied a stably stratified flow over a water surface with direct numerical simulation (DNS) for a wide variety of bulk Reynolds and Richardson numbers [6]. DNS does not require parameterization and allows operation with all physically significant scales up to the characteristic scales of viscous dissipation (i.e., up to the Kolmogorov scale). For relatively small Richardson numbers, DNS describes the statistically stationary turbulent regime with the vertical velocity and temperature profiles that conform to the Monin–Obukhov similarity theory. We investigated the transition from the turbulent to the laminar regime, dependent on both Reynolds and Richardson numbers, and compared the results with those given in [7]. In this work the laboratory and numerical experimental data were collected and a specific DNS was carried out to analyze the transition from the turbulent to laminar regime in terms of a turbulent Re_L number computed with the Obukhov length-scale and friction velocity. The main result obtained in [7] is that the stationary turbulent regime is sustained if $\mathrm{Re}_L < 100°$, while in the opposite case the flow becomes laminar. The results in [6] confirmed this criterion. Nevertheless, knowledge about the threshold regime is incomplete; in this regime the boundary layer can be considered as a statistically stationary turbulent regime and its behavior is described by the Monin–Obukhov similarity theory dependent on the stratification conditions. This study is aimed at laboratory and numerical investigation of this regime.

We performed both laboratory and numerical simulations of the turbulent wind flow over a water surface under the conditions of strong and weak stratifications. The laboratory and numerical experiments were carried out with the same Ri and Re numbers, which first allows comparison of the results of measurements and DNS.

The paper is organized as follows: In the first section we briefly formulate a prediction of the Monin–Obukhov similarity theory for the case of weak stratification of the boundary layer. In the second section we describe the scheme of the laboratory experiment, measurement techniques, and the numerical simulation procedure and compare their results. The Conclusions contains a discussion and inferences.

1. PREDICTION OF MONIN–OBUKHOV SIMILARITY THEORY FOR VELOCITY AND TEMPERATURE PROFILES IN THE CASE OF A WEAKLY STRATIFIED BOUNDARY LAYER

A stably stratified boundary layer is called weakly stable when the statistically stationary turbulent regime occurs despite the buoyancy effects [4]. In this weakly stratified flow of the boundary layer, the dependencies of the mean velocity $U(z)$ and of the deviation of the mean temperature from the reference value in the vicinity of the surface, $(T(z) - T_0)$, on height z are described by the Monin–Obukhov similarity theory [1] in the domain of the constant turbulent stress in the form:

$$\frac{U(z)}{u_*} = \frac{1}{\kappa}\left(\ln\frac{z}{z_{oU}} + C_U\frac{z}{L}\right), \tag{1}$$

$$\frac{T(z) - T_0}{T_*} = \frac{\mathrm{Pr}_t}{\kappa}\left(\ln\frac{z}{z_{0T}} + C_T\frac{z}{L}\right), \tag{2}$$

where κ is the Karman constant, C_U and C_T are empirical dimensionless constants, and Pr_t is the turbulent Prandtl number. The typical values for the most of the field and laboratory studies are $\kappa = 0.4$, $C_U = 2$, $C_T \sim C_U$ and $\mathrm{Pr}_t = 0.85$. The turbulent temperature- and velocity-scales denoted by u_* (friction velocity, in m/s) and T (in K) are expressed in terms of turbulent momentum and heat fluxes τ and F as

$$u_* = \sqrt{\tau}, \quad T_* = F/\sqrt{\tau}, \tag{3}$$

where τ and F are taken at a sufficiently large distance from the surface, where they approach their asymptotic values. The turbulent Prandtl number, Pr_t, is determined by

$$\mathrm{Pr}_t = \frac{u_*}{T_*}\frac{dT}{dz}\left(\frac{dU}{dz}\right)^{-1}. \tag{4}$$

The Obukhov turbulent length-scale L (in m) is given by

$$L = \frac{u_*^2}{(g/T_0)T_*}, \tag{5}$$

where g is the free fall acceleration. Note that our definition of Obukhov scale L, see (5), does not contain the Karman constant κ whereas the common version of this scale $\tilde{L}$ does contain κ in the denominator $\tilde{L} = L/\kappa$. Hence, the second term in the right-hand side of

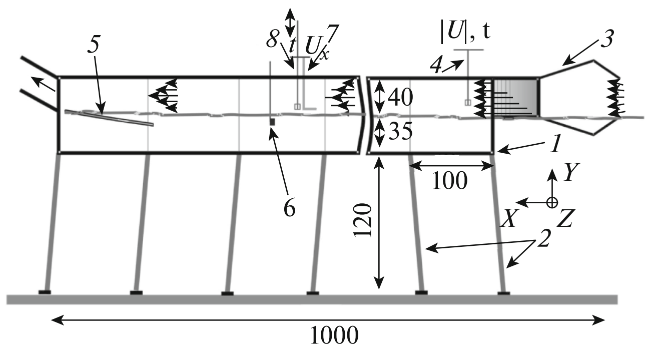

Fig. 1. The scheme of the wind–wave flume with equipment and mounted contact measurement facilities. Dimensions are given in centimeters: (*1*) wind-wave flume; (*2*) vertical bearings; (*3*) reducer; (*4*) thermal mass flow meter at the flume inlet for parameter monitoring; (*5*) wave suppressor; (*6*) is the water temperature sensor; (*7*) Pitot tube on the scanning device; and (*8*) air temperature sensor.

Eqs. (1) and (2) turn into $C_U \frac{\eta}{\kappa \tilde{L}} = \tilde{C}_U \frac{\eta}{\tilde{L}}$ and $C_T \frac{\eta}{\kappa \tilde{L}} = \tilde{C}_T \frac{\eta}{\tilde{L}}$, where $\tilde{C}_U = \frac{C_U}{\kappa}$ and $\tilde{C}_T = \frac{C_T}{\kappa}$, respectively.

In the case of an aerodynamically smooth flat surface, roughness lengths z_{0U} and z_{0T} are determined by the common relationships (see, for instance, [1])

$$z_{0U} = \frac{\nu}{u_*} \exp(-5\kappa),$$

$$z_{0T} = \frac{\nu}{u_*} \exp(-2.5\kappa),$$

where ν is the kinematic air viscosity.

The bulk Reynolds and Richardson numbers are given by

$$\mathrm{Re} = \frac{U_0 \delta}{\nu},$$

$$\mathrm{Ri} = g \frac{\Delta T}{T_0} \frac{\delta}{U_0^2},$$

where δ is the characteristic height (thickness) of the boundary layer, $U_0 = U(z = \delta)$, and $\Delta T = T(z = \delta) - T_0$. We note that according to Eq. (1) the answer to the question of whether the wind velocity increases or decreases with respect to the bulk velocity with an increase in the stratification influence (i.e., with growth of Ri) depends on the behavior of both the friction velocity u_* and the Obukhov scale L which are determined by the turbulent momentum and heat fluxes.

2. THE LABORATORY EXPERIMENT, NUMERICAL CALCULATIONS, AND COMPARISON OF RESULTS

The laboratory experiment was performed on the wind–wave flume (WWF) installed in the large thermostratified tank (LTST) at Institute of Applied Physics of the Russian Academy of Sciences. A detailed description of the test rig was presented in [8]. The principal scheme of the experiment is depicted in Fig. 1. Measurements were carried out for two cases: the strong and weak stratifications of the wind flow. To model the stable stratification of the boundary layer, the inlet wind flow was pre-heated to 35°C; the temperature of the water surface was kept constant, 15°C. Such a regime could be sustained, because the entire water volume in the basin of the LTST is large (approximately 120 m^3) and the area occupied by the WWF is only 4 m^2 (less than 5% of the entire area of the LTST basin). Therefore, the water heating via the wind was negligible during the experiments. Thus, the bulk temperature difference between the air and water under the weak stratification was 4°C, under strong stratification, approximately 20°C. In both cases the bulk wind velocity was in the range of 2–3 m/s. Such conditions of the laboratory experiment provide values of the bulk numbers in ranges Re ≈ 40000–60000 and Ri ≈ 0.01–0.04, respectively. The profile of the mean wind velocity was measured in the operating section placed at a distance of 7.5 m from the entrance into the wind–wave flume with a Pitot tube mounted on the scanning device (Fig. 1). The film thermometer was set near the Pitot tube on the scanning device, which allowed measurement of the profile of the mean airflow temperature. To reduce the statistical error, profile averaging by five different experimental samples was performed.

The Pitot tube gives only the mean characteristics of the airflow velocity, which does not allow one to obtain information about the flux of the turbulent momentum (the shear turbulent stress). To measure wind velocity fields we used a method based on visualization of the fluid and gas flows, that is, the particle image velocimetry method. The general scheme of the PIV method (Fig. 2) is based on the use of continuous laser illumination and is similar to the one employed in [8]. To visualize the airflow in the first section of the wind–wave flume, polyamide particles with a size of 20 μm (Fig. 2) were injected in the airflow. In the operating section (at 7.5 m from the flume beginning) a vertical laser knife was formed in the middle of the flume along the wind direction. The motion of particles in the area of the laser knife was fixed with a Videoscan (Videosprint) high-speed camera (with a shooting speed of 3012 s^{-1}, an exposure time of 100 μs, a frame size of 1280 × 166 pixels (250 × 32 mm), and a scale factor of 195 μm/pixel). For every regime 20 recordings were made with a duration of 0.5–2 s for each recording. The instantaneous velocity fields were obtained with cross-correlation analysis of the displacements of particles in the consecutive frames. We utilized the subpixel three-point interpolation of the cross-correlation function spike to make the displacement (velocity) determination more accurate. The obtained instantaneous velocity fields were filtered via the difference between the local velocity value and the mean value at a given height. The profiles of the mean velocity were obtained by averaging the filtered velocity fields by time and horizontal coordinate. The mean velocity fields were employed to assess the field of velocity fluctuation which was then averaged in a similar manner. Thus, for every recording we obtained the mean velocity profiles and the momentum flux. The resolution along the vertical coordinate was approximately 2.5 mm. The direct numerical simulation of the stably stratified Couette flow was carried out under the same Reynolds and Richardson numbers as in the laboratory experiment. The numerical experiment parameters were identical to the laboratory ones. Cartesian coordinates were chosen such that the x axis is oriented along the wind flow, the z axis is directed vertically, and the y axis is perpendicular to the airflow. We took the periodic boundary conditions along the x and y axes. The no-slip boundary conditions were prescribed for the upper and lower horizontal boundary planes divided by the distance D and moving in opposite directions along the x axis with velocities $\pm 0.5U_0$. The conditions of stable stratification were achieved using the temperature $T = T_0$ at the lower boundary, and by using $T = T_0 + \Delta T$, where $\Delta T > 0$, at the upper boundary. Since the bulk wind velocity in the laboratory experiment is comparatively small (less than 3 m/s) the surface wind waves were practically absent and the water surface remained aerodynamically smooth. Therefore, when using DNS we also considered the aerodynamically smooth (flat) water surface.

The numerical algorithm was based on integration of the full three-dimensional Navier–Stokes equations for an incompressible fluid under the Boussinesq approximation (see [7]). The governing parameters in DNS were the bulk Reynolds and Richardson numbers given by

$$\mathrm{Re} = \frac{U_0 D}{\nu},$$

$$\mathrm{Ri} = g\frac{\Delta T}{T_0}\frac{D}{U_0^2}.$$

In DNS we took Re = 60000 and Ri = 0 for the non-stratified case and Re = 40000 and Ri = 0.04 for the stratified one, which corresponded to the conditions of the laboratory experiment. The organization of the DNS procedure was similar to the material discussed in [7]. The velocity field in DNS was prescribed as a weakly velocity-perturbed Couette laminar flow and the initial perturbation of the temperature field was set equal to zero. The integration was performed until the time of the settling of the statistically stationary regime. Samples were then taken for the velocity and temperature fields, by which the mean vertical profiles were calculated with averaging over time and x and y coordinates.

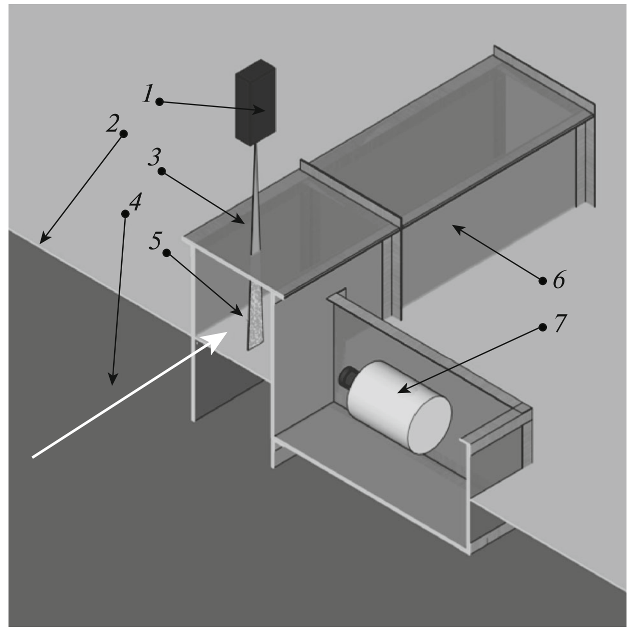

Fig. 2. A transverse section of the flume: *1* is a continuous laser; *2* is the water surface; *3* is a laser knife; *4* is the wind direction; *5* is PIV particles; *6* is the underwater part of the flume; and *7* is a high-speed camera.

In Fig. 3 we show the comparison of the mean velocity and temperature profiles obtained in the laboratory and numerical experiments and the profiles that were expected theoretically from Eqs. (1)–(5). The velocity experimental profiles are normalized by the maximum (bulk) velocity $U_0 = U(z = H_0)$ which is achieved at approximately the middle of the flume at a height $z = H_0 \approx 24$ cm. The air temperature profiles with respect to the water surface are also normalized using the bulk temperatures $\Delta T(H_0)$. The profiles obtained in DNS are in turn normalized by the mean velocity and temperature in the middle of the computational area under $z = 0.5D$.

Figure 3 demonstrates the very good agreement between the laboratory, numerical, and theoretical results within the Monin–Obukhov similarity theory. We note that the illustrated agreement was obtained for the value $C_T = 6$. From Fig. 3 it is also seen that the stratification intensification leads to a decrease in the mean velocity compared with the bulk velocity over the entire boundary layer thickness.

We also note that the heat flux in the laboratory experiment was not measured. We utilized the heat flux from the numerical experiment to predict the solution by the Monin–Obukhov similarity theory. However, since the DNS parameters were prescribed on the basis of the laboratory experiment data and the

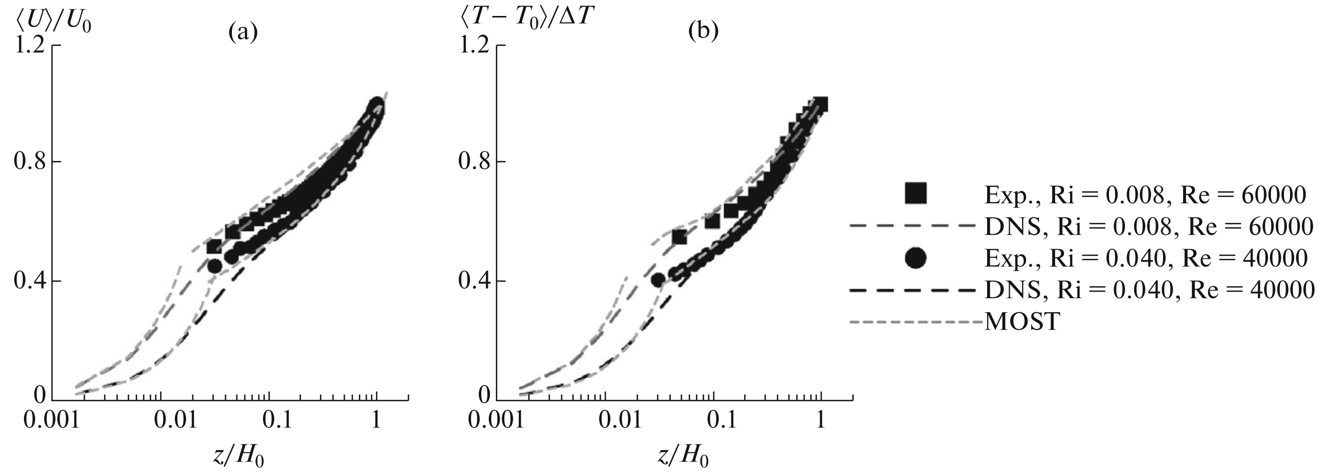

Fig. 3. The vertical profiles of the mean velocity (a) and temperature (b) for weak and strong stratified boundary layers over a smooth water surface obtained in the laboratory experiment (symbols) and in DNS (black dashed lines). The prediction of the Monin–Obukhov similarity theory is denoted by the gray dashed line.

figure shows good agreement between the numerical and laboratory experiments for velocity, as well as for temperature, we may conclude that the Obukhov scale in DNS is close to its value in the laboratory experiment.

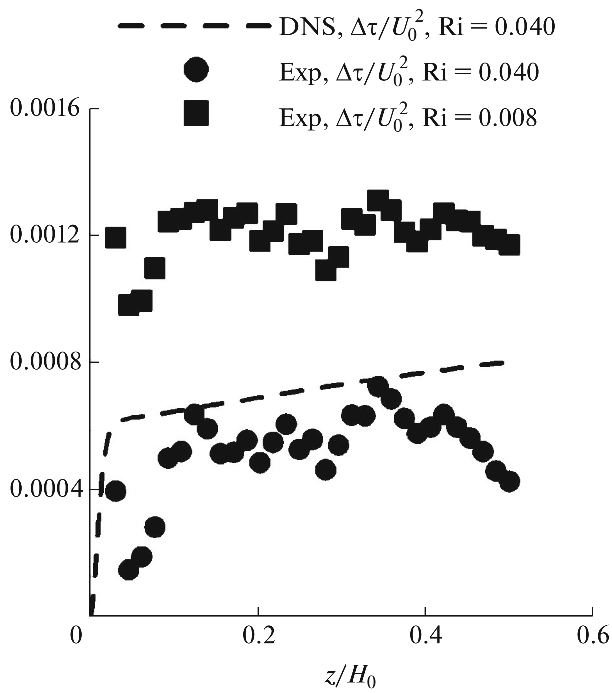

Fig. 4. The vertical profile of the turbulent flow of the momentum normalized by the square of the bulk velocity τ/U_0^2 obtained in the laboratory experiment at a weak stratified regime with Ri ≈ 0.008 (squares) and the relative decrease in momentum flow $\Delta\tau/U_0^2$, which was also obtained in the laboratory experiment and in the DNS with Ri ≈ 0.04 (circles and dashed line, respectively).

The flow realized in DNS reflects the case of a statistically stationary turbulent regime of the stratified boundary layer according to the criteria from [6]. The authors of this work collected the known laboratory and numerical data and performed their DNS to analyze the transition between the turbulent and laminar regimes in terms of the turbulent Reynolds number, Re_L, expressed through the Obukhov length-scale and friction velocity as

$$\mathrm{Re}_L = \frac{Lu_*}{\kappa\nu}.$$

The main result obtained in [6] is the statement (deduced by asymptotic analysis) that the stationary turbulent regime is sustained if $\mathrm{Re}_L > 100$. In the opposite case the turbulence decays and the flow become laminar. In our DNS computations $u_* \approx 0.018U_0$ and $L \approx 0.37D$; therefore, $\mathrm{Re}_L \approx 270$.

Figure 4 presents (i) the vertical profile of the turbulent momentum flux normalized by the square of the bulk velocity τ/U_0^2 obtained in the laboratory experiment under the weakly stratified regime with Ri ≈ 0.008 and (ii) the relative decrease in the momentum flux $\Delta\tau/U_0^2$ obtained in the laboratory experiment and in DNS for Ri ≈ 0.04. The figure demonstrates a considerable decrease in the flux of the turbulent momentum (more than 50%) under the conditions of strong stratification.

CONCLUSIONS

We carried out a laboratory experiment and direct numerical simulation of the turbulent wind flow over a water surface under the conditions of stable stratification. We performed both experiments with the same bulk Reynolds and Richardson numbers, which allowed direct comparison of the results. In both studies we investigated the cases of weak and strong stratification. For strong stratification the temperature difference between the water and air approached 20°C in the laboratory experiment and the wind velocity was approximately 3 m/s. This allowed the achievement of a comparatively large value of the bulk number Ri ≈ 0.04 and the corresponding bulk number Re ≈ 60000. We measured the wind velocity using contact (the Pitot tube) and noncontact (PIV) methods. Simultaneously, we measured the air temperature using a group of contact sensors. The same bulk Reynolds and Richardson numbers were used for the direct numerical simulation, in which the turbulent Couette flow was a model of the near-water boundary atmospheric layer with constant stress.

The results of the laboratory experiment and DNS demonstrate good agreement with each other and with the prediction of the Monin–Obukhov similarity theory. While in the strong stratification case an abrupt decrease in turbulent momentum and heat flux is observed, the prediction of the Monin–Obukhov similarity theory is nevertheless a good approximation for profiles of the wind velocity and temperature.

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