Investigation of the influence of nonbreaking waves on the turbulence using PIV methods within laboratory modelling of the upper layer ocean dynamics

D A Sergeev, A A Kandaurov and Yu I Troitskaya
Institute of Applied Physics RAS, Nizhny Novgorod, Ulyanova 46, 603950, Russia

E-mail: daniil@ipfran.ru

Abstract. The influence of nonbreaking waves on the mixing processes in the upper layer of the ocean during wind-wave interaction was investigated under the conditions of laboratory modeling at the Thermostratified Wind Wave Tank (TSWiWaT) of IAP RAS. Experiments of three types were performed. In the first experiment, shear flow in water was induced using a weak wind to avoid the excitation of surface waves. In the second experiment, in the absence of wind, only a long smooth surface wave was generated using an underwater paddle wavemaker. The third type of experiment combined the conditions of the previous two, i.e. at the same time the wave generator was working and the wind was blowing. In all experiments, the underwater flow characteristics were measured using the PIV method. Vertical profiles of the mean velocity and fluctuations for two components were obtained. It was shown that the presence of waves leads to an increase in the average drift current, as well as, more importantly, on the level of fluctuations over the entire depth of the recorded profile by more than 3 times. This was observed for horizontal and vertical turbulent velocity components both.

1. Introduction
Investigations of the turbulence in ocean is of special interest with problems physical oceanography, whether and climate numerical modeling and other marine environmental researches. Turbulence strongly influenced on the mixing and formation of the vertical temperature (density) distribution – stratification. Waves play an important role in the turbulence production and mixing in the upper layer. The influence of nonbreaking waves on the turbulence is not so obvious process in a contrast with intensively breaking waves with formation. The turbulence induced by nonbreaking surface waves was first noted in the research [1]. It was postulated that the production is due to the straining associated with the waves and is balanced by viscous dissipation. In [2] further investigations of the interaction of turbulence with a monochromatic irrotational surface wave were carried out using a model based on rapid distortion theory. The results of modeling demonstrated that the turbulence distorted by surface waves behaves in a way similar to that of Langmuir turbulence, but strikingly different from the turbulence distorted by mean shear. The dominant turbulence structure is attributed to Stokes drift, which tilts the vertical vorticities into the horizontal and subsequently stretches them into elongated streamwise vortices. The potential impact of this mechanism in the upper ocean was suggested by [3] and [4], who showed the importance of wave-induced turbulence in the attenuation of swell propagating across the Pacific Ocean.
A number of laboratory experiments have been carried out to show evidence of the turbulence generated by nonbreaking surface waves. The incipience of turbulence was detected on mechanically generated laboratory waves using dye dispersion in [4] and using Particle Image Velocimetry (PIV) in [5]. The investigation [6] reproduced the experimental setup of [5], also using dye to visualize turbulent mixing; their experiments, however, showed no evidence of turbulent mixing. The work [7] on the other hand, observed significant enhancement in thermal destratification in the presence of surface waves. An active thermography technique was used within laboratory experiments in the work [8] to quantify turbulent velocities at the water surface. The thermal image of the water surface clearly revealed an elongated streaky structure, which indicates the formation of streamwise vortices beneath the water surface. Thus, it was confirmed the production of wave-induced turbulence with a growth rate consistent with the model proposed in [2].

In [9] numerical simulation of monochromatic surface waves propagating over a turbulent field was conducted to reveal the mechanism of turbulence production by nonbreaking waves. The numerical model solves the primitive equations subject to the fully nonlinear boundary conditions on the exact water surface. The result predicts growth rates of turbulent kinetic energy. To verify the results of numerical modeling the precision measurements of the weak processes of the turbulence production should be carried out. Present investigation demonstrated applying PIV-methods for carrying out such measurements in laboratory experiments.

2. Experimental setup and PIV-measurements description.

Experiments were carried out on the TSWiWaT of IAP RAS. Principal scheme is shown on the figure 1. In order to study the effect of waves on the characteristics of turbulence in the near-surface layer, three types of experiments were carried out. In the first experiment, shear flow in water was induced using a weak wind (about 2 m/s along the channel axis) to avoid the excitation of surface waves. In the second experiment, in the absence of wind, only a surface wave was generated using an underwater paddle wavemaker. Wave generation mode at a frequency of 1.63 Hz with a fixed amplitude of 14 mm.

In this case, in the working section, where the measurements were carried out, the amplitude was already about 6 mm. Thus, we had an unbreakable quasi-monochromatic wave. The third type of experiment combined the conditions of the previous two, i.e. at the same time the wavemaker was working and the wind was blowing. At the same time, the measurements of the wire wave gauge demonstrated the absence of the effect of wind on the wave parameters (the spectrum did not change).

In all experiments, the underwater flow characteristics were measured using the PIV method on the distance of 7.5 m from the start of the flume. For this propose polyamide microparticles with a diameter (50 μm, density 1.03 g/cm3) were used to seed the flow. An underwater continuous diode blue laser was used to create the illumination. Side view shooting was performed with an Optronis CamRecord CR3000x2 high-speed camera housed in a semi-submerged box. The shooting frequency is 200 Hz, the exposure time is 5 μs. The scale of the image is 0.016 mm/pixel. Image size 27.6×27.8 mm (1696×1710 px).

In each experiment, after waiting 20 minutes for the settling time, 5 records were performed with a step of 20 minutes. Each recording was about 50 seconds long (9800 frames). Such survey parameters guarantee the possibility of studying the parameters of currents, including turbulent characteristics, with a high spatial and temporal resolution. PIV image processing was carried out in one pass with a window of 128×128 on a rectangular grid of pixels with 50% overlap. Consecutive frames were compared. Before processing, images were pre-filtered from dynamic background noise.

A curvilinear coordinate system was used, associated with the shape of the surface during the image processing and obtaining velocity fields, and then calculating the profiles of parameters averaged over the phase. The distance to the surface and the phase of the wave were calculated for each point of the velocity measuring at each frame. Then data binning was performed in depth and phase (22 windows in depth from 0 to 3 cm and 10 windows in phase). The filtered velocity fields were averaged for each of the 10 phases separately, which made it possible to obtain the average velocity profiles for each phase. Sequent averaging these profiles made it possible to obtain the correctly vertical profiles of the mean velocity components over the entire record without errors. Fluctuations (turbulent components) for each
phase in depth and in phase were calculated by subtracting the average value for this basket. Vertical profiles of fluctuations of the velocity components were obtained separately for each phase, as well as averaged over all phases.

3. Analysis of obtained data and comparison with previously obtained results of numerical modelling.

Results of measurements are presented on the figure 2 in dimensionless variables. It was shown that waves lead to an increase in the average drift current, and the fluctuations over whole measured depth by more than 3 times. This was observed for both horizontal and vertical turbulent velocity components.

Data of laboratory experiments were compared with previously obtained results of numerical modeling in [9]. In both cases, the maximum intensity of fluctuations occurs near the wave crests demonstrating good qualitative agreement. The quantitative differences are apparently related to the
difference in the initiation of turbulent fluctuations. In a more idealized numerical experiment, they develop from the initial perturbation. In a laboratory experiment, closer to natural conditions, a constant turbulent stress is maintained on the water surface.

Figure 3. Distribution of the intensity of turbulent fluctuations of velocity over the phase of the wave (a, b) – laboratory experiment of the present investigation, (c, d) – results of numerical modeling obtained in [9] (a, c) – horizontal velocity fluctuations (b, d) – fluctuations vertical speed.

4. Conclusion
A method for studying the influence of waves on the processes of generation and development of turbulence in the near-surface ocean layer in the framework of laboratory modeling on wind wave facilities was developed. It was demonstrated that waves lead to an increase in the initial seed turbulence, induced by shear stress from the air flow above the water surface. The obtained data confirmed the previously obtained results of numerical simulation.

Acknowledgements
This work was supported by Russian Foundation Basic Research project 21-55-52005. The experiments were carried out at unique scientific facility "Complex of large-scale geophysical facilities of IAP RAS".

References
[1] Phillips O 1961 *J. Geophys. Res.* 66 2889
[2] Teixeira M and Belcher S 2002 *J. Fluid Mech.* 458 229
[3] Ardhuin F and Jenkins A D 2006 *J. Phys. Oceanogr.* 36 551
[4] Babanin A V 2006 *Geophys. Res. Lett.* 33 L20605
[5] Babanin A V and Haus B K 2009 *J. Phys. Oceanogr.* 39 2675
[6] Beyá J F, Peirson W L and Banner M L 2012 *Exp. Fluids* 52 1319
[7] Dai D, Qiao F W, Sulisz L Han and Babanin A 2010 *J. Phys. Oceanogr.* 40 2180
[8] Savelyev I B, Maxeiner E, and Chalikov D 2012. *J. Geophys. Res.* 117 C00J13
[9] Tsai W, Chen S, and Guan Lu 2015. *J. Phys. Oceanogr.* 45 174–180