



京都大学防災研究所

Disaster Prevention Research Institute

Kyoto University

Short-term Research Visit

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台風モデルのための風波による大気乱流への 影響

Investigation of turbulence kinetic energy
budget in wind-generated ocean waves and
its effect on typhoon modeling

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Kyoto University Collaborative Research – Final Report

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Project title: Investigation of turbulence kinetic energy budget in wind-generated ocean waves and its effect on typhoon modeling

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Objective and significance: Wind-generated waves play a crucial role in air-sea interactions due to their influence on atmosphere, upper ocean hydrodynamics and nearshore morphodynamics. Accurate modeling of wind-waves can enhance typhoon modeling and climate modeling, ultimately benefiting society and ecosystems. To improve the accuracy of fully coupled atmosphere-wave-ocean models, resolving the multiscale processes governing upper ocean turbulence is crucial yet challenging. Existing parameterizations for turbulence in these models often fail to capture wave-induced effects on the turbulent kinetic energy (TKE) budget. By analyzing laboratory measurements of air and water flow fields over wind-generated waves at Texas A&M University and collaborating with coupled model researchers at DPRI, this research aims to enhance the understanding of energy transfer mechanisms through multiscale studies with the following objectives:

- (1) To understand how wind stress is transferred from the atmosphere to wind-induced waves and how this process drives wave-induced turbulence.
- (2) To investigate the mechanisms of energy transfer between wind and subsurface turbulence, including typhoon conditions.
- (3) To enhance model parameterizations for turbulence by improving the understanding of wave-induced effects on the TKE budget.

Research plan: Given the relatively short duration of the stay, conducting new experiments on such a complex and challenging topic is not feasible. Instead, the plan is to analyze existing data collected from the Texas A&M wind-wave flume and collaborate with DPRI numerical modelers to gain a deeper understanding of the multiscale problems. Both air and water flow fields, with a field of view on the order of 0.1 m, were captured using the Particle Image Velocimetry (PIV) method.

The air flow field data was sampled at a rate of 2400 Hz to account for its high velocity and turbulence, while the water flow field data was sampled at an adequate rate of 200 Hz. The spatial resolution for velocity vectors is 2 mm. The analysis of the air flow, including the turbulent kinetic energy (TKE) budget, has been published in Do *et al.* (2024). However, the analysis of the water-side data is still ongoing.

The principal investigator (PI) plans to complete the analysis of the water-side data and summarize the findings using a similar and proven approach as employed in the successful air flow analysis.

The biggest challenge lies in understanding the fundamental physics at the air-water interface, as outlined in the research objectives above. Our analysis of air-side turbulence revealed that the TKE budget does not close, showing an excessive energy production. Similarly, preliminary analysis of the water-side TKE budget, driven by wind stresses, also indicates a lack of closure, with excessive energy dissipation observed. These findings lead to the hypothesis that TKE transfer occurs across the air-water interface.

The research team plans to investigate this mechanism using both laboratory data and numerical simulations to better understand this small-scale physical phenomenon. The anticipated outcome is the development of an improved energy transfer model at the air-sea boundary through enhanced parameterizations for turbulence, ultimately improving model accuracy. Additionally, this effort aims to foster interdisciplinary and international research collaboration to address this highly challenging problem in air-sea interactions and climate modeling.

Scientific Achievements:

The PIs and collaborators have been analyzing laboratory data of wind-generated water waves at three different fetches (i.e., three different wave ages), obtained under a constant free-stream wind speed of 8.0 m/s (or 10 m wind of 12.2 m/s). Measurements were acquired using time-resolved PIV techniques, where a continuous green laser (10W) illuminates a thin light sheet, and two high-speed cameras (4K resolution, 10-bit dynamic range, operating at 200 Hz) capture free surface and two-dimensional flow velocity.

Analysis at the first two fetches (6.2 m and 8.5 m), each with 5 repeated experiments, is complete. At the final fetch (10.7 m), analysis is ongoing; 1 out of 5 repeated experiments has been completed. The total size of the imagery is substantial, and identification of the free surface in each image is challenging and time-consuming, resulting in steady but relatively slow progress. We anticipate completing the analysis for this last fetch in May, after which the effect of fetch and thus the wave age can be fully revealed and summarized.

The results derived from the time-resolved PIV technique are novel and highly promising. These findings will deepen our understanding of the underlying physics and provide quantitative insights into the effects of wind. Notably, some important discoveries include:

- Vertical distributions of turbulent kinetic energy (TKE) and Reynolds stress were obtained. These results provide important insights into the transfer mechanisms of momentum, energy, and gases in wind-generated waves.

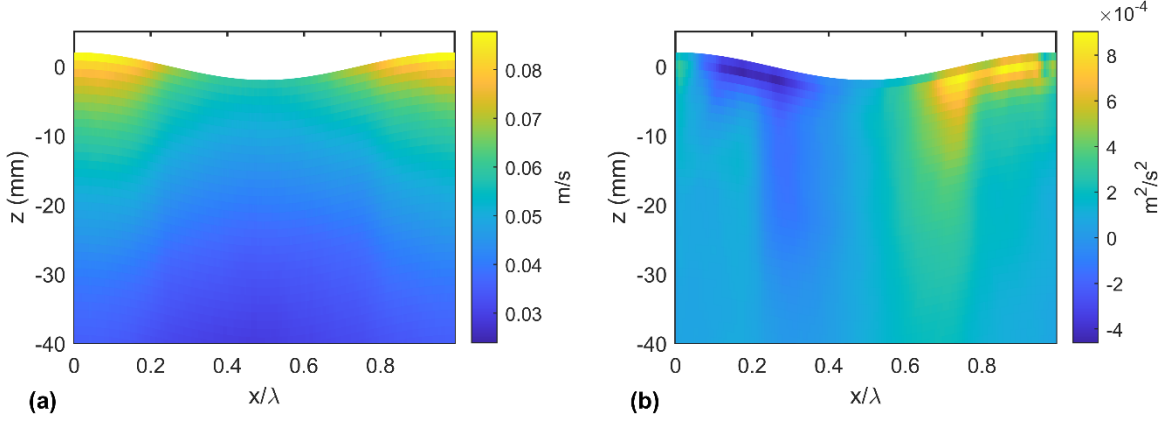


Fig. 1. (a) Turbulent kinetic energy (TKE); (b) Reynolds stresses at Fetch 2 ($F = 8.5$ m) under a free stream wind speed (U_{ref}) of 8.0 m/s.

- The power spectral analysis revealed a $-5/3$ slope within a thin layer approximately one wave height (12 mm) beneath the free surface, characteristic of the turbulent kinetic energy cascade. Below this layer, a slope of -3 was observed, suggesting that TKE becomes insufficient to sustain energy transfer to smaller eddies, resulting in slowed mixing and increasingly two-dimensional flow.

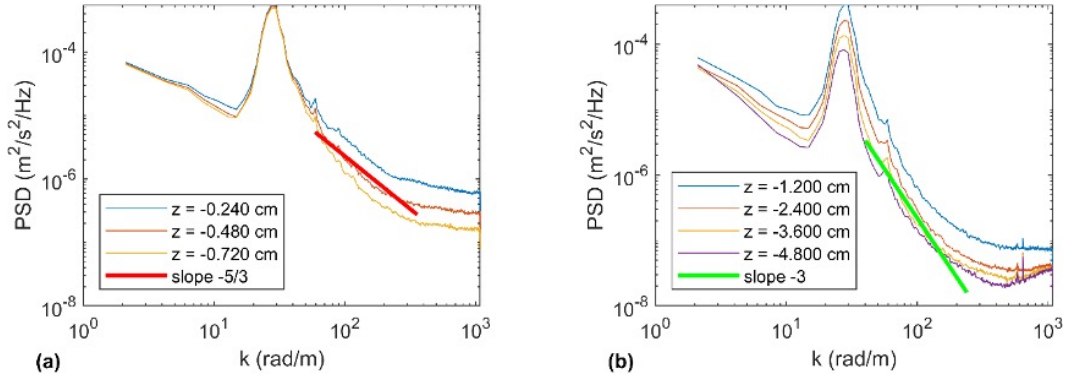


Fig. 2. (a) Power spectral slope near the free surface within one wave height follows the $-5/3$ slope; (b) Power spectral slope below one wave height changes to -3 .

- Eddy size analysis, using swirling strength, indicated that eddies within the same thin layer (one wave height beneath the surface) increase in size with depth, but this growth ceases shortly beyond the edge of the layer – consistent with the spectral findings above.

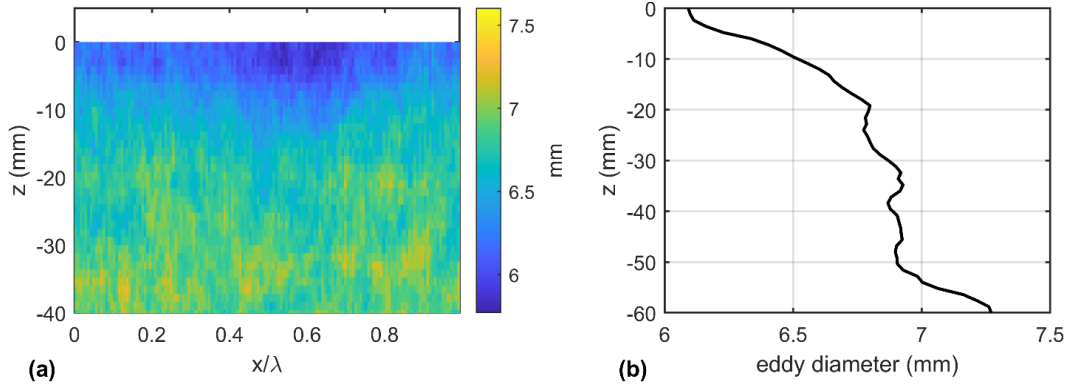


Fig. 3. (a) Eddy size distribution under wind waves ($F = 8.5$ m, $U_{ref} = 8.0$ m/s); (b) variation of eddy size as a function of water depth

- The turbulent dissipation rate estimated using the spectral method is higher than that obtained from the direct method. This discrepancy arises because the PIV resolution is larger than the Kolmogorov length scale, preventing the direct method from resolving smaller eddies.

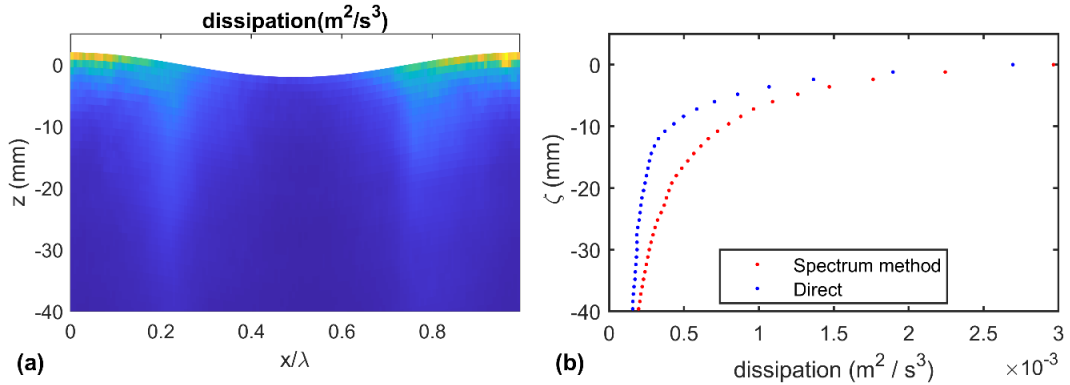


Fig. 4. (a) Turbulence dissipation rate under wind waves ($F = 8.5$ m, $U_{ref} = 8.0$ m/s); (b) Turbulence dissipation rate variation with water depth estimated from two different methods

- Reynolds stress measurements exhibited a linear proportionality to depth, with maxima occurring close to the free surface. These quantitative results offer a direct assessment of free surface shear stress, which is typically unavailable in most studies.

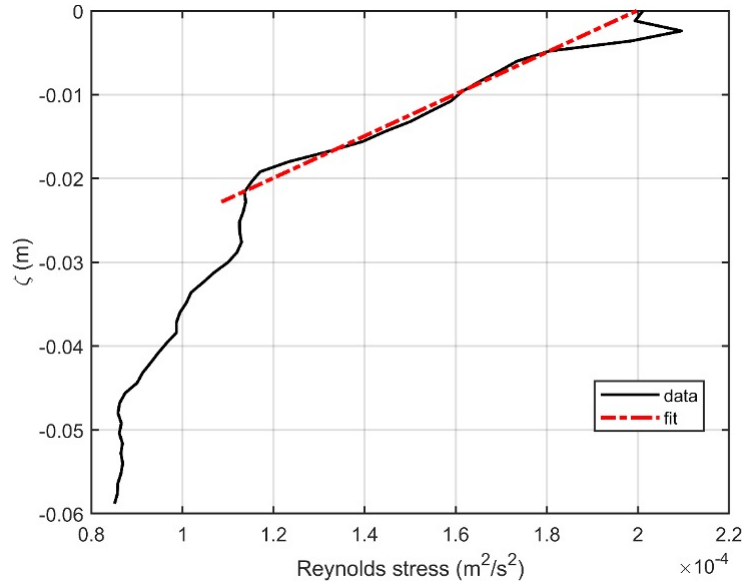


Fig. 5. Reynolds stress versus water depth. The linear fitted line is to the region of about two wave heights beneath the surface.

Expected Final Product and Timeline:

The progress and findings outlined above will be consolidated and prepared for publication in a peer-reviewed journal article. We anticipate drafting the manuscript in early summer, with submission planned for the end of summer. Given the significance and impact of the results, as well as the unique experimental and analytical approaches, we intend to submit the work to a leading journal in fluid mechanics. The tentative title and author list for the submission are as follows:

Wu, T.-C., Do, J., Wang, B., Mori, N., & Chang, K.-A. (2026). Influence of wave age on turbulence properties beneath young wind-generated waves. *Journal of Fluid Mechanics*, in preparation for submission in summer 2026.