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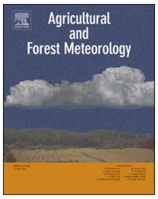

Coherent structures in wind shear induced wave–turbulence–vegetation interaction in water bodies

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ABSTRACT

Flume experiments with particle imaging velocimetry (PIV) were conducted recently to study a complex flow problem where wind shear acts on the surface of a static water body in presence of flexible emergent vegetation and induces a rich dynamics of wave–turbulence–vegetation interaction inside the water body without any gravitational gradient. The experiments were aimed at mimicking realistic vegetated wetlands and the present work is targeted to improve the understanding of the coherent structures associated with this interaction by employing a combination of techniques such as quadrant analysis, proper orthogonal decomposition (POD), Shannon entropy and mutual information content (MIC). The turbulent transfer of momentum is found to be dominated by organized motions such as sweeps and ejections, while the wave component of vertical momentum transport does not show any such preference. Reducing the data using POD shows that wave energy for large flow depths and turbulent energy for all water depths is concentrated among the top few modes, which can allow development of simple reduced order models. Vegetation flexibility is found to induce several roll type structures, however if the vegetation density is increased, drag effects dominate over flexibility and organize the flow. The interaction between waves and turbulence is also found to be highest among flexible sparse vegetation. However, rapidly evolving parts of the flow such as the air–water interface reduces wave–turbulence interaction.

1. Introduction

Flume experiments with particle imaging velocimetry (PIV) were conducted recently to mimic realistic wetlands where the water body is subjected to wind flow in the presence of flexible protruding vegetation without any gravitational gradient (Banerjee et al., 2015). Wind shear produces traveling waves on the water surface and the flexible vegetation are subjected to wind induced oscillations, the combination of which generates a rich and complicated dynamics inside the water body featuring wave–turbulence–vegetation interaction. The experiments were aimed at mimicking realistic wetlands and understanding this complicated interaction can help towards the development of better models for sediment and nutrient transport as well as greenhouse gas (such as methane and carbon dioxide) emission mechanisms from vegetated wetlands, which are important pieces in local and global carbon budgets. However, operational models for wetland flow use zeroth order models using an effective friction factor, which misses the intriguing and rich dynamics occurring throughout the depth of the fluid, which further motivates our study to uncover these interactions.

A large body of literature involving flow through vegetated channels and wetlands is reviewed in Banerjee et al. (2015) and not repeated here except the ones published between the years 2015–2016. Tse et al. (2016) reported experimental measurements both on air and water sides in presence of emergent vegetation and described how the "wind interacting with the vegetation generates coherent billows which are the dominant source of momentum into the wetland water column". Lal et al. (2015) found different flow regimes across depth in wetlands with dense emergent vegetation under wave forcing. Zhang et al. (2016) performed sensitivity studies for wave height, water depth and vegetation density in the context of wave–current–vegetation interaction in coastal waters. Several other studies also reported experimental and numerical modeling of flow through vegetated wetlands, focusing on sediment transport, flow attenuation and energy dissipation (Hu et al., 2015; Jin and Ji, 2015; Truong et al., 2015; Zhu and Chen, 2015; Carlin et al., 2016; Chakrabarti et al., 2016; Chen et al., 2016; Marsooli et al., 2016; Silinski et al., 2016; Tambroni et al., 2016; van Rooijen et al., 2016; Chao et al., 2016). However, most studies involving waves considered wave forcing on the whole body of fluid unlike in Banerjee et al.

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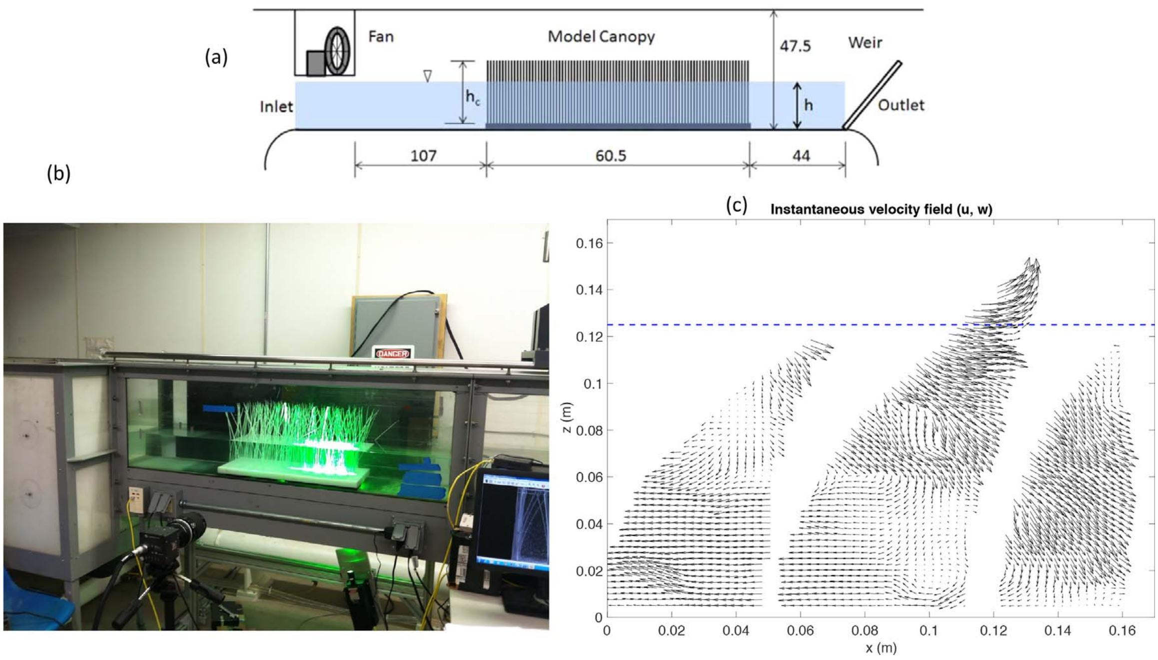

Fig. 1. The top panel (a) shows a schematic of the experimental set up. The bottom panel (b) shows a picture snapshot of the experiment. The flume, the vegetation, the laser light sheet along with the illuminated area, the high speed camera and the image acquisition system can all be observed in the figure. Photo taken by the first author. Panel (c) shows an instantaneous velocity field for the flexible sparse scenario computed from PIV. The blue dashed line shows the water level for this case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(2015) and Tse et al. (2016) where wave action is generated on the air water interface because of wind shear. After Banerjee et al. (2015), only Tse et al. (2016) studied the full complexity of the interaction between wind shear, wave, turbulence and emergent vegetation to the best of the authors' knowledge.

Several factors such as wind speed, water depth, vegetation density and flexibility were found to influence the nature of this interaction as illustrated by first and higher order statistics obtained from separated wave and turbulence time series, the details of which can be found in Banerjee et al. (2015). All possible combinations of three different wind speeds (low, medium and high) and three different water depths (deep, intermediate and shallow) were tested for each of the five scenarios (with their abbreviations to be used throughout this article), i.e., no vegetation (NV), rigid sparse vegetation (RS), rigid dense vegetation (RD), flexible sparse vegetation (FS) and flexible dense vegetation (FD). As concluded in Banerjee et al. (2015), there are similarities between the no-vegetation scenario and an inverted boundary layer, in the sense that the air–water interface behaves like the wall in a regular boundary layer flow. Turbulence is generated by the disturbance at the interface and at sufficient depth, an extensive inertial subrange can be found. Wave motions are also generated at this interface in the form of rolling motions of impinging orbitals. These orbitals are damped deep inside the flow. The flexible dense vegetation adds vegetative drag in the mix and enhances fine scale inertial turbulence. The dominant wave frequency band of 4 Hz is found to be diffused by the oscillation of the vegetation between 2 and 5 Hz. The turbulent component of the momentum flux is found to be maximum at the middle depths, while in contrast, the wave component of the momentum flux is found to be maximum close to the air–water interface. The intensity (described as standard deviation of the streamwise and vertical velocity fluctuations) for wave and turbulence also display different behavior. The turbulence intensity is higher than wave intensity in all cases, and it also penetrates deeper into the flow than the wave intensity for larger flow depth scenarios. The wave intensity is highest close to the interface as well. The 'quasi-isotropic' nature of the flow is another interesting feature-meaning the vertical and longitudinal velocity components exhibit similar patterns of energy and momentum transfer. However, further analyses are required to have a more detailed understanding of coherent structures in such a complicated flow, which encompasses the objective of this study.

Turbulent structures, also called quasi-coherent structures, are difficult to define precisely but have been described by Pope (2001) as "regions of space and time (significantly larger than the smallest flow or turbulent scales) within which the flow field has a characteristic coherent pattern". Kline and Robinson (1990) and Robinson (1991) categorized several types of coherent structures in channel and boundary layer flows, among which sweeps, ejections and vortical structures will be investigated in the present work. The relative contributions of sweeps and ejections in turbulent and wave momentum transfer will be studied. To study vortical motions, proper orthogonal decomposition (POD) will be conducted on the velocity fields. Furthermore, to study the degree of organization of the complex eddy motions and the interaction and exchange of information between wave and turbulence, some techniques from nonlinear dynamics such as Shannon entropy and mutual information content (MIC) will be employed as these methods "provide 'scalar measures' that can be related to the system's complexity (Wesson et al., 2003; Poggi et al., 2004)". To reveal the nature of the coherent structures in the context of this complex process, the present work aims at answering the following questions:

1 What is the dominant mode of vertical momentum transport for wave and turbulence and how is it affected by changes in water height, wind speed, vegetation density and flexibility?
2 How do the most energetic coherent structures look like for wave and turbulent transport of energy and momentum and what is the effect of water height, wind speed, vegetation density and flexibility on these features?
3 What is the degree of complexity and flow organization across the different scenarios and how is that affected by the control parameters such as water height, wind speed, vegetation density and flexibility?
4 How to quantify the interaction between wave and turbulence and how does it vary with the aforementioned control parameters?

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