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Residence time in aquatic canopies in wave-dominated flows

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Abstract

The large-scale ecological and environmental impact of coastal canopies is tightly limited by the exchange of water across their boundaries. In coastal environments, where the flow is typically wave-dominated, vertical mixing is believed to be the dominant process controlling residence time (T_{res}). Recent experiments of wave-driven flows over rough boundaries, however, have revealed the generation of a strong onshore mean current (up to 50% of the orbital velocity far above the canopy) near the canopy top. It is therefore imperative to understand that these two processes, i.e. horizontal advection and vertical mixing, can control residence time in coastal canopies. Through consideration of a Peclet number (the ratio of diffusive to advective time scales), this study presents a framework for quantitative prediction of residence time in these environments. Results reveal that Pe depends heavily on wave and canopy properties and may vary significantly in real coastal canopies. Quantitative predictions for residence time in the limit of $Pe \ll 1$ (mixing-dominated exchange) and $Pe \gg 1$ (advection-dominated exchange) are presented. For $Pe \sim O(1)$, characterization of each process will be necessary in describing residence time in these systems.

Introduction

Seagrass meadows are primary producers that provide important ecosystem services, such as improved water quality through the direct uptake of nutrients and dissolved organic matter [15, 10], as well as the production of oxygen [10]. The drag exerted by aquatic canopies has a significant impact on the local hydrodynamics by reducing the in-canopy velocity [12] and dissipating wave energy [8], which in turn lead to enhanced sedimentation [6] and retention of particulate material within the meadow [5].

Most of these ecological services provided by seagrass meadows are tightly limited by the exchange of water across canopy boundaries. In coastal canopies, which are typically subjected to wave-dominated flows, vertical mixing is believed to be the dominant process controlling the rate of material exchange into and out of the canopy. Vertical exchange has indeed been shown to have a tremendous impact on transport of pollen [3], dispersal of seeds [16] and sediment accumulation in these systems [6].

Recent studies of wave-dominated canopy flows, reveal generation of a strong, shoreward mean current (up to 50% of the near-bed orbital velocity), near the canopy-water interface [13, 1]. This shoreward drift, which has been observed both in the laboratory [11, 13] and field [14], can have a significant impact on canopy residence time by introducing a second method of water renewal (other than vertical mixing) through horizontal flushing of dissolved and particulate material. Thus, although coastal systems are typically wave-dominated [9], the impact of roughness-induced mean currents on residence time may not be negligible.

Model development

Vertical mixing

In coastal canopies, the drag exerted by the canopy elements results in a vertical gradient of orbital velocity across the canopy-water interface. That is, the velocity within the canopy, U_c^{rms} (with the superscript "rms" referring hereafter to the root-mean-square of the oscillatory velocity and the subscript "c" referring to the in-canopy average), is attenuated from its value far above the canopy, U_∞^{rms} (Figure 1a). The difference between the above- and within-canopy RMS velocities is denoted as ΔU. This velocity attenuation, which is greater for denser canopies [12, 17] (Figure 1a), creates an inflectional shear layer in the vertical profile of oscillatory velocity. This leads to the generation of Kelvin-Helmholtz vortices (refer to as KH-vortices, hereafter) under certain conditions (Figures 1b) [7]. The existence of these vortices can significantly enhance the rate of vertical exchange of dissolved and particulate material as seen in steady flows.

Our recent experimental study reveals that, in wave-dominated flows, vertical mixing is characterized by a coupled contribution from both shear- and wake- driven mixing [2] such that

$$D_{t,z} = 0.043\Delta U L_D + 0.58\sqrt[3]{\frac{d}{L_D}}U_c^{rms}d \quad (1)$$

where $D_{t,z}$ is the vertical turbulent diffusivity and d is the stem diameter. L_D is the drag length scale and is defined as:

$$L_D = \frac{1-\lambda_P}{C_D a} \quad (2)$$

where λ_p is the solid fraction of the canopy, a is the canopy frontal area per unit volume and C_D is the drag coefficient.

Horizontal advection

Vertical velocity gradients across the top of submerged coastal canopies drive an asymmetry in particle motion over the wave cycle. This causes fluid particles (located adjacent to the canopy top) to move faster in the shoreward direction above the canopy under a crest than in the seaward direction within the canopy under a trough. The open orbit resulting from this mechanism leads to the generation of a mean current in the direction of wave propagation as illustrated in Figure 2.

The amplitude of this current ($\overline{u}$) is greatest at the top of the canopy, where the shear is maximized. The current strength increases with the vertical particle excursion at that height, ξ_T, and the canopy drag (indicated by the drag length scale L_D).

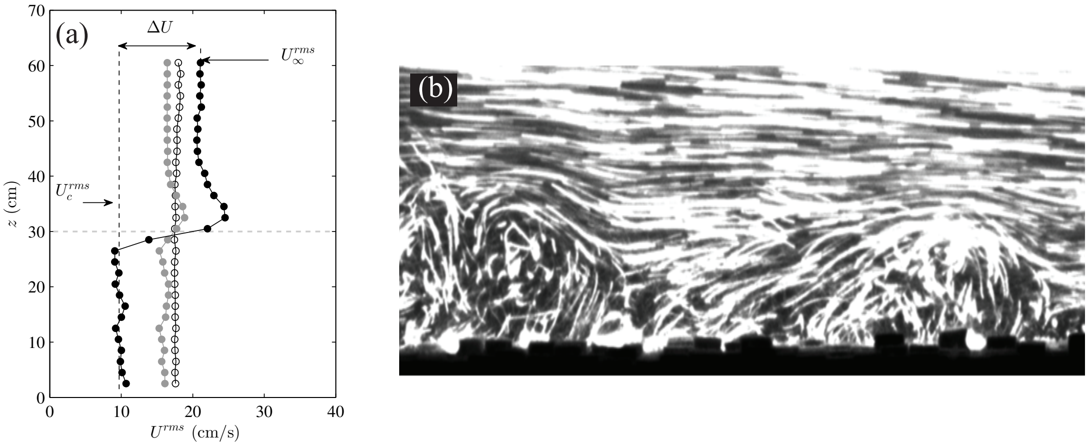

Figure 1: Canopy-induced shear and the subsequent vortex generation in wave-dominated flows. (a) Vertical profiles of RMS velocities for identical waves ($U_\infty^{rms} = 17$ cm/s) over a dense canopy (10% by volume, black circles), a sparse canopy (1% by volume, gray circles) and a bare bed (white circles) suggest an increasing velocity attenuation with canopy density [1]. Values of the in-canopy RMS velocity, U_c^{rms}, the above-canopy RMS velocity, U_∞^{rms}, and the velocity attenuation, ΔU, are indicated for the dense canopy. The gray dashed line indicates the top of the canopy. (b) Image showing the KH-vortices generated in an oscillatory canopy flow in the laboratory [7].

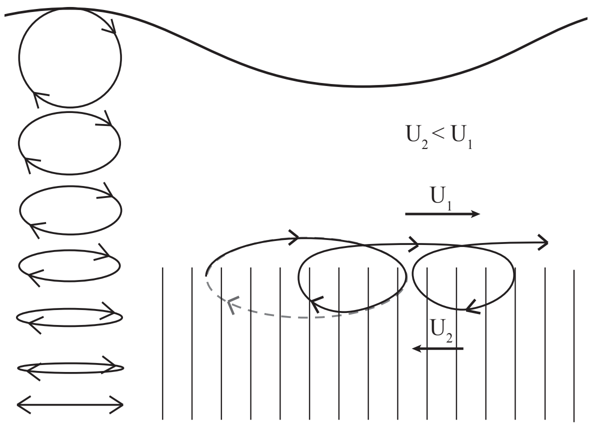

Figure 2: Lagrangian view of the shoreward mean current generated at the top of the canopy. A fluid particle above the canopy, will have a greater velocity at the wave crest, U_1 (solid line), than at the wave trough, U_2 (dotted line), such that $U_2 < U_1$. This generates a mean drift in the direction of wave propagation (right).

For shallow water waves, i.e. $kh \ll 1$ (with k being the wave number and h the water depth) [4], $\overline{u}_{max}$ is given by:

$$\overline{u}_{max} = 0.38\, U_\infty \left(\frac{\xi_T}{L_D}\right)^{0.4} \tag{3}$$

where U_∞ is the amplitude of the orbital velocity far above the canopy (where the flow is assumed to be unaffected by the canopy drag) [1]. For shallow water waves, ξ_T can simply be related to the wave height H through

$$\xi_T = H \frac{h_c}{h} \tag{4}$$

where h_c is the canopy height.

Residence time in coastal canopies

The overall residence time in coastal canopies exposed to a purely wave-driven flow will be dictated by the relative importance of the horizontal flushing (due to the roughness-generated mean current) and vertical mixing. This can be understood by consideration of the Peclet number, Pe:

$$Pe = \frac{T_{mix}}{T_{adv}} \tag{5}$$

where T_{mix} and T_{adv} are the diffusive and advective time scales, respectively. These time scales are described by:

$$T_{mix} = \frac{{h_c}^2}{D_{t,z}} \tag{6}$$

and

$$T_{adv} = \frac{L}{\overline{u}_{max}} \tag{7}$$

where L is the canopy length. Through substitution of (7) and (6) into (5), it can be seen that the Peclet number, that governs residence time in coastal canopies, is given by

$$Pe = \frac{\overline{u}_{max}\, {h_c}^2}{L\, D_{t,z}} \tag{8}$$

Evaluation of Pe will provide an enhanced understanding of the dominant mechanism controlling residence time in coastal canopies. When $Pe \ll 1$, residence time is controlled by vertical mixing and can be evaluated through (6) and (1); conversely, when $Pe \gg 1$, residence time is controlled by advection, and can be evaluated through (7) and (3). When $Pe \sim O(1)$, both advection and diffusion will influence the residence time of dissolved and particulate species in aquatic canopies.

Results and discussion

The value of Pe for marine canopies can be highly variable as it depends heavily on both wave and canopy conditions, properties that vary widely between sites, seasons and species [13, 7]. This is illustrated in Table 1 in which ranges of important wave and canopy properties for a typical seagrass meadow, *Posidonia australis*, are presented. Thus, even for a particular species, Pe values may span a wide range.

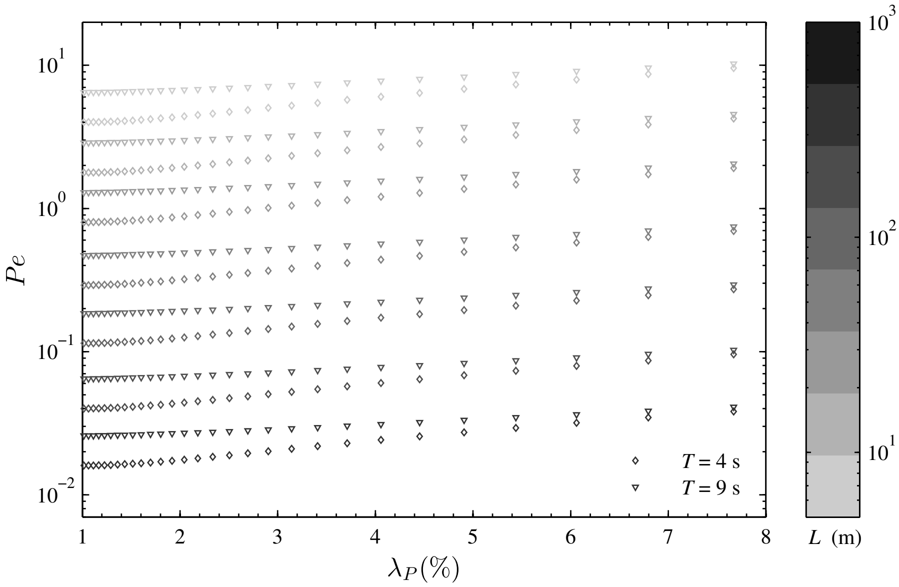

Figure 3: Variation of *Pe* with canopy density (indicated as λ_P) under different wave conditions. *Pe* increases with λ_P due to the enhanced advection in dense canopies (Equation (3)). The darkness of the markers is proportional to the canopy length (indicated in the colourbar). The Peclet number decreases with canopy length, such that vertical mixing controls exchange in long canopies.

Table 1: Typical wave and canopy conditions in a *Posidonia australis* meadow.

	Variable		Range
Wave condition	U_∞ (cm/s)		$O(1-100)$
	T (s)		$O(10)$
	h (m)		$O(1-15)$
Canopy condition	L_d (cm)		$O(1-100)$
	w (cm)		$O(1-1.4)$
	h_c (cm)		$O(30-60)$
	L (m)	small	$\lesssim 100$
		Medium	$O(100-300)$
		Large	$\gtrsim 300$

Figure 3 describes how *Pe*, defined in (8), may vary in a *Posidonia australis* meadow. In this figure, typical values of blade width ($w = 1.2$ cm), canopy height ($h_c = 40$ cm) and water depth ($h = 2$ m) were employed. Moreover, two wave periods (4 and 9 s) and a wide range of canopy lengths ($5 < L < 1000$ m), were examined. As seen, real canopies can have $Pe \ll 1$, $Pe \sim O(1)$ or $Pe \gg 1$ based on wave and canopy properties. Peclet number increases with increasing the canopy density due to the enhanced advection in dense canopies [2]. Moreover, the length of the canopy has a strong influence on *Pe* with which the flow may span a wide range of *Pe* centered around one.

The limit of $Pe \ll 1$

When the canopy is sufficiently long ($\gtrsim O(100$ m$)$, Figure 3), $Pe \ll 1$ and vertical mixing controls residence time. Thus, residence time can be predicted by Equation (6) and (1). The variation of canopy residence time in this limit with wave and canopy properties is examined in Figure 4. While residence time decreases simply with increasing wave height (H), there is a complex dependence of residence time on canopy density. Although T_{mix} decreases with increasing canopy density for sparse canopies, it starts to increase again after reaching a threshold value ($\lambda_p \gtrsim 3\%$) due to the resultant reduction in in-canopy velocity and an ultimate decrease in the rate of wake-driven mixing [2]. Eventually, as canopy density increases, shear-layer-driven mixing becomes important and offsets the reduction of wake-driven mixing. Thus, T_{mix} becomes essentially independent of λ_P at high canopy density.

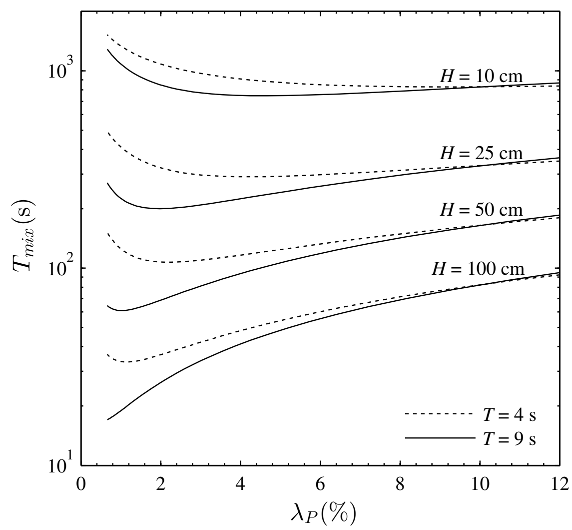

Figure 4: Variation of canopy residence time with canopy density in the limit of $Pe \ll 1$ (based on Equations (6) and (1)). Despite a clear dependence of T_{mix} on wave height, it becomes increasingly independent of λ_P as the canopy density increases.

The limit of $Pe \gg 1$

For small patches ($L \lesssim 10$ m), horizontal advection becomes increasingly important such that for a sufficiently high *Pe*, the minor impact of vertical mixing can be ignored and residence time can be predicted through T_{adv} (Equation (3) and (7)). This is illustrated in Figure 5 in which T_{adv} plotted against λ_P. Increasing canopy density will result in a lower residence time as it enhances the magnitude of $\overline{u}_{max}$ (Equation (3)). Also, a direct proportionality between T_{adv} and canopy length is observed such that a longer canopy leads to a greater T_{adv} and ultimately a greater exposure time of dissolved and particulate species (such as nutrients, oxygen, pollen, seeds, etc.).

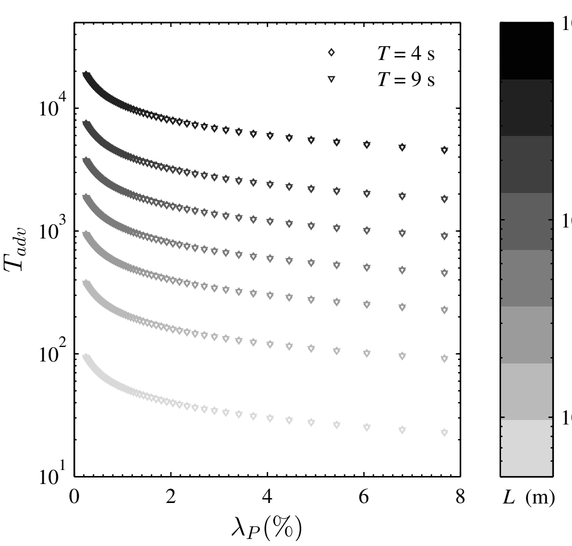

Figure 5: T_{adv} variation with λ_P in the limit of $Pe \gg 1$. While a longer canopy leads to a greater T_{adv}, increasing the canopy density reduces T_{adv} due to the enhancement of $\overline{u}_{max}$.

Conclusion

In this study we present a framework for predicting residence times in coastal canopies. In marine environments, where the flow is typically wave-dominated, residence time is believed to be predominantly controlled by vertical mixing. This assumption is challenged by recently improved understanding of flow in these environments which reveals the generation of a strong onshore mean current (up to 50% of the orbital velocity far above the canopy) near the canopy-water interface. By quantification of the Peclet number Pe, as the ratio of diffusive to advective time scales, this study represents a real understanding of residence time in typical coastal canopies. Prediction of residence time in the limit of $Pe \ll 1$ (mixing-dominated exchange) and $Pe \gg 1$ (advection-dominatd exchange) were presented. For $Pe \sim O(1)$, where both vertical mixing and horizontal advection contribute in controlling residence time, evaluation of each process will be equally important.

Acknowledgements

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