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The impact of waves on aquatic canopy flow

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Abstract

Benthic canopies (e.g., seagrass meadows, coral reefs and kelp forests) are important parts of coastal environments, providing a range of ecosystem services. The drag exerted by these complex bottom roughnesses profoundly impacts the mean flow and turbulence structure and, consequently, the physical and biogeochemical processes within these ecosystems. While previous studies have mainly focused on steady flow environments (e.g., rivers, lakes and tide-dominated estuaries), many submerged canopies in coastal environments are subjected to oscillatory flows driven by surface waves. This study aims to investigate dynamics generated under steady and wave flows over submerged canopies to understand similarities and differences between the two environments. Accordingly, flow, turbulence and mixing were compared within identical model canopies subjected to comparable steady and wave-dominated flows. Results revealed that despite general similarities (e.g., velocity attenuation and vortex generation at the canopy top), there are significant differences between steady and wave-driven flows. In particular, velocity attenuation and, thus, the strength of the shear layer vortices are much stronger in steady flows. Trends of velocity attenuation and vertical transport indicate that the Keulegan-Carpenter number (KC) is the key parameter describing the impact of oscillation on the flow structure. When KC reaches $O(100)$, the flow, turbulence and mixing essentially resemble those in unidirectional flow environments.

Introduction

Aquatic canopies (such as those formed by seagrass meadows, coral reefs and kelp forests) are ubiquitous in rivers and coastal environments, providing a range of ecosystem services; including, oxygen production [16], carbon sequestration [17], nutrient trapping and cycling [7], and support of marine biodiversity [8]. The presence of these large bottom roughnesses directly modifies the local hydrodynamics by reducing the in-canopy velocity [11, 1] and dissipating wave energy [14] which, in turn, lead to enhanced sedimentation [9, 5] and retention of particulate material within the meadow [13].

Previous studies have shown that the drag exerted by submerged canopies reduces the velocity within the canopy and creates a pronounced inflection point in the mean velocity profile [11]. The strong shear resulted from this results in instability at the canopy-water interface and, ultimately, the generation of Kelvin-Helmholtz vortices in this region. In steady flows, these large scale shear-driven vortices have shown to be the dominant mechanism that controls rates of vertical mixing across the canopy water-interface [11]. Thus, by controlling rates of mixing and transport of ecologically significant species (e.g., pollen, seeds and nutrients) these vortices can have a tremendous impact on health and propagation of aquatic canopies [22].

In wave-dominated flows, the shear-driven vortices are only generated when the wave period is long enough to allow the generation of shear-driven KH-vortices. This condition is met when the Keulegan-Carpenter number KC, defined as

$$KC = \frac{U_\infty T}{L_D} \tag{1}$$

exceeds the threshold value; i.e., $KC > 5$ [12]. In equation (1), U_∞ is the amplitude of the velocity far above the canopy and T is the wave period. The drag length scale L_D is defined as

$$L_D = \frac{1-\lambda_P}{C_D a}, \tag{2}$$

where λ_P is the solid fraction of the canopy, a is the canopy frontal area per unit volume and $C_D \approx 1$ (following [1]) is the drag coefficient.

Recent research has revealed that while wake turbulence (the small scale turbulence generated behind each canopy stem) plays a significant role in mixing when $KC < 5$, vertical turbulent diffusivity is predominantly controlled by shear-driven mixing at high KC values (i.e., when $KC > 18$ [2]). Thus, KC is expected to be an important and relevant parameter in describing flow and mixing in wave-dominated canopy flows.

Despite the improved understanding of flow, turbulence and mixing in steady and wave-dominated canopy flows [11, 18, 3], a real understanding of the extent to which these mechanisms differ between the two types of hydrodynamics is still lacking. Previous studies into canopy-flow dynamics have looked at steady (i.e., current-dominated) and unsteady (i.e., wave-dominated) flows, separately. However, vegetated flows can be linked through the Keulegan-Carpenter number which is, in fact, the ratio of the timescale of flow oscillation T to the timescale of shear formation L_D/U_∞ [12]. Therefore, when $T \to \infty$ (i.e., $KC \to \infty$), we expect the flow to approach steady conditions. Thus, through an extensive laboratory study, this research investigates similarities and differences between canopy hydrodynamics under these two forcings and the subsequent impacts on critical ecological and biological processes. This will, ultimately, provide a unifying framework of canopy-flow hydrodynamics for steady and wave-dominated environments.

Methods

Experimental setup

Steady flow experiments were carried out in a 24-m long and 38-cm wide recirculating flume. A constant water depth of $h = 47$ cm was employed and a range of flow velocities $U_\infty = 4.5-22$ cm/s was examined. Oscillatory flow experiments were conducted in a 50-m long, 1.2-m deep, and 1.2-m wide wave

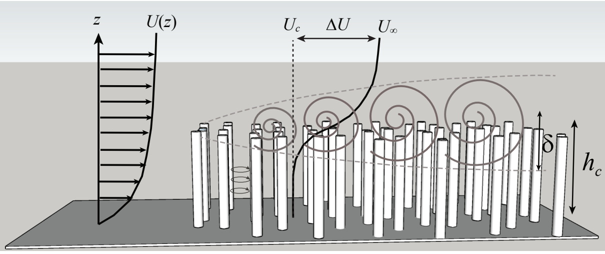

Figure 1: A schematic view of the canopy-induced shear and the subsequent vortex generation at the canopy-water interface ($z \approx h_c$). In wave-driven flows, wake turbulence have shown a substantial impact on rates of vertical mixing.

flume. A constant water depth of $h = 76$ cm was employed and 19 wave conditions were examined by varying the wave period ($T = 5-9$ s) and wave velocity ($U_\infty = 3-22$ cm/s). All generated waves were shallow-water waves with $kh \leq 0.35$ (with k being the wave number) [6], typical of coastal canopies [15, 20].

Model canopies consisted of circular wooden dowels with diameter $d = 0.64$ cm, and negligible oscillation or deflection) hammered into perforated PVC boards, creating 6-m- and 9-m-long canopies in steady and oscillatory flow experiments, respectively. The height of the canopy h_c was 13.9 cm in steady flows and 30 cm in wave-dominated flows. The dimensionless frontal area of the canopy ad was varied between 0.02 to 0.07 in steady flows and 0.02 to 0.13 in wave-driven flows (spanning a wide and realistic range of aquatic meadows, [4, 21]). The wave and canopy conditions tested here resulted in $1 < KC < 40$.

Velocity and turbulence measurements

Here, x is defined as the direction of wave propagation (and left to right for steady flows), y as the lateral direction and z as the vertical direction (positive upward), with $z = 0$ at the bed. Velocity components along x, y and z directions are denoted (respectively) by u, v and w.

Instantaneous 3-D velocity measurements (u, v, w) were taken mid-width and mid-length along the canopy, using an Acoustic Doppler Velocimeter (ADV). A sampling time of 6 min (40 - 70 wave cycles) was employed (see [1, 3], for details of data filtration). To Velocity components were decomposed into mean and turbulent fluctuations such that velocities (in the horizontal direction) for unidirectional and oscillatory flows are

$$u = \overline{u} + u', \tag{3}$$

and

$$u = \overline{u} + \tilde{u} + u', \tag{4}$$

respectively. Here, the overbar, the prime and the tilde indicate the time-averaged, the turbulent fluctuations and the phase-averaged velocity, respectively. The velocity attenuation ΔU was calculated as

$$\Delta U = U_\infty - U_c, \tag{5}$$

where U_∞ and U_c are the above- and in-canopy velocities (figure 1). Note, U is defined, hereafter, as the time-averaged velocity in steady flows and the root-mean-square velocity in oscillatory flows, allowing a faithful comparison between steady and wave-dominated flows (as has been done by [2, 18]).

In oscillatory flows, the horizontal velocity and, thus, Reynolds stress $u'w'$ switches sign as the flow reverses. Therefore, the time-averaged Reynolds stress $\overline{u'w'}$, and thus, vertical mixing of momentum tends to zero [12, 3]. Thus, to accurately estimate

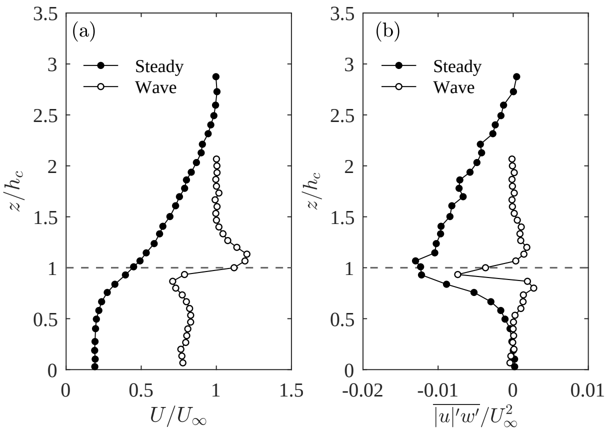

Figure 2: Vertical profiles of (a) velocity and (b) dimensionless Reynolds stress in comparable (in terms of U_∞) unidirectional and wave-dominated flows over canopies with $ad = 0.05$. (a) There is a stronger velocity attenuation in steady flows than that in oscillatory flows. This resulted in a (b) stronger Reynolds stress at the canopy top in steady flows, suggesting a more efficient mixing of momentum in these environments.

the total rate of downward mixing of momentum, $\overline{|u|'w'}$ was calculated here.

Rates of vertical mixing were characterized through gauging the evolution of vertical profiles of concentration of a dye sheet injected into the flow. In steady flows, a flux-gradient model was used to estimate rates of vertical turbulent diffusivity of the injected dye $D_{t,s}$ (see [10] for details). In wave-dominated flows, instantaneous measurement of the variance of the vertical concentration distribution allowed the estimation of a vertical turbulent diffusivity $D_{t,w}$ (see [1] for details).

Results and Discussion

Vertical variation in flow and turbulence

Vertical profiles of velocity and Reynolds stress in submerged canopies (with $ad = 0.05$) when subjected to comparable steady and oscillatory flows ($U_\infty \approx 14$ cm/s) are shown in figure 2. As expected, there is a notable reduction of velocity within the canopy in both environments (figure 2a). Nevertheless, this velocity reduction is much greater (by a factor of 3) in steady flows. This is consistent with the model developed by [18] which suggests that the in-canopy velocities in wave-dominated flows are always greater than those of comparable steady flows.

The reduced velocity attenuation in oscillatory flows and, subsequently, a weaker shear layer in these environments results in a diminished Reynolds stress at the top of the canopy (figure 2b). Importantly, the shear layer is much thicker in steady flows and $\overline{|u|'w'}$ penetrates deeper into the canopy such that the penetration depth δ (defined as the depth where $\overline{|u|'w'}$ decays to 10% of its interfacial value) in the steady flow is approximately twice that of the oscillatory flow. This suggests a greater penetration of KH-vortices and, thus, a greater depth over which the canopy is rapidly flushed. A deeper penetration may also impact the near-bed processes such as re-suspension and flux of material at the sediment-water interface.

The impact of flow oscillation

As noted earlier, the Keulegan-Carpenter is an important parameter that can provide insight into oscillatory flow behaviour. This is supported in figure 3 where the dimensionless veloc-

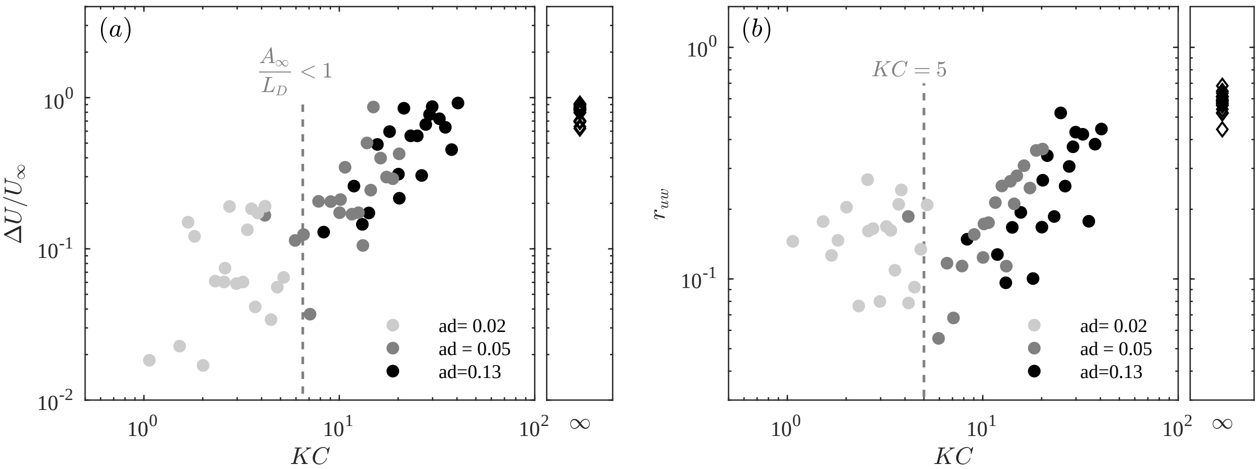

Figure 3: (a) The increase of dimensionless velocity attenuation $\Delta U/U_\infty$ and KC. While velocity attenuation in steady flows (where $KC \to \infty$) is invariably higher than that in wave-driven flows, $\Delta U/U_\infty$ approaches unidirectional values (diamonds in the right-hand side panel) when KC is sufficiently high; i.e., $KC \to \infty$. Similarly, (b) the efficiency of vertical mixing of horizontal momentum r_{uw} increases with KC and approaches unidirectional values (diamonds in the right-hand side panel) when $KC \sim O(100)$.

ity attenuation $\Delta U/U_\infty$ increases monotonically with KC (figure 3a). Notably, $\Delta U/U_\infty$ can be as low as 0.01 under some wave conditions but it increases to 0.9 when $KC \approx 40$. This is due to the fact that increasing KC is associated with the dominance of drag over the inertial force which, in turn, lead to a greater velocity attenuation by the canopy [18, 19]. Additionally and for the same reason, runs with $A_\infty/L_D \lesssim 1$ (with A_∞ being the horizontal wave excursion) are less affected by vegetation drag and, thus, characterized by weaker velocity attenuation [23]. The absence of clear inflection points in the vertical profiles of U caused the scatter of data in these runs.

The dimensionless velocity attenuation in steady flows; i.e., in the limit of indefinitely high KC ($KC \to \infty$) are also presented in figure 3a (the right-hand side panel). While velocity attenuation in steady flows invariably exceeds oscillatory flow values, $\Delta U/U_\infty$ approaches 'steady' conditions when KC is sufficiently high; in particular, when $KC \sim O(100)$.

To understand the impact of canopy turbulence on vertical transport, the efficiency of vertical mixing of horizontal momentum r_{uw}, defined as

$$r_{uw} = \frac{\overline{|u|'w'}}{u_{rms} w_{rms}}, \tag{6}$$

was calculated. In equation (6), u_{rms} and w_{rms} are root-mean-square of the horizontal and vertical turbulent fluctuations, respectively.

Our results showed a clear peak in the magnitude of r_{uw} at the canopy top for runs with $KC > 5$; i.e, when large scale shear-driven vortices are present (results not shown). The magnitude of r_{uw} (measured at the canopy-water interface) increases with increasing KC (figure 3b). Not surprisingly, the efficiency of the downward mixing of momentum in steady flows (presented in the right-hand side panel) is greater than those of oscillatory flows. However, consistent with figure 3a, the magnitude of r_{uw} approaches unidirectional values when $KC \sim O(100)$. Thus, KC is an important and relevant parameter in describing the impact of flow oscillation on canopy hydrodynamics. Finally, when $KC < 5$, r_{uw} do not show a clear response to increasing KC, indicative of the absence of shear layer vortices at low KC [12].

Impact on vertical mixing

The final question to be answered here concerns how these differences in flow and turbulent characteristics impact mixing of mass in steady and wave-dominated flows. To answer this question, a direct comparison between rates of vertical turbulent diffusivity in steady ($D_{t,s}$) and wave-dominated flows ($D_{t,w}$) was performed (figure 4). Comparable steady and wave-driven flows (in terms of U_∞) over identical canopies (in terms of ad) were extracted from [10] and [2], respectively. These runs included 12 flows with $U = 4 - 14$ cm/s over canopies with $ad = 0.02 - 0.05$ which resulted in $KC = 1 - 13$. Con-

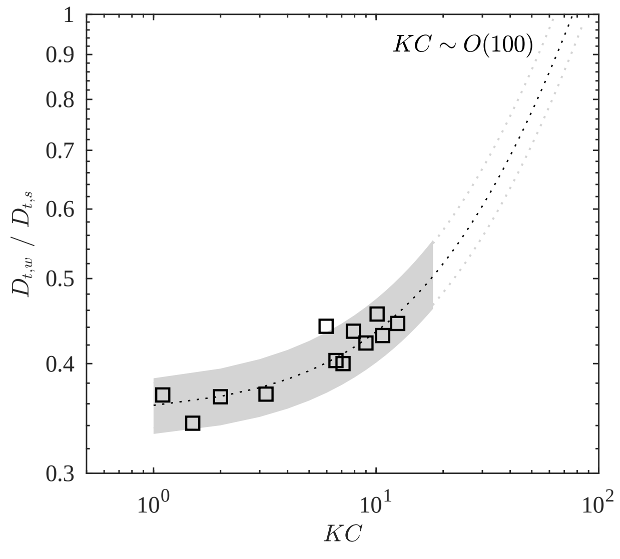

Figure 4: The relative magnitude of vertical turbulent diffusivity in wave ($D_{t,w}$) and steady flows ($D_{t,s}$) as a function of KC. While vertical turbulent diffusivity in wave dominated flows is always less than those in steady flows, $D_{t,w}/D_{t,s}$ increases monotonically with KC. Consistent with vertical mixing of momentum (figure 3b), vertical mixing of mass appears to approach unidirectional values around $KC \sim O(100)$, as indicated by the general trend (the grey band and extrapolated dashed lines) best-fit line (dotted line).

sistent with momentum transport, vertical mixing of mass in steady flows continuously exceeds those of oscillatory flows. While we currently have insufficient data to speculate the relative magnitude of mixing in steady and wave-dominated flows for higher *KC* values, the general trend and the linear fit on the data suggests $D_{t,s}/D_{t,w} \approx 1$ when $KC \sim O(100)$ (figure 4). This result further implies the importance of *KC* in characterising oscillatory flow behaviour.

Conclusions

A direct comparison of the flow, turbulence and vertical mixing in steady and wave-driven flows revealed that despite general similarities (e.g., velocity attenuation and vortex generation at the canopy-water interface), there are significant differences between these two systems. In particular, the velocity attenuation and, thus, the strength of the shear layer is much stronger in steady flows. This results in a weakened shear-layer vortices in wave-dominated flows which will, in turn, lead to a lower vertical turbulent diffusivity in these environments compared to the corresponding steady flows. Moreover, the Keulegan-Carpenter number (*KC*) has proven to be an important and relevant parameter in describing the impact of oscillation on flow structure. For example, there is a clear dependency between velocity attenuation, the efficiency of vertical momentum transport and ultimately, vertical mixing of mass with *KC*. Importantly, this parameter defines the transition from wave-dominated conditions (at low *KC*) to quasi-steady flow conditions (at high *KC*). At sufficiently high *KC* (i.e., $KC \sim O(100)$), parameters describing the flow, turbulence and mixing take on the same values as those in a purely steady flow. Finally, the results of this study provide predictive insights into the extent to which the flow oscillation in coastal systems (due to, e.g., tides, infragravity waves, swell and wind waves) will be significant in modifying the hydrodynamics of submerged canopies.

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