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Modified hydrodynamics in canopies with longitudinal gaps exposed to oscillatory flows

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SUMMARY

Longitudinal gaps are commonly found in aquatic canopies. While the ecological significance of gaps may be large, we know little about their impact on the hydrodynamics within the canopy. We used laboratory experiments to investigate the effect of longitudinal gaps within canopies exposed to a wave field. In rigid submerged and emergent vegetation, wave velocities were reduced compared to the case without vegetation. Flexible canopies also attenuated waves, but this attenuation was lower than for rigid canopies. The presence of the gap modified the mean current associated with the waves in both the gap and the lateral vegetation. A gap within a canopy of 5% solid plant fraction did not show differences in the wave attenuation between the gap and the lateral vegetation. In contrast, gaps within canopies of 10% solid plant fraction resulted in large differences between the gap and the lateral vegetation. In all the experiments, the effect of a gap within a canopy reduced the wave attenuation within the lateral vegetation adjacent to the gap when compared with a canopy without a gap. In canopies with rigid plants, the lateral vegetation modified the wave attenuation in the nearby gap. In contrast, the lateral flexible vegetation did not produce any effect on the wave attenuation of the adjacent gap. Canopy density, plant height and plant flexibility were critical for determining the hydrodynamics throughout the canopy and in the gap.

1. Introduction

Salt marshes, seagrass meadows and mangroves forests are characteristic of shallow coastal and littoral zones and support a large variety of infauna relative to bare substrate areas (Feller and McKee, 1999; Fredriksen et al., 2010; Hendriks et al., 2011; Coulombier et al., 2012). These vegetated systems cover less than 0.5% of the seabed but account for up to 70% of the carbon storage in ocean sediments. Submerged and emergent aquatic plants also influence the spatial distribution of key water quality parameters. Therefore, aquatic plants are recognized as water quality indicators and their restoration and protection is a priority given that their regrowth is slow and variable (Moore et al., 2000; Orth et al., 2009). Submerged coastal canopies reduce ambient flows and turbulence (Koch et al., 2006; Pujol et al., 2010, 2013a, 2013b) and attenuate waves (Granata et al., 2001; Lowe et al., 2005; Luhar et al., 2010; Pujol et al., 2013a), resulting in a reduction in sediment resuspension (Gacia and Duarte, 2001; Bouma et al., 2007; Hendriks et al., 2008; Coulombier et al., 2012). Emergent vegetation reduces turbulence depending on wind stress, solar irradiative forcing and macrophyte mechanical forcing (Coates and Folkard, 2009). Aquatic vegetation ranges in flexibility, from rigid emergent mangroves to highly flexible canopies such as submerged seagrasses. Coral reefs can also be considered to be a rigid structure. Pujol et al. (2010, 2013a) found that flexibility and canopy density play a major role in the effectiveness of the canopy to attenuate waves and turbulence.

Salt marshes, seagrasses and mangroves are vulnerable to environmental changes. Sagittal channels in meadows run perpendicular to the coast and are formed by return currents transporting wind- and/or wave-mixed surface waters to depth. Erosive intermattes appear like oval potholes in seagrass mattes and are probably formed by whirling currents carrying rocks and stones to depth, locally destroying the mattes (Bianchi and Buia, 2008). The formation of gaps within meadows may also be triggered by human activities such as anchoring, trawling, fish farming, laying cables and pipes (Boudouresque et al., 2012). Once formed the gap changes the local environmental conditions and Ewel et al. (1998) found that water temperature, salinity and light in mangrove forest gaps were all higher than those within the canopy. Similarly Folkard (2011) found different flow regimes in

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unidirectional flows through transversal gaps of submerged vegetation and showed that Reynolds number (based on canopy overflow speed and the gap depth) and the gap aspect ratio were the most important parameters in determining the modification of bed shear stress.

Despite their variety, little research has been done to elucidate the effects of gaps on adjacent vegetation, especially in wave-dominated domains. Therefore this study investigates the effect of a longitudinal gap within a canopy (with the main axis of the gap in the same direction as the wave propagation) on the hydrodynamics within the canopy and in the gap. Attention is paid to the modification of ambient hydrodynamics as a function of the ratio of gap width to plant height. Laboratory experiments were conducted on a longitudinal gap using a model canopy exposed to waves, mimicking structural disturbances of canopies in benthic salt marshes and seagrasses that are dominated by waves in shallow conditions. Two vegetation models (rigid and flexible), two gap sizes (0.25 and 0.375 of the flume width), two vegetation densities (solid plant fraction, SPF, of 5 and 10%), one wave frequency ($F = 1.2$ Hz) and two plant heights (submerged and emergent) were considered, along with a case without plants, totalling 15 experiments (Table 1). The specific objectives of our study were firstly to identify and quantify patterns of mean flow and turbulence found in the interior of simulated longitudinal gaps, and secondly to determine how these gaps affected the hydrodynamic environment within the adjacent vegetation patches. Special attention was paid to the effects of both the gap width to plant height ratios and the canopy density on the hydrodynamics within the gaps.

2. Methods

2.1. Laboratory setup

The experiments were performed in a flume (6 m × 0.5 m × 0.5 m), with a mean water height of 0.3 m. A schematic view of the experimental setup is shown in Fig. 1a. The flume was equipped with a vertical paddle-type wave maker that was placed at the beginning of the flume. The vertical paddle was driven by a variable-speed motor that operated at a frequency of 1.2 Hz. This frequency was chosen in accordance to the frequencies used by other authors (Bradley and Houser, 2009; Hansen and Reidenbach, 2012; Pujol et al., 2013a). Furthermore, with this frequency, waves had a wavelength of 1.03 m, which corresponds to transitional water waves, typical for regions dominated by the presence of aquatic vegetation. Following Pujol et al. (2013b), a plywood beach of slope 1:3 was situated at the end of the flume. It was covered in foam to better attenuate incoming waves. For details of the experimental set up see Pujol et al. (2013a). We define the longitudinal direction as x, and $x = 0$ at the wavemaker; y is the lateral direction and $y = 0$ at the centreline of the tank, and z is the vertical direction, with $z = 0$ at the flume bed.

The model canopies were 2.5 m long and they were situated at the centre of the flume. A rigid canopy model was considered with two heights: submerged (plant height $h_v = 14$ cm) and emergent (plant height $h_v = 29$ cm). Following Pujol et al. (2013a, 20013b), emergent canopies were defined as vegetation whose height was emergent for nearly half of the wave cycle. Rigid plants consisted of PVC cylinders, 1 cm in diameter. Two canopy densities of 640 and 1280 shoots m^{-2} were considered and a model of flexible vegetation was studied for the 1280 shoots m^{-2} submerged canopy to compare the results with the rigid canopy model. A summary of the different experimental conditions is presented in Table 1. Typical vegetation densities in salt marshes vary from 296 stems m^{-2} to 505 stems m^{-2} (Capehart and Hackney, 1989). Paul and Amos (2011) found that a seagrass population of *Zostera noltii* had strong seasonal variability, from 4600 shoots m^{-2} in summer to 600 shoots m^{-2} in winter. Fonseca and Cahalan (1992) found densities of 1900–2870 shoots m^{-2} for *Halodule wringhtii*, 230–1350 shoots m^{-2} for *Syringodium filiforme*, 850–1500 shoots m^{-2} for *Thalassia testudinum* and 750–1000 shoots m^{-2} for *Zostera marina*. Neumeier and Amos (2006) reported densities of 1140 and 1450 shoots m^{-1} for a salt marsh canopy of *Spartina anglica*. Therefore, the plant densities used in the present study would represent intermediate to high canopy densities. The SPF is defined as the fractional plant area at the bottom occupied by stems i.e. SPF (%) $= n_{stems}A_{stem}/A_{total} \times 100$, where n_{stems} is the number of stems, A_{stem} is the horizontal cross sectional area of each stem ($A_{stem} = \pi d^2/4$), d is the plant diameter and A_{total} is the total horizontal area. Therefore, the solid plant fractions for the two canopy densities considered (640 and 1280 shoots m^{-2}) corresponded to SPF of 5% and 10%, respectively.

A region free of plants (hereafter called the gap) was situated at the centre of the flume in the y-direction and extended longitudinally the full length of the canopy (Fig. 1). Two different gap widths (GW), were considered (0.25 and 0.375 of the flume width; Fig. 1), therefore the ratios GW/h_v were ~0.9 and 1.3 for the submerged canopies and ~0.4 and 0.6 for the emergent vegetation.

Experiments with flexible vegetation were also carried out for 10% SPF and 0.25 gap width. The flexible canopy model was constructed following Pujol et al. (2013a), i.e., six individuals of high-density polyethylene blades of 0.14 m length and 0.004 m width were attached with a plastic band to a PVC dowel (2-cm long × 1-cm diameter). The thickness of the plastic blades was ~0.075 mm. As stated by Pujol et al. (2013a), the model plants were dynamically and geometrically similar to typical seagrasses.

Velocity measurements were made with an Acoustic Doppler Velocimeter (16 MHz-ADV, Sontek Inc.) that recorded the three instantaneous velocity components at a single depth situated 5 cm from the tip of the probe with a sampling volume of 0.09 cm^3. The ADV was placed in the flume in a downward-looking configuration and connected to a PC with data acquisition software.

The ADV was configured to transmit 50 signals per second over a sampling window of 10 min (30,000 records per sample). The ADV was mounted in a frame and velocity profiles measured from 1 to 23 cm from the bottom of the flume, with a vertical resolution of 1 cm. Five independent velocity measurements were completed for each case at four selected depths, in order to estimate measurement error. Velocity measurements near the surface were limited by both wave shape and the 5-cm sampling volume of the ADV. To avoid spikes, beam correlations lower than 80% were removed. At two vertical positions ($z = 8$ cm and $z = 20$ cm above the bottom) low correlation was obtained. These "weak spots" occur when the

Table 1
Summary of the different experimental conditions. A is the horizontal area and b is the width of the flume.

SPF (%)	n/A (shoots/m^2)	GW/b	h_v (cm)	Type
5	640	0.25	14	Rigid
5	640	0.375	14	Rigid
5	640	0	14	Rigid
10	1280	0.25	14	Rigid
10	1280	0.375	14	Rigid
10	1280	0	14	Rigid
5	640	0.25	29	Rigid
5	640	0.375	29	Rigid
5	640	0	29	Rigid
10	1280	0.25	29	Rigid
10	1280	0.375	29	Rigid
10	1280	0	29	Rigid
10	1280	0	14	Flexible
10	1280	0.25	14	Flexible
0	0	–	–	–