The influence of vegetation on turbulence and flow velocities in European salt-marshes

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ABSTRACT

Flow hindrance by salt-marsh vegetation is manifested in the structure of the tidal current; it has a significant impact on sediment transport and causes increased sediment accretion. The flow characteristics in 3 different vegetation types (*Spartina maritima*, *Sp. anglica* and *Salicornia/Suaeda maritima*) were measured on 3 salt-marshes in Portugal and England. Skimming flow develops above the *Spartina* canopy when the vegetation is fully submerged. In this situation, a low turbulence zone with nearly constant velocity in the denser canopy is separated from the skimming flow above by an interface characterised by high Reynolds stresses. In the low turbulence zone, a positive relationship exists between turbulence intensity and shoot density, which is due to wake turbulence generated locally in the canopy. The rate of particle settling will be increased in that zone; this affects the sediment dynamics. The lower limit of skimming flow is best predicted by the height within the canopy that includes 85% of the biomass. For emergent *Spartina* canopies and the short *Salicornia/Suaeda* marsh, the maximal velocity-gradient is shifted upwards compared to a standard boundary layer over bare sediment and the turbulence is attenuated near the bed, but to a lesser extent than for fully submerged *Spartina* canopies. A turbulence reduction near the bed was observed in all measured profiles; that should enhance sediment deposition and protects the bed against subsequent erosion.

Keywords: Sediment transport, Intertidal vegetation, Salt-marsh, Hydrodynamics

INTRODUCTION

Coastal salt-marshes have an important influence on the sediment dynamics of upper intertidal areas (French and Reed, 2001). They enhance sedimentation, especially close to a sediment source such as a creek (Carling, 1982; French *et al.*, 1995; Reed *et al.*, 1999); and they protect the bed against subsequent erosion (Allen and Duffy, 1998; Brown, 1998). The resulting increased accretion is of particular importance when the relative sea-level rises (Schwimmer and Pizzuto, 2000). Salt-marshes also afford a protection against storms by damping waves passing above them (Knutson *et al.*, 1982; Möller *et al.*, 1999). As a result, the energy reaching the shoreline is reduced, and consequently the engineering structures of coastal defence could be made smaller (Erchinger, 1995; King and Lester, 1995). These salt-marsh characteristics are due to flow hindrance by the canopy. Though the consequences have been studied extensively, the mechanisms by which stabilization is achieved are still poorly understood. This is due to the difficulties of getting accurate field measurement of water flow within the canopy, and difficulties of reproducing a natural canopy in a laboratory flume.

Most knowledge on the flow dynamics in and around salt-marsh canopies originated from time-average measurements of unidirectional flow. Several studies have shown the reduction of water speed by the salt-marsh canopy (e.g., Stumpf, 1983; Wang *et al.*, 1993; Christiansen *et al.*, 2000; Shi *et al.*, 2000; Van Proosdij *et al.*, 2000). More detailed results in laboratory flumes (Pethick *et al.*, 1990; Shi *et al.*, 1995; Shi *et al.*, 1996) and in the field (Leonard *et al.*, 1995; Neumeier and Ciavola, 2004) showed a flow reduction correlated with the local vegetation density and an absence of a boundary layer with logarithmic velocity-profile within the canopy. If the vegetation is fully submerged, skimming flow can develop above the denser part of the canopy. This faster flow generally presents a logarithmic profile, and the vegetation may be simply considered as a form of macro-roughness (Neumeier and Ciavola, 2004).

Little information is available on flow turbulence within a salt-marsh canopy although it has a significant influence on sediment transport. Turbulence controls particle settling rate and, through the bed shear stress, bed erosion. It also influences geochemical exchanges in the water column and biological processes such as pollination or dispersion and recruitment of seeds and larvae, (Ackerman, 1986; Csanady, 1993; Fingerut *et al.*, 2003). The presence of a canopy modifies profoundly the turbulence structure compared to a standard boundary layer. Leonard and Luther (1995), and Leonard and Reed (2002) measured reduced turbulence intensities under unidirectional flow in the canopy using hot-film anemometry. Nepf (1999)

and Nepf and Vivoni (2000) looked at turbulence under unidirectional flow in laboratory experiments with artificial structures representing vegetation.

The aim of the present paper is to quantify the attenuation of turbulence in a salt-marsh canopy and in so doing quantify the reduction in momentum transfer to the bed. This work complements a previous study on velocity profiles on a *Spartina maritima* marsh in southern Portugal (Neumeier and Ciavola, 2004) and presents results from two English salt-marshes (4 sites with various densities of *Sp. anglica*, and 1 site with a *Salicornia*/*Suaeda maritima* marsh).

STUDY AREAS

Ramalhete, southern Portugal

The Ramalhete salt-marsh is located in the western part of the Ria Formosa lagoon, just south of the airport of Faro (southern Portugal, Fig. 1). The Ria Formosa lagoon is sheltered from the Atlantic Ocean by a chain of barrier islands and includes over 80 km^2 of tidal flats and salt-marshes with some subtidal channels. The tides are semidiurnal, with a mean spring tide range of 2.7 m.

The studied salt-marsh is located northward of the Ramalhete Channel (N37°0'20", W7°58'15") and occupies an intertidal embayment of 200 × 300 m bounded by seawalls. This marsh is dominated by *Sp. maritima* (Fig. 2a) and is divided by several unvegetated areas of muddy sediments. Velocity profiles were measured at two locations on a flat ridge near the channel. This ridge is 40-50 m wide and is probably a relict structure. Location B was on the flat top of the ridge, at 0.63 m above mean sea-level (MSL). Location C was on the slope of the ridge towards the main channel (gradient 3-5°) at 0.55 m above MSL. The distance to the vegetation edge is, respectively, above 20 m (in upstream direction during experiment) and 8 m. The salinity (practical salinity scale) was 37 during the experiments. Results of the vegetation survey for both locations are summarized in Table 1. See Neumeier and Ciavola (2004) for a full site description.

East Chidham, southern England

The East Chidham salt-marsh is near the landward termination of Bosham Channel, which is one of the branches of Chichester Harbour, a very shallow, bar-built estuary of 28.5 km^2 on the south coast of England (Fig. 1). The inner reach of Bosham Channel is 300-600 m wide

and drains completely at low water. It is rimmed partially with salt-marshes. The salinity varies between 33 and 35. The mean spring tide range is 4 m.

The study area (N50°49'54", W0°52'6") is at the outer edge of a 100 m wide salt-marsh, just south of a small embayment where the currents are stronger. The salt-marsh is composed only of *Sp. anglica*, and is dissected by creeks, gullies and patches of bare substrate (Fig. 2c). It is sheltered in the inner part of the estuary; the maximum fetch is about 1 km.

Velocity profiles were measured at two locations. Location E is just at 2.2 m from the vegetation edge where the plants are sparse and small. The edge of a minor creek is 5 m away. Location F is in the centre of a denser salt-marsh area surrounded by gullies 3-5 m away, but is more than 15 m away from the marsh edge.

Freiston Shore, eastern England

Freiston Shore lies on the northwest shore of The Wash (east coast of England, Fig. 1). The Wash is a large embayment (600 km^2) of which about 45% is intertidal. Tides are semi-diurnal with a spring tidal range of 6.8 m. The shoreline is formed by continuous seawalls, which are rimmed by minerogenic salt-marshes 500-1000 m wide. At Freiston Shore, the 500 m wide salt-marsh is bordered by a muddy and sandy tidal-flat 1.5 km wide (Collins *et al.*, 1981). The lower salt-marsh is dominated by *Sp. anglica*, and it terminates with a 150 m wide pioneer-zone of *Salicornia sp.* and *Suaeda maritima* (Fig. 2d). The salt-marsh and tidal flat can be regarded as accretional (Ke and Collins, 2000), and hence are typical of this sub-environment.

The study area (E0°5'24", N52°57'22") is located near the seaward limit of vegetation, at the outer edge of the *Spartina* marsh, which forms dense patches 10-20 m across. There are several small creeks in the vicinity, which are 0.2-0.4 m deep and oriented roughly shore-normal. The next large creek is 70 m away. The salinity was 33 during the experiments. Velocity profiles were measured at three locations, one on the *Salicornia*/*Suaeda* marsh and two on the *Spartina* marsh.

Location G is on a flat surface of firm mud with only pioneering, low *Salicornia*/*Suaeda* marsh with some *Spergularia marina*. Vegetation samples taken after the experiment showed that the contributions of the different plants to the biomass were *S. maritima* 48%, *Salicornia sp.* 33%, undifferentiated green algae 12%, and *S. marina* 7%. The next gully is 4 m away. The next *Spartina* stand is laterally at 2.6 m (but never in upstream direction during experiment). Location H is in a small *Spartina* patch (dimension 5 × 20 m). During the flood,

the distance to the vegetation edge was ~2.6 m in the upstream direction; during the ebb it was more than 4.5 m. Location I is about 25 m more landward, in a larger Spartina patch with taller vegetation. Distance to the vegetation edge was 6 to 10 m, depending to flow direction. Some data from the present experiment have been presented in Neumeier and Amos (2005) to illustrate damping of orbital wave-velocities by vegetation. In that publication, locations H and I were called locations A and B, respectively.

Vegetation description

Sp. anglica and *Sp. maritima* are perennial angiosperms. Both species have a stem of 3-6 mm diameter and several oblique upward leaves, but the leaves of *Sp. anglica* are slightly more horizontal (Fig. 2). The stem and the leaves are stiff. *Sp. anglica* is taller (up to 130 cm, commonly 30-60 cm) than *Sp. maritima* (up to 50 cm, commonly 25-35 cm). *Sp. maritima* is the common pioneer salt-marsh plant in Portugal. In England *Sp. anglica* is the first pioneer plant that is taller than 15 cm. Its vegetation density decreases during the winter season due to temperature effects (Neumeier, 2005). The canopy of *Sp. maritima* in Portugal does not show significant seasonal change.

The canopies of *Sp. anglica* and *Sp. maritima* are very similar. The stands are often practically monospecific, but the canopies are characterized by a complex architecture: large plants are mixed with small young plants, standing dead plants, and various organic debris lying on the ground or entangled in the canopy. This was particularly pronounced in Portugal, where the lower part of the *Spartina* plants was commonly encrusted by green algae and other epiphytes, that acted to bind dead *Spartina* plants to the canopy in an upright position (Fig. 2a).

Salicornia sp. is an annual with upright, fleshy stems of 2-4 mm diameter that are sometimes branched (Fig. 2d). It is up to 40 cm tall, but is commonly between 10-20 cm. *S. maritima* is an annual with fleshy stems and leaves (leaf size: 2-3 × 20 mm). It can grow up to 30 cm tall, but at Freiston Shore it was only 10-20 cm tall (Fig. 2d). It may be lying on the ground or erect, as it was at Freiston Shore. Both species die back in the winter, but some dried shoots remain upright on the mudflat until the spring. The cover at location G during the summer was relatively dense, but still much less than the cover of *Spartina* or upper marsh.

METHODS

Water flow measurements

The water flow was recorded with an Acoustic Doppler Velocimeter (ADV): a Nortek/Vector instrument was used at Ramalhete; a Nortek/NDVfield instrument was used at East Chidham and Freiston Shore. The Vector ADV measured at 16 Hz in a volume of 2 cm^3. The NDVfield ADV measured at 25 Hz in a volume of 0.5 cm^3. The ADV was mounted on a vertical sliding mechanism, used to move the sensor rapidly between different heights above the bed. Since an ADV is sensitive to the presence of objects between the probe and the sampling volume, a hole was cut in the canopy around the probe trajectory; the hole diameter was ~20 cm for the Vector ADV and ~10 cm for the NDVfield ADV. A full description of the mechanism is given by Neumeier and Ciavola (2004).

Vertical profiles of 6-10 points were recorded. The lowest point was 1-2.5 cm above the bed. The highest point was 6-12 cm below the water surface for the NDVfield ADV, it was 20-25 cm below the water surface for the Vector ADV (Fig. 3). Two kinds of vertical profiles were measured. To compute mean-current profiles, 15 seconds were recorded at each point (an entire profile consisted of two repetitions and was collected in 3-5 minutes). Turbulence analysis requires longer time-series; therefore 30-60 seconds were recorded at each point for turbulence profiles. This relatively short duration of turbulence measurement was necessary in order to obtain data at several heights with one ADV within a time-frame (5-10 minutes) over which the tidal flow (velocity and direction) and the water depth could be assumed constant. Turbulence profiles were also used to compute mean-velocity profiles.

Water level and waves were recorded with a pressure transducer (PT). At Ramalhete and Freiston Shore, the PT was mounted 10 cm above the bed on the rig holding the ADV (horizontal distance ADV–PT: ~0.8 m). At East Chidham, the PT was combined with an electro-magnetic current-meter, which was installed at 3.5 m from the ADV.

Methods of analysis

The ADV results were examined to check that: (1) the flow direction was approximately constant within a profile (the variations were generally less than 30°); (2) for repeated velocity profiles, the two points at the same heights yielded similar flow values (differences were generally less than 20%); and (3) that, for each measured point, raw data and the internal quality data of the ADV do not show technical problems. The measurements were of good quality and very little data was discarded.

Classical fluid dynamic theory describes a boundary layer in the vicinity of a smooth bed by the Law of the Wall (Soulsby, 1997): Under turbulent or transitional flow, the boundary layer starts with a viscous sublayer where the flow is laminar, overlain by a buffer layer. Together, these two layers are only a few millimetres thick. Above them, there is an outer layer, where the flow is fully turbulent and the velocity profile has a logarithmic shape (Dyer, 1986). This logarithmic profile may be described by the Kármán-Prandtl equation: $U_z = U_* \ln(z/z_0) / \kappa$, with z: height above the bed, U_z: velocity at height z, U_*: shear velocity, z_0: roughness length, κ: Kármán constant (0.4). The presence of the salt-marsh canopy prevents the development of a logarithmic profile near the bed, but such profiles can exist above the canopy if the water depth is sufficient (Shi *et al.*, 1996). When the measured velocity-profiles presented a section with logarithmic shape above the denser part of the canopy, it was assumed that the velocity there follows the Kármán-Prandtl equation, and the boundary layer parameters (shear velocity U_* and roughness length z_0) were computed from the relevant profile points using the traditional method of analysis (Bergeron and Abrahams, 1992).

For the turbulence analysis, the instantaneous velocities u, v, and w (downstream, cross-stream and vertical directions, respectively) were decomposed into the time-averaged velocities U, V, and W, and the turbulent components u_t, v_t, and w_t, using the formula $u = U + u_t$. The turbulence intensities i_u, i_v, and i_w were computed as the root mean square of u_t, v_t, and w_t, respectively, that are the standard deviations of the u, v and w time series. The turbulent kinetic energy (TKE) was computed as follows:

$$ \text{TKE} = \tfrac{1}{2} \rho \left(\overline{u_t^2} + \overline{v_t^2} + \overline{w_t^2} \right) $$

where ρ is the water density. In addition, TKE was differentiated in the horizontal component (TKE_{horiz}, computed from u_t and v_t) and the vertical component (TKE_{vert}, computed from w_t). The two-dimensional Reynolds stress τ_{xz} and the three-dimensional Reynolds stress τ_{xyz} were computed as follows:

$$ \tau_{xz} = -\rho \overline{u_t w_t} $$

$$ \tau_{xyz} = \rho \left(\overline{u_t w_t}^2 + \overline{v_t w_t}^2 \right) $$

with w and w_t positive upward.

Vegetation quantification and SSC measurements

The shoot density and the above ground biomass (dried 48 hours at 80°C) for each location were the average from three circular areas of 16 or 19 cm diameter, which were selected

randomly within 0.6 m of the ADV location. The vertical density variations in the canopy were estimated by two methods (for details, see Neumeier, 2005). The vertical biomass distribution was determined from harvested plants that were cut in 2.5 cm slices. For the lateral obstruction, a 10 cm thick canopy was photographed laterally in front of a coloured background in order to quantify the lateral obstruction (Fig. 2b); the vegetation was differentiated from the background using image processing software; the obstruction percentage was then computed from the binary images. The canopy height is defined here as the height, below which 99 % of the biomass is found.

Suspended sediment concentration (SSC) was measured during experiment H in the Spartina marsh at 4.5 m from the ADV location and 4 m from the vegetation edge. The canopy height was 40 cm. Water was taken at 4 heights (7.5, 15, 30, and 56 cm above the bed) with an inlet opening of 3 cm diameter, pumped through 30-m tubes (diameter 12.5 mm) at a rate of 2 l/min, and sampled manually. SSC was determined by gravimetric method using Whatman GF/F filters. The accuracy of the SSC results was calculated from the potential error in measuring water volumes and weighing filters.

RESULTS

Vegetation variations

The 7 studied locations from the 3 salt-marshes sites have markedly different canopy characteristics that are presented in Table 1 and illustrated in Fig. 3. The differences are summarized as follows: (1) a relatively dense and short *Sp. maritima* canopy at locations B and C; (2) a sparse *Sp. anglica* canopy near the vegetation edge at location E; (3) a *Sp. anglica* canopy of medium density at location F; (4) a relatively dense *Sp. anglica* canopy near the vegetation edge at location H; (5) a dense and tall *Sp. anglica* canopy at location I; and (6) a *Salicornia*/*Suaeda* canopy at location G.

Neumeier (2005) monitored at Freiston Shore the seasonal variations of a *Spartina* marsh (near location H) and a *Salicornia*/*Suaeda* marsh (at location G). Both canopies showed strong variations, with an increase in biomass from spring to autumn of 3 times and 6 times, respectively (Neumeier, 2005). Experiments G, H, and I were conducted in June, before the *Spartina* canopy and the *Salicornia*/*Suaeda* canopy were fully developed. The biomass of both canopies was in the lower third of the annual range, and the canopy heights were respectively 70% and 40% of the maximum height. However, the density and lateral obstruction were already close to the annual maximum.

Profiles of time-averaged velocity

In the present paper, only profiles unaffected by waves are examined, due to complexities of the turbulence structures and velocity profiles resulting from wave-current interactions (Grant and Madsen, 1979). The standard deviation in the downstream velocity component, i_u, was used to determine which profiles were affected by waves. Plots of raw velocity data were also visually inspected to determine if peaks in i_u were due to turbulence, or exhibited a periodicity corresponding to wave passage. An example of wave interference is evident at location I, when the canopy was submerged (e.g., profiles I4, I7, and I14, Fig. 3). For this reason, the relevant profiles will not be discussed here. These profiles have been illustrated and discussed in Neumeier and Amos (2005).

A representative selection of velocity profiles for each location is represented in Fig. 3. The size of i_u is plotted as the error bar. The configuration used at location B and C produced unusually high instrument noise when the ADV was about 18 cm above the bed (interference between the echoes of two successive pings emitted by the ADV), which is illustrated by the greater i_u at these heights.

On submerged vegetation (i.e., water level above the canopy top), a skimming flow (i.e., a relatively fast flow above a layer of immobile or slow water) was generally present above the denser part of the canopy when the free-stream velocity was faster than ~2 cm s^{-1} (e.g., profiles B7 C8, E13, F18). When the vegetation was emergent and occupied the entire water column, there was no space for skimming flow and the velocity increased more rapidly from the bed than when the vegetation was submerged (e.g., profiles B2, G3, G18, H19, I1).

The boundary layer parameters (shear velocity, U_*, and roughness length, z_0) were computed from the profiles with submerged vegetation, where the skimming flow exhibited a logarithmic velocity profile (Table 2). The lower limit of the skimming flow can be defined using z_0 in these cases. On other profiles, a well-defined skimming flow existed, but the velocity profile was not logarithmic. Therefore, the lower limit of skimming flow was defined visually for all *Spartina* profiles as the lower end of the strong velocity gradient (z_{visual}, Tables 2 and 3). z_{visual} was always higher than z_0 computed from the logarithmic profiles, and a linear correlation was observed between these two parameters (r^2=0.88, p<0.01, Fig. 4). For all velocity profiles without logarithmic shape, z_{visual} was converted to z_0 for consistency (Table 3). The average z_0 values at each location are presented in Table 4.

Turbulence distribution

Figure 5 summarises the turbulence parameters for a representative selection of profiles. The turbulence over submerged *Spartina* canopies (profiles B9, E10, F17, and H9) was generally strongly reduced in the denser part of the canopy, evident as the low TKE (turbulent kinetic energy) and Reynolds stresses. The reduction in TKE_{vert} was stronger than that of TKE_{horiz}. Turbulence increased upward from the upper part of the canopy. A zone with high Reynolds stresses often existed near the canopy top, near the base of the skimming flow (profiles B9 and H9). Nepf and Vivoni (2000) observed a similar turbulence distribution in a flume experiment with artificial vegetation. This flow structure was also reproduced in a laboratory flume with natural *Sp. anglica* plants (Neumeier, submitted). Turbulence sometimes increased towards the water surface (profiles E10, F17, H9), perhaps as a result of small wind-wavelets.

The 10 cm high canopy of the *Salicornia*/*Suaeda* marsh was submerged during all measurements. The turbulence distribution was similar to that in submerged *Spartina* canopies, except that the region of low turbulence within the dense canopy was absent because of the much smaller canopy height. Turbulence always increased just above the bed (profiles G2, G5, and G9). At the top of the canopy, there was a region of turbulence maximum evident in both the TKE and Reynolds stresses.

For emergent *Spartina* canopies (profiles B1, H17 and H20), TKE generally increased upwards and the Reynolds stresses were highly variable. Figure 6 illustrates the flow evolution at the end of the ebb during experiment H. As the water level dropped and the salt-marsh was drained, the flow accelerated; the velocities near the bed increased the most. Turbulence in the lower part of the canopy (represented by TKE) decreased simultaneously; this was particularly marked when the water level dropped below 30 cm. The significant wave height (H_{m0}) was computed from the PT records with the standard spectral method (Tucker and Pitt, 2001). Turbulence decreased in parallel with to the decrease in the small surface wavelets (Fig. 6). As the water surface dropped to the denser canopy, the wavelets were increasingly attenuated. Normally, flow acceleration would be expected to increase the turbulence. The turbulence decrease that occurred here was associated with decreasing surface wavelet. This suggests that the turbulence was produced partially by small surface wavelets.

Suspended sediment concentrations

SSC profiles were measured at 4 moments during experiment H (Fig. 7). Within the canopy, SSC increases towards the bed for profiles A and C; no clear trend exists within the canopy for profiles B and D. SSC above the canopy is generally similar to the SSC in the upper canopy. However, 3 times higher SSC was measured in the skimming flow than within the canopy for profile B. Possible explanations are: (1) passage of a cloud of suspended sediment, which has not penetrated the slower moving water in the canopy at the time of the SSC profile; (2) a change in flow direction at high water with a delay between skimming flow and slow flow below; (3) rapid settling in the slow, low-turbulence flow below the skimming flow. This would imply (with a upstream distance to the vegetation edge of 7 m, a current of 1-4 cm/s in the canopy, and a height of 30 cm) a settling velocity of 0.75-3.0 mm/s or faster, which corresponds to rounded quartz grains of 23-46 μm diameter (Soulsby 1997).

DISCUSSION

Natural variability in velocity profiles and turbulence

The successive velocity and turbulence profiles, which were measured at a fixed location over a tidal cycle, often present significant differences. This variability is related to the unsteadiness of tidal currents (influenced by the irregular topography of the tidal flat), the changing water depth, and the heterogeneity of the vegetation. The last point is of particular importance because the flow direction changes several times over a tidal cycle. As a result, the vegetation upstream of the ADV, which determines the measured flow-characteristics, also changes. The canopy structure and density is never uniform. This has a particularly high impact near the vegetation edge and in short vegetation like the *Salicornia*/*Suaeda* marsh.

Shape of the velocity profile

Velocity profiles can be described as follows: (1) when the vegetation is emergent the velocity gradient near the bed is high, and the velocity profile is often linear; (2) a skimming flow develops over submerged vegetation above the denser part of the canopy, often exhibiting a logarithmic profile, while in the denser part of the canopy the velocity is slow and nearly constant; and (3) when the surface velocity ($U_{surface}$) is slow, these characteristics are

less well developed. Similar observations were made by Leonard and Luther (1995), Shi *et al.* (1995), and Neumeier and Ciavola (2004).

A secondary velocity maximum was sometimes observed in the lower part of *Spartina* canopies by Pethick *et al.* (1990), Leonard and Luther (1995), Leonard *et al.* (1995), and Shi *et al.* (1995, 1996). This was explained by a lower vegetation density of the canopy near the bed (Leonard and Luther, 1995). We very rarely observed this phenomenon. Less than 10 of the 133 profiles in *Spartina* marshes showed a weak secondary maximum near the bed; the most evident was in profile H1 (Fig. 3). All these cases were in shallow water, when the water flow could not move above the canopy (skimming flow) but is forced through the canopy. At this time, small differences in canopy densities likely influence the water flow.

The reason for the absence of a secondary maximum may be due to the different canopy structure. The *Sp. maritima* and *Sp. anglica* canopies that we studied are complex, with plants of different sizes and numerous dead standing stalks as well as debris near the bed. Pethick *et al.* (1990) and Shi *et al.* (1995, 1996) used clean *Sp. anglica* plants of equal height in their laboratory-flume experiment. Leonard and Luther (1995) and Leonard *et al.* (1995) presented field results, but the North American species, *Sp. alterniflora*, is taller, and therefore the canopy structure may be different. In addition, they took their measurements in emergent vegetation only, thus emphasizing this type of flow.

The flow inside the canopy is relatively independent of skimming flow when the vegetation is submerged. There is sometimes a weakly positive correlation between the depth-averaged velocity below z_0 (marking the lower limit of skimming flow) and $U_{surface}$. It is always statistically insignificant except for experiment F: even in this case, the velocity below z_0 ranges only 0.3-0.9 cm s^{-1} while $U_{surface}$ ranges 1.4-8.8 cm s^{-1}.

Lower limit of skimming flow

The position of the lower limit of skimming flow is of special importance, because it determines the flow structure above the canopy. This can be especially useful to compute local water fluxes or to run large-scale hydrodynamic-flow models in estuarine environments. The lower limit of skimming flow can conveniently be defined by the z_0 value calculated from the logarithmic velocity profile above the vegetation. This z_0 is interpreted as the roughness length associated with the surface of the submerged vegetation. It is several orders of magnitude greater than z_0 on bare sediments.

The dataset of the profiles with skimming flow was used to explore the parameters that affect z_0 in a *Spartina* canopy. Each location (B, C, E, F and H) was characterized by biomass, shoot density, and canopy height. The following parameters were also determined for each profile: water depth, distance from vegetation edge (in upstream direction at the profile time), surface velocity ($U_{surface}$), and z_0. This dataset comprises 29 profiles with z_0 computed from the log-shaped velocity-profile, and 16 profiles with z_0 computed from z_{visual}; the second group is less accurate and was used only when each location was examined separately (see below). As these were field measurements, parameters could not be controlled separately. Often relationships are not statistically significant due to the small size of the dataset. However, interesting tendencies can be seen.

Table 4 presents the mean z_0 values for each location. The fraction of canopy biomass below z_0 is generally around 85%; this seems to be a better predictor of z_0 than the ratio z_0 to canopy height (Table 4). z_0 shows significant, positive correlations with the biomass (r=0.49, p=0.007), the distance to vegetation edge (r=0.47, p=0.011; a better correlation was found using the inverse of the distance, r=-0.55, p=0.002), and the shoot density (r=0.42, p=0.023). The correlations with canopy height, water depth, and $U_{surface}$ are not statistically significant. The relationship of roughness length to biomass is $z_0 = $ biomass $\times$ 0.101 + 0.069, where z_0 is in m and biomass is in kg m^{-2}.

It is difficult to distinguish the influence of each parameter, because the parameters often vary simultaneously. For this reason, a multiple regression analysis was undertaken to derive a predictive formula for z_0. Various combinations of parameters were tested. The best "physically sound" solution was combined (starting with the greatest influence on the model) the inverse of distance to the vegetation edge, water depth, biomass, and canopy height (Table 5). The significance level of the model was p=0.005, with r^2=0.45. This confirms the positive relationship between z_0 and biomass, canopy height and distance to the vegetation edge and reveals a negative relationship between z_0 and water depth. However, it assumes a linear relationship between z_0 and the parameters, which may be incorrect, and it explains only about half of the variation of z_0 (r^2=0.45). Thus we recommend using z_0 derived from the height including 85% of the biomass.

Each location was also examined separately. The relationships between z_0 and the various parameters are not statistically significant (p>0.05), because the datasets at each location were small. Nevertheless some observed tendencies were apparent. At each given location, z_0 is generally correlated positively with the distance to the vegetation edge. This suggests a progressive rise of z_0 from the vegetation edge, as also shown by the laboratory experiment of

Pethick *et al.* (1990). z_0 is correlated negatively with $U_{surface}$. In a standard bed boundary layer, z_0 should be independent of the flow velocity. However, an increase in $U_{surface}$ seems to slightly depress z_0. The relationship between water depth and z_0 is highly variable from one location to the next.

Turbulence

Due to the absence of a standard boundary layer in the canopy, the usual assumptions on turbulence distribution near the bed are not valid. Within the canopy, turbulence results from (1) wakes generated locally by the flow around the canopy elements, (2) the shear turbulence generated by the local velocity gradient, (3) the turbulence transmitted vertically, (4) the turbulence advected horizontally (this is significant near the frontal edge of the canopy), and (5) the orbital velocities of waves if present (which is not discussed here).

The *Spartina* canopy consists mainly of vertical stems (cylinders of 3-6 mm diameter) and leaves with oblique orientation (thin, 3-8 mm width, up to 30 cm long). The Reynolds number associated with the water flow through the vertical stems is computed using the formula $Re = U \times d / \nu$, where u: velocity, d: stem diameter, ν: kinematic viscosity (Tritton, 1988). The Reynolds numbers range from 75 to 500 (velocity 3-10 cm s^{-1}, stem diameter 3-6 mm). These values correspond to unsteady flow and the beginning of fully turbulent conditions (Tritton, 1988). It is more complex to define a Reynolds numbers for the leaves, which do not have a cylindrical shape. In addition, the dense canopy forms a three-dimensional lattice. Unfortunately, the complexity and the irregularity of the structure prevent the use of a mesh Reynolds number (Frenkiel *et al.*, 1979).

The greatest production of shear turbulence exists at the base of the skimming flow over submerged canopies, and is due to the strong velocity gradient. In the denser canopy below, the velocity is nearly constant, and therefore the production of shear turbulence is small, except very close to the bed.

The zone with high Reynolds stress, which often exists near the canopy top, is related to (1) the turbulence transport from the turbulent skimming-flow downward to the much calmer canopy, and (2) shear turbulence produced by the strong velocity gradient at the base of the skimming flow. Nepf and Vivoni (2000) observed a similar zone with high Reynolds stress, which they called the "vertical exchange zone".

The low values of τ_{xyz} and the low vertical turbulence (represented by TKE$_{vert}$ on Fig. 5) in the dense canopy indicate that downward transported turbulence does not penetrate far into the canopy. The stronger attenuation of TKE$_{vert}$ compared to TKE$_{horiz}$ probably results from: (1) the oblique leaves forming flow hindrances to vertical movements, which dissipate the vertical turbulence, especially in the upper canopy; and (2) the horizontal current around the vertical canopy elements creates horizontal eddies (Tritton, 1988). The former effect illustrates the inadequacy of modelling submerged *Spartina* canopies with simply vertical cylinders.

A multiple regression analysis of the TKE values in the dense canopy was undertaken for well-submerged *Spartina* vegetation. Mean TKE in the bottom 14 cm (TKE$_{canopy}$) was computed for 79 profiles from locations B, C, E, F, and H with a water depth at least 10 cm greater than the canopy height. The height limit of 14 cm was selected because, below this level, TKE was relatively constant compared to the increase in the upper canopy. The best solution combined (starting with the greatest influence on the model) water depth, biomass, canopy height, maximum TKE measured above 14 cm, distance to the vegetation edge, and U$_{surface}$; all $p<0.05$ (Table 6). The significance level of the model was $p<0.001$, with $r^2=0.60$. A similar model is obtained when biomass is replaced by shoot density. All parameters show a positive relationship with TKE$_{canopy}$, except water depth and distance to the vegetation edge. The influence of the mean velocity in the lower 14 cm is not significant.

TKE$_{canopy}$ is the result of wake turbulence generated locally and turbulence transmitted from the high turbulence zone above (i.e., from the turbulence in the skimming flow and from the shear generated turbulence at the base of the skimming flow). TKE$_{canopy}$ was always less than the turbulence higher in the water column.

The positive correlation of TKE$_{canopy}$ with biomass or shoot density suggests that the vegetation density in the lower canopy increases wake-turbulence generation. The positive correlations of TKE$_{canopy}$ with U$_{surface}$ and maximum TKE measured above 14 cm indicate that skimming flow influences the turbulence in the dense canopy. TKE$_{canopy}$ decreases with distance to the vegetation edge suggesting that the horizontally advected turbulence from outside the canopy is progressively attenuated. TKE$_{canopy}$ decreases also with greater water depth, because more space is available for the skimming flow, and consequently: (1) the velocity gradient at the base of the skimming flow (generating shear turbulence) is weaker; and (2) less water is forced through the lower canopy.

Leonard and Luther (1995) measured turbulence in emergent, North American vegetation: they found that turbulence intensities in the canopy are inversely related to shoot density and

to the distance from the creek for *Spartina alterniflora* and *Juncus roemerianus*. They also observed a downward increase of turbulence and velocity near the canopy base, which was explained by the mainly tubular shape in the lower part of these emergent plants. Leonard and Reed (2002) made similar observations for *Sp. alterniflora*. However, the geometry of these plants is quite different from *Sp. anglica* or *Sp. maritima*, the European species. For *Distichlis spicata* (which possesses a flow hindrance similar to that of *Sp. anglica*), Leonard and Luther (1995) observed a strong attenuation of the turbulence intensity in the 25-cm high, submerged canopy, compared with the skimming flow above.

Salicornia/Suaeda marsh

The *Salicornia*/*Suaeda* marsh is sparser and much shorter than the higher salt-marsh. Its height was 10 cm in June during the experiment G, though it can reach 20 cm at the end of the season. Despite being smaller, the vegetation clearly influences the velocity profile in various ways (Fig. 3, Location G): linear velocity increases in the lower 10-20 cm (generally with shallow water depth); skimming flow with a z_0 value of 1.7-2.9 cm (generally during fast free-stream velocity); or skimming flow with a limit at 5-10 cm (generally during slower free-stream velocity). Despite this variability, the canopy always shifts the velocity gradient higher into the water column. The z_0 values are about two orders of magnitude greater than over sand or gravel beds, and also greater than that over a rippled sand bed (Soulsby, 1997). Unlike *Spartina*, a low turbulence zone is evident in the lower part of the canopy, even if the turbulence decreases towards the bed.

Consequences on sediment dynamics

Turbulence influences sediment transport in two ways. (1) Within the water column, the vertical movement of suspended sediment particles is a function of the vertical mean flow, the settling velocity, and the turbulent diffusion, which is directed from higher to lower particle concentration (Dyer, 1986). Turbulent diffusion is proportional to the sediment diffusion coefficient, which depends on the vertical turbulence intensity and the size of turbulent eddies (Allen, 1985). (2) Very close to the bed, turbulence influences the bed shear stress, which controls the deposition or the erosion of particles (Soulsby, 1997).

The attenuation of vertical turbulence in the dense canopy reduces the sediment diffusion coefficient, which enhances sediment settling. This effect is negligible for the *Salicornia*/*Suaeda* marsh because the low canopy height prevents the formation of a slow, low turbulence layer. The lower turbulence level is also likely to affect flocculation of cohesive particles. A low turbulence level increases the flocculation compared to still water by facilitating interactions between particles; stronger turbulence reduces the flocculation by disrupting the flocs (Dyer, 1989). The upper end of the turbulence range observed in this study (τ_{xyz}=0.4 Pa, TKE=2 J m^{-3}, Fig. 5) is close to the turbulence level producing the maximum flocculation (Manning, 2004). Therefore, the reduced turbulence in the canopy is likely to reduce flocculation.

The SSC profiles give indications on sediment behaviour in the water column. The SSC gradient increases with decreasing diffusion in steady state (Allen 1985). The measured SSC increase in the lower part of profiles A and C (Fig. 7) suggests a reduced diffusion due to lower turbulence. However, the SSC profiles do not reveal a clear trend for sediment transport, probably because SSC was low and only very fine sediments (with perhaps a significant organic fraction that has a slower settling velocity) were in suspension during these summer, fair-weather experiments. That illustrate the importance of storms for sediment dynamic on salt-marshes (Carling, 1982).

Pethick *et al.* (1990) suggested that only suspended sediments, which are within the slow velocity and low turbulence zone below the skimming flow, are likely to settle. They argued that the lower zone is isolated from the skimming flow above due to the high shear stress in the upper layer. The SSC profiles in Fig. 7 are not enough conclusive to validate or invalidate this theory. However, the turbulent sediment-diffusion depends on the relative sediment concentrations. Usually turbulent diffusion is directed opposite to sediment settling; but if a layer with low concentration exists below a layer with higher concentration, the resultant turbulent transport would be downward to compensate the concentration difference. Therefore all sediments suspended in the water column are likely to settle, also in the presence of a skimming flow.

The canopy shelters the bed from high turbulence and fast flow, especially when the vegetation is fully submerged. Therefore the salt-marsh offers protection from erosion during high-energy events (Brown, 1998).

CONCLUSIONS

This paper presents results of mean flows and turbulence within tidal waters flowing through and over salt-marsh canopies. Several interesting points were evident from this work.

In submerged *Spartina* vegetation, a low turbulence zone of near-constant velocity exists in the denser canopy. It is often separated from the skimming flow (faster and more turbulent) above by an interface of high Reynolds stresses. The lower limit of skimming flow, which is defined by z_0 (the vegetation roughness), is best predicted by the height that includes 85% of the canopy biomass. z_0 is positively correlated with biomass, canopy height, and distance to the vegetation edge. A secondary velocity maximum in the lower part of the canopy, which was observed in some previous studies, is not characteristic of European *Spartina* canopies.

In emergent *Spartina* vegetation, the flow structure is less well defined. Generally the velocity increases approximately linearly with the height from the bed. TKE also generally increases upward. Small surface wavelets may contribute significantly to near-bed turbulence in shallow water.

In *Salicornia*/*Suaeda* vegetation, the velocity gradient is shifted upward and the turbulence reduced near the bed, but a zone of slow velocity and low turbulence was not found.

Turbulence reduction near the bed should favour sediment deposition. In addition, the zone with low vertical turbulence, which exists in the denser part of submerged *Spartina* canopies, should increase sediment settling. The vertical mixing in these canopies is strongly limited.

ACKNOWLEDGEMENTS

NOMENCLATURE

ADV Acoustic Doppler Velocimeter
d stem diameter

H_{m0} significant wave height

i_u, i_v, i_w turbulence intensities

Re Reynolds number

SSC suspended sediment concentration

TKE turbulent kinetic energy

TKE_{canopy} mean TKE in the lower 14 cm of the canopy

TKE_{horiz} horizontal component of TKE

TKE_{vert} vertical component of TKE

U_* shear velocity

u, v, w instantaneous velocities in downstream, cross-stream and vertical directions, respectively

U, V, W time averaged velocities

u_t, v_t, w_t turbulent velocity components

$U_{surface}$ surface velocity

z_0 roughness length

z_{visual} visually defined lower limit of skimming flow

ν kinematic viscosity

ρ water density

τ_{xyz} three-dimensional vertical Reynolds stress

τ_{xz} two-dimensional vertical Reynolds stress

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FIGURE LEGENDS

Fig. 1. Position of Ramalhete (A) in Portugal, and East Chidham (B) and Freiston Shore (C) in England.

Fig. 2. Illustrations of studied salt-marsh vegetation. (a) *Spartina maritima* at Ramalhete; canopy height is 30 cm. (b) *Spartina anglica* in front of a red background, example of picture used to compute the lateral obstruction; picture height is 34 cm; picture depth is 10 cm. (c) *Spartina* marsh at East Chidham. (d) Low pioneer marsh with Salicornia *sp.* and *Suaeda maritima* at Freiston Shore; length of yellow ruler is 8 cm.

Fig. 3. Selection of profiles of mean horizontal velocity with i_u (or downstream standard deviation) presented as the error bars. Each velocity profile is labelled with its profile name (e.g., "B1") and, in brackets, the water depth during measurements. The vertical density variation of the canopy is represented on the left hand side by the vertical biomass distribution and/or by the lateral obstruction of a 10 cm thick canopy.

Fig. 4. Relationship between z_{visual} (lower limit of the skimming flow defined visually from the plots) and z_0 for all *Spartina* profiles with a skimming flow exhibiting a logarithmic velocity profile. The statistically significant linear regression is shown.

Fig. 5. Profiles of flow parameters: Mean horizontal velocity (U) with i_u (or downstream standard deviation) represented by the error bars, horizontal and vertical TKE, two-dimensional and three-dimensional Reynolds stresses (τ_{xz} and τ_{xyz}). The horizontal dotted lines mark the top of the dense canopy and the canopy height, respectively. Profiles B1 and B9 are in a *Sp. maritima* marsh; profiles E10, F17, H17, H20, and H9 are in a *Sp. anglica* marsh; profiles G2, G5, and G9 are in a *Salicornia*/*Suaeda maritima* marsh.

Fig. 6. Ebb flow during experiment H (*Sp. anglica*, 32 cm tall): 5 successive velocity profiles (mean U) with the corresponding profiles of turbulent kinetic energy (TKE). On the right hand side are shown the time in minutes after high water, the height of the water level, and the significant wave height (H_{m0}). The flow accelerated as the water level dropped, the associated reduction in TKE is probably not due to the velocity increase but the decrease of surface wavelets (shown by H_{m0}).

Fig. 7. SSC profiles measured in the salt-marsh at Freiston Shore during experiment H. The dotted horizontal line marks the canopy height. The time before/after high water is specified for each profile. The width of the markers indicates the accuracy of each measurement.

Table 1. Characteristics of experiment locations

ID	Location	Vegetation	Date experiment	Elevation (m) [1]	Max. water depth of experiment (m)	Canopy height (m)	Shoot density (m^{-2})	Above ground biomass (kg m^{-2})	Lateral obstruction[2]	Distance edge (m) [3]
B	Ramalhete	*Sp. maritima*	9 Apr 01	0.63	0.74	0.25	2340	0.93		11
C	Ramalhete	*Sp. maritima*	10 Apr 01	0.55	0.75	0.24	3030	0.92		4-8
E	E. Chidham	*Sp. anglica*	16 Apr 03	1.12	0.92	0.19	560	0.32	28%	2.2-5
F	E. Chidham	*Sp. anglica*	17 Apr 03	1.10	1.16	0.34	1290	0.59	49%	3-12
G	Freiston	*Salicornia / S. maritima*	12 Jun 03	2.65	0.43	0.10	2140/ 540[4]	0.10[5]	29%	
H	Freiston	*Sp. anglica*	13 Jun 03	2.56	0.86	0.32	1450	0.68	52%	2.5-11
I	Freiston	*Sp. anglica*	14 Jun 03	2.59	0.86	0.47	1850	1.29	57%	6-10

[1] elevation above mean sea level.

[2] mean lateral obstruction of the lower 20 cm of a 10 cm thick canopy, except for location G, where only the lower 10 cm of the canopy are considered.

[3] distance from experiment location to vegetation edge in the upstream directions during the experiment.

[4] shoot density of *Salicornia sp.* and *Suaeda maritima*, respectively.

[5] contributions of *Salicornia sp.* and *S. maritima*: respectively 41% and 59%.

Table 2. Calculation of z_0 from the logarithmic shaped velocity-profile above the canopy; visually estimated lower limit of the skimming flow (z_{visual}).

Profile #	n^1	Water depth cm	r^2	z_0 cm	z_{visual} cm
B7	4	70	0.9284	15.5	22
B8	3	72	0.9874	15.4	19
B11	3	72	0.8736	18.1	26
B12	4	69	0.9670	15.3	19
C6	4	60	0.9651	15.7	18
C7	4	66	0.9694	13.5	17
C8	4	69	0.9727	17.5	22
C9	4	75	0.9972	15.8	21
C11	5	74	0.9015	13.2	17
E9	6	91	0.9625	3.5	7
E10	6	92	0.9774	7.7	11
E11	4	89	0.9410	6.6	8
E14	6	70	0.9789	11.0	15
E15	4	62	0.9839	15.3	22
E16	5	54	0.9911	14.6	17.5
E17	5	47	0.9813	7.9	12
F7	4	87	0.9736	15.1	24
F8	4	95	0.9464	14.2	20
F13	4	113	0.9548	9.4	14
F14	5	106	0.9538	11.9	14
F15	5	98	0.9436	13.5	17
F16	4	91	0.9977	14.0	17
G1	3	16	0.9998	2.5	
G2	4	21	0.9910	2.9	
G3	5	26	0.9920	1.7	
G4	8	34	0.8983	2.4	
G5	5	38	0.9951	1.9	
G10	8	42	0.9840	1.9	
G12	5	38	0.9863	6.3	
H4	5	49	0.9573	4.6	6
H8	4	76	0.9853	10.5	15
H9	6	82	0.9888	10.6	15
H10	4	84	0.9628	16.4	20
H11	4	85	0.9965	15.6	20
H12	4	77	0.9746	23.9	25
H14	4	63	0.9859	23.3	25

[1] Number of points of the velocity profile that were used for the regression.

Table 3. Visually estimated lower limit of the skimming flow (z_{visual}) for the profiles without logarithmic shaped velocity-profile, z_0 computed with the formula $z_0 = 0.837\, z_{visual} - 1.16$.

	Water depth cm	z_{visual} cm	z_0 cm
B4	53.8	18	13.9
B5	57.3	14	10.6
B6	62.9	18	13.9
C5	51.4	18	13.9
C11	74.0	22	17.3
C13	62.7	18	13.9
E8	83.1	20	15.6
E13	79.4	20	15.6
F9	104.4	18	13.9
F11	114.5	25	19.8
F17	84.1	25	19.8
F18	77.6	25	19.8
H3	40.0	20	15.6
H5	57.7	6	3.9
H7	71.0	15	11.4
H15	54.7	21	16.4

Table 4. Mean roughness length z_0 (± standard deviation) for each *Spartina* location.

Location	z_0 (cm)	z_0 / H_{canopy}	Biomass[1]
B	14.9 ±2.0	0.60	88%
C	15.3 ±1.7	0.63	87%
E	11.0 ±4.7	0.56	85%
F	15.3 ±3.6	0.45	83%
H	16.1 ±4.9[2]	0.51	77%

[1] Fraction of canopy biomass below z_0.

[2] Excluding two extreme low outliers (4.6 and 4.8 cm).

Table 5. Multiple regression to predict z_0. All parameters are in SI units (m, kg).

	Unstandardized Coefficients		Standardized Coefficients	Sig.
	B	Std. Error	Beta	
(Constant)	0.1526	0.0531		0.008
Biomass	0.0465	0.0362	0.227	0.212
Canopy height	0.1838	0.1532	0.225	0.242
1 / Distance[1]	-0.1563	0.0592	-0.437	0.014
Water depth	-0.0779	0.0534	-0.266	0.158

[1] distance to the vegetation edge

Table 6. Multiple regression to predict the average TKE in the lower 14 cm of the canopy. All parameters are in SI units (m, kg, s).

	Unstandardized Coefficients		Standardized Coefficients	Sig.
	B	Std. Error	Beta	
(Constant)	0.0614	0.0612		0.319
Water depth	-0.3276	0.0630	-0.468	0.000
Biomass	0.2331	0.0677	0.386	0.001
Canopy height	0.6852	0.2040	0.283	0.001
max TKE[1]	0.0095	0.0040	0.212	0.021
Distance[2]	-0.0091	0.0038	-0.231	0.020
$U_{surface}$	0.7371	0.3451	0.187	0.036

[1] maximum TKE measured above 14 cm

[2] distance to the vegetation edge