Flow dependent processes in settlement of intertidal bivalve larvae
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CHAPTER 6

MEASUREMENTS OF NEAR-BED FLOW UNDER DIFFERENT TURBULENCE LEVELS

Iris E. Hendriks, Luca A. van Duren and Peter M.J. Herman
ABSTRACT

Not only large-scale flow is important for settlement studies of bivalve larvae, also near-bed flow on small scales (centimeters) should be taken into account. Even in turbulent flows there is a thin near-bed layer where turbulence is overcome by viscosity. Direct measurement of this viscous sub-layer is problematic since the layer is close to a boundary. The thickness of this layer ($\delta_v$) is usually inferred through calculations based upon measurements in the logarithmic part of the Boundary Layer (BL). Particularly in near-bed flow the shape of the BL may differ from the standard model, which may influence estimates of $\delta_v$. Since $\delta_v$ has consequences for biological processes, such as larval settlement, we evaluate different indirect estimates of $\delta_v$ by a direct way to visualise this layer. We compare the Particle Image Velocimetry (PIV) technique with Acoustic Doppler Velocimeter (ADV) measurements for this purpose. Measurements were conducted on near-bottom flow (0 - 0.03 m). We use two turbulence treatments and two free stream velocities ($U_\infty = 0.05$ and 0.15 m s$^{-1}$) resulting in four different turbulent regimes for comparison. ADV measurements show higher velocities than PIV profiles. Reynolds stresses ($u'w'$) are in the same order of magnitude. Calculations based upon the logarithmic part of the BL estimate $\delta_v$ between 10.8 and 1.5 mm while PIV measurements estimate $\delta_v$ in the order of 1.3 to 4.7 mm. Visual observations of $\delta_v$ confirm these ranges. We discuss implications of these estimates for larval settlement through this layer.
**INTRODUCTION**

Water flow is important for benthic community processes on many scales (Svendsen 1997, Jumars and Nowell 1984, Koehl and Powell 1994). Large-scale flow on an estuary scale, for instance, is important for dispersal of propagules of sessile organisms (Scheltema 1971, Banse 1986, Jackson 1986, Scheltema 1986, Abelson and Denny 1997). A good example is the distribution pattern of benthic populations of shellfish, which is largely determined by dispersal of their pelagic larvae (Butman 1989, Roegner and Mann 1995, Chícharo and Chícharo 2001). When larvae reach the stage where they are competent to settle and metamorphose, they need to cross the velocity gradient layer (benthic boundary layer) near the sediment in order to reach the substratum. Suspended larvae settle on the bottom by a combination of passive sinking, turbulent mixing (Bouma et al. 2001) and possibly active swimming behaviour swimming. Turbulence also plays an important role in determining the probability of hydrodynamic resuspension during the critical period between larval touchdown (McNair 2000) and successful attachment to the substratum (Crimaldi et al. 2002). Hence, not only large-scale flow but also near-bed flow on small scales (centimeters) in the benthic boundary layer should be taken into account in settlement studies (Eckman 1983, Nowell and Jumars 1984, Butman 1989).

Within the lower part of a turbulent boundary layer, the velocity profile is logarithmic (Jumars and Nowell 1984) and it is possible to apply the Prandtl-von Karman equation or "law of the wall" (see chapter 5). Theory predicts that underneath this log-layer, just above the sediment surface a layer exists where at the smallest scale molecular forces become important. Eddies are overcome by viscous forces and start to lose energy as heat (Peters and Redondo 1997). Viscosity effects become dominant in this layer, which is called the viscous sublayer. The flow profile is linear in this region and can be described for hydraulically smooth flow as (Chriss and Caldwell 1984):

\[
u(z) = \frac{u_*^2}{\nu} z
\]

Where \(\nu\) is the kinematic viscosity (units: m²s⁻¹). Direct measurement of this layer is difficult since it is very thin (in the order of mm or less) and positioned near a boundary (the sediment surface), which renders acoustic measurement techniques, such as an Acoustic Doppler Velocimeter (ADV), ineffective because of the reflection of the acoustic signal on the boundary. Instead of direct visualisation, the viscous sublayer is usually inferred through calculations based upon measurements in the logarithmic part of the boundary layer. The thickness of the viscous sublayer (δ\(_v\)) in hydraulically smooth flow (Roughness Reynolds number: \(Re < 3\)) (Nowell and Jumars 1987) can be calculated according to Nikora et al. (2002):

\[\delta_v = 10 \frac{\nu}{u_*}\]

Such indirect estimates clearly depend strongly on an accurate characterisation of \(u_*\) near the bed. Any deviation from the “ideal” law-of-the-wall shape of the turbulent boundary layer can render estimates of \(u_*\) inaccurate (Kim et al. 2000), with obvious repercussions for estimates of \(\delta_v\).

The properties of the viscous sublayer are important when studying biological processes at the sediment-water interface. The velocity gradient in the VSL influences the transport of nutrients and oxygen to the (sessile) benthos living at the sediment surface (Vogel 1994). It is also a region of interest for settlement studies. Jonsson et al. (1991) showed that bivalve larvae might get confined in the viscous sublayer. In
Measurements of near-bed flow flume experiments, at 0.05 and 0.10 ms\(^{-1}\) larvae seemed to be trapped in the near-bottom flow, swimming and drifting very close above the bottom (0 to 0.5 mm). When free-stream velocities exceeded 0.10 ms\(^{-1}\) penetration of eddies in the viscous sublayer became more frequent and at 0.15 ms\(^{-1}\) larvae could not retain a smooth drift over the sediment surface but began to tumble in bed-load transport with frequent resuspension events. Possibly larvae are prevented from swimming upwards by near-bottom shear. This would retain bivalve larvae close to the bottom (Jonsson et al. 1991). This effect could be equally applicable to other invertebrate larvae. For instance Pawlik et al. (1991) showed confinement of polychaete larvae in the near-bottom region. Both experiments were performed in a flume with smooth flow. A question is whether near-bottom transport (and confinement) of larvae will occur in the field. Flow in field situations is unsteady and topography is often complex, which would make the flow pattern much more complicated. Some authors propose that sediment selection by larvae may be achieved through an active choice to stay at a site or go (swim upwards into the boundary layer) (Keough and Downes 1982, Butman 1986, Butman et al. 1988). In this case drifting close to the bottom would allow more frequent sampling of the sediment surface (Jonsson et al. 1991).

In flume situations turbulent kinetic energy and Reynolds stress in the boundary layer are lower compared to field situations, but these parameters can be enhanced in the flume by e.g. introducing a turbulence grid upstream of the test section throughout the water column to increase turbulence intensity (TI) (Chapter 5).

In an earlier study, (Chapter 5) we investigated the effect of the ratio between advection and turbulent motion on transport of larvae through the turbulent layer. This work was not conclusive on whether the viscous sublayer decreased or increased in thickness, as a consequence of increased turbulence. Depending on the method of calculation of \(u_r\), and the interpretation of the estimates of roughness length, both cases are possible. For instance the log profile method indicated decreasing shear velocity (\(u_r\)) with increasing turbulence levels, which would lead to a calculated increase in \(\delta_v\) under more turbulent conditions. But induced turbulence in the water column of the flume might also cause erosion of the viscous sublayer. An indication for this erosion process is a decreasing roughness height (\(z_0\)) calculated at the same effectual bed roughness in the test section when a grid inducing turbulence is placed throughout the water column. This points at a decrease in height of the viscous sublayer caused by increased turbulence. The mechanism causing this erosion could be more frequent sweep and burst events, disrupting the continuity of the layer and thus causing its erosion. A decrease in thickness or erosion of the layer would promote more transport towards the bottom layer. Since both \(u_r\) and \(z_0\) are extrapolations from the law of the wall obtained by ADV measurements higher up in the boundary layer we now aim to look closer to the bottom at a smaller scale to get better insight into processes in the viscous sublayer. We try to answer the question whether the height of this layer increases or decreases in under normal flume conditions and increased turbulence conditions, which should be more realistic for field situations (see Chapter 5).

The technique we propose to study detailed velocity profiles near the sediment surface is the Particle Image Velocimetry (PIV) technique (Stamhuis and Videler 1995). The PIV technique yields information on velocity gradients on a fine scale (mm), close to the boundary. The spatial variability can be resolved on a very detailed (cm) scale but our set-up (dual frames instead of time series) limited analysis of the temporal scale of variability. Since the measuring volume of the ADV is about 9 mm high and 6 mm in diameter (according to the manufacturer, Nortek), the spatial resolution of ADV measurements is generally coarser than that of PIV. The ADV however, yields point measurements of all three velocity components, and derives turbulence parameters from temporal variability in time series. Sufficiently long time (e.g. 330 seconds) series at a high enough frequency allow the derivation of the turbulence spectrum and a direct estimate of the Kolmogorov length scale. We compare near-bottom PIV measurements with data collected under similar circumstances measured over a larger spatial and temporal scale with an ADV to evaluate the performance of the PIV measurement technique.
Our aim is to (a) resolve the question raised by previous flume experiments (Chapter 5), whether the viscous sublayer erodes or increases in thickness under more turbulent conditions, and to (b) evaluate the usefulness of the PIV technique for measuring near-bottom flow on small scales. We use larval settlement probability as a case study to discuss the implications of size fluctuations of the viscous sublayer for biological processes.

**METHODS**

Experiments were conducted in the large racetrack flume described in chapter 5. The downstream part of the working section contains a test section with a transparent wall. Measurements of flow under ‘normal’ turbulence levels in the flume were compared to increased turbulence levels generated by the placement of a vertical grid throughout the water column. Properties of the grid are described in chapter 5. The grid was placed at different distances (three, six and nine meters) from the test section, where the measuring equipment was mounted to increase the turbulence length scale in the experimental treatments. Two free stream velocities, $U_\infty = 0.05$ and $U_\infty = 0.15 \text{ m s}^{-1}$ were used. Water temperature was $15 \pm 0.5 \, ^\circ\text{C}$ and salinity ranged from 29 to 32 ‰. The sediment surface consisted of a smooth bed of silica sand with an average grain size ($k_s$) of $249 \pm 13 \, (\text{SE}) \, \mu\text{m}$ diameter.

**ADV measurements.**

Flow velocity profiles were determined from 330 sec measurements at 25 Hz (Chapter 5). Within the profiles measuring points were taken at 1 cm intervals. Autocorrelation spectra of flow in the horizontal direction ($u$) were calculated at 10 and 40 mm height, using fast Fourier transformation. Data series were truncated to 8192 measurements and after transformation a 25-point Parzen window smoothing was applied. If no energy is added by the mean flow, nor removed by viscous dissipation, the energy flux across the high-frequency region (the inertial sub-range) is constant and equal to the energy dissipation rate at the small-scale end of the spectrum. In a fully turbulent regime this spectrum falls off proportional to $k^{-5/3}$, where $k$ is the wave number. This is known as the Kolmogorov $-5/3$ law (Tritton 1988, Tennekes and Lumley 1999). Using Taylor’s ‘frozen turbulence’ hypothesis, which allows time scales to be converted into spatial scales, we can use the autocorrelation spectra of the velocity components measured with an ADV to examine if the slope in the inertial sub-range follows the $-5/3$ law (Nikora et al. 1997) and also to identify the length scale of the eddies below which the energy dissipates due to viscosity (Tennekes and Lumley 1999). This size range of the smallest eddies in the flow regime is generally known as the Kolmogorov length scale ($\eta$). Through graphs of autocorrelation spectra we estimate this length scale by identifying where the slope of the inertial sub range trails off and dividing the frequency by local flow speed.

**PIV measurements**

We applied laser sheet Particle Image Velocimetry (PIV) (Stamhuis and Videler 1995) to analyse near bottom flow under normal and increased turbulence levels in the flume. The PIV set-up was obtained from DVS systems at Breda, the Netherlands. The flow was seeded with pvc particles, which were assumed to follow water flow accurately. These particles were irregular in shape and typically $150 \pm 40 \, (\text{SD}) \, \mu\text{m}$ long and $100 \pm 25 \, \mu\text{m}$ wide. We used a laser light sheet (thickness approximately 1 mm) to illuminate
the particles in one plane, in line with the flow direction, in the test-section. The laser sheet allows 2-D measurement of near-bottom flow structures without interference of measuring equipment. To produce the light sheet we used a semiconductor-diode laser (Coherent, $\lambda = 675$ nm, power output = 350 mW). The light sheet was positioned in the flume parallel to the main flow.

A black and white digital camera (Basler A113P, resolution 1024 x 1024 pixels) with LCD shutter (Display Tech Inc., VS 2200) was used to obtain images. A 55 mm lens (Nikon) with macro setting was fitted, resulting in a total field of view of approximately 0.04 m height. A frame grabber (Matrox Meteor 2 dig) took dual snap shots, at 2 different time intervals between frames. At $U_{\infty} = 0.05$ ms$^{-1}$ frame rates of 25 and 50 ms between 2 frames and an exposure time of 5 ms per frame were used. At $U_{\infty} = 0.15$ ms$^{-1}$ frame rates of 10 and 15 ms between 2 frames and an exposure of 2 ms per frame was used.

Measurements for each treatment were obtained at five different planes in the test section, at 0.10, 0.12, 0.14, 0.16 and 0.18 m from the wall. In total 13 consecutive pictures in 5 planes per treatment were taken. To increase seeding density and to assure good quality pictures, two dual-snap frames in one plane were combined. This adds up to 12 usable measurements per plane. These measurements were averaged per treatment to obtain a time-average flow profile near the sediment bed.

Both the image collection part of the process as well as the image-processing step is performed by the Swift package (DVS, Breda, the Netherlands). The PIV routine is based on pattern recognition. It determines the average displacement of a cluster of particles between two frames. This resulted in flow diagrams with uniform vector distribution. Calculated vectors were imported into a spreadsheet and further processed to obtain a detailed velocity profile.

**Data processing**

The average boundary shear stress due to turbulence can be calculated from the boundary shear velocity $u_\tau$ ($\text{Schlichting, 1979}$). Values for shear velocity $u_\tau$ were determined from the log profile relationship (described in Gross and Nowell 1983). For ADV data we used values in the boundary layer, away from the substrate (40 mm height and above) to prevent interference of the measuring equipment with the boundary. PIV data were collected much closer to the boundary since no interference is expected. Here we used data from 20 mm and up (maximum picture height is around 0.035/0.040 m). From each flow field vectors were horizontally averaged to produce one single vertical profile that can be compared to the ADV data. Additionally, we also estimate shear velocity ($u_\tau$) from ADV data by the covariance method (Kim et al. 2000), and from PIV data by linear regression of the velocity profile in the bottom 10 mm.

Reynolds stresses ($u'w'$, in ms$^{-1}$) are calculated directly from the velocity – time records from the ADV. For PIV data, all replicates were combined to calculate a time-average $u'w'$ profile per treatment.
Results

Time-averaged near bottom velocity profiles ($\bar{u}$ in m s$^{-1}$) show an increased velocity gradient with increased turbulence (Figure 1). PIV measurements are more detailed, but also show more scattered data compared to ADV measurements. We omitted Standard Error (SE) for ADV measurements because 8250 measurements were taken for each height and values for SE are very small. ADV measurements consistently show higher flow velocities than PIV profiles from 0.03 m down. Close to the boundary, where the ADV is unable to measure, PIV measurements show lower flow velocities than expected from ADV profile extrapolations. The velocity gradient near the surface is very steep.

Reynolds stresses ($u'w'$) were of the same order of magnitude for PIV and ADV measurements. We normalised Reynolds stress by dividing with the local velocity at a measuring point to obtain a measure for turbulence intensity (Figure 2). Normalised stresses measured with the ADV are very small, while stresses calculated from the PIV profiles are higher and show more scatter. This could be caused by the instantaneous nature of the PIV measurements.

Table 1. Shear velocity ($u^*$) in mms$^{-1}$ for flow in a flume under different free stream velocities ($U_\infty$) measured with a hot-film probe (Jonsson et al. 1991), ADV (Chapter 5) and PIV techniques (this chapter).

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>Treatment</th>
<th>Jonsson et al.</th>
<th>Chapter 5 Log-profile &gt; 4 cm</th>
<th>Chapter 5 covariance</th>
<th>This chapter Log-profile</th>
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</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td>1.9</td>
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</tr>
<tr>
<td>50</td>
<td>NO</td>
<td>2.2</td>
<td>3.0</td>
<td>1.9</td>
<td>3.2</td>
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<tr>
<td></td>
<td>9 m</td>
<td>2.1</td>
<td>2.0</td>
<td>3.6</td>
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<td></td>
<td>6 m</td>
<td>2.6</td>
<td>1.3</td>
<td>3.0</td>
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<td></td>
<td>3 m</td>
<td>2.5</td>
<td>2.0</td>
<td>4.4</td>
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<tr>
<td>100</td>
<td></td>
<td>3.6</td>
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<tr>
<td>150</td>
<td>NO</td>
<td>9.1</td>
<td>4.3</td>
<td>7.9</td>
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<tr>
<td></td>
<td>9 m</td>
<td>9.5</td>
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<td>6.7</td>
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<td></td>
<td>6 m</td>
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<td></td>
<td>3 m</td>
<td>5.8</td>
<td>6.1</td>
<td>10.7</td>
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</table>

Table 2. $\delta$ in mm (calculated from $u^*$ according to Nikora et al. 2002) for flow in a flume under different free stream velocities ($U_\infty$) measured with a hot-film probe (Jonsson et al. 1991), ADV (Chapter 5) and PIV techniques (this chapter).

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>Treatment</th>
<th>Jonsson et al.</th>
<th>Hendriks et al. Log-profile &gt; 4 cm</th>
<th>Hendriks et al. covariance</th>
<th>This chapter Log-profile</th>
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<tr>
<td>20</td>
<td></td>
<td>7.4</td>
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<tr>
<td>50</td>
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<td>6.4</td>
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<td>9 m</td>
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<td>6 m</td>
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<td></td>
<td>3 m</td>
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<td>100</td>
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<td>150</td>
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<td>3 m</td>
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</table>
Figure 1. (Time-)averaged near bottom velocity flow profiles \(u\) in ms\(^{-1}\) from PIV (circles + SE) and ADV (line) measurements. Figures on the left side represent low (0.05 ms\(^{-1}\)) free stream velocities, on the right high (0.15 ms\(^{-1}\)) free stream velocities. Grid a) not present, b) 9 m, c) 6 m, d) 3 m in front of the test-section.
Figure 2. Velocity normalised Reynolds stress ($\frac{u'w'}{u^2}$) for PIV (circles + SE) and ADV (line) measurements. Figures on the left side represent low (0.05 ms$^{-1}$) free stream velocities, on the right high (0.15 ms$^{-1}$) free stream velocities. Grid a) not present, b) 9 m, c) 6 m, d) 3 m in front of the testsection.
Table 1 compares calculated shear velocities ($u_*$) obtained by PIV to literature data collected in the same flume with an ADV (Chapter 5) and in a different flume, where a hot-film probe was used (Jonsson et al. 1991). $U_*$ from this latter study is not directly comparable but included for approximate comparison since in this study larvae were shown to be trapped in the viscous sublayer. Calculation of $u_*$ using a log profile on PIV measurements above the bottom are in the same order of magnitude as calculations using the covariance method (Kim et al. 2000) and the log-profile method from ADV data. We estimate the thickness of the viscous sublayer ($\delta_v$, Nikora et al. 2002) (Table 2) between 1.3 and 4.7 mm. Apart from an increase in $\delta_v$ measured with the log-profile method on ADV data (Chapter 5) all other data show erosion of $\delta_v$ (Jonsson et al. 1991), (Chapter 5: covariance method, this chapter) with increasing turbulence (assuming that a higher flow speed is more turbulent).

The linear velocity profile of the viscous sublayer is clearly visible in one PIV velocity profile (Figure 1d, 0.05 ms$^{-1}$). For this profile, the viscous sublayer should be between 7.0 and 3.2 mm thick according to our calculations (Table 2). We fitted this data set with a combined linear-logarithmic profile. In the fitting, the height of the transition between the linear and the logarithmic parts was a free fitting parameter. However, we reduced the number of free parameters by imposing continuity constraints between the two pieces of the regression model (continuity of both the value of the current velocity and of its first derivative with respect to height). In that way, a smooth two-parameter curve as given by the following equation was fitted:

$$ u(z) = \begin{cases} 
\frac{a}{c(1 - \ln(c))} z & z \leq c \\
\frac{a(1 + \ln(z))}{(1 - \ln(c))} & z \geq c
\end{cases} $$

In this equation $c$ represents the height of transition between linear and logarithmic parts. The fit of this equation to the data (using non-linear least squares fitting) was excellent (Figure 3) ($a=0.0795$; $c=0.0041$, $r^2=0.90$) and a clear improvement upon a simple logarithmic profile ($u=a+b*\ln(z)$, $a=0.061$, $b=0.00080$, $r^2=0.79$). The estimate of the parameter $c$ in the linear-logarithmic model can be considered as an independent estimate of the thickness of the viscous sub-layer. It’s value (4.1 mm) corresponds reasonably well with the estimate of 3.2 mm based on extrapolating the log-profile above 20 mm (Table 1).

Figure 3 Near-bottom velocity profile ($u$ in ms$^{-1}$) from PIV with a grid at 3 m in front of the test section. Free stream velocity 0.05 ms$^{-1}$. Full line is the fitted linear-logarithmic profile with continuity constraints, fitted to the full dataset with a non-linear least-squares fitting routine.
Figure 4. Autocorrelation spectra of the horizontal velocity components from ADV measurements at 10 and 40 mm height above the bottom for all treatments. The added solid line represents a $-5/3$ slope. Figures on the left side represent low (0.05 ms$^{-1}$) free stream velocities, on the right high (0.15 ms$^{-1}$) free stream velocities. Grid a) not present, b) 9m, c) 6m, d) 3m in front of the test-section.
Measurements of near-bed flow

From autocorrelation spectra of the low velocity treatment, it is apparent (Figure 4). At 10 mm the inertial sub-range falls off with an approximate slope expected according to Kolmogorov’s $-5/3$ law. At 40 mm this is also the case although at the lower velocity treatment (0.05 m$^{-1}$) for the flume without a turbulence grid there appears to be a difference between the slopes at 10 and 40 mm, where the latter slope is less steep. This could be due to loss of energy caused by viscosity in the bottom water layer.

In the neighbourhood of the Kolmogorov length scale, turbulence diminishes and what remains is the baseline white noise from the ADV. We estimated this parameter for all treatments (Figure 5) using the autocorrelation spectra at 10 mm height. Under normal flume conditions, the Kolmogorov length scale is estimated as 0.05 m, while under enhanced turbulence conditions, this length scale is estimated as a fairly constant 0.02 m approximately.

**DISCUSSION**

Even under reasonably high flow velocities (0.15 m$^{-1}$) and increased turbulence levels, we find an obvious viscous sublayer. Estimations of the thickness of this layer range between 1.5 and 10.8 mm depending on calculation method and flow velocity.

The results described in this paper show that the PIV method is in principle suitable for near-bottom flow measurements and visualisation of the viscous sublayer. For precise measurements on the near bed region, fine scale measurements are needed with a suitable non-intrusive measurement device such as PIV or LDA (Laser Doppler Anemometry) (Poggi et al. 2002). Heated thermistors have been used in the past for near-bed field measurements (Caldwell and Chriss 1979) but this method is intrusive and requires calibration.

With an ADV we can only estimate the thickness of the viscous sublayer in an indirect way using the law-of-the-wall since its measuring volume is relatively large. Inaccuracies in the measurement can occur if part of the measuring volume overlaps with the bottom (Finelli et al. 1999). However, this is only a part of the problem with ADV measurements near the bed. The law-of-the-wall describes the ideal boundary layer. This concept of a turbulent log-layer with constant stress, one value for $u^*$, is often not applicable to ‘real’ flow (Chriss and Caldwell 1982, Kim et al. 2000). When internal boundary layers occur, there
are usually very few measurements within one layer available for a regression line (Chriss and Caldwell 1982, Jonsson et al. in prep.). There should also be a transition layer between the laminar VSL and the turbulent log layer, further complicating the estimate of $u^*$ and $\delta_v$. This makes indirect exploration of the VSL, using flow measurements higher up in the water column, questionable.

More fundamentally, it was debatable whether in macro-flow, e.g. in the field or in a big flume-tank, a substantial viscous sublayer, capable of trapping larvae would occur at all. Chriss and Caldwell (1984) and Caldwell and Chriss (1979) showed good evidence for the presence of a viscous sub-layer on the Oregon continental shelf. They estimated that the thickness of this layer was of the order of several mm. They conducted their experiments in a low flow environment ($U_\infty$ of a few cms$^{-1}$) at a depth of 200 m, well away from any possible turbulence enhancement due to wave action. This environment is not comparable to the shallow estuaries where many species of bivalves occur. The experiments described in this manuscript, show that such a sublayer can also persist at intermediately high flow velocities and under enhanced turbulence levels. However, Chriss and Caldwell (1984) also indicate that the near-bed flow adjusts very slowly to upstream roughness. Influences on the viscous sublayer due to roughness may even extend to tens of meters. In shallow estuaries with numerous biogenic structures (such as beds of bivalves) the viscous sublayer may well be reduced to a thickness less than the size of a settling larva.

ADVs yield direct estimates of the fluctuating velocity components, provided they are set to measure at a sufficiently high frequency, for long enough. The downside of our PIV set-up is that it lacks the proper temporal scale to evaluate the occurrence of turbulent events like burst and sweep incidents. A burst is defined as a fluid ejection process in the viscous sublayer, which interacts with the overlaying flow. The burst structures can account for up to 70% of the time-averaged Reynolds stress. This phase is usually closely followed by a sweep structure, where overlaying fluid from upstream is injected towards the bottom and sweeps out the near-bed fluid. This is generally known as the burst-sweep cycle of events (Thomas and Bull 1983). According to theory, the viscous sublayer is characterised by long periods of laminar flow interrupted occasionally by injections and interruptions of turbulent fluid as the large, energetic eddies in the outer part of the turbulent boundary layer penetrate all the way to the bed (Kline 1967, Grass 1971, Beljaars et al. 1981, Nowell and Jumars 1984). Sweep events may be the main mechanism responsible for the delivery of nutrients and/or particles (e.g. larvae) from the outer region to the biologically active interfacial sublayer (Nikora et al. 1997).

Observed differences in turbulence intensity in the logarithmic part of the boundary layer (Chapter 5) measured with ADV seem to extinguish close to the substrate resulting in similar conditions with dominant viscous forces under different turbulent conditions in the water column. Our PIV obtained estimations of $u^*$ points to a thinning layer under more turbulent free stream flow. Previous ADV based evidence, such as decreasing roughness height ($z_0$) calculated at the same effectual bed roughness in the test section when a grid is placed throughout the water column (Chapter 5, Table 2) and literature values (Jonsson et al. 1991) do suggest a thinning layer.

A decrease in thickness or erosion of the layer would promote transport towards the bottom and hence facilitate larval settlement but might also prevent larvae from anchoring to the substratum. Time between stress events (lowered by more turbulence) over a certain threshold could determine anchoring or resuspension of larvae. Instantaneous effects might be more important than time averaged (Reynolds) stresses. Is the confinement of larvae in the viscous sublayer an artefact? If instantaneous stress events determine anchoring probability of larvae (Crimaldi et al. 2002) then this probability decreases with increased turbulence levels. On the other hand transport of larvae to the sediment would increase. Confinement in the viscous sublayer could either lead to entrapment in the wrong habitat while the larva is unable to escape or, conversely provide the larva with the opportunity to sample the sediment of a favourable site and anchor before being dislodged. PIV measurements indicate reasonably high shear stresses present close to the bottom (Table 1). This could be an argument for the entrapment of larvae...
in the viscous sublayer. More PIV measurements closer to the boundary are necessary to finally solve the question. The set-up could be much improved by a more careful positioning of the camera resulting in measurements closer to the sediment.

In addition to PIV measurements direct observations and tracking of individual larvae under varying turbulent conditions would provide us with the best evidence. However, the high magnification required, combined with the large field of view that is desirable for tracking, may prove to be a technical challenge.

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