# TURBULENCE IN SMALL SUBTROPICAL ESTUARY WITH SEMI-DIURNAL TIDES

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Abstract: In natural estuaries, contaminant transport is driven by the turbulent momentum mixing. The predictions of scalar dispersion can rarely be predicted accurately because of a lack of fundamental understanding of the turbulence structure in estuaries. Herein detailed turbulence field measurements were conducted at high frequency and continuously for up to 50 hours per investigation in a small subtropical estuary with semi-diurnal tides. Acoustic Doppler velocimetry was deemed the most appropriate measurement technique for such small estuarine systems with shallow water depths (less than 0.5 m at low tides), and a thorough post-processing technique was applied. The estuarine flow is always a fluctuating process. The bulk flow parameters fluctuated with periods comparable to tidal cycles and other large-scale processes. But turbulence properties depended upon the instantaneous local flow properties. They were little affected by the flow history, but their structure and temporal variability were influenced by a variety of mechanisms. This resulted in behaviour which deviated from that for equilibrium turbulent boundary layer induced by velocity shear only. A striking feature of the data sets is the large fluctuations in all turbulence characteristics during the tidal cycle. This feature was rarely documented, but an important difference between the data sets used in this study from earlier reported measurements is that the present data were collected continuously at high frequency during relatively long periods. The findings bring new lights in the fluctuating nature of momentum exchange coefficients and integral time and length scales. These turbulent properties should not be assumed constant.

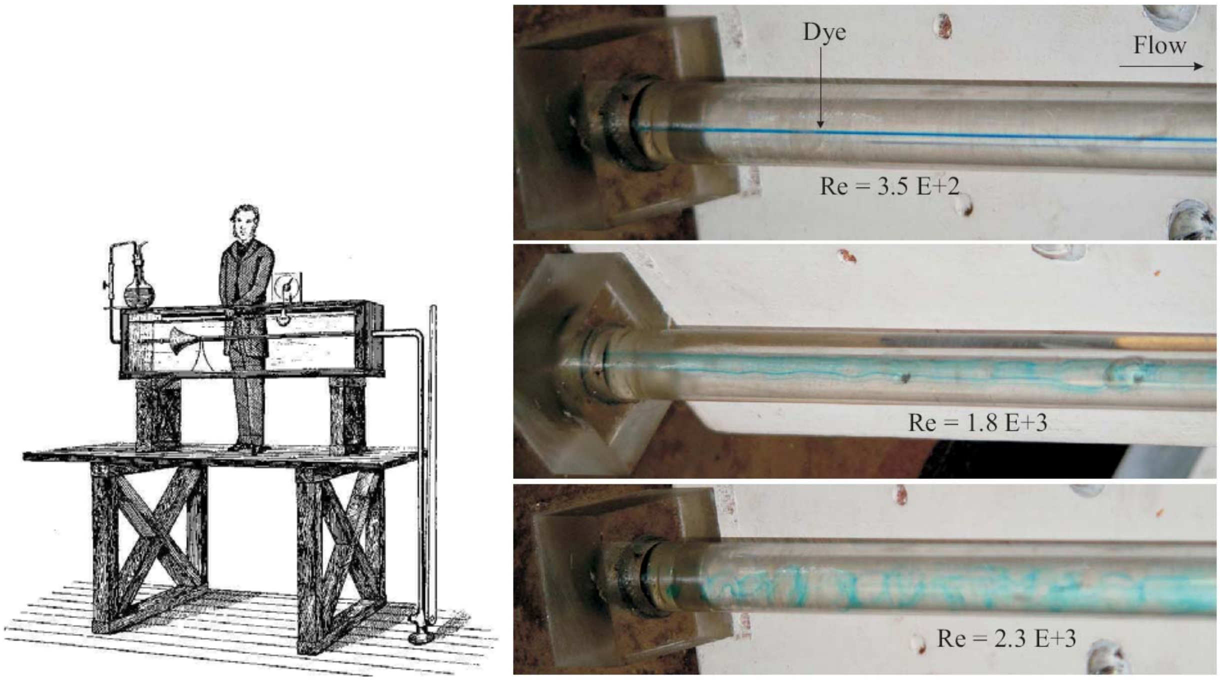
Keywords: Turbulence, Subtropical estuary (sub-tropical estuarine system), Momentum mixing, Turbulent Reynolds stresses, Integral time scales, Dissipation time scales, Acoustic Doppler velocimetry, Field measurements.

## 1. INTRODUCTION

In natural waterways and estuaries, a basic understanding of turbulent mixing is critical to the knowledge of sediment transport, release of organic and nutrient-rich wastewater into ecosystems and storm-water runoff during flood events. The predictions of contaminant dispersion in estuaries can rarely be predicted analytically without exhaustive field data for calibration and validation. Why is it? Because the flow is turbulent and we lack some fundamental understanding of the turbulence structure in estuaries.

In natural estuaries, the flow Reynolds number is typically within the range of 1E+5 to 1E+8 and more. The flow is turbulent! Any turbulent flow is characterised by an unpredictable behaviour, a broad spectrum of length and time scales and its strong mixing properties. In his classical experiment, Osborne REYNOLDS (1842-1912) illustrated this key feature with the rapid mixing of dye of a turbulent flow (REYNOLDS 1883). This is seen in Figure 1 showing the original Reynolds experiment (Fig. 1, Left) and a modified Reynolds experiment (Fig. 1, Right) in the Gordon McKay Hydraulics Laboratory at the University of Queensland. In turbulent flows, the fluid particles move in very irregular paths, causing an exchange of momentum from one portion of the fluid to another, as shown in Figure 1 (Right) where dye is rapidly dispersed in the turbulent flow regime. In natural waterways, strong momentum exchanges occur and the mixing processes are driven by turbulence. Note that REYNOLDS (1887) himself was involved in the modelling of rivers and estuaries.

Herein the turbulence characteristics of a small subtropical estuary with semi-diurnal tides are examined. It is shown that turbulence field measurements must be conducted continuously at high frequency for relatively long periods. Detailed field measurements highlight the large fluctuations in all turbulence characteristics during the tidal cycle. While the bulk parameters fluctuate with periods comparable to tidal cycles, the turbulence properties depend upon the instantaneous local flow properties, and the structure and temporal variability of turbulent characteristics are influenced by a variety of mechanisms.



(Left) Gravure of the experimental apparatus of Osborne REYNOLDS (Right) Photographs of dye injection for Re = 3.5E+2, 1.8 E+3 and 3.2 E+3 (flow from left to right)
Fig. 1 - Dye dispersion in laminar and turbulent flows

Turbulence properties

Turbulent flows have a great mixing potential involving a wide range of eddy length scales. Although turbulence is a "random" process, the small departures from a Gaussian probability distribution are some of the key features of the turbulence. For example, the skewness and kurtosis give some information on the temporal distribution of the turbulent velocity fluctuation around its mean value. A non-zero skewness indicates some degree of temporal asymmetry of the turbulent fluctuation (e.g. acceleration versus deceleration, sweep versus ejection). The skewness retains some sign information and it can be used to extract basic information without ambiguity. An excess kurtosis larger than zero is associated with a peaky signal: e.g., produced by intermittent turbulent events.

In turbulence studies, the measured statistics include usually (a) the spatial distribution of Reynolds stresses, (b) the rates at which the individual Reynolds stresses are produced, destroyed or transported from one point in space to another, (c) the contribution of different sizes of eddy to the Reynolds stresses, and (d) the contribution of different sizes of eddy to the rates mentioned in (b) and to rate at which Reynolds stresses are transferred from one range of eddy size to another (BRADSHAW 1971). The Reynolds stress is a transport effect resulting from turbulent motion induced by velocity fluctuations with its subsequent increase of momentum exchange and of mixing (PIQUET 1999). Turbulent transport is a property of the flow. The Reynolds stress tensor includes the normal and tangential stresses. The Reynolds stresses are also called the turbulent stresses. Note that there is no fundamental difference between normal stress and tangential stress. For example, $(v_x+v_y)/\sqrt{2}$ is the component of the velocity fluctuation along a line in the xy-plane at 45° to the x-axis; hence its mean square $(v_x^2 + v_y^2 + 2*v_x*v_y)/2$ is the component of the normal stress over the density in this direction although it is a combination of normal and tangential stresses in the x-y axes.

# 2. TURBULENCE MEASUREMENTS IN SMALL ESTUARIES

## 2.1 Presentation

> "*Turbulence is a three-dimensional time-dependent motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow*" (BRADSHAW 1971, p. 17).

Turbulence measurements must be conducted at high frequency to characterise the small eddies and the viscous dissipation process. They must also to be performed over a period significantly larger than the characteristic time of the largest vortical structures to capture the "random" nature of the flow and its deviations from Gaussian statistical properties. Turbulence in natural waterways is neither homogeneous nor isotropic. Altogether detailed turbulence measurements are almost impossible in unsteady estuarine flows unless continuous sampling at high frequency is performed over a full tidal cycle. Indeed the estuarine flow conditions and boundary conditions may vary significantly with the falling or rising tide. In small estuaries and inlets, the shape of the channel cross-section changes drastically with the tides as shown in Figure 2. Figure 2 illustrates a sampling site with less than 0.6 m of water at low tide and more than 3 m depth at high tide.

All these requirements place some constraints on the selection of a suitable, rugged instrumentation for field deployment. Traditional propeller and electro-magnetic current meters are adequate for time-averaged velocity measurements, but they lack temporal and spatial resolution. Velocity profilers do not work in shallow waters (e.g. less than 0.6 m) while lacking resolution. It is the writers' experience that suitable instrumentations for turbulence measurements in small estuaries are limited, although these might include miniature micro-propellers and acoustic Doppler velocimeters (ADV). The former instrument may be easily damaged while the latter technique (ADV) is adversely affected by "spikes", noise and disturbance.

(A) End of flood tide on 16 May 2005 with poles supporting the instrumentation visible across the creek

(B) Low tide on 23 Nov. 2003 - The water depth was less than 0.6 m in the deepest channel next to the ADV poles during spring tide conditions

(C) Field work staff gives the scale of shallow waters at low neap tide on 18 May 2005

Fig. 2 - Eprapah Creek sampling site, mid-estuary (AMTD 2.1 km), looking upstream (A and B)

Table 1 - Turbulence field measurements at Eprapah Creek QLD, Australia

| Ref. (1) | Dates (2) | Tidal range (m) (3) | ADV system(s) (4) | Sampling rate (Hz) (5) | Sampling duration (6) | Sampling volume (7) |
|---|---|---|---|---|---|---|
| E1 | 4/04/03 | 1.84 | 10 MHz | 25 | 9 × 25 min | AMTD 2.1 km, 14.2 m from left bank, 0.5 m below surface. |
| E2 | 17/07/03 | 2.03 | 10 MHz | 25 | 8 hours | AMTD 2.0 km, 7.7 m from left bank, 0.5 m below surface. |
| E3 | 24/11/03 | 2.53 | 10 MHz | 25 | 7 hours | AMTD 2.1 km, 10.4 m from left bank, 0.5 m below surface. |
| E4 | 2/09/04 | 1.81 | 10 MHz | 25 | 6 & 3 hours | AMTD 2.1 km, 10.4 m from left bank, 0.052 m above bed. |
| E5 | 8-9/03/05 | 2.37 | 10 MHz | 25 | 25 hours | AMTD 2.1 km, 10.4 m from left bank, 0.095 m above bed. |
| E6 | 16-18/05/05 | 1.36 | 10 MHz & 16 MHz | 25 | 49 hours | AMTD 2.1 km, 10.4 m from left bank, 0.2 & 0.4 m above bed. |
| E7 | 5-7/06/06 | 1.38 | 10 MHz & 16 MHz | 25 & 50 | 50 hours | AMTD 3.1 km, 4.2 m from right bank, 0.2 & 0.4 m above bed. |

Note: AMTD: Adopted Middle Thread Distance measured upstream from river mouth.

### 2.2 Field experiments in a small subtropical estuary with semi-diurnal tides

A series of detailed turbulence field measurements were conducted in a small subtropical estuary of Eastern Australia with a semi-diurnal tidal regime (Table 1). The estuarine zone is 3.8 km long, about 1 to 2 m deep mid-stream, and about 20-30 m wide (Fig. 2). This is a relatively small estuary with a narrow, elongated and meandering channel (CHANSON 2003, CHANSON et al. 2005a). It is a drowned river valley (coastal plain) type with a small, sporadic freshwater inflow, a cross-section which deepens and widens towards the mouth, and surrounded by extensive mud flats. Although the tides are semi-diurnal, the tidal cycles have slightly different periods and amplitudes indicating that a diurnal inequality exists (TREVETHAN et al. 2006).

Turbulent velocities were measured with acoustic Doppler velocimetry. The turbulent velocity measurements were performed continuously at high frequency for between 8 to 50 hours during spring and neap tide conditions (Table 1, columns 5 & 6). A thorough post-processing technique was developed and applied to remove electronic noise, physical disturbances and Doppler effects (CHANSON et al. 2005b). The field experiences demonstrated that the "raw" ADV data were unsuitable, and often inaccurate in terms of time-averaged flow properties. Herein only post-processed data are discussed.

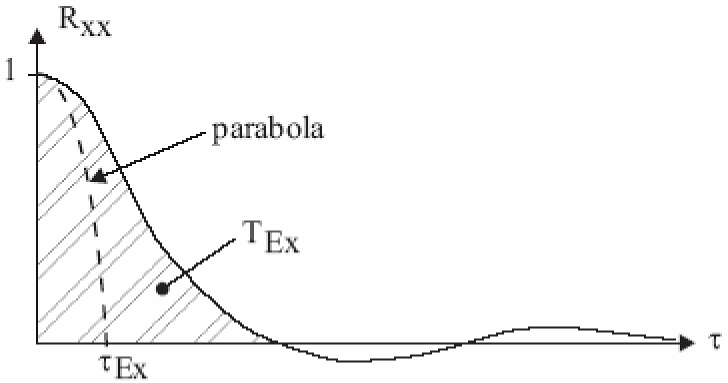


Fig. 3 - Definition sketch of a velocity auto-correlation function

### 2.3 Calculations of turbulence properties

The post-processed data sets included the three instantaneous velocity components $V_x$, $V_y$ and $V_z$ where x is the streamwise direction positive downstream, y is the transverse direction positive towards the left bank and z is the vertical direction positive upwards. A basic turbulence analysis yielded the four statistical moments of each velocity component, their respective dissipative and integral time scales, as well as the tensor of instantaneous Reynolds stresses, and the statistical moments of the tangential Reynolds stresses.

The turbulent velocity fluctuation is: $v = V - \overline{V}$ where V is the instantaneous velocity component and $\overline{V}$ is the time average velocity component. When the flow is gradually time-variable, $\overline{V}$ is the low-pass filtered velocity component or variable-interval time average (VITA). A cut-off frequency must be selected with an averaging time greater than the characteristic period of fluctuations, and smaller than the characteristic period for the time-evolution of the mean properties, while an upper limit of the filtered signal is the Nyquist frequency. In a natural estuary, the selection of the cut-off frequency is a critical process. Herein all turbulence data were processed using samples that contain 5,000 data points (200 s) and re-calculated every 10 s along the entire data sets. The sample size of 5,000 samples was chosen to be much larger than the instantaneous velocity fluctuation time scales, to contain enough data points to yield statistically meaningful results, and to be considerably smaller than the period of tidal fluctuations. In a study of boundary layer flows, FRANSSON et al. (2005) proposed a cut-off frequency that is consistent with the selected sample size.

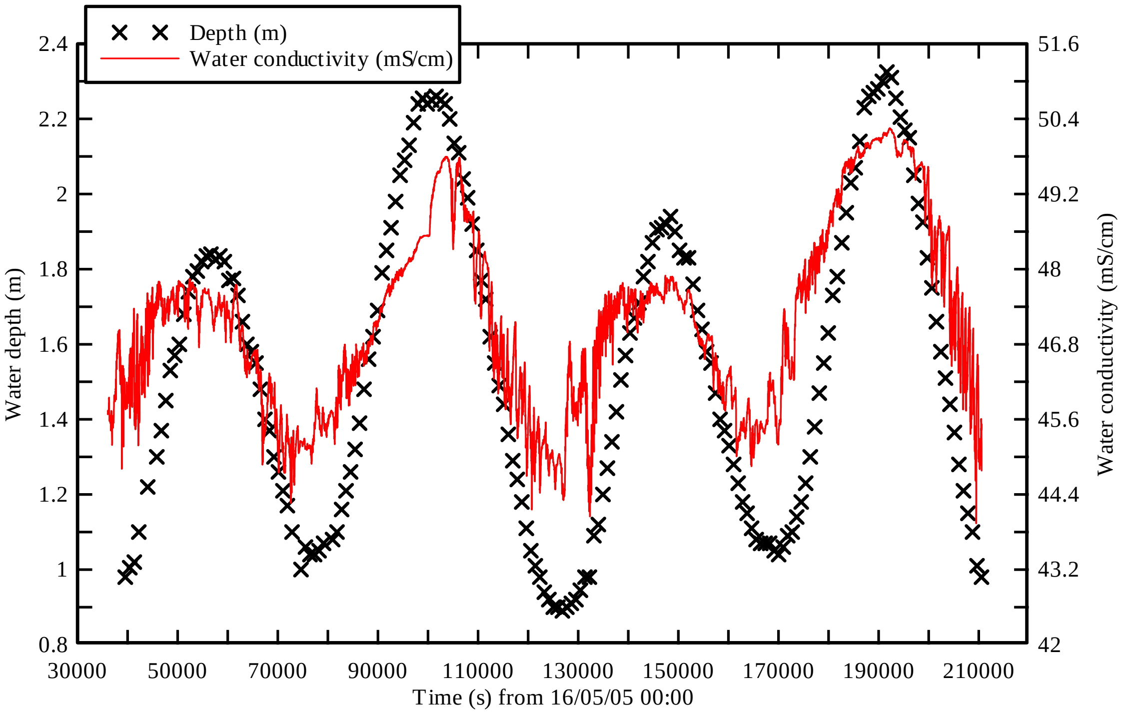
An auto-correlation analysis yielded further the Eulerian dissipation and integral time scales for each velocity component (Fig. 3). The dissipation time scale represents a measure of the most rapid changes that occur in the fluctuations of a velocity component, and it is the smallest energetic time scale. It was calculated using the method of HALLBACK et al. (1989) extended by FRANSSON et al. (2005) and KOCH and CHANSON (2005). The integral time scale, or Taylor macro time scale, is a rough measure of the longest connection in the turbulent behaviour of a velocity component. Further details on the auto-correlation analyses were discussed in TREVETHAN et al. (2006).

Lastly the turbulence calculations were not conducted when more 20% of the 5,000 data points were corrupted/repaired during the ADV data post-processing.

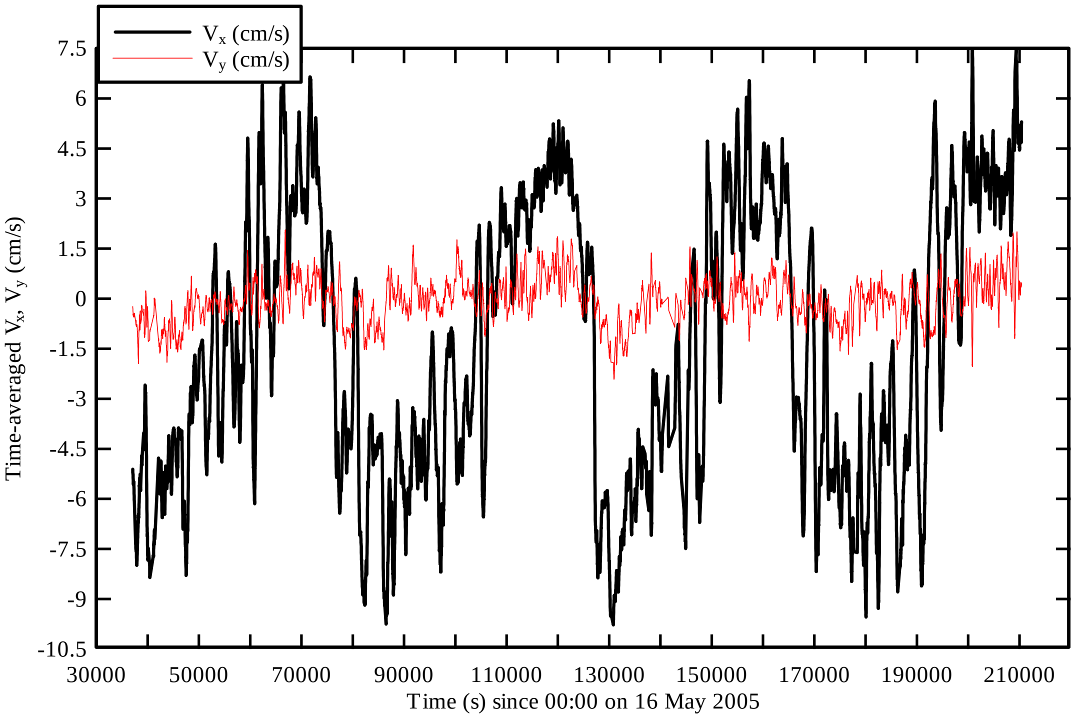
## 3. TURBULENCE PROPERTIES IN A SMALL ESTUARY

### 3.1 Bulk flow properties

The estuarine flow is an unsteady process. The bulk parameters including the water depth and time-average streamwise velocity are time-dependant and they fluctuate with periods comparable to tidal cycles and other large-scale processes. This is illustrated in Figure 4 showing the water depth, conductivity and time-averaged velocities recorded mid-estuary during the field work E6 (Table 1).



(A) Measured water depth (m) and water conductivity (mS/cm)



(B) Time-averaged streamwise and transverse velocity data - 2D microADV (16 MHz) probe sensor: 0.2 m above bed - Time-averages calculated for 5,000 data points every 10 s along data set

Fig. 4 - Measured water depth, water conductivity and time-averaged velocities during the field work E6 on 16-18 May 2005 (neap tide conditions)

Figure 4A presents some water depth and conductivity data. The results highlight the slight tidal asymmetry during a 24 hours period with a smaller (minor) tidal cycle followed by a larger (major) tidal amplitude. The water conductivity variations were driven primarily by the ebb and flood tides. The moderate range of specific conductivity was typical of neap tide conditions in absence of freshwater runoff. Some small oscillations in conductivity were observed throughout the field work. Figure 4B presents the time-averaged streamwise and transverse velocities recorded at 0.2 m above the bed in the middle of the deepest channel (Fig. 2B). The largest velocity magnitude occurred around the low tide, and flood velocities were always larger than ebb velocities. KAWANISI and YOKOSI (1994) observed similarly maximum flood and ebb velocities around low tide, with larger flood velocities, during some field works in an estuarine channel in Japan.

The velocity data showed some multiple flow reversal events around high tides and some long-period velocity oscillations around mid-tide. Figure 4B shows an example around high tide between t = 50,000 and 75,000 s where the time t is counted since 00:00 on 16/05/2005. These low-frequency velocity oscillations were possibly generated by some resonance caused by the tidal forcing interacting with the estuary geometry and the outer bay system (CHANSON 2003, TREVETHAN et al. 2006). These effects were more noticeable in neap tide conditions.

### 3.2 Turbulence properties

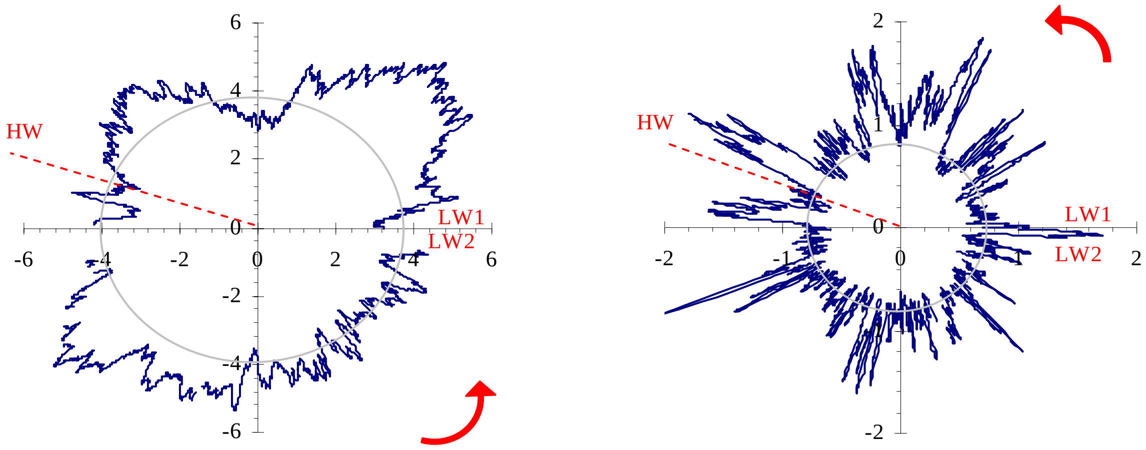
The field observations showed systematically the large standard deviations of all velocity components at the beginning of the flood tide for all tidal cycles. Typical field measurements of standard deviations of the streamwise velocity $v_x'$ are shown in Figure 5 for two tidal cycles in spring and neap tides. Figure 5 shows the magnitude of $v_x'$ from a low water (LW1) to the next one (LW2), and the data are presented in a circular plot. The high and low waters are indicated. From the first low water, the time variations of the data progress anticlockwise until the next low water.

Note the different scales for Figures 5A and 5B. The standard deviations of all velocity components were two to four times larger in spring tides than in neap tides. Figure 5 highlights the large velocity standard deviations in spring tide conditions (Fig. 5A). In Figure 5, the grey circles represent an approximate mean standard deviation of streamwise velocity. The presentation illustrates that $v_x'$ was systematically larger during the flood tide than during the ebb tide

The horizontal turbulence intensity $v_y'/v_x'$ showed no discernable tidal trend, while the vertical turbulence intensity $v_z'/v_x'$ increased with increasing streamwise velocity magnitude. The horizontal turbulence intensity $v_y'/v_x'$ was approximately equal to 1, indicating that turbulence fluctuations in the streamwise and transverse directions were of similar magnitude. They were larger than laboratory observations in straight prismatic rectangular channels which yielded $v_y'/v_x' = 0.5$ to 0.7 (NEZU and NAKAGAWA 1993, KOCH and CHANSON 2005). The vertical turbulence intensities $v_z'/v_x'$ were approximately half of the horizontal turbulence intensities implying some form of anisotropy.

The tangential Reynolds stresses varied with the tide during all field works. Figure 6A illustrates the trend for two fields studies by showing the time-averaged Reynolds stress $\rho*\overline{v_x*v_z}$ as a function of time-averaged streamwise velocity. $\rho*\overline{v_x*v_z}$ was predominantly positive during the flood tide and negative during the ebb tide (Fig. 6A). The finding is consistent with the data of OSONPHASOP (1983) and KAWANISI and YOKOSI (1994) in tidal channels. The magnitudes of the time-averaged tangential Reynolds stresses were at least an order of magnitude larger during spring tides than those for neap tide conditions. The larger magnitude of Reynolds stresses derived from the increased tidal forcing.

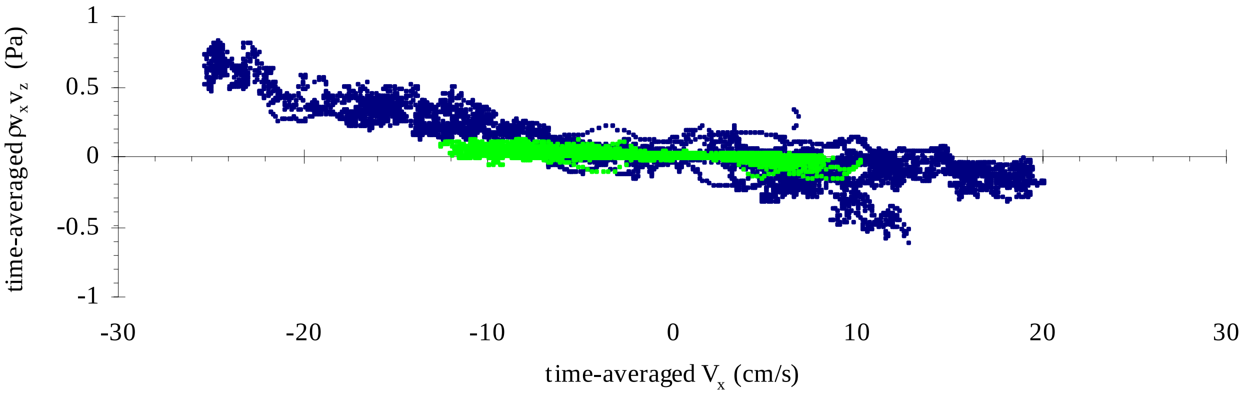
The standard deviations of tangential Reynolds stresses increased with increasing streamwise velocity magnitude. The magnitude of the standard deviations of all tangential Reynolds stresses were one order of magnitude greater in spring tides than those observed at neap tides (Fig. 6B). Figure 6B presents some data for both a minor tidal cycle and a larger major tidal cycle during the same field studies as in Figure 6A.



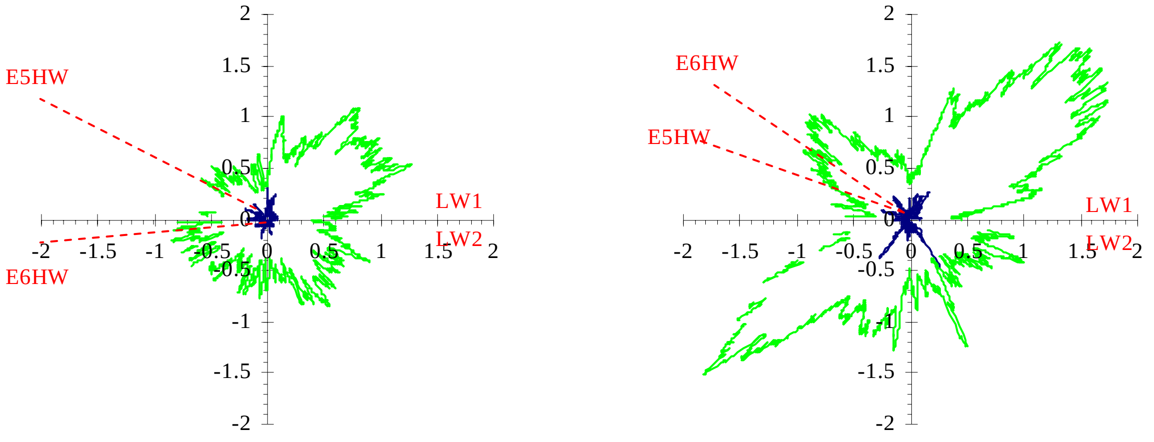
(A) Major tidal cycle, field work E5 (spring tide), ADV sensor at 0.1 m above bed

(B) Major tidal cycle, field work E6 (neap tide), 3D-ADV sensor at 0.4 m above bed

Fig. 5 - Standard deviations of the streamwise velocity $v_x'$ (cm/s) during a tidal cycle in spring and neap tide conditions



(A) Time-averaged Reynolds stress $\rho*\overline{v_x*v_z}$ as a function of time-averaged streamwise velocity



(B1) Minor tidal cycle

(B2) Major tidal cycle

(B) Standard deviations of tangential Reynolds stress $(\rho*v_x*v_z)'$ (Pa) during a tidal cycle

Fig. 6 - Tangential Reynolds stress $\rho*v_x*v_z$ during the field works E5 and E6 - Reynolds stresses calculated for 5,000 data points every 10 s along the entire data set - Legend: [•] field work E5, [•] field work E6

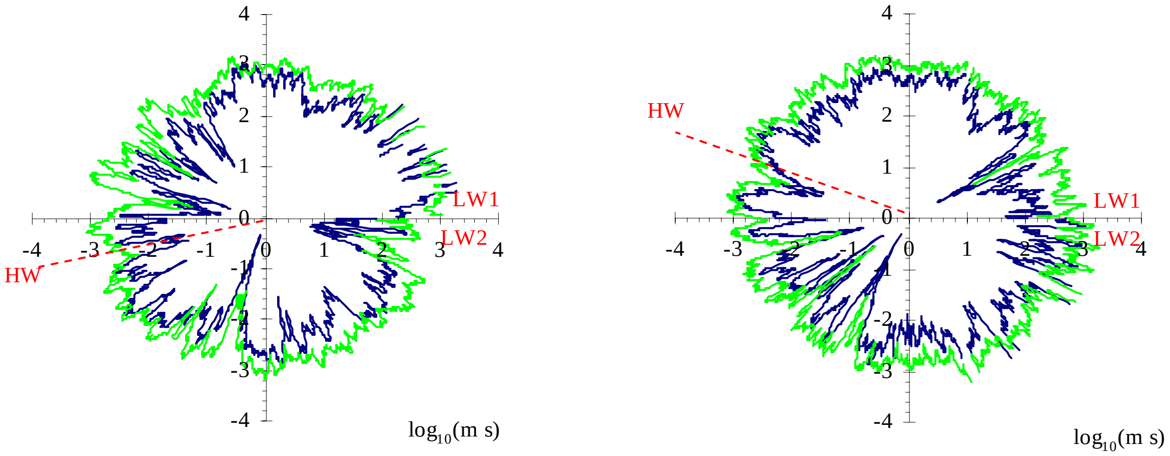
The skewness and kurtosis of tangential Reynolds stresses showed trends related to the tidal cycle, and their magnitude exceeded the expected Gaussian distribution values. In terms of the tangential Reynolds stress $\rho * v_x * v_z$, the Eprapah Creek data were of a similar order magnitude as OSONPHASOP's (1983) data. Further both studies (OSONPHASOP's and present studies) demonstrated that the probability distribution functions of the tangential Reynolds stress $\rho * v_x * v_z$ were not Gaussian.

### 3.3 Turbulence time scales

The integral time scale of a velocity component is a measure of the longest connection in the turbulent behaviour of that velocity component. Some time-variations of streamwise integral time scales $T_{Ex}$ are shown in Figure 7 for two tidal cycles at two vertical elevations (0.2 and 0.4 m above the bed) during the same field study. Note that the axes have a logarithmic scale and the units are ms. The integral time scales of streamwise velocity $T_{Ex}$ were larger during the flood tide than during the ebb tide (Fig. 7). The horizontal integral time scales were typically between 0.4 and 2 s at 0.2 m above the bed and between 0.06 and 1 s at 0.4 m above the bed.

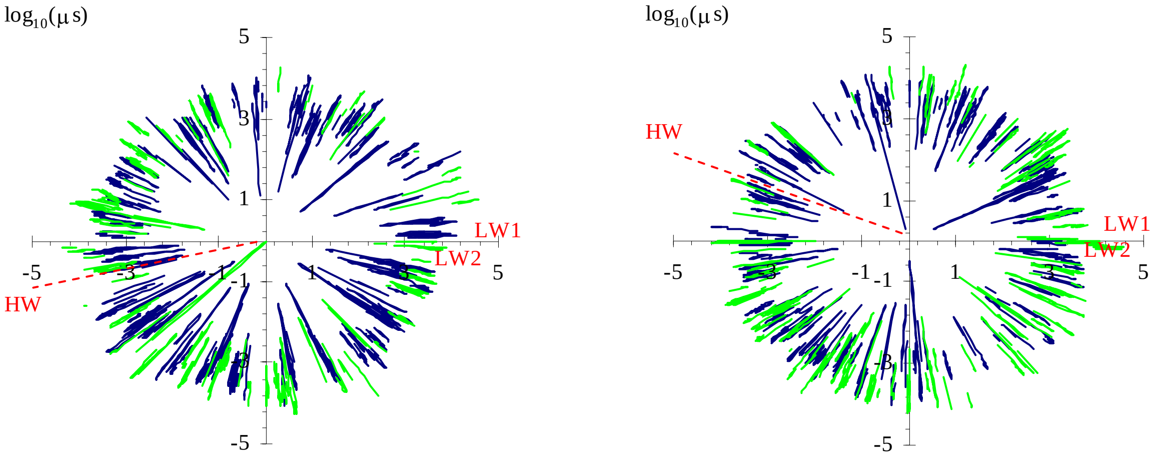
The dissipation time scale, also called Taylor micro scale, is a measure of the most rapid changes that occur in the fluctuations of a velocity component. It is a characteristic timescale of the smaller eddies which are primary responsible for the dissipation of energy. Dissipation time scale data seemed independent of the tidal phase (Fig. 8). They were typically about 0.002 to 0.02 s for all field studies. Such dissipation time scales were consistently smaller than the time between two consecutive samples: e.g., $1/F_{scan} = 0.04$ s for $F_{scan} = 25$Hz. The findings highlighted that high-frequency sampling is required and the sampling rates must be at least 20 to 50 Hz to capture a range of eddy time scales relevant to the dissipation processes.

The analysis of integral and dissipation time scales of all velocity components showed no obvious trends with tidal phase for both neap and spring tide conditions. During the present field studies, the dimensionless transverse and vertical integral time scales were respectively: $T_{Ey}/T_{Ex} \sim 1$ and $T_{Ez}/T_{Ex} \sim 2$ to 3. In a tidal channel in Southern Australia, OSONPHASOP (1983) observed $T_{Ey}/T_{Ex} \sim 1.7$ and $T_{Ez}/T_{Ex} \sim 2.2$. In the present studies, the dimensionless transverse and vertical dissipation time scales were respectively: $\tau_{Ey}/\tau_{Ex} \sim 1$ to 4 and $\tau_{Ez}/\tau_{Ex} \sim 4$ to 7.



(A) Minor tidal cycle (B) Major tidal cycle

Fig. 7 - Streamwise integral time scales $T_{Ex}$ (units: ms) at two vertical elevations during the field work - E6 - Legend: —— data at 0.2 m above bed; —— data at 0.4 m above bed - The axes have a logarithmic scale and the units are milliseconds



(A) $\tau_{Ex}$ for a minor tidal cycle (B) $\tau_{Ex}$ for a major tidal cycle

Fig. 8 - Horizontal dissipation time scale at two vertical elevations - Field work E6 - The axes have a logarithmic scale and the units are microseconds - Legend: —— data at 0.2 m above bed; —— data at 0.4 m above bed

Some estimates of integral length scales may be derived using Taylor hypothesis: $\Lambda_f = \overline{V_x} * T_E$. The integral scale is some measure of the longest connection between the velocities at two points of the flow field (HINZE 1975). In the present studies, the horizontal integral length scales were between 0.5 and 10 cm while the vertical integral length scales were about 2 to 10 cm.

## 5. SUMMARY AND CONCLUDING REMARKS

Mixing and contaminant transport in estuaries are turbulent processes. The properties of turbulent flows are highly fluctuating, they involve a wide range of eddy time and length scales, and they are characterised by very strong mixing. In turn, a large number or parameters are needed to characterise the turbulence structure in estuarine systems and its variations during the tidal cycle. The turbulence is neither homogeneous nor isotropic in natural estuaries, and its behaviour deviates from that for equilibrium turbulent boundary layer induced by velocity shear only. It is not a Gaussian process, and the small departures from Gaussian probability distributions are possibly the most important features of the turbulent flow motion.

The field experiences in a small estuary with semi-diurnal tides showed that turbulence measurements must be conducted at high frequency to characterise the small eddies and the viscous dissipation process, while a continuous sampling is necessary to characterise the time-variations of the instantaneous velocity field and Reynolds stress tensor during the tidal cycle. A striking feature of the present data sets is the large fluctuations in all turbulence characteristics during the tidal cycles. This aspect was rarely documented in previous studies, but an important feature of this study is that the present data were collected continuously at high frequency during relatively long periods. The findings bring new lights in the fluctuating nature of turbulent structure, integral time and length scales, and momentum exchange coefficients. These turbulent properties should not be assumed constant.
Lastly it is believed that the present results provide a picture general enough to be used, as a first approximation, to characterise the flow field in similar small subtropical estuaries with semi-diurnal tides.

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