19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Turbulence Measurements in a Shallow Tidal Estuary: Analysis Based On Triple Decomposition

K.A. Suara[1], R.J. Brown[1] and H. Chanson[2]

[1]Science and Engineering Faculty
Queensland University of Technology, Queensland 4000, Australia

[2]School of Civil Engineering
The University of Queensland, Queensland 4072, Australia

Abstract

In an estuary, mixing and dispersion are the result of the combination of large scale advection and small scale turbulence which are both complex to estimate. A field study was conducted in a small sub-tropical estuary in which high frequency (50 Hz) turbulent data were recorded continuously for about 48 hours. A triple decomposition technique was introduced to isolate the contributions of tides, resonance and turbulence in the flow field. A striking feature of the data set was the slow fluctuations which exhibited large amplitudes up to 50% the tidal amplitude under neap tide conditions. The triple decomposition technique allowed a characterisation of broader temporal scales of high frequency fluctuation data sampled during a number of full tidal cycles.

Introduction

Mixing and dispersion in estuaries are complex phenomena induced by the transition and strong competition between ocean and river. The estuarine circulation is characterised by tidal currents, energetic turbulence, and complex bathymetry among other factors [5]. In an estuary, mixing and dispersion result from the combination of small scale turbulence and large scale advection [6]. Several studies were carried out continuously at high frequency over a few tidal cycles in small estuaries, including during king tidal conditions and neap tides after moderate rainfall [3,13,14,15]. A double decomposition technique implemented in the previous studies identified resonance of the tidal forcing as a key characteristic with periods smaller than the tidal period but larger than the turbulence timescales. The more advanced triple decomposition method (TDM) separates organised flow motion from 'true' turbulence and was previously applied to the laboratory environmental flows and field applications [2,7,9].

Herein high frequency measurements of flow and physiochemical parameters were recorded in a small subtropical estuary during neap tidal conditions with no prior rain for about 7 days in the catchment. The study introduces a triple decomposition technique to allow the separation of the mean flow field, the tidal, resonance (large-scale, slow fluctuation) and the 'true' turbulence (small-scale, fast fluctuation) components. The application of the triple decomposition method (TDM) to high frequency tidal scale estuarine flow measurements is detailed. The results highlight the important characteristics of resonance (slow fluctuation) in the overall flow field and the transport of scalars in general.

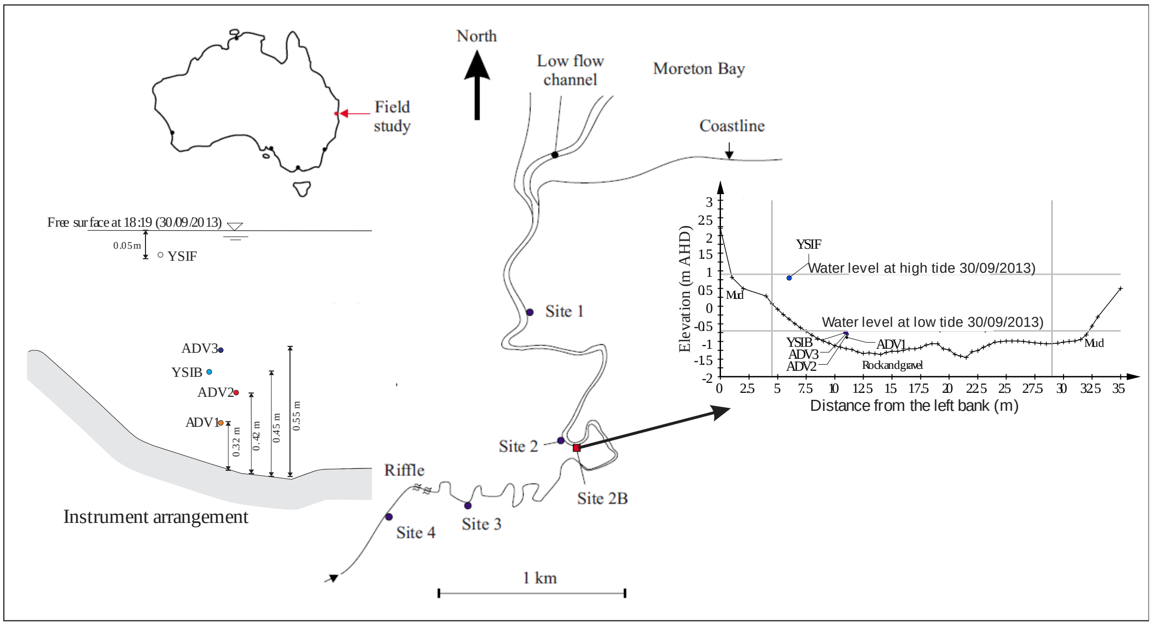

Figure 1. Eprapah Creek estuarine zone, including surveyed sampling cross section on 29 Sept. 2013 and instrumentation arrangement.

Data Collection and Analysis

A field study was conducted at Eprapah Creek (Longitude 153.30º East, Latitude -27.567º South), a sub-tropical stream located in Eastern Australia [3] between 29 September and 1 October 2013. The catchment is about 39 km^2 consisting of a main channel and two other tributary channels. The estuarine zone (Figure 1) is about 3.8 km long and flows into Moreton Bay adjacent to the Pacific Ocean at Victoria point, with a typical semi-diurnal tidal pattern [13,14]. The total rainfall for September 2013 was between 17–23 mm at the weather stations within 20 km radius of the catchment and the cumulative rainfall for the last 7 days immediately prior to the field study was nil [1]. The river discharge was expected to be insignificant. The wind speed was 1.5 m/s on average from the North-North-East direction during the duration of the field study.

Turbulent velocities were measured with three acoustic Doppler velocimeters (ADVs) Sontek^{TM} microADV. The ADV1 was a 3D side-looking probe micro-ADV (16 MHz), the ADV2 was a 2D side-looking probe micro-ADV (16 MHz) and the ADV3 was a 3D down-looking probe micro-ADV (16 MHz). The ADVs were mounted on a bracket held by structural poles whose wakes did not affect the sampling volumes. The ADVs were sampled continuously at 50 Hz with the sampling volumes located vertically above each other at 0.32 m, 0.42 m and 0.55 m above the bed (Figure 1). Some physiochemical properties were measured using two multi-parameter water quality probes, YSI6600 (YSIB &YSIF) deployed and sampled at 0.1 Hz near the bed and next to the free surface. The probes recorded conductivity, salinity, temperature, pH, dissolved oxygen, chlorophyll A and turbidity. Some manual sampling of physiochemical properties was also performed every 15 minutes. All measurements were recorded over a 48 hours period. The site cross section was surveyed on 29 September 2013 (figure 1, site 2B).

Quality Control

The raw ADV velocity data might contain some level of noise, spikes and low correlated outputs which are spurious but could be mistaken for physical processes in high-turbulence environmental flows. Conventional despiking can detect a large amount of erroneous data points which are not a true representation of any physical process [4,8]. Herein the ADV data sets were post processed using the software WinADV32 version 2.029 developed by U.S. Bureau of Reclamation, with the removal of communication errors, data with correlation less than 60% and signal-noise-ratio less than 5 dB [2,4]. The data sets were also despiked using the phase-spaced thresholding technique [8]. A MATLAB algorithm was developed to fill gaps with previous valid data points for further analyses and repaired data were flagged.

Triple Decomposition Method

A triple decomposition method (TDM) was applied to the instantaneous velocity and pressure data. Figure 2 shows a hypothetical energy spectrum of the instantaneous field in a tidal channel within period equivalent to a few tidal cycles. The instantaneous velocities and pressure were decomposed as:

$$V_i = \langle V_i \rangle + [V_i] + v_i \qquad (1)$$

where $<V_i>$ is the mean (tidal) component, $[V_i]$ is the slow fluctuating component, v_i is the turbulent component and the subscript i indicates the coordinate (x, y, or z). Herein $<V_i>$ is the low-pass filtered data with a cut-off frequency of F_{cl}. The slow fluctuating component $[V_i]$ is the band-passed signal with the lower and upper cut-off frequencies set at F_{cl} and F_{cu}. In applying the TDM, a key issue was the determination of the characteristic frequencies (upper and lower cut-offs) for separating the organised and random turbulent motions from the instantaneous fields. The frequencies were identified using visual observations, statistical analyses, as well as power spectra analyses of raw signals.

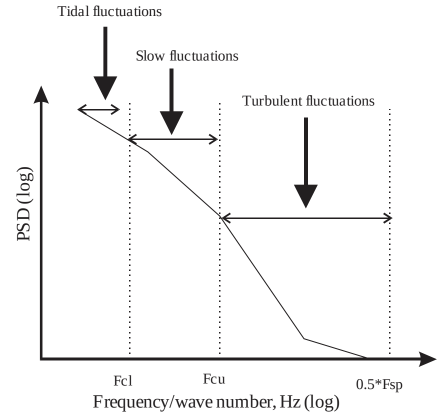

Figure 2. Sketch of a hypothetical power spectral density of an instantaneous field flow measured in a tidal channel.

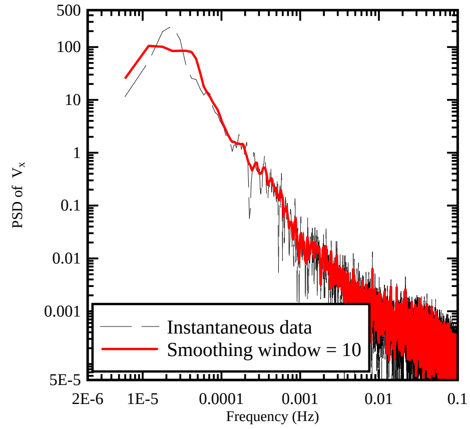

Figure 3. Spectral analysis of fluctuations of streamwise velocity V_x, Probe sensor: 0.32 m above the bed, 11.1 m from left bank; Note that the higher frequency portion (0.1–25 Hz) was cropped out for clarity.

In addition to the discernable tidal trend, the velocity data revealed some slow fluctuations, seen for example in the form of flow reversals at slack water; the largest with a period of about 3000 s through visual inspection of the time series. Figure 3 shows some spectra of velocity with smoothed curves highlighting distinctive features in the power spectrum density function of the instantaneous V_x data. The distinctive peak in power spectral density at about 0.00004 Hz seemed related to the tidal fluctuation. The following peaks and troughs suggested some energetic events with frequencies corresponding to the periods of the visually observed slow fluctuations. These observations suggested a lower cut-off frequency could be generalized as

$$\frac{4}{P_{\min}} \leq F_{cl} < \frac{1}{P_{fluc}} \qquad (2)$$

where P_{min} (herein ~42,000 s) is the period of the shortest tidal cycle observed and P_{fluc} (herein ~3,000 s) is the period of the longest slow fluctuations.

Some sensitivity analyses were conducted on the flow field data to investigate the effects of the cut-off frequencies on the decomposed velocity components and pressure. The results indicated that $<V_i>$ was little affected by F_{cl} less that 0.0001 Hz, while $\langle V_i \rangle$ contained some signatures of the slow fluctuation for F_{cl} greater than 0.0001 Hz. The mean turbulent velocity $\widetilde{v_i}$, and its standard deviation were nearly independent of the upper cut-off frequency F_{cu}. above 0.01 Hz while the skewness of test points, along the data set, converged to zero at F_{cu}. ~ 0.5 Hz, that is for a value expected of a normal distribution.

Herein $\langle V \rangle$ was the low-pass filtered data with a cut-off frequency of 0.0001 Hz (1/10,000 s^{-1}). The slow fluctuating component [*V*] was the band-passed data with the upper and lower cut-off frequencies set at 0.5 Hz and 0.0001 Hz (1/2 s^{-1} and 1/10,000 s^{-1} respectively). The turbulent component *v* was the high-pass filtered data with a cut-off frequency of 0.5 Hz (1/2 s^{-1}). All the statistical properties of the turbulent velocity components were calculated over a 200 s interval (10,000 data samples) as [13,14]. Statistical properties were not calculated for sections with more than 10% removed and flagged data during post-processing.

Basic Observations

The water elevation and all the physiochemical properties of the Creek showed discernable tidal trends. The variations in specific conductivity of water (Figure 4) were primarily influenced by tidal incursion. The ebb tides exhibited some well-mixed condition, more so than the flood tides. A few instances of dense water being advected over less dense waters were recorded (e.g. at t =128,000 to 132,000). Table 1 summarises the averaged physiochemical properties of Eprapah Creek at Site 2B during the study period. The specific conductivities were on average of 47 mS/cm and 43.7 mS/cm next to the surface and next to the bed, respectively. This was close to an averaged water conductivity of 49 mS/cm obtained on 2 September 2004, over a full tidal cycle during a drought period [15]. The result confirmed that a moderate range of conductivity level was a characteristic of neap tidal conditions with negligible freshwater runoff. The physio-chemistry of the channel suggested that the water column was reasonably mixed for conductivity, temperature, DO, turbidity and chlorophyll while it was partly stratified in terms of pH.

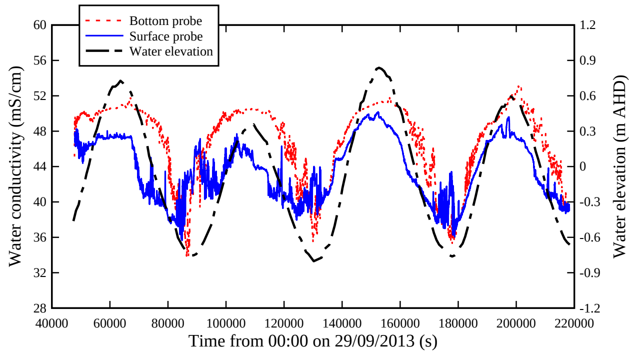

Figure 4. Measured water conductivity and water depth as functions of time.

The instantaneous velocity and pressure data showed some substantial fluctuations in Eprapah Creek. Herein, the streamwise velocity, V_x is positive downstream (i.e. facing toward the mouth of the Creek), the transverse velocity, V_y is positive towards the left bank and the vertical velocity, V_z is positive upwards. The data contained the superimposition of pseudo-periodic fluctuations occurring at many different periods. Figure 5 shows the instantaneous velocity and water depth as functions of time for the field study. The streamwise velocity showed strong tidal incursion about low water with the maximum velocities around 0.19 m/s and 0.16 m/s during the late ebb and early flood tides, respectively. Similar flood and ebb tide maxima were observed at various locations in Eprapah Creek [3,13,14]. The magnitude of the maximum ebb velocity was on an average greater than that of the flood tide. The transverse velocity data showed some tidal influence linked with the proximity of a meander downstream of site 2B. The main current flowed through the outer radius of the meander during the flood tide and the maximum values occurred at low water (not shown). However, slow and fast fluctuations dominated both the transverse and vertical velocities.

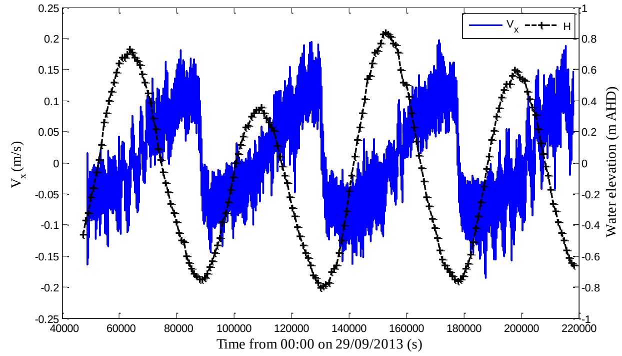

Figure 5. Instantaneous longitudinal velocity V_x and water level as functions of time; data collected at 0.32 m above the bed.

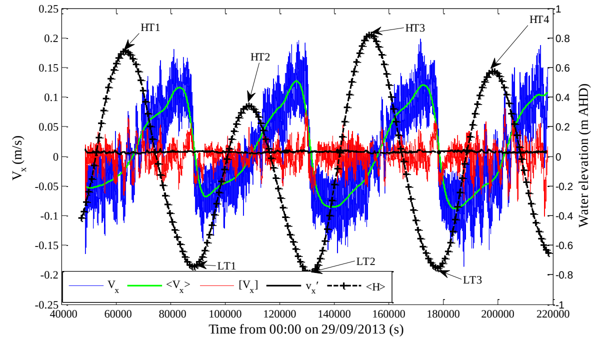

Figure 6. Decomposed components of longitudinal V_x and tidal scale water level as functions of time; data collected at 0.32 m above the bed.

Decomposed Flow Field and Turbulence Properties

Figure 6 shows the decomposed longitudinal velocity V_x data for the ADV sampling at 0.32 m from the bed. The tidal component $\langle V_x \rangle$ presented a distinctive periodic variation expected of a tidal wave. The flood and ebb tide maxima occurred just before and after the low tides respectively. This was consistent with the instantaneous measurements. The phase-lag which is primarily a function of the ratio between the bank convergence and the tidal wavelength [13] was computed from $\langle V_x \rangle$ and $\langle H \rangle$. The high tides, HT occurred about 42 min before the high water slacks while the low tides, LT occurred around 8-15 min before the change of flow direction. The phase-lags suggested that the channel exhibited a mixed-type wave and fell into the category of the alluvial estuaries with a typical phase lag of 0.3 (π/10.47).

The slow fluctuations were related primarily to resonance resulting from the reflection of tidal forcing on landmarks. Large amplitude fluctuations were observed around slack tides. These were observed in the form of episodic flow reversals and periodic rise and fall in water level. The slow fluctuation had amplitudes up to 0.08 m/s at slack water and of period about 3,000 s (Figure 6), that is about half of the tidal amplitude. Similar fluctuations were observed previously in Eprapah Creek at sites 2B [13] and 3 [15], but were not isolated specifically. Figure 7 shows the standard deviation of the streamwise velocity fluctuations as a function of time. The standard deviations of [*V*] were the same order of magnitude with the turbulence fluctuation (Figure 7). The large amplitudes, periods and deviations of $[V_x]$ suggested that the slow fluctuations were important to the transport of scalars within the channel and similar shallow water estuaries.

Statistical analyses were carried out on the 'true' turbulence data. The mean values of v calculated along the data were approximately zero. The standard deviations of all velocity components were large during the early flood tides. For all ADV units, the horizontal turbulence ratio v'_y/v'_x ranged between 0.5–0.9. These values were similar to laboratory observations in straight prismatic rectangular channel v'_y/v'_x =0.5–0.7 reported by Nezu and Nakagawa [10] and smaller than values previously observed in Eprapah Creek during a spring tide v'_y/v'_x ~1 [13]. The vertical turbulence ratio v'_z/v'_x was on average 1 at z = 0.32 m while v'_z/v'_x was approximately 0.5 for the ADV3 (z = 0.55 m).

These results implied some anisotropy of the turbulence field which increased away from the bed. The skewness and kurtosis values for all velocity components varied with streamwise velocity through the observation period. The skewness appeared within the range of -4 and +2. Over 65% of the skewness values fell within the range expected of a finite Gaussian distribution [11]. The bulk of the excess kurtosis values (over 70%) fell within the range of -0.5 and +2. Some events of large kurtosis (magnitude up to 18) were observed and were possibly linked with intermittency of the turbulence field and the motion of fishes around the ADV probes.

Averaged physiochemical properties								
Sample	Air Temp. (Celsius)	Water Temp. (Celsius)	Conductivity (mS/cm)	DO (mg/L)	pH	Turbidity (NTU)	Salinity (ppt)	Chlorophyll (μg/L)
Manual	21.8	24.24	52.04	6.7	7.86	-	-	-
Bottom	-	24.7	46.9	4.93	8.11	9.1	30.5	2.92
Surface	-	24.8	43.7	4.84	7.51	7.79	28.2	2.87

Table 1. Averaged physiochemical conditions of Eprapah Creek site 2B (29/09/2013 to 1/10/2013).

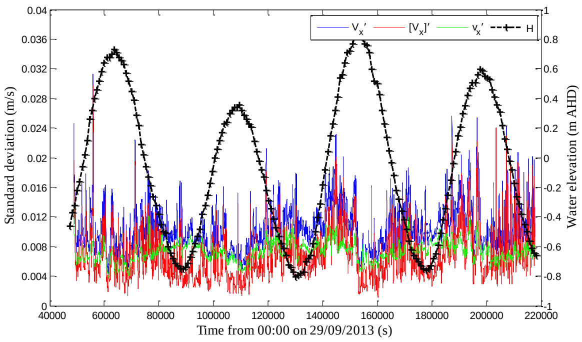

Figure 7. Time variations of standard deviations of slow and fast fluctuations relative to standard deviation of V_x; data collected at 0.32 m above the bed.

Conclusion

Flow field and physiochemical data were sampled continuously at relatively high frequency for about 48 hours in a subtropical estuary. The flow field was highly fluctuating and contained some combination of slow and fast fluctuations. A triple decomposition method was introduced in the data analysis. The tidal scale stage-velocity analysis revealed that the channel exhibited a mixed-type wave indicated with normalized phase-lag about 0.04π–0.12π. The slow fluctuations presented large amplitudes, periods and standard deviation of $[V_x]$ which implied a significant contribution of the slow fluctuations to turbulent mixing and scalar transport within the estuarine channel. The analysis of the 'true' turbulence field showed some anisotropy similar to classical boundary layer results and differed slightly from previous observations in Eprapah Creek, then analysed using a double decomposition technique. The bulk skewness and kurtosis values were Gaussian, although some occasional high values were observed. The triple decomposition technique described herein allowed the characterisation of broader temporal scale of fluctuations of high frequency data sampled within the durations of few tidal cycles.

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