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Detailed measurements during a transient front in a small subtropical estuary

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Abstract

High-resolution measurements of velocity and physio-chemistry were conducted before, during and after the passage of a transient front in a small subtropical system about 2.1 km upstream of the river mouth. Detailed acoustic Doppler velocimetry measurements, conducted continuously at 25 Hz, showed the existence of transverse turbulent shear between 300 s prior to the front passage and 1300 s after. This was associated with an increased level of suspended sediment concentration fluctuations, some transverse shear next to the bed and some surface temperature anomaly.

Keywords: transient front; tidal intrusion; subtropical estuary; high-frequency measurements

1. Introduction

Estuarine fronts have received some increased attention in the last decades. A front may be defined as an interface along which some water properties (often the density) change abruptly (Officer, 1976; Dyer, 1997; Lewis, 1997). There are different types of fronts (Bowman, 1998), but direct observations of transient fronts are rare especially in terms of the turbulent velocity field. Transient fronts appear for a few hours of a tidal cycle. Their presence may influence the horizontal dispersion and residual circulation, and have significant impacts on the local chemical and biological processes (Wolanski and Hamner, 1988; Largier, 1992, 1993).

Tidal intrusion fronts are a relatively common feature at or near the mouth of some estuaries (e.g. Kirby and Parker, 1982; Dyer, 1997; Neill et al., 2004; Thain et al., 2004). They are often seen forming a distinctive V-shape of foam and debris at the surface. A front is basically a zone of marked local gradients that indicates some form of singularity in terms of one or more parameters.

In the present study, the authors observed the passage of a transient front in a small subtropical estuary. The channel cross-section was fully instrumented, and both the turbulence and physio-chemistry probes were all sampling continuously at a high-frequency during the time period under consideration. It is the aim of this note to detail the experimental observations.

2. Study site and instrumentation

2.1. Presentation

Eprapah Creek is a subtropical stream in Eastern Australia, close to the city of Brisbane. The stream flows directly into the Moreton Bay at Victoria Point off the Pacific Ocean. The estuarine zone is about 3.8 km long, and the river bed is muddy. This is a relatively small estuary with a narrow, elongated and meandering channel (Fig. 1). It is a drowned river valley (coastal plain) with a wet and dry subtropical hydrology. Eprapah Creek estuary has been closely monitored over

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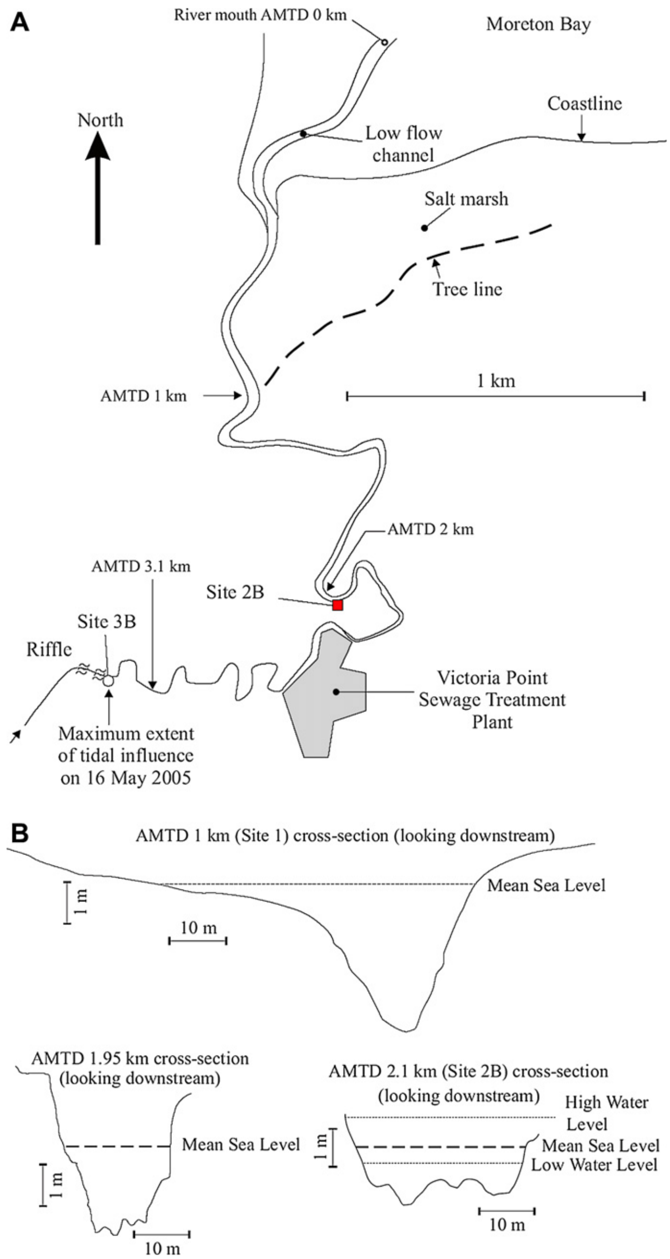

Fig. 1. Eprapah Creek estuary. (A) Sketch of the estuarine zone from an aerial photograph. (B) Surveyed cross-sections.

30 years by Redland Shire Council, Queensland Environmental Protection Agency (EPA) and local community groups, while several detailed field experiments were conducted since 2003 (Chanson et al., 2005; Trevethan et al., 2006). The estuary is typically partially mixed. Although the estuary tends to be partially stratified during ebb tides, it can display some stratification after some freshwater runoff events.

The tides are semi-diurnal with some slight asymmetry. On the data acquisition day, 16th May 2005, the tidal range was 0.87 m mid-estuary (Site 2B, Fig. 1A) corresponding to neap tide conditions. The maximum extent of the tidal influence was about 3.3 km from the river mouth (Site 3B, Fig. 1A). The wind conditions were calm to moderate, and there was no wind wave present at the sampling site. The creek freshwater runoff was zero, and the influence of any groundwater runoff was small and not detectable. A sewage treatment plant (Fig. 1A, AMTD 2.5 km) discharged an average of 0.07 m^3/s, with two daily peak discharges of 0.1 to 0.17 m^3/s each morning and early evening. The estuarine hydrodynamics was primarily tide dominated.

2.2. Instrumentation

At 2.1 km upstream of the river mouth, the channel cross-section was instrumented with two acoustic Doppler velocimeters (microADV, 16 MHz and ADV, 10 MHz), six In-Situ Troll LTS9000 probes and one YSI6600 probe (Trevethan et al., 2006). Fig. 2 shows the surveyed cross-section with the locations of the probe sensors and of the water level at 12:20 on 16 May 2005. The ADV sampling volumes were located at 0.2 m and 0.4 m above the bed in the deepest channel (Fig. 2). A YSI6600 probe was laterally offset by 0.3 m from the ADV which was at 0.4 m above the bed. The LTS9000 probes were spread transversally. The poles supporting the probes are seen in Fig. 3. The ADV and YSI6600 probes were supported by the tripod arrangement seen in Fig. 3C (foreground), with the ADV sampling volume directly underneath the yellow flag (for colour see the web version). All the probes were sampled continuously, but with different rates. The ADVs were sampled at 25 Hz, the YSI probe at 0.0833 Hz (every 12 s), and the LTS900 probes at 0.167 Hz (every 6 s).

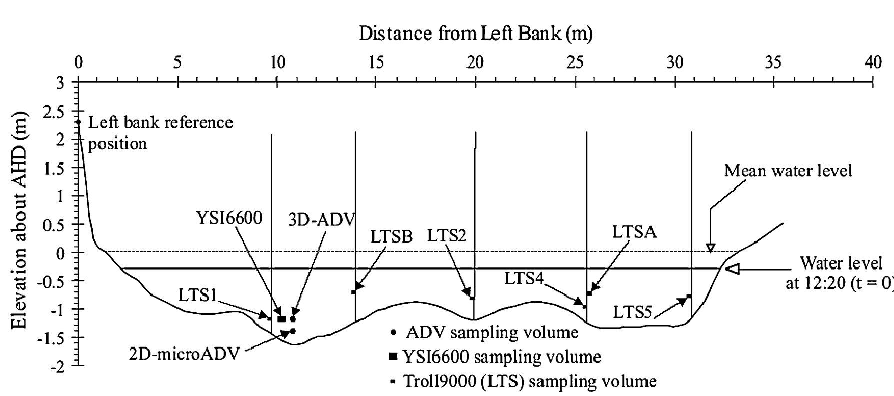

Fig. 2. Surveyed cross-section of the sampling site (looking downstream) and probe positions with the water level at 12:20 on 16 May 2005.

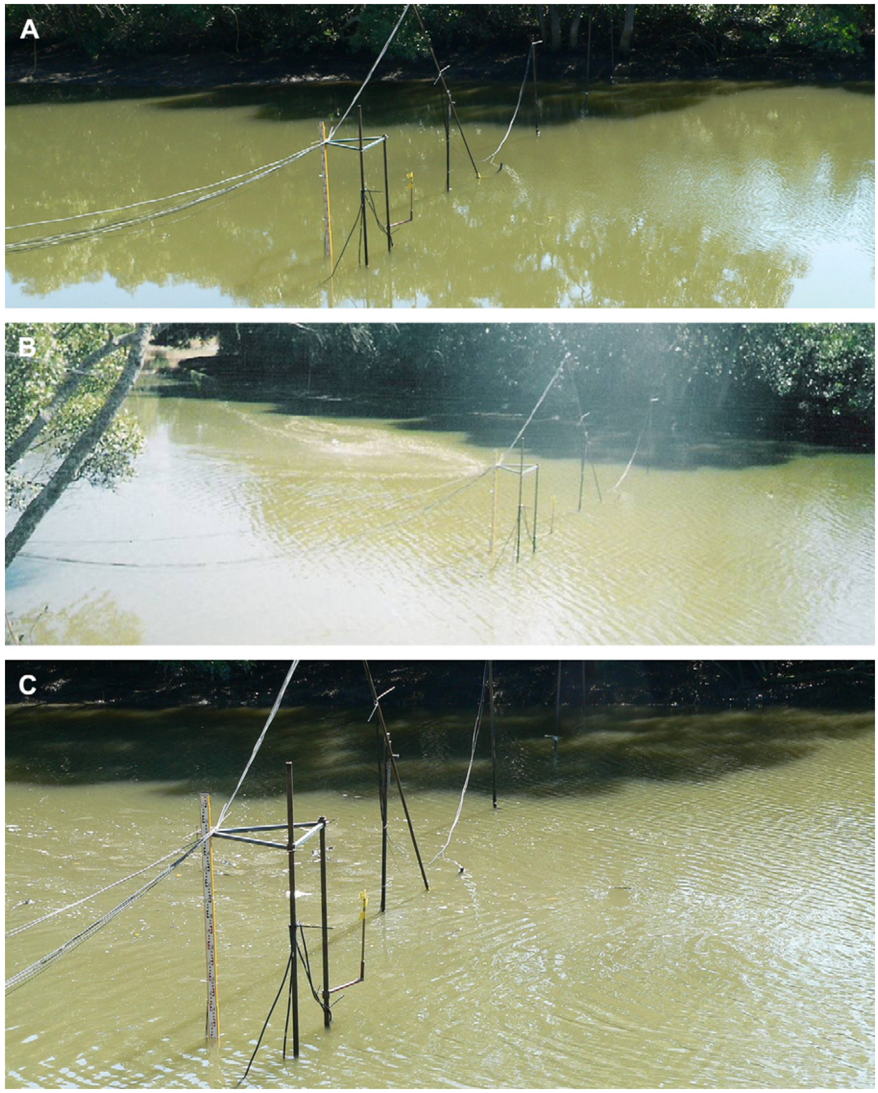

Fig. 3. Photographs of the front observed at Site 2B Eprapah Creek between 12:00 and 13:22 on 16 May 2005. Views from the left bank. (A) Experimental cross-section at 12:03 (LW + 1 h 50 min) before front arrival. (B) Front approaching the experimental cross-section shortly before 12:20 (LW + 2 h 10 min). Front leading edge is highlighted by surface slicks, foams and floating debris. (C) Front crossing the experimental cross-section at 12:22.

With the microADV system located at 0.2 m above the bed, some experiments were conducted in laboratory under controlled conditions using water and soil samples collected in the estuary to test the relationship between acoustic backscatter strength and suspended sediment load (Chanson et al., 2006). The data showed some monotonic function between suspended sediment concentration (SSC) and acoustic backscatter intensity (BSI), where the backscatter intensity is defined as: $BSI = 10^{-5} \times 10^{0.043 \times \mathrm{Ampl}}$ with Ampl the average signal amplitude in counts. The results were applied to the present field observations.

2.3. Data accuracy

The accuracy on the velocity measurements was 1%, whilst the physio-chemistry probe YSI6600 gave ±5% accuracy for turbidity. Note that the turbidity spike filter was on. Furthermore the data accuracy was ±0.5% for conductivity, ±0.15 °C for temperature, ±0.2 unit for pH, ±2% of saturation concentration for dissolved oxygen.

3. Experimental observations

A transient front was observed propagating upstream about 2 h after the field study started during the flood tide (Table 1). Table 1 summarises the chronological events. The measurements were carried out continuously between 16 May 2005 (10:00) and 18 May 2005 (midday). At approximately 12:20 on 16 May (LW + 2 h 10 min), the leading edge of the surface front reached the experimental cross-section 2.1 km upstream of the river mouth (Fig. 3B). The leading edge had a distinctive V-shape of "white" foam at the surface that was followed by substantial surface debris. The traces of the front were seen until approximately 13:22 (LW + 3 h 10 min) when the last observation of surface slicks, foam or floating debris was recorded at the sampling site.

Table 1
Transient front: chronological events on 16 May 2005 at Eprapah Creek. Notes: AHD, Australian Height Datum; AMTD, Adopted Middle Thread Distance, measured upstream from the river mouth

Time	Description	Remarks
09:30	Start of instrument installation at Site 2B (AMTD 2.1 km)	
10:00	End of equipment installation and start of continuous high-frequency sampling	Water depth at ADV site: 1.076 m
10:05	Low tide at Brisbane river mouth (Moreton Bay)	Water level: -0.344 m AHD
10:12	Lowest water level at Site 2B (AMTD 2.1 km)	Water depth at ADV site: 1.067 m
11:45	Dinghy activity close to the instruments.	Water depth at ADV site: 1.210 m
12:20	Leading edge of the surface front reached the experimental cross-section (Site 2B)	Water depth at ADV site: 1.333 m
12:20–13:00	Large amount of surface debris around the instrumentation poles (Site 2B)	
13:06	Significant recirculation (flow reversals) next to both left and right banks (Site 2B)	Water depth at ADV site: 1.517 m
13:22	End of front traces at the experimental cross-section (Site 2B)	Water depth at ADV site: 1.596 m
15:40	High tide at Brisbane river mouth (Moreton Bay)	Water level: +0.482 m AHD
15:48	Highest water level at Site 2B (AMTD 2.1 km)	Water depth at ADV site: 1.933 m

During that period, the front propagated upstream with an average speed $U \approx 0.15$ to 0.2 m/s. Fig. 3 shows various stages of the front propagating upstream through the experimental cross-section. No front was subsequently observed on 16 May evening, 17 and 18 May 2005, although the sampling site was continuously monitored.

The effects of the front passage on the turbulence and physio-chemistry were carefully analysed. Figs. 4–7 present

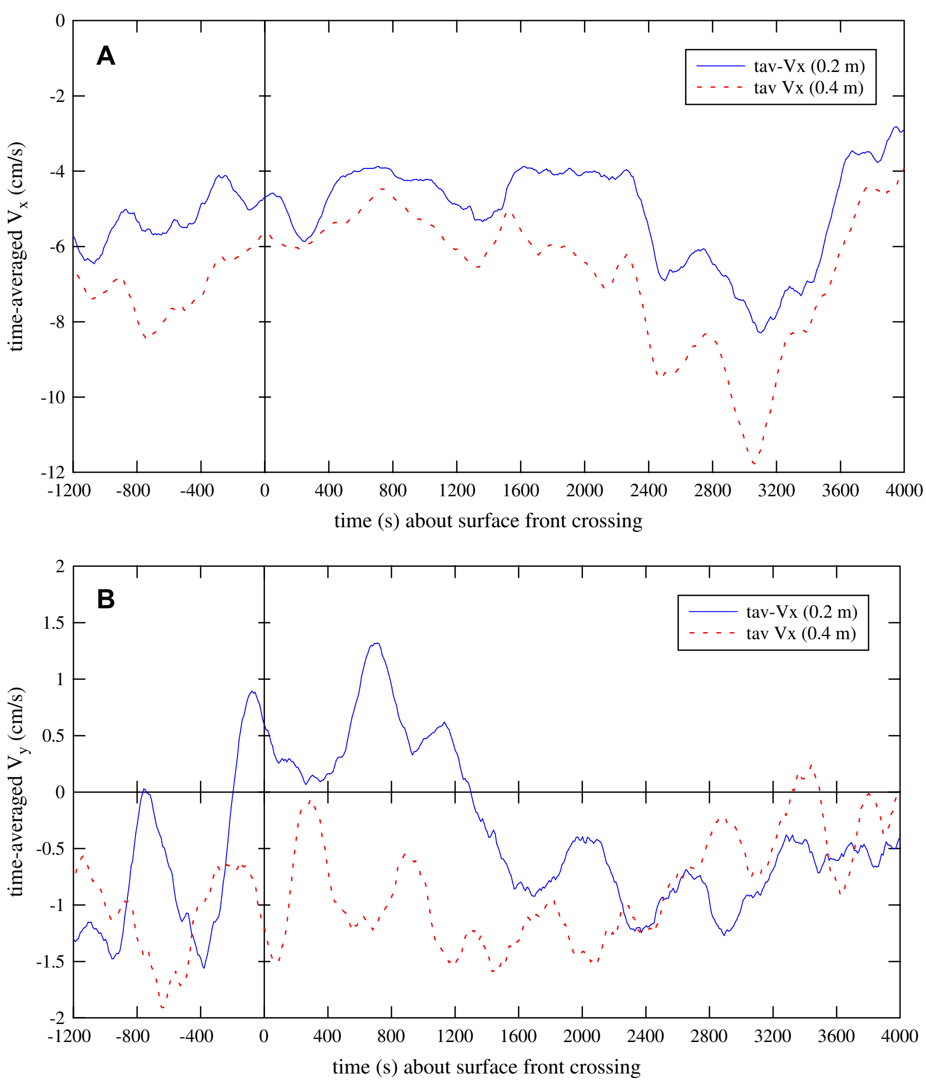

Fig. 4. Time-averaged velocity data collected during the front passage on 16 May 2005. Data at 0.2 m and 0.4 m above the bed were collected by the 2D microADV (16 MHz) and 3D ADV (10 MHz) systems, respectively, both located at 10.7 m from left bank. Legend: - - - - velocity data 0.2 m above the bed; ——— velocity data 0.4 m above the bed. (A) Time-averaged streamwise velocity $\overline{V_x}$. (B) Time-averaged transverse velocity $\overline{V_y}$.

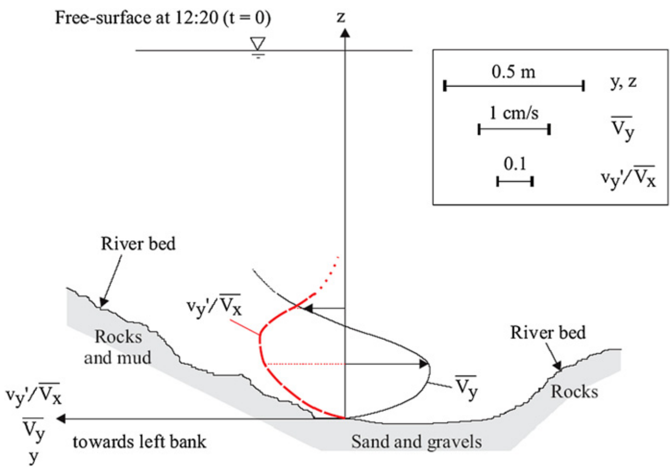

Fig. 5. Dimensioned sketch of the vertical profiles of transverse velocity $\overline{V_y}$ and turbulence intensity $v_y'/\overline{V_x}$ at the sampling site at 12:20 on 16 May 2005 (looking downstream).

some results. In Figs. 4–7, the time t is shown in seconds with $t = 0$ when the front leading edge was first observed reaching the experimental cross-section, i.e., 12:20 on 16 May 2005 (LW + 2 h 10 min). The passage of the front seemed to coincide with some anomaly in terms of the time-averaged velocity data (Fig. 4). Little effect of the front passage was observed in terms of the longitudinal velocity $\overline{V_x}$ (Fig. 4A), but the time-averaged transverse velocity $\overline{V_y}$ was affected by the passage of the front (Fig. 4B). Here V_x is positive downstream and V_y is positive towards the left bank. Between $t = -300$ and 1300 s, the transverse velocities $\overline{V_y}$ recorded at 0.2 and 0.4 m above the bed flowed in opposite directions, i.e., towards the left and right banks, respectively. This relatively long-duration anomaly was not observed during the rest of the field study. The results are summarised in the form of a dimensioned sketch (Fig. 5) showing the vertical profiles of transverse velocity $\overline{V_y}$ and of turbulence intensity $v_y'/\overline{V_x}$ at 12:20 ($t = 0$) next to the channel bed, where v_y' is the standard deviation of the transverse velocity. The present findings highlighted the occurrence of some secondary currents and strong transverse shear at the sampling location during the front passage. In the Conway Estuary (UK), Simpson and Turrell (1985) recorded transverse velocity profiles during a tidal intrusion front. They observed a secondary circulation cell linked with some axial convergence of the front, but they did not observe some transverse shear as shown in Fig. 4B and illustrated in Fig. 5.

The instantaneous suspended sediment data (recorded at 0.2 m above the bed) showed some increase in suspended sediment concentrations and SSC fluctuations (Fig. 6). Fig. 6A shows that the standard deviations of the SSC increased by about 50% between $t = -300$ s and $t = 1300$ s. The increase in SSC fluctuations might be linked with some enhanced transverse turbulent stresses sketched in Fig. 5. This is seen in Fig. 6B showing the time-averaged tangential stress $\rho v_x v_y$ during the passage of the transient front. The tangential stress $\rho v_x v_y$ is related to the transverse flux of the x-momentum, which induces an additional shear stress (i.e., the turbulent stress). The data (Fig. 6) showed an increase in the magnitude of tangential stress between about −300 s and +600 s, and the peak in both SSC and SSC fluctuations was closely linked with this maximum in turbulent stress.

The physio-chemical data suggested that the front migration had little effect on the water quality parameters, but on some water temperature reading. The physio-chemical data, which were collected by the YSI6600 probe located at 0.4 m above the bed next to the ADVs, showed no obvious influence of the front. Fig. 7 shows the water temperature data collected by the six LTS9000 probes and by the YSI6600 probe. Some effect on the water temperature was observed with one probe (sensor LTSB), which was located the closest to the water surface next to the main navigation channel (Fig. 2). The sensor was located 0.45 m below the free-surface at 12:20 on 16 May 2005. The temperature readings remained higher than all other probes for all the duration of the front passage (about 1 h). For the rest of the field work (44 h), this temperature sensor (LTSB) did not show any such marked difference with the other sensors.

4. Discussion

Tidal intrusion fronts are a relatively common feature in estuaries. Fronts like the one observed on 16 May 2005 are considered to be a natural process and some tidal intrusion fronts were documented (e.g. Neill et al., 2004; Thain et al., 2004). However, this was the first observation at the Eprapah Creek estuarine zone by the authors despite several earlier and subsequent field investigations. The front was observed once only during the first flood tide on 16 May 2005. It was not seen for the next 3 days.

Previous studies distinguished between buoyancy-driven and non-buoyant fronts (Wolanski and Hamner, 1988; Simpson, 1997). In the present study, measured vertical profiles of water conductivity on 17 May 2005 showed that the estuary was partially stratified during the ebb tide. Some measurements are shown in Fig. 8 at 1 km and 2 km upstream of the river mouth. These two longitudinal locations are highlighted in Fig. 1. At 2 km upstream of the river mouth, next to the sampling site, the conductivity data showed a 1.5 m thick layer of brackish waters above denser saltwaters (Fig. 8B). The estimated density difference was about 2.6 kg/m^3, and the total water depth was about 3.2 m. For such characteristics, the observed front propagation speed would yield a Froude number $U/\sqrt{g' \times h} \sim 0.8$ to 1 where g' is the reduced gravity constant. The result would be consistent with the average speed of gravity current with some mixing (e.g. Simpson, 1997). It is, however, possible that the front was caused by the interactions between the tidal forcing and some creek topographic features, namely the sharp river bends. Fig. 1B presents three surveyed cross-sections illustrating the gradual reduction in channel cross-section with increasing distance from the river mouth. In the present study, the sampling site was located after three sharp bends located at about 1.1 km, 1.6 km and 2 km from

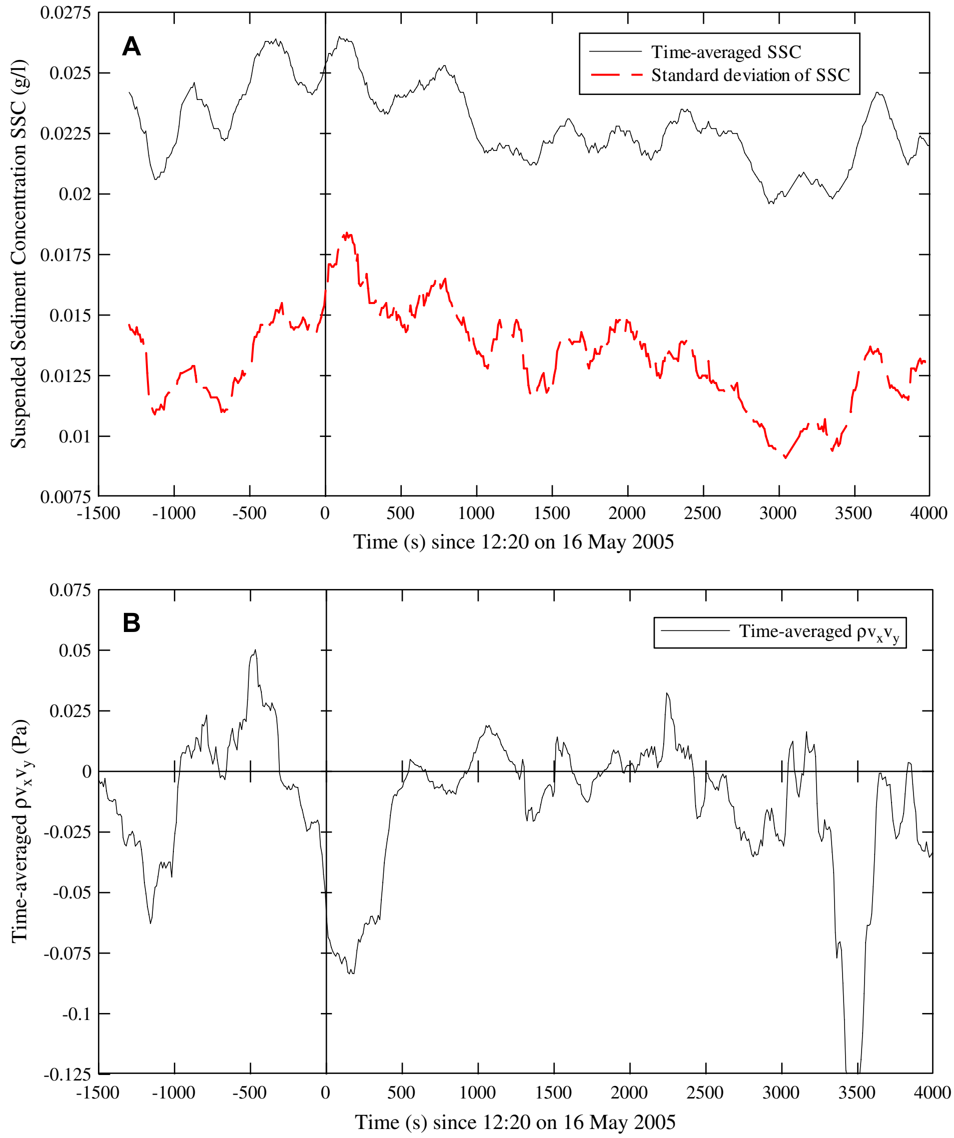

Fig. 6. Suspended sediment concentration, and tangential stress $\rho v_x v_y$ during the front passage on 16 May 2005. Data at 0.2 m above the bed were collected by the 2D microADV (16 MHz) system located at 10.7 m from left bank. Time averages and standard deviations were calculated for 5000 data points every 10 s. (A) Time-averaged and standard deviation of the suspended sediment concentration. (B) Time-averaged turbulent stress $\rho v_x v_y$.

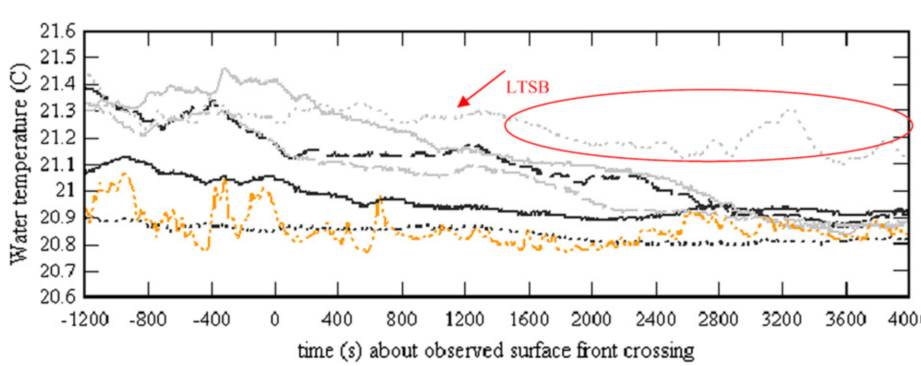

Fig. 7. Water temperature data collected at Site 2B, Eprapah Creek on 16 May 2005 around the passage of the front. Data were collected using six LTS9000 probes sampled every 6 s and YSI6600 probe sampled every 12 s with $t = 0$ when leading edge of front reached the cross-section. Legend: ——— LTS1 probe; —— —— LTS2 probe; — — — YSI6600 probe; - - - - LTS4 probe; ——— LTS5 probe; —— —— LTSA probe; - - - - LTSB probe.

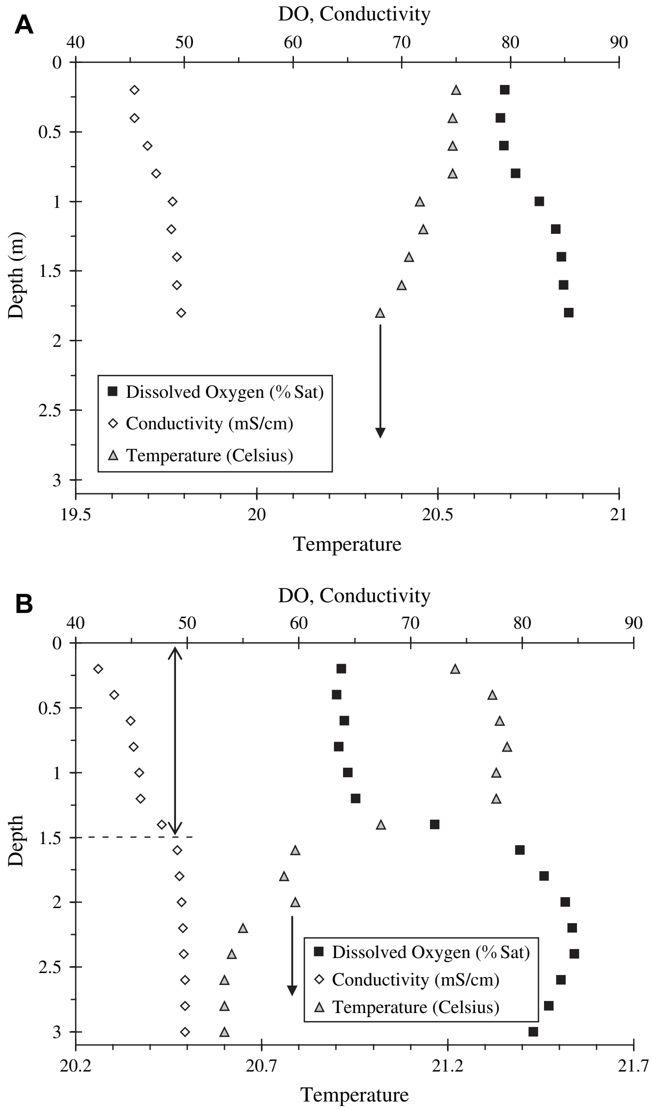

Fig. 8. Measured vertical profiles of water temperature, conductivity and dissolved oxygen on 17 May 2005 between 8:00 and 9:00 (mid-ebb tide). (A) At 1 km upstream of the river mouth. (B) At 2 km upstream of the river mouth (immediately downstream of the sampling station).

the mouth (Fig. 1A). In the sharp river bends, some separation was typically observed next to the inner bank, while some outer secondary cells were seen (Rozovskii, 1957; Blanckaert and Graf, 2001). Separation and recirculation cells were documented at Eprapah Creek and they were seen as feeding grounds of fish and birds (Ferris et al., 2004). These recirculation regions at and downstream of the channel bends may have played a major role in concentrating buoyant particles on 16 May 2005, and the debris were subsequently advected upstream by the flood tide.

The conductivity and temperature data recorded on 16 May 2006 showed no detectable transverse gradient in water conductivity or temperature during the transient front. Although the front leading edge had a V-shape, the measurements suggested no active axial convergence induced by transverse density gradient at the sampling site (e.g. Lewis, 1997).

5. Conclusion

During a series of detailed experiments in a small subtropical estuary, a transient front was observed under neap tide conditions, and the turbulent velocities and physio-chemistry were sampled continuously at high-frequency during the entire front passage. The passage of this front seemed to have some effect on the transverse velocity with some opposite transverse velocity directions at 0.2 m and 0.4 m. This secondary current pattern (Fig. 5) was observed from 300 s prior to the front leading edge reaching the sampling site up to 1300 s after. The suspended sediment concentration next to the bed showed high levels of fluctuations during the same period. Additionally, some water temperature anomaly was noted below the surface. Other effects were not noticeable despite the continuous high-resolution sampling.

Acknowledgments

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