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A NOTE ON BURST EVENT DETECTION IN UNSTEADY NATURAL FLOWS

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Abstract

Turbulent bursting events play a major role in natural systems in terms of sediment scour, transport and accretion as well as contaminant mixing and dispersion. The "bursts" were extensively studied in laboratory experiments under steady flow conditions, but rarely tested in unsteady natural flows. Herein a technique is described for the detection and analysis of turbulent events within large continuous data sets collected in unsteady natural flows, in particular natural estuaries. This study highlights and addresses several key issues related to burst event analysis in unsteady flows. These issues include the selection of individual sample size and event threshold value, the effect of flow reversal, and a comparison of individual samples over the entire data set. Some initial findings are presented as part of a broader investigation aimed to optimise the turbulent burst event detection technique for unsteady geophysical flows.

Key Words : Turbulence, Burst events, Unsteady geophysical flows, Field measurements

1. INTRODUCTION

While the fluctuating turbulent properties are often represented by the statistical moments, the turbulence is not a Gaussian process particularly in Nature. Many conceptual frameworks and theories are based upon assumptions of quasi-steady state equilibrium, but any turbulent flow is often dominated by coherent structure activities and turbulent events. A turbulent event may be defined as a series of turbulent fluctuations that contain more energy than the average turbulent fluctuations within a studied data section. These turbulent events are often associated with coherent flow structures such as eddies and bursting (e.g. Kline et al., 1967; Rao et al., 1971), and they play a major role in terms of sediment scour, transport and accretion as well as contaminant mixing and dispersion (e.g. Nezu and Nakagawa 1993). Bursting is the quasi-cyclic turbulent energy production in turbulent boundary layers first identified by Kline et al. (1967). There have been many progresses in their physical description in laboratory and in the field. Turbulent event analyses were successfully applied to laboratory open channel flows (e.g. Nakagawa and Nezu, 1981), wind tunnel studies (e.g. Lu and Willmarth, 1973) and atmospheric boundary layer flows (e.g. Narasimha et al. 2007). These were however rarely applied to unsteady open channel and geophysical flows.

Early turbulent event analysis studies conducted in unsteady geophysical flows (e.g. Heathershaw, 1974) collected individual short duration samples at various stages of the tidal cycle. These studies concentrated on analysis of burst events within individual samples and tended not to directly compare the individual samples over the tidal cycle. These individual samples tended to be analysed manually to find burst events using the techniques available at the time (e.g. quadrant analysis). A few later studies (e.g. French and Clifford, 1992) compared event analysis of individual samples collected over a tidal cycle to investigate variations in turbulent event structure. However, many early studies were limited by the poor instrumentation spatial and temporal resolution and data storage availability.

Recent advances in field instrumentation such as the acoustic Doppler velocimeter (ADV) allowed the collection of continuous high frequency turbulence data over several tidal cycles (e.g. Trevethan et al., 2008). However, the analysis of burst events cannot be performed manually on such large data sets collected over several tidal cycles. Trevethan and Chanson (2009) adapted and extended the technique of Narashima et al. (2007) to search automatically these large data sets for burst events and to provide some information on each individual bursting event. During the implementation and application of this burst event detection technique to a range of field data sets, Trevethan and Chanson encountered several issues (e.g. change in flow direction) that could conceivably affect the outcome of event analysis in natural unsteady flows. The aim of the present study is to highlight and address some key issues associated with burst event detection on continuous high frequency data collected over relatively long periods (e.g. 12 to 50 hours) in natural unsteady flows (e.g. estuaries, tidal channels).

2. FIELD STUDIES AND DATA PROCESSING

Herein several different field data sets were re-analysed to highlight the main issues involved in burst event detection in unsteady geophysical flows (Table 1). These field studies were collected at different sampling sites,under different flow conditions, with different instruments (Nortek and Sontek ADVs), and different sampling frequencies to provide a broad range of field variables to test the burst detection technique. The field study E5 and E10 were conducted mid-estuary at Eprapah Creek, a small subtropical estuary located on the Southeast coast of Australia (e.g. Trevethan et al., 2008). Alternatively, the field study JB1A was conducted in the relatively deep entrance channel of Jade Bay located on the Northwest coast of Germany.

Field Site	**Eprapah Creek (Australia)**		**Jade Bay (Germany)**
Study	**E5**	**E10**	**JB1A**
Date	03/2005	06/2007	04/2008
Duration (hrs)	25	50	16
Location	Mid-estuary	Mid-estuary	Entrance channel
Mean depth (m)	1.6	1.6	19.0
Tidal range (m)	2.5	1.6	4.5
Max. Velocity (m/s)	0.4	0.2	1.0
Instrument	Sontek 3D-ADV (1)	Sontek microADV (3)	Nortek Vector ADV (3)
f_{scan} (Hz)	25	50	32
Sampling elevation (m)	0.1	0.13, 0.38, 0.38	0.28, 1.36, 2.38

Table 1 - Information for field studies presented in this investigation

A thorough post-processing procedure was applied to the collected ADV data (Chanson et al., 2008b). This post-processing is essential to ensure the quality of the data set. Corrupted data are inherent to the ADV metrology. They are predominantly caused by poor signal quality (low correlation and low signal to noise ratio) and Doppler noise within the measured signal. All turbulence data measured with an ADV underwent three stages of post-processing before any turbulence analysis and burst event detection was undertaken (Chanson et al., 2008b). In the first stage the ADV data was read from the binary file and data points with low-correlation (< 60 %), low signal to noise ratio (< 5 dB) or communication errors were replaced. The second stage searched for possible large disturbances (e.g. navigation near probe, adjustments of probe) that may have occurred during a field study. Finally the phase-space thresholding method (Goring and Nikora, 2002) was used to find small disturbances generated by "spike" events and Doppler noise. All data points determined to be erroneous (corrupted) during each of the post-processing stages were replaced using the mean of the endpoints about the erroneous data. Each post-processed data set included three instantaneous velocity components V_x, V_y and V_z, and backscatter intensity I_b (e.g. Chanson et al. 2008a), 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). The turbulent fluctuations were defined as: $v = V - \overline{V}$ and $i_b = I_b - \overline{I_b}$, where V was the instantaneous (measured) velocity component; $\overline{V}$ was the variable-interval time average (VITA) velocity and $\overline{I_b}$ is the VITA backscatter intensity.

3. BURST EVENT DETECTION TECHNIQUE

Trevethan and Chanson (2009) proposed a method for the detection of turbulent bursting events based upon the technique of Narasimha et al. (2007) that was adapted and extended. While the method differs from the more traditional event detection techniques (e.g. Johansson and Alfredsson, 1982), it was found to be a robust method that is well-suited to the study of the unsteady geophysical flows (Narasimha et al., 2007, Trevethan and Chanson, 2009). A turbulent event is basically defined as a series of turbulent fluctuations that contain more energy than the average turbulent fluctuations within a studied data section. The method detects a bursting event within a data section by comparing the absolute value of an instantaneous turbulent flux q (e.g. $q = v_x v_z$) with the standard deviation q' of that flux over the data section. The turbulent event occurs if:

$$|q| > k\, q' \qquad (1)$$

where $|q|$ is the absolute value of the instantaneous flux q, k is a positive constant setting the threshold and q' is the standard deviation of the quantity q over the data section. Narasimha et al. (2007) conducted a sensitivity analysis on the positive multiplier threshold (k). Using data from three different sites, they showed that the total contribution from the events to the total flux remained roughly constant and stays close to 100% for threshold values $k \le 1$. The threshold value leading to the identification of the smallest number of events that account for all the flux yielded k = 1. Trevethan and Chanson (2009) also used k = 1 to facilitate a comparison between estuarine and atmospheric (e.g. Narasimha et al., 2007) boundary layer data. A threshold value of k = 1 is also used throughout this study, although a sensitivity analysis on the impact of k on the burst detection and statistics is presented in Section 4.2.

For a data section, the informations of each detected event regroup the event start/finish times, duration τ, dimensionless flux amplitude A and relative magnitude m. The event properties are used to compare individual turbulent events within a data set and between synchronised data sets collected simultaneously. Figure 1 introduces the definition of the duration and amplitude of an isolated event. The duration τ of the event is the time interval between the "zeroes" in momentum flux (e.g. $q = v_x v_z$) nearest to the sequence of data points satisfying Equation (1). Practically the event duration is calculated from the first data point with the same sign as the event to the first data point after the change in sign in momentum flux. The present method provides an accurate estimate of the event duration τ within the limitations of the sampling frequency. The dimensionless amplitude A of an event is the ratio of the averaged flux amplitude during the event to the long-term mean flux of the entire data section:

$$A = \frac{1}{\bar{q}} \int_{\tau} q \frac{dt}{\tau} \qquad (2)$$

where $\bar{q}$ is the averaged value of q over the data section and $dt = 1/f_{scan}$ (e.g. f_{scan} = 25 Hz). Trevethan and Chanson (2009) found some limitations of Equation (2) in unsteady geophysical flows, which Equation (2) cannot correctly represent the detected flux under certain conditions. Section 4 proposes some modifications to Equation (2) for application to continuous data sets collected in unsteady geophysical flows. The relative contribution of an event to the total momentum flux of the data section is called the relative magnitude m defined as:

$$m = \frac{A\, \tau}{T} \qquad (3)$$

where T is the total duration of the data section (T = 200 s herein, see Section 4.1). Trevethan and Chanson (2009) applied this technique to the momentum fluxes $v_x v_y$ and $v_x v_z$, and to the "pseudo" suspended sediment flux $v_x i_b$, where i_b is the instantaneous fluctuation in the ADV backscatter intensity. The same technique may also be applied to any flux of interest (e.g. $v_x v_x$).

The turbulent event properties may be presented as a time series of the dimensionless flux amplitude. Such a presentation shows the duration and dimensionless amplitude of each event in a simplified format (e.g. Fig. 2). Figure 2 presents the dimensionless event amplitude of $v_x v_z$ from some data collected during the field study JB1A (Table 1) at three vertical elevations, respectively 0.28 m, 1.36 m and 2.38 m above the bed. Figure 2 illustrates that the time series includes both positive and negative amplitude events, each event corresponding to a rectangular pulse. The pulse width is the duration τ and the height is the amplitude A, while the area beneath is proportional to the event magnitude m. One benefit of this presentation is the ease to compare the different fluxes (e.g. $v_x v_z$ and $v_x v_y$) and flux data sets collected at the same time. For example, the progression of a detected burst event through the ADV sampling volumes at 0.28 m and 1.36 m above the bed is highlighted in Figure 2.

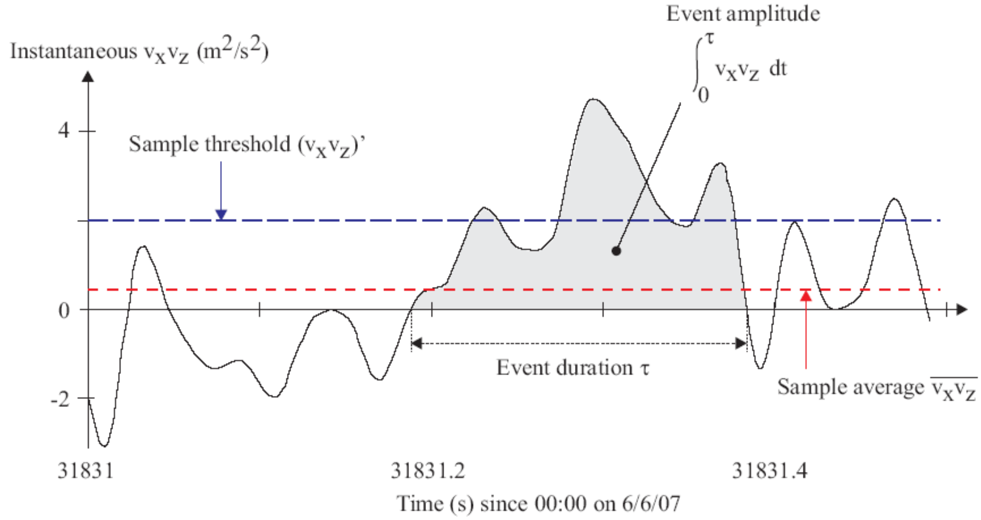


Fig 1. Definition sketch of flux event and event parameters.

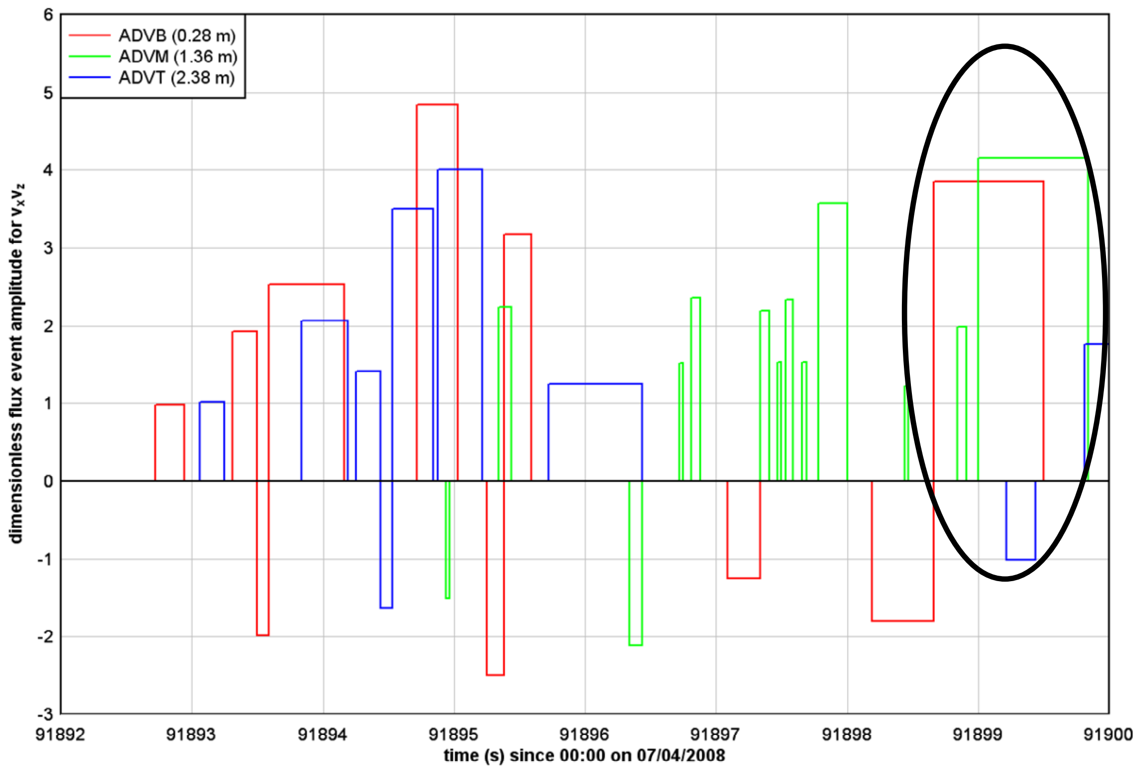
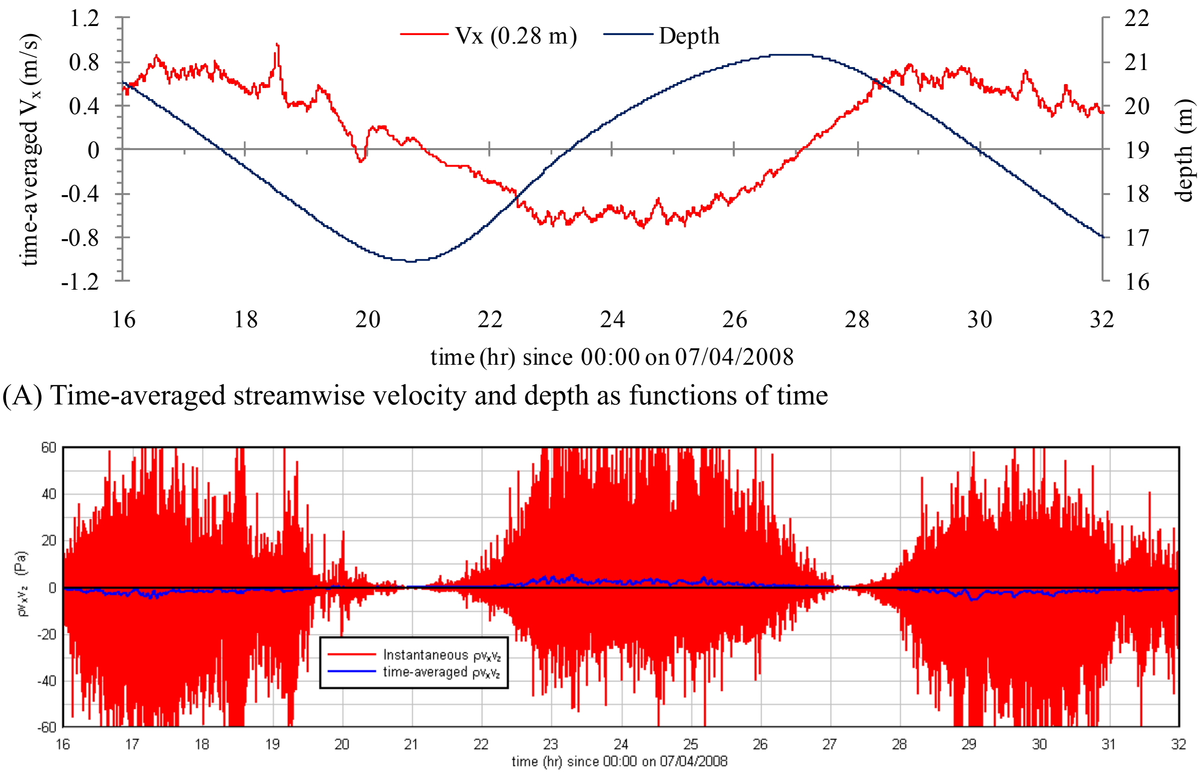


Fig 2. Example of dimensionless amplitude of detected turbulent events as functions of time. Data collected during study JB1A (Jade Bay, Germany) by 3 Nortek ADV units located at 0.28 m, 1.36 m and 2.38 m above bed

4. BURST EVENT DETECTION IN NATURAL UNSTEADY FLOWS

In estuaries and tidal channels the flow is unsteady with the flow direction changing over the tidal cycle as illustrated in Figure 3A. Figure 3 shows the time-variations of water depth, streamwise velocity and tangential Reynolds stress $\rho v_x v_z$ collected at 0.28 m above the bed for the field study JB1A. In Figure 3, the streamwise velocity is positive during the ebb tide and negative during the flood tide. Close to the bed in unsteady geophysical flows the time-averaged tangential Reynolds stress $\rho v_x v_z$ varies with an inverse relationship to the time-averaged streamwise velocity (Trevethan, 2008). This inverse relationship between $\rho v_x v_z$ and V_x can have a significant effect on burst event analysis, including the quadrant analysis. For example, in Figure 3B, the magnitude of fluctuations in

$\rho v_x v_z$ varies directly with the streamwise velocity magnitude, and a sample collected at slack water (e.g. t = 21 hr; Figure 3B) can hardly be compared to a data sample collected during the mid flood (e.g. t = 24 hr) or ebb (e.g. t = 30 hr) tides. Trevethan and Chanson (2009) highlighted that a comparison between samples collected during flood and ebb tides may be difficult because of the change in flow direction. This section highlights some key issues associated with the burst analysis in unsteady natural flows data sets collected continuously over at least a tidal cycle.



(A) Time-averaged streamwise velocity and depth as functions of time

(B) Instantaneous and time-averaged Reynolds stress as functions of time

Fig 3. Depth, streamwise velocity and tangential Reynolds stress $\rho v_x v_z$ as functions of time. Data collected at 0.28 m above bed in Jade Bay entrance channel (study JB1A)

4.1 Sample size

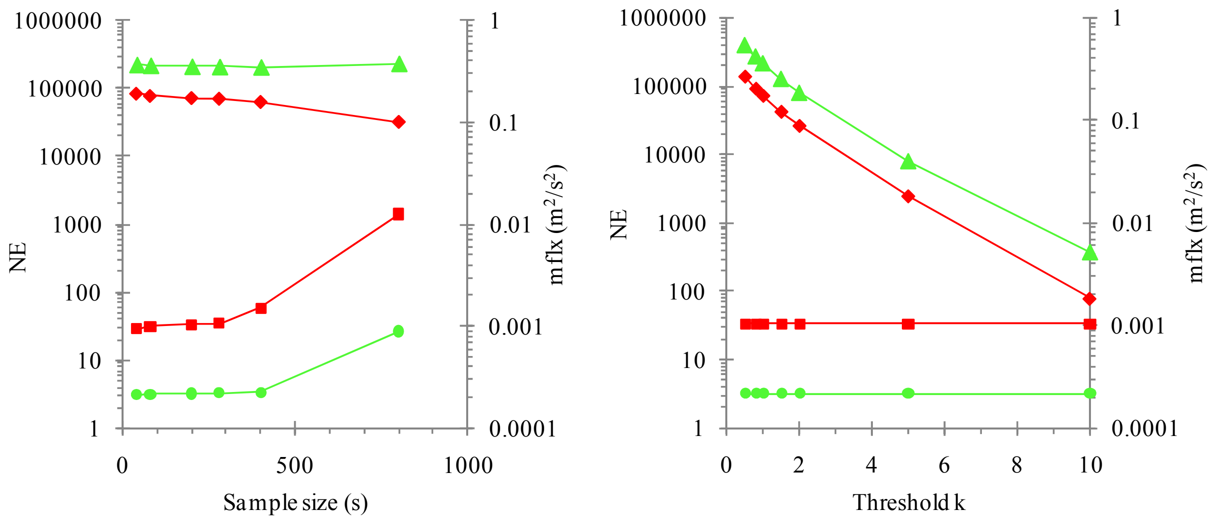
In unsteady geophysical flows such as estuaries, the selection of the sample period for the study of turbulence properties is critical because the flow is unsteady and gradually time-variable. The sample size for the calculation of the time-averaged velocity ($\overline{V}$) effectively acts as a low-pass filter threshold. The cut-off frequency affects the calculation of the turbulent velocity fluctuations v ($v = V - \overline{V}$) for a given data set, where V is the instantaneous velocity. The sample size must be selected to yield statistically meaningful results, and; it must be much larger than the relevant turbulent time scales and yet significantly smaller than the variation of the tides. Trevethan (2008) found that a sample size of approximately 200 s (e.g. 5,000 data points at 25 Hz) allowed approximately 99 % of all data samples from the field studies conducted at Eprapah Creek (e.g. study E5) to be statistically stationary. A related sensitivity analysis of other data sets collected in different natural unsteady flows (e.g. Jade Bay) showed a sample size of approximately 200 s to be close to optimum over a broad range of unsteady geophysical flows. It is however relevant to ask: does the sample size chosen for the technique outlined in Section 3 affect the number of events detected and the statistical properties of those detected events?

Herein a sensitivity analysis was undertaken to test the influence of the individual sample size on the outcome of the burst event analysis. Note that a constant event threshold of k = 1 was used with only the sample size being varied. The main findings are presented in Figure 4A. Figure 4 shows the affect of sample size and event threshold (k) on the number of events detected and the median flux amplitude (mflx) over the entire data set of studies E5 and JB1A. In Figure 4A, a sample size between 40 and 280 s seemed to have little effect on the number of detected events and on the median flux amplitude for studies E5 and JB1A. Some differences in terms of number of detected events and detected and median flux amplitude were observed for sample sizes greater than 400 s (Fig. 4A). Of interest, the variation of sample size had no significant influence of the probability distribution functions of turbulent event statistics (event duration and dimensionless amplitude). Therefore an individual sample size of approximately 200 s is recommended for the analysis in unsteady natural flows, including both turbulence statistics and bursting event properties.

4.2 Burst event detection threshold (k)

The event threshold (k) is used in the burst event detection technique (Equation (1)). Its selection is critical for the estimate of the magnitude and type of detected events. It is roughly "equivalent" to the "hole" threshold H used in a quadrant analysis (e.g. Lu and Willmarth, 1973; Heathershaw, 1974). Previous investigation on the effect of the variation of threshold H found that, as H increased, the number of events and their fractional contribution to the total time and stress decreased (e.g. French and Clifford, 1992). Lu and Willmarth (1973) noted some asymmetry between ejections and sweeps versus inward and outward interactions, and that the inward and outward interactions are attenuated more rapidly than ejections and sweeps with increasing threshold values.

Herein a sensitivity analysis was undertaken to determine the influence of the event threshold k on the outcome of the burst event analysis, with the main findings presented in Figure 4B. Note for the event threshold sensitivity analysis a constant sample size of 200 s was used, with only the value of k being varied. Figure 4B shows that the variation of k had little effect on the median flux amplitude of the data sets, but the variations in threshold k caused some significant change in the number of detected events. In Figure 4B, the number of events detected for $k < 2$ were of the same order of magnitude in both data sets, while for threshold values $k > 2$ there was a rapid decrease in the number of events detected. The threshold k had also a significant impact on the probability distribution functions of the detected event statistics (i.e. event duration and dimensionless amplitude), with both duration and dimensionless amplitude of the detected events increasing with k. Therefore it would seem that the choice of the value of threshold k is somewhat dependent of the investigated flux (e.g. influence of large events (bursts and sweeps) on sediment transport). In this study a threshold value of $k = 1$ was used for consistency with the earlier study of Trevethan and Chanson (2009).



(A) Sample size (B) Event threshold (k)

Fig 4. Effect of sample size and event threshold (k) on number of events detected (NE) and median flux amplitude of data set (mflx)

Legend: ♦ NE-JB1A; ■ mflx-JB1A; ● mflx-E5; ▲ NE-E5

4.3 Comparison of individual samples over large continuous data set

The original burst event detection technique proposed by Narasimha et al. (2007) was designed to find and compare burst events within some individual data sections. The application of the burst event analysis to large continuous data sets does not allow for a simple comparison of individual events detected in different data sections. A more robust technique is used herein by normalising the flux magnitude of each data section. This is achieved by dividing the median value of the flux magnitude of an individual data section by the median flux magnitude of the entire data set. Then each of the dimensionless event amplitudes is multiplied by this factor (e.g. Equation (4)) yielding a dimensionless event amplitude within the individual data sections relative to that of the entire data set:

$$\text{relative } A_i = A_i * \left(\overline{|q|}_{\text{data section}} \Big/ \overline{|q|}_{\text{data set}} \right) \qquad (4)$$

where $\overline{|q|}$ = median value of the flux (q) magnitude over defined sample size (e.g. data set).

4.4 Calculation of dimensionless event amplitude in unsteady flows

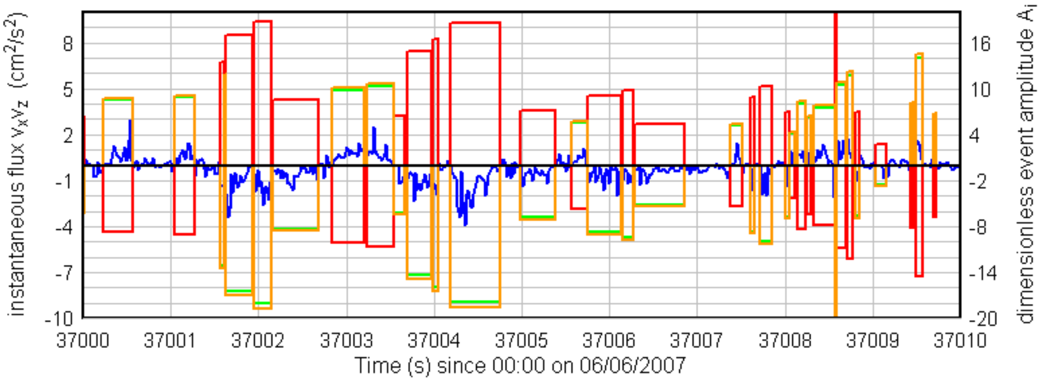
Trevethan and Chanson (2009) found that, in a small estuary, the flow direction changed several times during a complete tidal cycle as well as the sign of time-averaged fluxes. Furthermore, during some individual data sections (T = 200 s), the time-averaged flux term ($\bar{q}$) might be very small close to zero, yielding some meaningless physical interpretation of the amplitude sign. In other words, the interpretation of Equation (2) has some limitations in unsteady geophysical flows. Herein Equation (2) is compared to two alternative methods for the estimate of dimensionless event amplitude (A_i; Equations (5) and (6)). Equation (5) was first presented in Trevethan and Chanson (2009), while Equation (6) is another alternative investigated herein:

$$A_i = \frac{1}{\overline{|q|}} \int_{\tau_i} q \frac{dt}{\tau_i} \qquad (5)$$

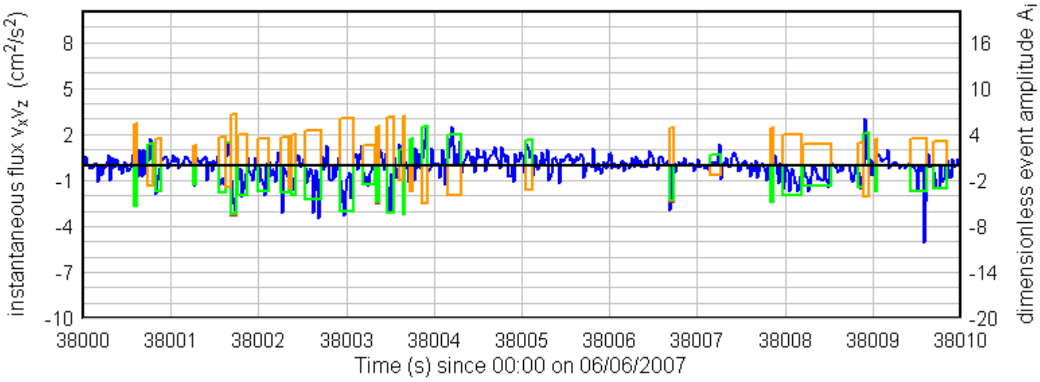
$$A_i = \frac{\text{sign}V_x}{\bar{q}} \int_{\tau_i} q \frac{dt}{\tau_i} \qquad (6)$$

where q = flux under investigation (e.g. $v_x v_z$) and $\text{sign}V_x$ = is averaged sign of streamwise velocity over that data section.

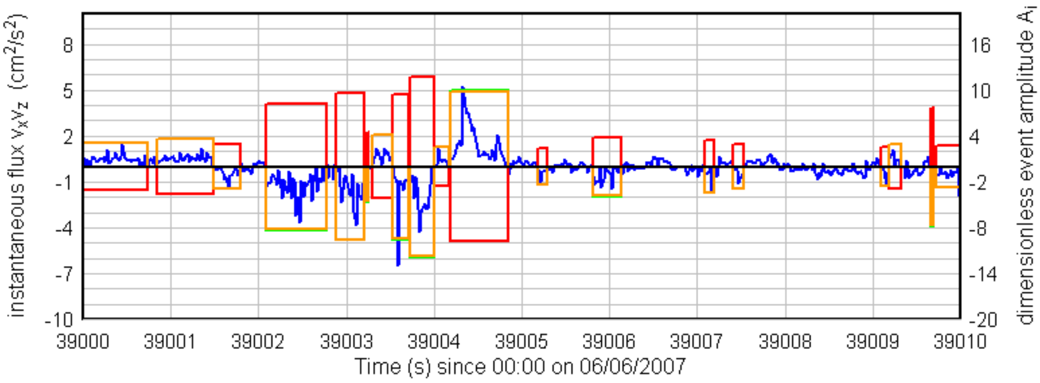
Each method was tested on three 200 s samples collected at the beginning of the field study E10, each during the flood tide (Figure 5). Figure 5 shows the instantaneous flux $v_x v_z$ and the dimensionless event amplitude from each method as functions of time for 10 s of each sample. In Figure 5, Equation (5) produced consistently some correct dimensionless amplitudes that represented the events found (i.e. same event amplitude sign), while the results from Equations (2) and (6) did not provide some consistent results over the three examples nor over the entire data set. Equation (6) introduced some influence of the streamwise velocity direction into the calculation of the dimensionless event amplitude suggesting that the sign of the data section flux rather than the sign of the data section streamwise velocity has the most important influence on the calculation of dimensionless event amplitude. Further testing over several different data sets collected in different estuaries (e.g. Jade Bay) showed that Equation (5) provided a more correct representation (e.g. sign of the event) of the burst events than Equations (2) and (6). Equation (5) gives a correct and consistent dimensionless event amplitude representation for all fluxes studied (e.g. $v_x v_y$) and different definitions of the fluxes (e.g. q = $v_x v_z$ or q = signVx* $v_x v_z$) used in burst event studies for unsteady and/or reversible flows (see Section 4.5). It is recommended therefore that Equation (5) be used to calculate the dimensionless event amplitude, independently of the flux definition used in both steady and unsteady flow conditions.



(A) Data section 1, here A_i calculated by Equations 5 and 6 match event amplitudes



(B) Data section 2, here A_i calculated by Equations 5 and 2 match event amplitudes



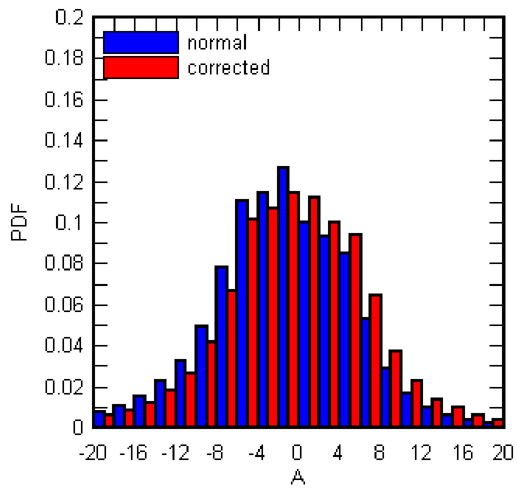
(C) Data section 3, here A_i calculated by Equations 5 and 6 match event amplitudes

Fig 5. Instantaneous flux v_xv_z and dimensionless event amplitude as functions of time. Data collected at 0.38 m above bed during study E10 at Eprapah Creek.

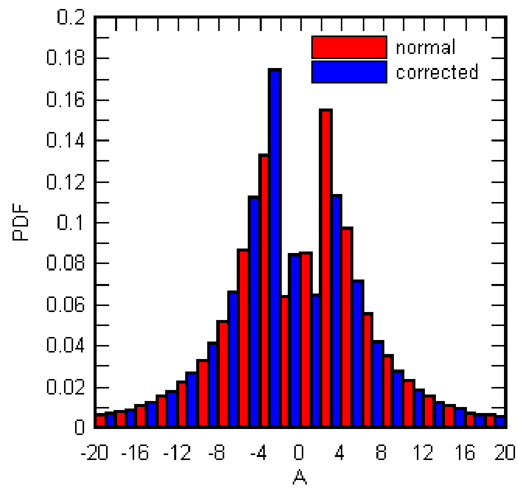
Legend: — flux v_xv_z ; — A_i by Equation 2; — A_i by Equation 5; — A_i by Equation 6

4.5 Reversal of flow direction

The reversal of flow direction in natural unsteady flows could conceivably affect the definition of individual events within quadrant analysis when the time-averaged streamwise velocity is negative (e.g. flood tide). French and Clifford (1992) applied a "sign correction" for the tidal phase to ensure that the time-averaged velocity is always positive as during previous results obtained in laboratory (e.g. Lu and Willmarth, 1973). Such an approach is relatively simple on some individual data samples collected sporadically over a tidal cycle, but become inappropriate for a data set collected continuously over a relatively long period (i.e. 12 to 50 hours). Herein a method for "correcting" the streamwise velocity component for flow reversal is demonstrated, involving the multiplication of the instantaneous flux of a sample by the averaged streamwise velocity sign of that sample (e.g. $q = \text{sign}V_x \; v_x v_z$). Figure 6 presents a comparison of the probability distribution functions of the dimensionless event amplitude for the unadjusted flux data (e.g. $q = v_x v_z$) with the corrected flux data (e.g. $q = \text{sign}V_x \; v_x v_z$) for the studies E5 and JB1A. In Figure 6, the corrected data shows a more negatively skewed distribution, indicting an increased number of negative events observed after the data correction. Further investigation is however required to determine if the output from this method truly represents the burst events.



(A) Study JB1AB



(B) Study E5

Fig 6. Probability distribution functions of dimensionless event amplitude A. before and after correction for flow reversal effects using $q = \text{sign}V_x \; v_x v_z$

Another possible method for the velocity sign correction presently under investigation is the adjustment of the streamwise velocity component through a filtering process before the instantaneous flux is calculated. In this method, the filtering is applied to separate the low and high frequency components of the data (e.g. cut-off frequency of 200 s herein), after which the high frequency component is added to the absolute value of the low frequency part. This method also produced a more negatively skewed distribution of A, vut the distribution seemed to vary slightly from that provided by the $\text{sign}V_x$ correction method shown above. Simply the investigation to determine the best method for velocity sign correction in unsteady natural flows remains on-going. Note that the same sign correction would have to be applied to the transverse velocity V_y.

5. CONCLUSIONS

A technique for the detection of turbulent burst events in unsteady estuarine flows was presented. This study outlined several key issues that must be addressed in any burst event analysis on long duration data sets collected continuously in unsteady geophysical flows. The key issues include:

- The selection of the size of the individual data sections. It is recommended a sample size of approximately 200 s for unsteady geophysical flows such as estuaries and tidal channels.
- The selection of the turbulent event threshold k (Equation (1)). The threshold value k had a significant effect on the number of events detected and the event duration and dimensionless amplitude.
- The effects of flow reversal and velocity magnitude must be taken into account when applying burst event analysis. For the burst event detection technique outline here, the unsteady flow conditions affected the calculation of the dimensionless event amplitude and the comparison of events detected in individual data samples over the entire study.

This work is on-going and it is believed that the outlined technique is a promising method well-suited to the study of burst events in a number of unsteady geophysical flows. To date the study of turbulent events in natural geophysical flows has been limited and a number of fundamental issues must be properly addressed before the behaviour of burst events in unsteady flows can be fully understood.

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