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Cluster dispersion of low Cost GPS-Tracked Drifters in a Shallow Water

Kabir Suara[1,*, a], Tim Ketterer[1,b], Helen Fairweather[2,c], Adrian McCallum[2,d],
Sh. M. Vanaki[1,e] Chris Allan[3,f] and Richard Brown[1,g]

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

[2] Environmental Engineering School, University of the Sunshine Coast, Sippy Downs, Australia

[3] Sunshine Coast Council, Caloundra, Australia

[a]k.suara@qut.edu.au, [b] timkett24@gmail.com, [c]hfairwea@usc.edu.au, [d]amccallu@usc.edu.au,
[e]s.mokhtarpourvanaki@qut.edu.au [f]Chris.Allan@sunshinecoast.qld.gov.au,
[g]richard.brown@qut.edu.au

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Abstract. Managing the inlet of an Intermittently Closed and Open Lake or Lagoon (ICOLL) adjacent to urban areas is important because of risk of flooding and need to maintain the natural habitat. However, the opening and closing processes can result in an unstable system dynamics. This work investigates the dynamics of an ICOLL using clusters of low cost global positioning system drifters during a neap tide under an open inlet condition. Cluster analysis was applied to estimate the dispersion coefficients and the differential kinematic properties (DKP) of the channel. The lateral dispersion coefficient varied with the tidal phase with a flood tide mean value of 0.42 m^2/s. Mean DKP values are in the order of 10^{-4} s^{-1}. Results show that dispersion in the channel during an open inlet condition is dominated by the strain field resulting in convergence and divergence of surface layers. Regions of enhanced mixing likely associated with resonance were also identified. This study provides baseline information upon which to further examine the effect of conditions at the river mouth on the dynamics and particle transport in the main channel.

Introduction

Measuring the transport, spreading and mixing of passive particles have wide practical application for environmental flow monitoring. Lagrangian field data in tidal shallow waters are rare but valuable for understanding the spatio-temporal flow structure water quality, validation of hydrodynamic and numerical models, and development of advection-diffusion models. Cluster analysis applied to drifters has proven useful in identifying dominant factors responsible for the horizontal transport of particles in large water bodies [1, 2]. The present research focusses on the use of cluster analysis of flocks of drifters to understand the dynamics of Currimundi Lake under different environmental conditions.

Field, drifter and experimental descriptions

Currimundi Lake (Longitude 153.13° East, Latitude 26.763° South) is a coastal lagoon located on Queensland's Sunshine Coast in Eastern Australia (Figure 1). The main channel is connected to the ocean and is therefore tidal. The channel is also connected to constructed fresh water body, known as Lake Kawana. Other connecting branches discharge storm water runoff into the main channel. Therefore, the main channel is an estuary where mixing processes play a significant role. The water quality and dynamics of the channel is unsteady. The system is also considered an Intermittently Closed and Open Lake or Lagoon (ICOLL). It is sometimes artificially disconnected from the ocean by blocking the river mouth to raise the water level to manage biting midge population by drowning midge larvae in the sand banks. The main catchment area management concerns include but are not limited to: obtaining spatio-temporal velocity, physiochemical properties, and sediment and particle transport distributions under various baseline conditions in order to predict the response of the system to extreme conditions.

Three different drifter experiments were carried out along the main channel under tidal, non-tidal and during the opening of the river mouth. This paper focuses on developing the cluster analysis approach to examine the effect of the tidal inlet condition on the dynamics of the channel. Results are limited to the baseline experiment (open river mouth) carried out over a neap tide with a 0.6 m tidal range.

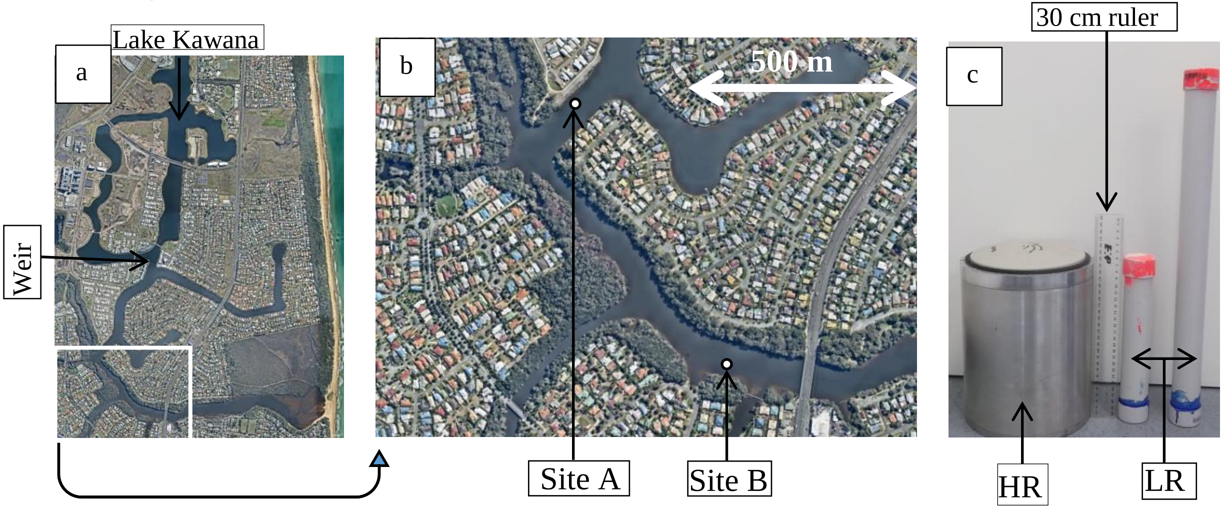

Fig. 1 (a) Aerial view of Currimundi Lake catchment (Nearmap, 2015); (b) Exploded view of the main channel (The insert box in (a)); (c) Picture of high and low resolution drifters

The drifters used in this study are similar in shape and design but different in dimension and electronics components to the high resolution (HR) drifter described in Suara et al., [3]. These low cost, low resolution (LR) drifters are made of PVC cylindrical pipes with 4 cm diameters and heights of 25 and 50 cm for the short and long types, respectively (Figure 1c). The drifters contain off-the-shelf Holux GPS data loggers with absolute position accuracy of 2-3 m, sampled at 1 Hz. The drifters were positively buoyant for continuous satellite position fixation with < 3 cm height unsubmerged in order to limit wind effects. This configuration results in direct wind slip, estimated as less than 1% of the ambient wind. This effect was not accounted for in this analysis.

The drifters have shown good agreement with surface velocity measurements of an Acoustic Doppler Current Profiler (ADCP) within 60 m radius (Suara et al., *manuscript under preparation*). However, the unfiltered measurement of the drifter is not suitable for measuring small scale processes in low flow applications because of the inherent position error which manifests as a large speed variance, $\sigma_M^2 \sim 0.0005$ m^2/s^2 in stationary tests at frequencies, F > 0.05 Hz.

A fleet containing 10 short and 10 long drifters were deployed during the ebb and flood tides on the 27/04/2015 and 18 drifters were retrieved at the end of the experiment while two drifters were lost. The ebb deployments were made at Site A (Figure 1) adjacent to the main channel while the flood deployment was made at Site B upstream of the bridge crossing the Currimundi Lake, which is closest to the river mouth. The drifters were deployed in a line abreast configuration with approximately 1 m separation. The experimental procedure was such that drifters trapped at the banks were collected and redeployed at the adjacent centreline. During the four hour ebb tide experiments, the number of times an individual drifter reached the banks varied from two to nine with an average of six per drifter. On the other hand, only five out of the 18 drifters were redeployed during the three hour flood tide experiments. This suggests that the ebb surface current induced many recirculation zones close to the banks, which trapped the drifters.

Data analysis

Raw drifter data were converted to a local East North Up (ENU) coordinates from a World Geodetic System (WGS84). The drifter position data set were quality controlled using velocity and acceleration de-spiking [3,9]. Sections of the trajectories where the drifters were not floated in the channel were removed using MATLAB scripts developed to work with the experimental event log. A lowpass filter with cut off frequency, F_c = 0.05 Hz, was then applied to the position time series. Drifter velocities relative to East and North were obtained by combining the quality controlled position and speed time series (Suara et al., *manuscript under preparation*) such that:

$$V_E(t) = Sp(t) \times Cos\theta(t), \quad V_N(t) = Sp(t) \times Sin\theta(t), \text{ and } \theta(t) = \arctan\left(\frac{N(t)}{E(t)}\right), \qquad (1)$$

where V_E and V_N are the Easting and Northing velocities, respectively, while θ is the direction based on the position time series (E,N), and *Sp* is a drifter speed at time *t*.

Because of the large number of interruptions in the ebb experiment, cluster analysis focusses on the flood experiment. The objective of the analysis is to estimate the time variation of the coefficient of dispersion, K and differential kinematic properties (DKP). Dispersion coefficient, K_C is obtained using the method described in List et al.,[4]. The key aspect of the method is to calculate the rate of change of a patch size with the assumption that the drifters are 'locked' to the 'patch' of fluid within which they were deployed. Using the local ENU coordinate, the centroid (represented with overbar) of a cluster is defined as:

$$\overline{E}(t) = \frac{1}{n}\sum_{i=1}^{n} E_i(t), \qquad \overline{N}(t) = \frac{1}{n}\sum_{i=1}^{n} N_i(t), \qquad (2)$$

where *i* is the drifter counter and *n* is the total of active drifters in a cluster at time, *t*. The variance of an individual drifter from the centroid of the cluster is then defined as:

$$\sigma_E^2(t) = \frac{1}{n-1}\sum_{i=1}^{n}[E_i(t) - \overline{E}(t)]^2, \quad \sigma_N^2(t) = \frac{1}{n-1}\sum_{i=1}^{n}[N_i(t) - \overline{N}(t)]^2. \qquad (3)$$

The cluster relative dispersion coefficient is calculated from the averaged variance such that:

$$K_C(t) = \frac{1}{2}\frac{\partial\sigma^2(t)}{\partial t}, \text{ and } \qquad \sigma^2(t) = \frac{1}{2}[\sigma_E^2(t) + \sigma_N^2(t)]. \qquad (4)$$

The dispersion coefficient estimated using this cluster method is an apparent dispersion coefficient because it also includes the effect of horizontal shear dispersion.

The estimate of DKP follows the method developed for oceanic Lagrangian data [5]. The method involves expanding the velocity components of Taylor's series about the centre of mass. The method assumes that the fluid domain is small and finite in size, velocity gradient is uniform across a cluster and cluster velocity is correctly represented in the linear term of a Taylor's series [6]. Individual drifter velocity can be described as:

$$V_E(t) = \overline{V}_E(t) + \frac{\partial \overline{V}_E(t)}{\partial E}[E(t) - \overline{E}(t)] + \frac{\partial \overline{V}_E(t)}{\partial N}[N(t) - \overline{N}(t)] + v_E(t)$$

$$V_N(t) = \overline{V}_N(t) + \frac{\partial \overline{V}_N(t)}{\partial E}[E(t) - \overline{E}(t)] + \frac{\partial \overline{V}_N(t)}{\partial N}[N(t) - \overline{N}(t)] + v_N(t) \qquad (5)$$

where $\frac{\partial \overline{V}_E}{\partial E}$, $\frac{\partial \overline{V}_E}{\partial N}$, $\frac{\partial \overline{V}_N}{\partial E}$ and $\frac{\partial \overline{V}_N}{\partial N}$ are linear centroid velocity gradient terms; v_E and v_N are non-linear turbulence velocity terms. The velocity gradient and non-linear terms are estimated using a least square approach [5]. DKPs are then described in terms of the resulting velocity gradients such that:

Horizontal divergence $\qquad \delta(t) = \frac{\partial \overline{V}_E(t)}{\partial E} + \frac{\partial \overline{V}_N(t)}{\partial N},$

$$\text{Vorticity} \qquad \zeta(t) = \frac{\partial \overline{V}_N(t)}{\partial E} - \frac{\partial \overline{V}_E(t)}{\partial N},$$

$$\text{Stretching deformation} \qquad a(t) = \frac{\partial \overline{V}_E(t)}{\partial E} - \frac{\partial \overline{V}_N(t)}{\partial N},$$

$$\text{Shearing deformation} \qquad b(t) = \frac{\partial \overline{V}_N(t)}{\partial E} + \frac{\partial \overline{V}_E(t)}{\partial N}. \qquad (6)$$

The horizontal divergence (δ) is a measure of change in the area of the cluster without a change in orientation or shape while relative vorticity (ζ) is a measure of the change in the cluster orientation without a change in area or shape. Shearing (b) is the measure of shape change produced by boundaries parallel to the cluster boundary without area or orientation while stretching (a) is shape change without change in area and orientation but caused by boundaries perpendicular to the cluster boundary [1].

Estimate of the K_C commenced after all the drifters were present in the channel. However, the initial 300 s where the drifter motion was affected by boat movement and initial deployment conditions were excluded. Estimates with drifter numbers, $n < 10$ were noisy and not included in the results. This reduces the bias level resulting from removal and reintroduction of drifters into the cluster. K_C estimates for long and short drifter clusters were similar for most part of the experiment. Therefore both drifter types were considered a single cluster to improve the stability of the estimate.

Results and discussion

Figure 2 shows the time variation of the cluster dispersion coefficient, K_C and centroid horizontal resultant velocity, V_H during the flood experiment. K_C and V_H varied throughout the flood experiment reflecting a tidal influence. A mean Kc value of 0.42 ± 0.34 m^2/s was obtained. This estimate is similar to $K_C = 0.5$ m^2/s, obtained in a similar independent drifter experiment at a tidal inlet [7]. The estimate is also similar to value of dispersion coefficient of 0.57 m^2/s obtained from absolute dispersion of high resolution drifters at Eprapah Creek, a smaller tidal channel [3]. However, time variation of the K_C reflected different stages characterized by divergence ($K_C > 0$; Stages 1 and 2) and convergence ($K_C < 0$; Stages 3 and 4) of the cluster. Regions in the channel corresponding to these stages are identified in Figure 2b showing the trajectories of the drifters colored by time. Magnitude of mean K_C for the stages was not significantly different from the overall mean. Of particular interest is the pronounced oscillation apparent in K_C and V_H and cluster area (Figure 3) manifested as two divergence/convergence events. This modulation of divergence and convergence has a period ~3000 s (e.g. Stage 2). This corresponds to an internal resonance/wave of length 3.3 km in shallow water with average depth, d ~ 0.5 m. This is likely due to resonance between the mouth and the fixed weir located 3.6 km from the channel inlet. The resonance effect is a reversible process manifested as cluster expansion/contraction [2]. However, this effect is expected to have some impacts on the dynamics of the surface layer of the channel by destroying stratification and enhancing mixing.

DKP of the cluster are presented in Figure 3(b –e). DKP varied temporally and spatially across the channel. Mean DKP values were in the order of 10^{-4} s^{-1}. Divergence and vorticity were predominantly positive whilst shearing and stretching deformation were negative. Observed values are an order of magnitude larger than observed in a non-tidal lake [2] and up to ten orders of magnitude lower than values in the ocean [1, 6]. Truesdell's kinematic vorticity number, $T_{K,}$ is defined to identify the periods (regions) of strain and vorticity field:

$$T_K = \sqrt{\frac{\zeta^2}{a^2 + b^2}} \,. \qquad (7)$$

$T_K > 1$ corresponds to vorticity dominance or the presence of stronger eddy-like structures regions whilst $T_K < 1$ corresponds to strain field dominance or periods (regions) of convergence or divergence where dispersion is stronger [2, 8].

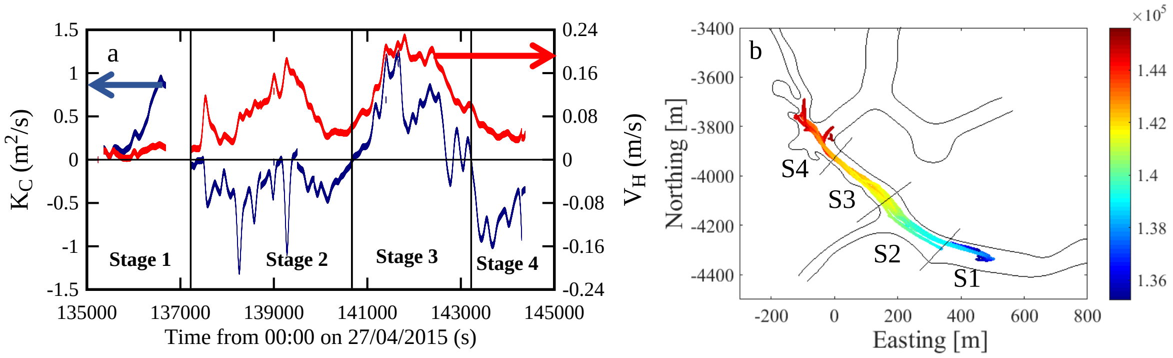

Figure 2: (a) Time variation of dispersion coefficient (Blue) and centroid velocity magnitude (Red) of drifter cluster (b) Drifter trajectory coloured by time (s), with cross lines separating Stages S1 - S4 in (a)

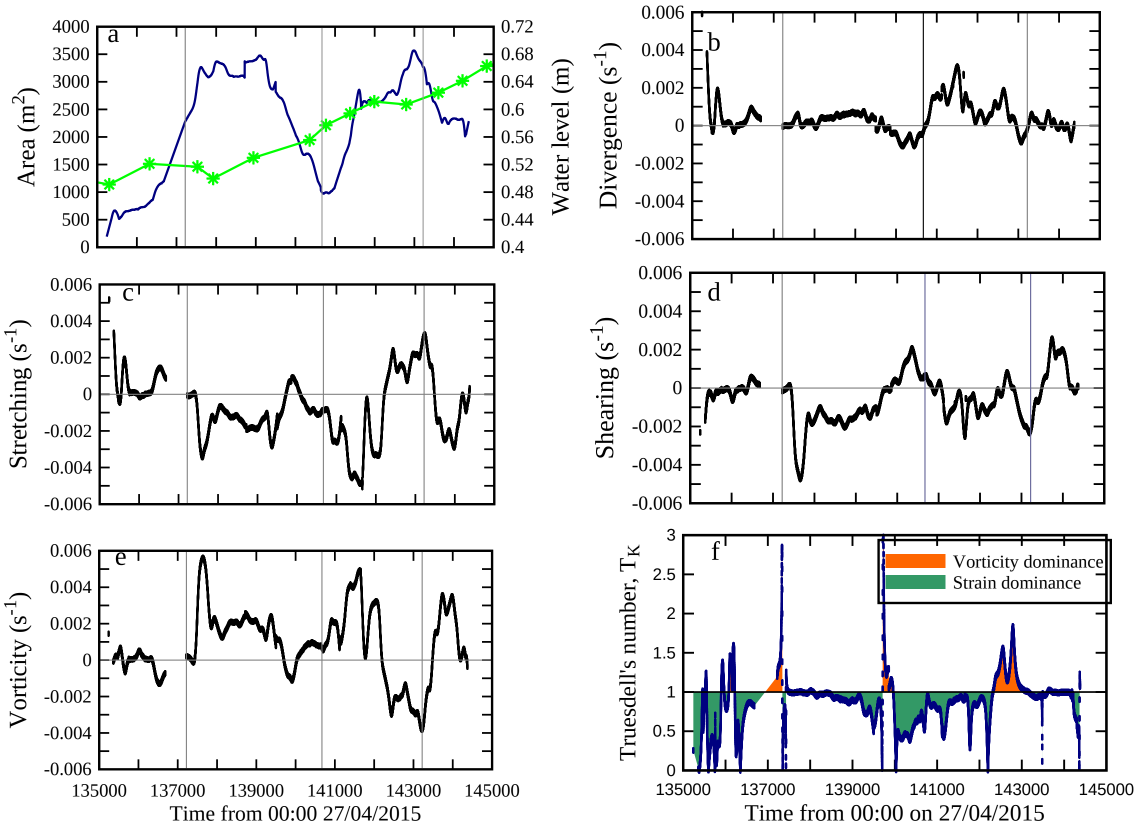

Figure 3. Time variations of cluster properties (a) Area and water level (m) in channel (* green line), (b) – (e) differential kinematic properties [Eq. 6], (b) Divergence (c) Stretching (d) Shearing (e) Vorticity (f) Time variation of Truesdell's kinematic (Blue line) vorticity number [Eq. 7]

Figure 3f shows the temporal variation of T_K. These data suggest that the channel was systematically dominated by strain field for most of the flood tide under the baseline tidal condition. Mixing in these areas is likely linked with irregular bathymetry and variation in the boundaries. However, some regions of vorticity dominance were observed. These regions correspond to divergence-convergence interphase linked with internal resonance within the channel as identified from the cluster dispersion.

Conclusions

Low cost GPS drifter data were used to investigate the dynamics of an ICOLL under the conditions of an open river mouth. Cluster analysis was applied to estimate the dispersion coefficients and the differential kinematic properties (DKP) of the channel. Consistent with similar estimates in tidal inlet and in-channel of a smaller estuary, the lateral dispersion coefficient varied with the tidal phase with a flood tide mean value of 0.42 m^2/s. Mean DKP values are in the order of 10^{-4} s^{-1}. Results showed that dispersion in the channel during an open inlet condition was dominated by the strain field resulting in convergence and divergence of surface layers. The possible role of internal resonance in enhancing the mixing in some regions within the channel was also identified. This work provides a baseline study for broader work on the identification of river mouth conditions on the dynamics and particle transport in the channel. Similar analysis is being carried out on a field data set collected while the mouth was closed and during its opening after a six week closure period.

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