‘Mixing and Dispersion in Adelaides Coastal Waters’

Rhys Jones

“This thesis is presented in the partial fulfillment of the degree of Bachelor of Engineering (Applied Ocean Science) from the Centre for Water Research, Faculty of Engineering, Mathematics and Computing”
Abstract
The investigation of mixing and dispersion rates is an important area of coastal research with significant implications for the management of nearshore contaminant discharges. Surf zone drifters developed by Johnson et al. (2003) were used to obtain Lagrangian measurements of dispersion rates in Adelaides’ coastal waters. The drifters were deployed on Henley Beach, near the Torrens River outflow, under contrasting seasonal conditions between the 1st and the 3rd of September 2004 and the from the 20th to the 23rd of March 2005. Data obtained from these deployments was used to estimate the dispersion coefficient \( K \) as well as the cross-shore and longshore dispersion coefficients, \( K_x \) and \( K_y \) respectively. During the September deployments the total dispersion coefficient was estimated as \( K = 0.11 \text{m}^2\text{s}^{-1} \) within a 95% confidence interval of \( \pm 0.08 \text{m}^2\text{s}^{-1} \), whilst during March \( K = 0.12 \pm 0.07 \text{m}^2\text{s}^{-1} \).

A significant volume of water is known to enter the nearshore zone along the metropolitan coastline through a variety of river, stormwater and wastewater discharges. During the post war period considerable marine environmental degradation, symptomised by a decrease in seagrass abundance close to shore, has been observed within the off Adelaides coast. This has been attributed to contaminants thought to be found within these coastal discharges. Through analysis of the drifter dispersion coefficients it was possible to demonstrate that dispersion in the nearshore zone is restricted due to a combination of low energy conditions and the bounding effects of the surf zone. This creates a barrier to offshore contaminant transport, with the result that materials that are discharged along the coast are confined to a zone of relatively low dispersion close to shore, substantially refuting the hypothesis that terrestrial contaminant discharges are directly responsible for seagrass losses offshore.

Dispersion coefficients were also calculated for 1m averaged bins of standard deviation, allowing the analysis of the scale dependence of the dispersion. Dispersion rates were found to correlate strongly with the 4/3 power law and were compared to the results of Okubo (1974) where an offset, of an order of magnitude, was noted. This was attributed to the effects of increased shear dispersion close to the coast, as noted by List et al. (1990). Eulerian measurements were obtained during the September deployments using an ADCP. This provided information pertaining to the vertical structure of the nearshore current system and the response of the nearshore hydrodynamic system to perturbations in the prevailing meteorological regime.
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1 Introduction
During the last few decades, significant marine environmental degradation has occurred in the coastal waters off the city of Adelaide, located on the west coast of the Gulf of St Vincent, South Australia. In particular, this degradation has been observed through the analysis of aerial photographs indicating the retreat of seagrass from the metropolitan coastline (ACWS, 2004). In 1999, it was determined that as much as 4000 hectares of seagrass beds had been lost from the nearshore meadows since 1949 (ACWS, 2004). The loss of seagrass is a serious marine environmental problem due to its ecologically significant role in marine environments. The various roles performed by seagrass beds were defined by Walker et al. (2001) under three broad classifications, namely; physical, chemical and biological processes. Physical roles refer to the enhancement of sediment accumulation and stabilisation, wave baffling and other hydrodynamic processes. Chemical roles include biogeochemical cycling whilst the biological roles of seagrass include the provision of floral and faunal abundance and diversity, primary and secondary production (including fisheries) and the cultural attributes including recreation, commercial and educational uses (Walker et al. 2001). As such, it is clear that the significant decline in the nearshore extent of seagrass beds observed in Adelaide’s coastal waters is a significant problem with many potential implications.

The South Australian state governmental response to the observed degradation in Adelaide’s coastal waters has been the establishment of the Adelaide coastal waters study (ACWS). The ACWS is a multidisciplinary study aimed at determining the causes of the long term decline in the metropolitan marine environment. A major focus of the ACWS is on determining the causes of the endemic seagrass loss, however other areas of focus include the observed loss of biodiversity and the increase in marine algae associated with the general decline of the marine environment. Many of these recorded impacts have been attributed to coastal discharges through a variety of stormwater, wastewater and river drainages. These discharges potentially contain a variety of contaminants, from the urban catchment area, which have the capability of impacting upon the marine environment. The exact composition of the coastal discharges is unknown and as such the contaminant inflows into the nearshore zone are unknown. Thus, in order to determine whether the contaminant inflows are potentially responsible for the observed environmental degradation, it is necessary to
understand the physical processes affecting their transport and rates of dilution upon their introduction to the marine environment. In this context, the rate of dispersion in Adelaide’s coastal waters is a key parameter describing the behaviour of discharged contaminants in the nearshore zone, thereby, allowing the analysis of the hypothesis that coastal discharges are responsible for the ongoing marine environmental degradation. This study is based on the field measurement of the physical process of dispersion along Adelaide’s metropolitan coastline and forms a part of the broader ACWS.

Field work was conducted using Lagrangian drifters, developed by Johnson et al. (2003). These drifters provide a spatially variable frame of reference in the analysis of the nearshore current structure as they are able move with the fluid, unlike Eulerian based measurement techniques which rely on a large array of spatially fixed sensors, which are difficult and expensive to deploy and monitor (Johnson, 2004). The drifters are tracked by the satellite-based Global Positioning System (GPS), which, following the removal of selective availability, is sufficiently accurate to measure the spatial scales of motion observed in the nearshore zone. By releasing clusters of up to five individual drifters within the nearshore zone and analysing their motion relative to each other it is possible to determine a coefficient K which describes the rate of dispersion.

Utilising this approach, this study aims to measure the dispersion rates that occur in Adelaide’s coastal waters. Through the analysis of these results it will be possible to describe the dispersive nature of the nearshore current regime and consequently, speculate on the likelihood of coastal discharges significantly impacting on the marine environment, and in particular seagrass beds located offshore from the study site. The larger scale transport mechanisms affecting nearshore waters are not addressed in this study and hence definitive results concerning the fate of contaminant discharges can not be obtained; however, the dispersion rates determined in this study will form key input parameters into numerical modeling aimed at achieving this outcome.
2 Literature Review

2.1 Study Area

2.1.1 Geographical and Historical Overview
Adelaide is located on the west coast of the Gulf of St Vincent. The Gulf is a semi-enclosed water body approximately 170 km in length, from 34°S to 35°30'S, by 60 km in width at its maximum dimensions. It is relatively shallow, with maximum depths rarely exceed 40 metres (South Australian Coastal Protection Board SACPB\(^a\), 1993).

![Figure 2.1: Bathymetry of the Gulf of St Vincent, South Australia (de Silva Samarasingha et al., 2003)](image)

At the time of European settlement the metropolitan coastline was dominated by a continuous sand dune ridge sequence that extended from Seacliff in the south to Outer Harbour. This dune systems width averaged between 200 and 300 metres in the southern region between Seacliff and Largs and was largely continuous, only interrupted by the Patawalonga River at Glenelg. In the north the nature of the dune system changed and was characterised by two or three parallel dune faces, each measuring 70 to 100 metres in width and separated by narrow swales (SACPB\(^a\), 1993). These prograded barrier systems were formed during periods in which sand accretion from external sources outweighed comparatively small losses due to longshore transport. Along the metropolitan coastline the height of the dune system averaged between 10 and 12 metres above mean sea level (MSL) however the highest point in the dune system occurred around Brighton where dunes were recorded to an elevation of 15 metres (SACPB\(^a\), 1993).
Since European settlement the nature of the Adelaide coastline has changed dramatically. In addition to the diversion of the Torrens River to Breakout Creek, there has been extensive development, particularly during the post-war period 1945 to 1965, of the coastal strip, to the point where only relics of the original dune formation remain (SACPB\textsuperscript{a}, 1993). The stabilising effect of this development has effectively eliminated much of the supply of sand into the nearshore region, with the effect of accelerating erosion.

2.1.1.1 Coastal Protection and Management

The consequences of intensified erosion were highlighted during five large storm events between April 1948 and July 1964 where high water levels and large seas led to extensive damage to coastal properties (SACPB\textsuperscript{a}, 1993). In response to the ongoing problems of coastal erosion during storm events, local councils and the South Australian Harbours Board began a program of coastal reinforcement which was dominated by the implementation of ‘hard’ engineering solutions (SACPB\textsuperscript{b}, 1993). This approach relied on the construction of expensive and visually intrusive storm protection walls. These walls were generally concave or vertical in profile and were largely unsuccessful. Rather than dissipating the incoming wave energy, they reflected it, which led to increased longshore currents and sediment transport (SACPB\textsuperscript{b}, 1993). Many of the original walls have subsequently been destroyed through undercutting or have been replaced by sloped ‘rip rap’ rock walling which consists of large rocks, and has the capacity to dissipate a far larger proportion of wave energy. There is currently about 5km of ‘rip rap’ walling installed as a ‘last resort’ mode of coastal protection along Adelaides’ coastline.

The management of Adelaides beaches is moving away from ‘hard’ engineering solutions such as storm walls and ‘rip rap’ (SACPB\textsuperscript{b}, 1993). The ‘Coast Protection Board’ (CPB) has recommended that further walls should only be constructed to replace existing structures and that beach protection strategies should focus on soft strategies such as beach nourishment (SACPB, 2004). Artificial beach nourishment is required due to littoral drift, the nett northerly transport of sediment within the nearshore zone due to the longshore current (Davis & FitzGerald, 2004). This transport is driven by predominantly south-westerly winds acting along a fetch length of 50 km across the Gulf of St Vincent which generate waves that propagate in a
north-easterly direction. These waves intercept the coastline obliquely with sufficient energy to initiate northerly sediment movement that is estimated at between 20,000 and 100,000 cubic metres per annum (Deans & Smith, 1999). The littoral sediment transport rate can be described as a function of the wave energy flux and the angle of the breaking wave crests, (Komar, 1998).

\[ I_l = 0.70(ECn)_b \sin(\alpha_b) \cos(\alpha_b) \]  

(1)

In this equation \( I_l \) is the immersed weight transport rate which is a function of the wave energy flux \((ECn)\) evaluated at the breaker zone and the angle of the breaking wave crests \(\alpha\). Thus, it can be seen that for a given wave energy the maximum value of \( I_l \) will occur when the angle of the breaking wave is 45 degrees to the shoreline. The value 0.70 is that of \( K \); a dimensionless proportionality constant derived from experimental data (Komar & Inman 1970).

Prior to the stabilisation of the coastal dune system, sediment was sourced from sand dunes within the southern section of the littoral cell, however, following the urbanisation of the metropolitan coastline the erosion of sediments to supply this transport is not possible (SACPB\(^b\), 1993). In order to maintain the equilibrium between retaining sufficient sediments on the southerly beaches and nett northerly transport, it is necessary to artificially supply sediments into the system (Dean, 2002).

### 2.1.1.2 Sediment Transport

Artificial sediment nourishment is currently performed along the Adelaide coastline using sand dredged from offshore locations at the rate of 200,000 cubic metres biannually, as well as relocating up to 60,000 cubic metres per annum, within the littoral cell from the northern beaches to the south via trucking (SACPB, 2000). Dredging operations are the preferred avenue for artificial sediment supply as the sand they obtain is imported into the littoral cell and hence increases the nett volume of sediment available within the littoral zone, rather than shifting the sediments within the system. Additionally, the sediments that are obtained from offshore dredging operations are characterised by a coarser grain size which increases the energy required for sediment transport and hence decreases the transport rate (SACPB, 2004). This is represented by Equation 2.

\[ \theta = \frac{0.5 fU_m^2}{(s - 1)gD_{50}} \]  

(2)
The Shields parameter reflects the balance between the shear forces acting on the sediment particle acting to mobilise it and the submerged weight of the particle, which acts to maintain stability (Dean & Dalrymple, 2002). When $\theta$ is greater than 0.05 sediment motion is possible, thus, all other factors remaining equal, an increase in the sediment size, $D_{50}$, will decrease $\theta$ and hence reduce the likelihood of sediment transport occurring.

Trucking of sediments within the littoral cell is also undertaken to a lesser extent, with the primary intention of providing immediate protection in severely eroded or vulnerable areas (CPB, 1992). From the point of view of coastal management, trucking of sand is a less favourable option than dredging, as rather than introducing new sediments into the littoral zone, it merely reallocates sand within the cell. Whilst this alleviates local pressure, it does little to manage the longer term implications of restricted sediment supply.
2.1.2 Breakout Creek and Henley Beach

Field studies using surf zone drifters, tracked using the satellite-based global positioning system (GPS), were conducted on Henley Beach near Breakout Creek, the outflow point of the Torrens River into Holdfast Bay. Breakout Creek is an artificial waterway that was constructed by the South Australian Government in 1937 in order to divert the course of the Torrens River (SACPB\(^a\), 1993). Prior to the construction of the concrete lined channel and weir, the Torrens River drained into a series of wetlands located to the east of the barrier dune system. These wetlands then drained naturally to the north primarily through the Port River system and to the south via the Patawalonga. The construction of the Breakout Creek outflow was deemed necessary in order to alleviate the flooding of these wetlands which regularly isolated the coastal communities of Grange and Henley (SACPB\(^a\), 1993). The effect of this diversion was that the natural process of filtering the river discharge through the wetland system was bypassed, leading to the direct discharge of stormwater and associated contaminants into the marine environment.

![Aerial view of Breakout Creek](image)

Figure 2.3: Aerial view of Breakout Creek, noting the weir and the northerly flow of the creek across the beachface (Adelaide Coastal Waters Study, 2004).

The outflow from Breakout Creek is highly seasonal with the majority of outflow occurring during the winter months; 80-95% of annual outflow occurs between June and November compared to 5% between December and February (Steffensen, 1985). It represents the coastal discharge of the largest watercourse within the metropolitan area and drains a significant catchment area. The catchment can be divided into two distinct zones; the upper zone which covers approximately 400km\(^2\) and is mostly covered by natural vegetation and the lower zone which is just 80km\(^2\) but is heavily urbanised. As much as 70% of the rainfall from this lower zone is directly discharged through the river system (Steffensen, 1985). The Kangaroo Creek Reservoir,
constructed in 1969, restricts the flow from the upper section; however, occasional overflows occur, resulting in large volumes of stormwater discharging to the ocean (Steffensen, 1985). The total annual discharge through Breakout Creek displays a high level of variation. The annual outflow during the period of 1978 to 1983, ranges between 20,000ML in 1980 and 83,000ML in 1981 whilst the maximum instantaneous discharge rate of 167 m³ s⁻¹ was recorded in 1979 (Steffensen, 1985).

Sediment transport along Henley Beach is congruous with its regional setting; longshore sediment transport is predominantly in a northerly direction and is driven by obliquely incident wind conditions. Sediment supply to the north of Breakout Creek is dependant on the level of bypassing of sediment that occurs around the outlet stream. Typically, northerly littoral transport of sand is not interrupted by the Torrens discharge; however, during peak flows sand can accumulate on the southern side of the river mouth (Deans & Smith, 1999). The natural bypassing of the river mouth by coastal sediments is assisted by realigning the path of the Torrens outflow at approximately yearly intervals. This is conducted by trenching across the southern beach face and trucking small volumes of sand to the north of the outlet stream (Deans & Smith, 1999).

2.1.3 Hydrodynamic and Meteorological Setting

2.1.3.1 Tides

Tides are fluctuations in the vertical and horizontal allocation of water throughout the world’s oceans generated through the interactions of gravitational and centrifugal forces between the Earth, moon and sun. The gravitational force is an attractive force which is directly proportional to the mass of the bodies between which it is acting, whilst it is inversely proportional to the square of the distance between them, Equation 3 (Davis & Fitzgerald, 2004).

\[ F = G \left( \frac{M_1 M_2}{R^2} \right) \]  

(3)

On the other hand, the centrifugal force is the apparent force which deflects masses radially outward from the axis of rotation, thus opposing the action of gravity. The action of the tides is the result of the imbalance of these two forces at any particular point on Earth. Considering just the Earth and the moon; on the moon side of the Earth, gravitational forces dominate and water is drawn towards the mass of the moon,
whilst on the opposite side of the Earth from the moon, centrifugal forces dominate, creating an elliptical variation in water level distribution, shown in Figure 2.4.

Figure 2.4: Idealised equilibrium tidal conditions showing individual ‘bulges’ due to the gravitational and centrifugal forces. This situation assumes the absence of continents, uniform depth ocean and that the moon is aligned with the equator (from Davis & Fitzgerald, 2004).

The effect of the moon on tides is greater than that of the sun, despite the fact that the same forces of gravity and centrifugal motion operate. This is because the moon is far closer to the Earth than the sun and since the gravitational force is inversely proportional to the square of the distance separating the two bodies, the effect of the Earth’s rotation around the sun is only 46% of the effect of the Earth and the moon rotating around each other (Davis & FitzGerald (2004); Verspecht, 2002).

Figure 2.5 The alignment of the Earth, Moon and Sun influence the relative magnitude of tides observed at a given location.
The relative alignment of the forces produced by the sun and moon can greatly influence the magnitude of tidal variations (Figure 2.5). When the sun and the moon are aligned on the same side of the Earth, a new moon, or on opposite sides of the Earth, a full moon, the lunar and solar components of tides act in unison creating higher tides, known as spring tides (Davis & FitzGerald, 2004). However, the angle of the moon to the Earth can vary. It is during these periods, first or third quarter moons, when the tidal influence of the sun and moon act perpendicularly to each other, that smaller, neap tides are observed (Davis & FitzGerald, 2004).

The tidal range along the Adelaide coastline is 2.4m and is taken as the range between the Mean High Water Springs and the Indian Spring Low Water Level (Deans & Smith, 1999). This tidal range can be classed as a mesotidal variation (2m<2.4m<4m), however, this represents the maximum variation over a spring tidal range and as such the ‘normal’ tidal range that exists for the majority of the cycle is lower than this range and can be classed as microtidal (<2m). The amplification of tidal ranges within the semi-enclosed Gulf of St Vincent is represented in Figure 2.6 and is primarily due to convergence effects.

![Figure 2.6 Modelled tidal range within the Gulf of St Vincent (right) and the Spencer Gulf (left) showing the amplification of the tidal range within the shallow Gulf areas, isolated from the open ocean (National Tidal Center, 2004).](image)

During periods of full and new moons (above) the inertial and gravitational forces of the moon and the sun align, leading to larger tidal oscillations or ‘neap’ tides. When the forces of the moon are acting at right angles to the sun (below), during first or third quarter moons, the tidal forces act in opposition and smaller ‘neap’ tides are observed. As the tidal front moves into the Gulf, the width narrows, effectively constricting the

_Literature Review_
Flow and thereby augmenting the height of the tidal flow (Komar, 1976). The form of the tidal regime can be determined by calculating the tidal form factor.

\[
F = \left( \frac{H_{K_1} + H_{O_1}}{H_{M_2} + H_{S_2}} \right)
\]

(4)

Utilising Equation 3 and the values contained in Table 2.1 the value of F, for Outer Harbour, and hence the Adelaide metropolitan beaches is found to be 0.416. This corresponds to a tidal regime of mixed, mainly semidiurnal tides. Within the Gulf of St Vincent the primary tidal constituents are the principal lunar component \(M_2\) and the principal solar component \(S_2\). These constituents are semidiurnal, meaning they produce only one tide per day, with periods of 12 hours 25 minutes and exactly 12 hours respectively. As a result of this difference, every 14.77 days they are in opposition and effectively cancel each other out (Grzechnik, 2000). During the periods, where the semi diurnal \(M_2\) and \(S_2\) constituents are out of phase by 90 degrees, ‘neap’ tides, tidal fluctuations are driven predominantly by the values of the luni-solar diurnal component \(K_1\) and the principal lunar diurnal component \(O_1\). As \(K_1\) and \(O_1\) are both diurnal components it is during these neap periods that the form of the tidal cycle changes from semi-diurnal to diurnal, leading to the mixed, mainly semidiurnal tidal classification. At equinoxes, the diurnal components of the tide also cancel each other out, producing a period of almost constant water level lasting for several days (Grzechnik, 2000). This skipping of the tidal cycle was first observed in the Gulf of St Vincent by Matthew Flinders and was named the ‘dodge’ tide, a term unique to South Australia.

Table 2.1: Tidal constituent data, Outer Harbour, Gulf of St Vincent. (Adapted from Grzechnik, 2000)

<table>
<thead>
<tr>
<th>Tidal Observation Station</th>
<th>Tidal Constituent (amplitudes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(O_1) (m)</td>
</tr>
<tr>
<td>Outer Harbour</td>
<td>0.17</td>
</tr>
</tbody>
</table>

The relevance of the tidal regime to dispersion in Adelaidese coastal waters lies in the ability of tidal oscillations to induce currents. This is a well known phenomena, that has been noted in estuaries (Simpson et al. 2005), coastal waters (Davies & Xing, 2001) and offshore sites, located near to the shelf edge (Xing & Davies, 2003). The tidally generated flow induces bed turbulence through friction between the water column and the sediments, leading to the mixing of the water column (Xing & Davies, 2003).
2.1.3.2 Wave Climate

Most waves are generated through friction and the action of wind blowing across the surface of a water body, although they may also be formed by a variety of other phenomena including submarine landslides, earthquakes, volcanic eruptions and tidal interactions. Within the Gulf of St Vincent the generation of waves by wind is the key mechanism. Initially, capillary waves with periods of less than 0.1s appear on the surface at wind speeds of approximately 1.1ms\(^{-1}\), however, with time and increased wind velocities gravity waves of larger magnitude and period will form. Wave form is described using:

1) the period, the amount of time it takes for identical points on successive wave crests to pass a specific point,
2) the wavelength which is the distance between identical points on successive wave fronts and
3) the amplitude of a wave, which is the distance from the mean water level to the wave crest or trough.

The height and periods of waves generated are dominated by three primary factors. The velocity of the wind, the duration over which that wind blows in the same direction, the depth and the fetch length, the distance over which the wind blows (Dean & Dalrymple, 2002). The energy flux of a wave train is directly proportional to the period of the waves and the square of the wave height. From this relationship it can be seen that the amount of power required to increase the magnitude of a long period wave is greater than the power transfer required to increase the size of a short period wave (Komar, 1998). Thus, long period waves are generally only created under storm conditions where high winds blow for long periods, such as in the Southern Ocean, whereas short period waves are created in restricted fetch environments such as the Gulf of St Vincent.

**SWAN Wave Model**

The waves generated by local winds are low to medium energy due to the limited fetch length within the Gulf of St Vincent. However, significant wave energy is able to penetrate into the Gulf from the Southern Ocean (Hemer & Bye, 1999). The Southern Ocean is highly energetic and the swell produced within it, to the south west of Australia, has been recorded as the largest of any in the world’s oceans (Chelton et al. 1981; cited in Hemer and Bye, 1999). Monitoring of the offshore wave climate at
seven sites between the 1150m and 75m depth contours was undertaken by Provis and Steedman (1985) over a period of 6 months from May to October, 1984. Significant wave heights of over 10m were recorded during a June storm event in addition to several occurrences of significant wave heights greater than 5m (Provis & Steedman, 1985; cited in Hemer and Bye, 1999). The significant wave period appeared to be independent of the significant wave height and remained relatively constant during the measurement period at around 15s. The wave spectra that is created in the Southern Ocean and is incident on the South Australian coastline does not display distinct wind sea and swell peaks except in periods of extremely low swell. This spectra is described as being unimodal and is due to the close proximity of the coastline to the source of the swell not allowing sufficient travel time for the wavefield to develop into a bimodal spectra (Young and Gorman, 1995).

Hemer and Bye (1999) modeled the wave climate of the semi-enclosed coastal waters of South Australia using the SWAN (Simulating WAves Nearshore) wave model. SWAN is a directional spectral wave model which incorporates many wave propagation processes including; refraction effects due to bottom friction and currents, blocking and opposing by currents, shoaling and effects due to obstacles. SWAN also accounts for wind generation of wave energy and dissipation effects that include the dissipation of wave energy due to wind induced white capping, depth induced wave breaking and bottom friction (SWAN, 2004). The major limitation of the SWAN model is that it does not take into account diffraction effects, which means that it is not suitable for locations in which the change in wave height is significant over a short length scale relative to the wavelength (SWAN, 2004). In the version of SWAN utilized by Hemer and Bye (1999), reflection effects around obstacles were not accounted for either, making SWAN unsuitable for steep beach face environments, however these reflection effects are included in latter SWAN versions. Hemer and Bye (1999) compared the results obtained from SWAN with those obtained from another model, the Bureau of Meteorology Southern Ocean Wave Model, WAM, as well as physical measurements. Following this comparison they were able to conclude that both the SWAN and WAM models could be successfully linked to provide reliable swell prediction formulae for the sheltered areas of South Australia’s coastline.
Results obtained from running SWAN suggest that the direction of swell propagation from the Southern Ocean is critical in determining the extent of intrusion into the Gulf of St Vincent. Kangaroo Island is located in the mouth of the Gulf of St Vincent which is connected to the Southern Ocean to the north, by Investigator Strait and to the south via Backstairs Passage (Figure 2.1). The island provides a significant level of blockage to the wave energy propagating towards the Gulf, and large wave heights are commonly observed off its coast. Most of the wave energy that enters the Gulf comes from a south westerly bearing (~230°) which allows largely unimpeded passage through Investigator Strait. As the water depth decreases the waves refract and ‘wrap’ into the strait becoming more perpendicular to the depth contours (Hemer & Bye, 1999). Despite substantial refraction occurring within the Investigator Straight, to the extent that the direction of propagation changes by a complete 180° on the north shore of Kangaroo Island, the dominant direction of wave propagation into the Gulf is northerly. However, a significant level of spreading does occur, dissipating the wave energy over a larger area.

Equation 5 was determined by Hemer and Bye (1999)² in order to predict the wave energy at various locations within the coastal seas of South Australia, including the Gulf of St Vincent and the Spencer Gulf.

\[
NWH = a_4 D_0^4 + a_3 D_0^3 + a_2 D_0^2 + a_1 D_0 + a_0
\]

The values of the constants \(a_{0-4}\) are dependant on the location under analysis, whilst the value of \(D_0\) represents the direction from which the incident waves are propagating. The normalised wave height returned is a function of the wave height (H) at the location being analysed divided by the offshore wave height (\(H_0\)). By finding the normalised wave height, rather than the absolute wave height, Equation 4 remains valid for any offshore wave height. The values of the coefficients \(a_0\) to \(a_4\) are shown in Table 2.2 for a location offshore from Adelaide in a water depth of approximately 10m. The wave heights calculated using Equation 4, and an offshore wave height of 3.5m over a variety of incident wave directions, are shown in Table 2.3.

| Table 2.2: The coefficients of equation 4, derived by Hemer & Bye (1999). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(a_4\) \((x10^7)\) | \(a_3\) \((x10^6)\) | \(a_2\) \((x10^5)\) | \(a_1\) \((x10^4)\) | \(a_0\)           |
| Coefficients    | 5.8435          | -4.8575         | 1.4918          | -1.9994         | 9.9339          |

Literature Review
Table 2.3: Wave heights calculated in 10m water depth offshore from Adelaide, using Equation 5 and the co-efficient values in Table 2.2.

<table>
<thead>
<tr>
<th>Wave Propagation Direction</th>
<th>230°</th>
<th>260°</th>
<th>160°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Height (m)</td>
<td>0.59</td>
<td>0.63</td>
<td>0.34</td>
</tr>
</tbody>
</table>

This data shows a substantial decline in the onshore wave height for all propagation directions as well as a significant variation between propagation directions. This is illustrated by the fact that the predicted swell is twice as large at the specified site if the direction of approach is from the south west, through Investigator Strait than if the direction of approach is from the south east and is largely blocked by Kangaroo Island (Hemer & Bye, 1999).

**Modeled Wave Conditions**

Nearshore wave modeling of the Gulf of St Vincent has recently been conducted using SWAN. The results from this work allowed the derivation of the mean wave conditions over the entire year, based on data recorded during 2003, as well as the calculation of mean conditions for the months in which drifters were deployed.

Figure 2.7 represents the mean wave conditions over the entire year. As can be seen, the primary source of wave energy propagation into the Gulf is through the Investigator Strait. The wave energy propagates in an easterly direction into the Gulf, diminishing in height relative to the distance of propagation. The areas of greatest sheltering are located in the lee of Kangaroo Island and at the head of the Gulf, approximately 160km north of opening. Significant levels of wave energy are incident upon the western coast of the Gulf; however the level of intensity decreases in the northerly direction, resulting in relatively limited conditions occurring offshore from Adelaide. At the study site, wave conditions are further reduced through the dissipation in wave energy experienced as the swell moves into shallower water close to the coast. As such, the mean wave height incident upon the study site, over the duration of the year, is less then 0.5m.

The seasonal variation in the prevailing wave conditions is significant and is represented in Figure 2.8. During September (Inset A), the level of wave energy propagation into the Gulf is large, due to the higher energy wave conditions in the Southern Ocean which are experienced through the winter and early spring due to the passage of high energy storm fronts through a subtropical ridge of high pressure.
located to the south of Australia (Petrusevics, 2004). In contrast, the amount of swell energy present in the Gulf during March is relatively low, as during the summer months, the subtropical high pressure ridge which contains the storms responsible for the high energy conditions during winter, moves further southwards (Petrusevics, 2004). The same general propagation characteristics within the Gulf apply throughout the year, however, the key input parameter, the incident wave energy through the Gulf of St Vincent, heavily influences the extent and magnitude of the wave energy propagation. During September it can be seen that the average wave height at the study site is of the order of 0.8-1m, whilst during March, it is significantly less then 0.5m. The directional components vary significantly, with westerly waves dominant at the study site during winter, whilst during summer south westerly waves dominate. This directional variability can in part be attributed to the prevailing wind conditions which vary between seasons and are incorporated in the SWAN model.

![Figure 2.7 Mean swell conditions in the Gulf of St Vincent, over the entire year, calculated using SWAN wave modeling software (Courtesy of B. Hollings, Center for Water Research, UWA).](image)

**Figure 2.7** Mean swell conditions in the Gulf of St Vincent, over the entire year, calculated using SWAN wave modeling software (Courtesy of B. Hollings, Center for Water Research, UWA).
2.1.3.3 Winds

The Adelaide metropolitan coastline is influenced by a full spectrum of wind directions throughout the year which are represented in Figure 2.9. This Figure also displays the relative distribution of the incident wind bearings and velocities, thus demonstrating that the prevalence of south-westerly conditions (between 180° and 270°) which make up over 40% of the total readings over a four year period. Due to the westerly facing aspect of the Adelaide coastline, along a north-south axis, winds with a component of westerly direction have the greatest impact on coastal processes, through the generation of waves that are incident upon the shoreline. In particular, the angle of incidence upon the shoreline of waves generated through the prevailing south westerly conditions, correlates with the optimal conditions for the promotion of a longshore current system, which in turn stimulates northward sediment transport. The likely influence of these conditions is further demonstrated through analysis of the high wind occurrences which finds that 74.3% of winds speeds greater than 10.8 m/s are recorded between the westerly and southerly bearings.

Figure 2.8 Mean wave conditions for the Gulf of St Vincent for September (A) and March (B) calculated using SWAN wave modeling software (Courtesy of B. Hollings, Center for Water Research, UWA).
Seasonal variation is also significant with north easterly conditions prevailing during the winter months of June through to August which is in comparison to the dominant south-south-westerly winds throughout the majority of the year. In contrast to the prevailing conditions through the rest of the year almost 40% of recordings taken during the winter months are between northerly and easterly bearings (Figure 2.10). Northerly and easterly winds have little impact on the Adelaide metropolitan coastline as they blow cross shore and offshore respectively and hence do not create waves that are incident upon the beaches on the eastern shore of the Gulf of St Vincent. During summer, the wind regime is dominated by south westerly to south easterly winds. These conditions are a result of the interactions between local and continental scale meteorological conditions, which will be explained in Section 2.1.3.4.

Figure 2.9: Wind rose of half hourly measurements from Adelaide airport showing prevailing south westerly conditions over the period 1994 to 1998 (Data courtesy of the Bureau of Meteorology).
2.1.3.4 The Sea Breeze

The sea breeze is a meso-scale meteorological feature that recurs on a relatively constant diurnal cycle along around two-thirds of the world’s coastlines, particularly in tropical and sub-tropical areas (Pattiaratchi et al. 1997). Sea-breeze activity is characterised by an onshore directed wind that typically gains in strength through the day, reaching a maximum in the late afternoon, and subsequently dissipates or even reverses direction creating a ‘land breeze’ overnight (Abbs & Physick, 1992; cited in Pattiaratchi et al. 1997). The sea breeze arises due to the differences in the thermal conductivity of the land and the sea respectively (Masselink & Pattiaratchi, 1997). Land has a relatively low thermal conductivity and as such, heats and cools more rapidly than the ocean. As such, during the day, the land heats more rapidly than the neighbouring sea. The heat being radiated from the land heats the air above the ground, causing it to expand, leading to a reduction in pressure. As the ocean, does not heat at the same rate as the land, the same affect does not occur over the ocean, leading to a pressure differential over a relatively minor distance. This induces a flow from the relative high pressure zone over the ocean to the lower pressure zone over the land (Masselink & Pattiaratchi, 1997). The strength of the sea breeze is directly proportional to the size of the pressure differential; typically this leads to an enhancement of the sea breeze during the summer months when the highest temperatures occur on the land (Masselink & Pattiaratchi, 1997). During the night, the
land cools more rapidly, resulting in the pressure over the land increasing relative to the ocean, inducing an offshore directed ‘land’ breeze (Abbs & Physick, 1992; cited in Pattiaratchi et al. 1997).

The recordings of afternoon (13:30-16:30) wind speeds and directions, during the summer and winter months respectively, are presented in Figure 2.11. This Figure clearly demonstrates the dominance of the south-westerly, sea-breeze, conditions during the summer afternoons, with 38% of total recordings occurring from a direct south westerly bearing and 77.92% of all measurements recorded between bearings of 180°’s and 270°’s. During winter the same sea-breeze pattern is no longer observed. The winter wind pattern is induced due to the northward migration of a sub-tropical ridge of high pressure during the winter months (Petrusevics, 2004). This ridge of high pressure produces northerly winds in southern Australia (Petrusevics, 2004), which can be clearly seen in the Figure 2.10.

Whilst these results indicate the presence of an active sea-breeze system during the summer months, they also indicate the presence of other factors influencing the direction of the breeze. This is because a ‘typical’ sea-breeze will blow perpendicular to the coastline, directly across the local pressure gradient (Pattiaratchi et al. 1997). In the case of Adelaide, the sea-breeze comes from the south west. This is due to the effects of the Coriolis force which acts to the left in the southern hemisphere, deflecting westerly winds towards the north, thereby creating south-westerly conditions (Pattiaratchi et al. 1997).

The impact of the sea-breeze on coastal processes within the Gulf on St Vincent has not been studied to the authors knowledge. However, it has been noted by Pattiaratchi et al. (1997) as well as Masselink & Pattiaratchi (1997) that in coastal regions, sheltered from the direct impact of swell and storm activity, locally generated wind waves play a dominant role in controlling nearshore and foreshore processes. The investigations conducted by Pattiaratchi et al. (1997) referred specifically to the sheltered coastline of south west Western Australia, where sea-breeze conditions are accepted to be amongst the strongest in the world, with maximum values known to exceed 20m/s. Pattiaratchi et al. (1997) demonstrated that the intensification of the sea-breeze leads to a rapid response within the nearshore hydrodynamic environment with significant increases observed in the incident wave energy, the velocity of the
longshore current and cross-shore undertow. Mixing and dispersive processes were not addressed.

Whilst, Adelaides’ metropolitan coastline is not regularly exposed to the same intensity of sea breeze as Western Australia, the magnitude of the breeze is still significant, with an average velocity of 11.47m/s recorded between 13:30 and 16:30 in the summer months of November through to March (1994-1998). The sheltered nature of the Gulf of St Vincent from major storm and swell activity ensures that locally generated wind waves are a key source of energy in driving coastal hydrodynamic processes. In these respects the sheltered coastlines of south west Western Australia and the Gulf of St Vincent are quite similar. Consequently, it is not unreasonable to suggest that the impacts of the sea breeze observed by Pattiaratchi et al. (1997) would be equally applicable to the sheltered South Australian coastline.
No observations were missing. Wind flow is FROM the directions shown.

Figure 2.11 Wind roses depicting the mean afternoon wind conditions between 13:30 and 16:30 in summer and winter respectively. The dominant south westerly conditions during the summer months illustrate the presence of a sea breeze system. The winter wind rose does not display the same sea breeze pattern. This is interpreted as being due to the northward transgression of the sub-tropical high pressure system, during the cooler months, resulting in an increase in south westerly through north westerly conditions.
2.2 Beach Morphology

The beachface and the associated nearshore zone is a particularly active and dynamic area which is in a constant state of change, driven by meteorological and hydrodynamic features. Whilst no two beaches are identical, there are certain morphological components which are commonly found across most beach types. The relative dimensions of these features and indeed their presence or absence altogether, will vary depending on an array of variables. These include; the relative exposure, including fetch length, of the beach in relation to predominant meteorological conditions, hydrodynamic properties including tidal ranges and the amount of wave energy supplied to the beach face, as well as the sediment properties, such as grain size and fall velocity.

It is necessary to define and locate the various features of a beach profile and the associated hydrodynamic features of the nearshore zone in order to thoroughly investigate the processes that act within and delineate these regions.

2.2.1 Beach Profile

The relative locations of the individual beach face features are shown in Figure 2.12 and are described below, starting from the offshore zone moving towards the beach.

a) The Offshore Zone: The offshore zone refers to the comparatively flat section of seafloor that extends from the edge of the continental shelf to the beginning of the breaker zone (Komar, 1998).

b) The Nearshore Zone: The nearshore zone extends from the edge of the offshore zone to the beginning of the foreshore zone at the mean low water level at low tide, or the maximum drawback level of swash at high tide. The inshore zone may contain features such as longshore bars, which are ridges of sand running parallel to the shoreline. In low energy environments longshore bars commonly do not exist, whilst in high energy surf areas, parallel series of longshore bars may extend offshore for some distance (Komar, 1998). Additionally, in areas of high tidal range, longshore bars may become fully exposed at low tides. Trough features are also known to form within the inshore zone and are depressions that lie parallel to the shoreline and are often associated with bars (Dean & Dalrymple, 2002).

c) The Foreshore Zone: The foreshore zone (also known as the swash zone) is highly active and comprises the sloping portion of the beach between the berm
crest (if present) and the inshore zone. If a berm is not present, then the upper limit of the foreshore zone can be defined by the limit of the swash run-up (Komar, 1998). The foreshore zone contains the beach face which is the active zone over which the action of swash run-up and retreat occurs. The relative position of the foreshore zone is directly influenced by tidal fluctuations (Dean & Dalrymple, 2002).

d) **The Backshore Zone:** The backshore zone is bounded by the berm crest or the upper level of swash run-up on one side and the point of vegetation growth or physiography change on the landward side (Komar, 1998). The backshore zone can contain berm formations which are horizontal sections of sediment created through the deposition of particles from receding swash. Berms are not always present on beaches and are rarely found in low energy environments (Komar, 1998).

---

**Figure 2.12** Schematic diagram taken perpendicular to the beach showing major features.

### 2.2.2 Hydrodynamic Zones

The waters close to the coast may also be divided into a number of identifiable and distinct regions. These sections are represented schematically in Figure 2.13 and are described below, starting from offshore.

a) **The Offshore Zone:** This section represents the open ocean seaward of the point at which waves reach instability and break.

b) **The Nearshore Zone:** The nearshore zone refers to everything between the offshore zone and the high water mark. It is divided into three separate sections as follows:

I. **The Breaker Zone:** The breaker zone is the most seaward of the zones within the nearshore region. It includes the area where the incoming
swell reaches instability and breaks. This occurs at a depth that can be estimated using the following relationship.

\[ \gamma = \frac{H_b}{h_b} \]  \hspace{1cm} (6)

In this relationship a first order approximation of \( \gamma = 0.78 \) is valid and allows the calculation of the breaking depth, given the breaker height (McCowan, 1894; Sverdrup & Munk, 1946; cited in Komar, 1998). On wide, high energy beaches the breaker zone may re-occur closer to shore from the original breaking point.

II. The Surf Zone: This zone extends from the breaking point of the wave through to the swash zone. It is characterised by translational ‘broken’ waves that are constantly moving shorewards and inducing local turbulence, mixing and dispersion. This area is highly active with ongoing sediment transport, bar formation and nearshore current development (Dean & Dalrymple, 2002). The presence and width of a surf zone is primarily a function of the beach slope and tidal stage.

III. The Swash Zone: Also known as the foreshore or beach face, the swash zone exists between the highest level of the swash run-up on the beachface and the lowest level exposed during backwash.

\[ \text{Figure 2.13: Schematic diagram taken perpendicular to the beach and representing the major hydrodynamic zones.} \]

For the purposes of investigating mixing and dispersion within Adelaide’s coastal waters, the primary zones of interest within the nearshore region are the breaker and surf zones.

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*Literature Review*
2.2.3 Low Energy Beaches

The beach profiles in Figures 2.12 & 2.13 both represent beach systems with relatively high energy inputs driving dynamic processes such as sediment transport leading to a level of variability in the beach form. In contrast, beaches in low energy settings are known to display significantly different profiles, owing to the lack of forcing mechanisms that create morphological features in more energetic environments. Low energy beaches in Western Australia were found to consist of four primary profiles shown in Figure 2.14. These morphotypes were found to be strongly controlled by sediment characteristics, particularly mean particle size (Hegge et al., 1996).

![Figure 2.14: Low energy beach morphotypes (Hegge et al., 1996)](image)

Low energy beaches often have secondary features similar to those found in high energy environments, but are often smaller in scale (Jackson et al., 2002). Common diagnostic features that occur on low energy beaches include longshore and transverse bars, swash bars, vegetation and wrack accumulations, larger particles such as pebbles or shells and small aeolian dunes (Jackson et al., 2002). The beaches along the Adelaide metropolitan coastline display many of these features suggesting that they may be classed as low energy systems. Jackson et al. (2002) suggested a simple set of conditions for the classification of low energy beaches.

1) Non-storm significant wave heights are minimal (<0.25m).
2) Significant wave heights during strong onshore winds are minimal (<0.5m).
3) Beachface widths are minimal.
4) Morphological features include those inherited from high energy events.

Classification of the Adelaide beaches according to these parameters is not possible without the collection of detailed wave height data. However it is likely that any such study would conclude that the coastline is not strictly low energy, due to the occurrence of significant wave heights over 2m during storm events and the presence of a relatively active sea breeze system. Rather, it is likely that the area is characterised by seasonal variations in the dominant wave climate and hence beach profiles.
2.3 Nearshore Hydrodynamics

Surf-zone hydrodynamics is a highly complicated topic that addresses waves and wave generated phenomena within the nearshore region. Waves breaking on a sloping beach near to the shoreline release large amounts of energy which is predominantly expressed as turbulence in the water column (Svendsen & Putrev, 1996). As the waves progress towards the shore they increasingly interact with the bottom topography, the friction effects of which induce decreases in the momentum flux and wave height. This transfer of momentum instigates the formation of longer period waves and currents (Svendsen & Putrev, 1996) that ultimately drive processes such as mixing and dispersion within the surf zone.

2.3.1 Waves

Meaningful analysis of dynamics within the surf zone requires the detailed understanding of the mechanisms driving wave breaking and the creation of turbulence. This section addresses several key quantitative measures of the effect that incident waves have on nearshore hydrodynamics and current systems.

2.3.1.1 Wave Energy

The energy of a wave or wave train entering the nearshore zone is a key parameter driving coastal processes. Airy theory provides equations that describe the energy of a wave, that are based on the displacement of water particles due to the wave motion. Airy theory states that as a wave passes through a point the particles in that location will be displaced, moving through an orbit that is dependant on water depth, before returning to their original position and hence not resulting in a nett displacement of mass. The shape of the orbital path traversed by a particle varies with water depth, from circular offshore, to elliptical in shallow water. The energy of a wave is the sum of its kinetic and potential energy. The potential energy of a wave is a function of the variation in the free surface elevation of the water body due to the motion of the wave whilst the kinetic energy is derived from the orbital motion of the particles under the wave (Komar, 1998). These factors are integrated over the length of the wave to determine the formula for the total energy density, Equation 7.

\[
E = \frac{1}{8} \rho g H^2
\]

\[
E = \frac{1}{L} \int_0^L \int_0^h (\rho gz)dzdx + \frac{1}{L} \int_0^L -\frac{1}{2} \rho (u^2 + w^2)dzdx
\]

Since this energy density is dependant on the wave height, E will not remain constant as the wave travels into shallow water and breaks, as the wave height H varies.
significantly during this progression. The energy flux $P$ which is the total energy of the wave (as opposed to the energy density $E$ within the wave) follows the laws of conservation of energy and can be determined using Equation 8. In this equation $C$ is the celerity, $C_g$, is the group velocity and $n$ is a dimensionless ratio of wave group velocity to wave phase velocity. The value of $n$ varies between $1/2$ in deep water and 0 in shallow water.

$$P = E C n = EC_g$$ (8)

$P$ represents the wave power per unit crest length and is valuable as it is not susceptible to variation in the manner that $E$ is as the wave front approaches the beach (Komar, 1998).

2.3.1.2 Mass transport and Momentum

A flaw in the linear Airy theory is that a key assumption, particle motion in closed circular or elliptical orbits, does not take into account the mean motion of the water in the surf zone towards the shore (Dean & Dalrymple, 2002). That is, the elliptical particle orbits, which are assumed to be closed, actually involve a nett shoreward progression in the nearshore zone. It is possible to determine the mass transport towards the shoreline using Equation 9.

$$M = \int_{t_1}^{t_2} \int_{-h}^{\eta} \rho u(x, z) dz dt$$ (9)

$$M = \frac{E}{C}$$

The time interval between $t_1$ and $t_2$ must be significantly longer then the wave period in irregular wave conditions, or at least one wave period in regular conditions (swell). The integration is then carried out from the bottom to the free surface elevation $\eta$ in order to calculate $M$ accurately; if the mean surface level is used than the value of $M$ derived is equal to 0 (Dean & Dalrymple, 2002). Equation 9 shows that there is non-linear mass transport in the direction of wave propagation and it also shows that mass transport increases with more energetic wave conditions. Mass transport always has momentum associated with it, which can be found as the product of the group velocity and mass transport using Equation 10.

$$M = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \int_{-h}^{\eta} (\rho u) u dz dt$$ (10)

$$M = MC_g = En$$
The transfer of momentum through the action of breaking waves results in a force known as radiation stress.

### 2.3.1.3 Radiation Stress

Longuet-Higgins and Stewart (1964) developed the concept of radiation stress and defined it as the ‘excess flow of momentum due to the presence of waves’. This occurs because there is a large forward flux of momentum under the wave crest that is not balanced by the backward transport of momentum under the trough. Longuet-Higgins and Stewart (1964) designated the radiation stress as the sum of the momentum flux and the dynamic pressure. The dynamic pressure is calculated as the difference between the hydrostatic pressure and the absolute pressure and is used to ensure that the momentum being assessed is due solely to the presence of waves (Komar, 1998). These properties are related in Equation 11.

\[
M + \frac{1}{2} \rho g h^2 = S_{xx} + \frac{1}{2} \rho g (h + \eta)
\]

(11)

In Equation 11, the radiation stress is denoted by \(S_{xx}\) where the x-axis is placed in the direction of wave advance whilst the y-axis is parallel to the breaker line. As such \(S_{xx}\) represents the flux in the x direction of the x component of momentum (Dean & Dalrymple, 2002). Also included in Equation 11 is the mean water level set-down in the trough offshore from the breaker line, denoted by \(\eta\) where:

\[
\eta = \left( \frac{H^2 k}{8 \sin(2kh)} \right)
\]

By substituting this result as well as Equation 10 into Equation 11, it is possible to derive an equation for \(S_{xx}\). The radiation stress across the plane x (constant parallel to the shore)

\[
S_{xx} = E \left( \frac{kh}{\sinh(2kh)} \right)
\]

(12)

\[
S_{xx} = E \left( 2n - \frac{1}{2} \right)
\]

In deep water \(n = \frac{1}{2}\) such that \(S_{xx} = E/2\), whereas in shallow water \(n = 1\) and hence \(S_{xx} = 3E/2\) (Komar, 1998). Equation 12 is valid for waves traveling in the x-direction, however if waves approach from an angle \(\theta\) to the x-axis then the following radiation stress will apply (Dean & Dalrymple, 2002).

\[
S_{xx} = E \left[ n \left( \cos^2 \theta + 1 \right) - \frac{1}{2} \right]
\]

(13)
As can be seen in the preceding Equations (12&13), the value of the radiation stress \( S_{xx} \) is dependant on the energy density of the wave, as determined in Equation 7.

### 2.3.1.4 Wave Set-up and Set-down

Waves entering the shallow near shore region undergo a variety of transformations, increasing in amplitude and steepness before breaking. This process induces radiation stress and momentum balance stipulates that changes in the shorewards component of the radiation stress must be balanced by changes in the mean water level as shown in Equation 14 (Horikawa (ed), 1988). Through this process, variations in the mean water level elevation are able to develop known as wave set-up and set-down.

\[
\frac{\delta S_{xx}}{\delta x} = -\rho gh \left( \frac{\delta \eta}{\delta x} \right) 
\]

\[ (14) \]

Moving offshore, outside of the surf zone, wave height and hence radiation stress increase due to wave shoaling. The resulting positive gradient in radiation stress must be balanced by a corresponding decrease in the water surface gradient. This results in a lowering of the water level elevation immediately offshore from the surf zone, known as wave set-down, which is described by Equation 15, which is derived through the integration of Equation 14 (Horikawa (Ed.), 1988).

\[
\bar{\eta} = -\frac{1}{8} \left( \frac{H^2k}{\sinh(2kh)} \right)
\]

\[ (15) \]

Within the surf zone, wave breaking dissipates energy and decreases wave height leading to a negative gradient in the radiation stress. This negative gradient is balanced by an increase in the water surface gradient, resulting in an elevated water surface in the surf zone (Dean & Dalrymple, 2002). By assuming that the height of the broken wave decreases linearly towards the shoreline of a planar beach it is possible to determine the set-up at the shoreline using Equation 16 (US Army Corps, 2002; Olsson, 2004).

\[
\bar{\eta}_s = \bar{\eta}_b + \left( \frac{1}{1 + \frac{8}{3\gamma_b^2}} \right) h_b 
\]

\[ (16) \]

In this Equation \( \gamma_b \) refers to the breaker depth index, \( \eta_s \) is the set-up at the shoreline and \( \eta_b \) is the set-down at the breaking point (US Army Corps, 2002).
2.3.2 Currents

Nearshore currents are primarily driven by waves that are incident on the coastal region; however tidal fluctuations and winds blowing in the longshore direction can also influence current magnitudes (Komar, 1998). They are central to the transport of sediment within the nearshore zone and as such are important factors in driving morphological change. The study of nearshore currents also presents a key concept in the determination of transport, mixing and dispersion of pollutants in the nearshore, as they represent direct controls on these processes. The total current in the nearshore zone can be represented as the sum of a number of forcing mechanisms, each acting on different scales, as shown in Equation 17.

\[ u = u_w + u_t + u_a + u_o + u_i \]  

(17)

This represents the steady current \( u \) as the sum of the action of breaking waves \( u_w \), currents driven by strong local winds \( u_a \), tidal current \( u_t \), infragravity waves \( u_i \) and oscillatory flows due to wind waves \( u_o \) (US Army Corps, 2002).

2.3.2.1 Types of Nearshore Currents

Nearshore current systems can be separated conceptually into two key classifications based on temporal and spatial variability. Quasi-steady currents are relatively stable in a temporal and spatial sense. They exist for extended periods of time and display nett long term average velocities (Johnson, 2004). In contrast, a large number of variable nearshore currents also exist. These are characterised by shorter periods and a high degree of spatial and temporal variability, and thus they are associated with zero long term mean flows (Johnson, 2004).

**Governing Equations**

Nearshore currents can be defined from the equations of momentum and continuity, which ensures conservation of mass, shown in Equations 19, 20 and 21 (US Army Corps, 2002; cited in Olsson, 2004). These equations relate the primary driving force of nearshore currents, the momentum flux due to breaking waves, to the bottom friction, wind and wave forcing and lateral mixing.

Continuity equation:

\[ \frac{\delta(Ud)}{\delta x} + \frac{\delta(Vd)}{\delta y} = 0 \]  

(18)
Equation of momentum in the x-direction:

\[
U \left( \frac{\partial U}{\partial x} \right) + V \left( \frac{\partial U}{\partial y} \right) = -g \left( \frac{\partial \eta}{\partial x} \right) + F_{bx} + L_x + R_{bx} + R_{xx} \tag{19}
\]

Equation of momentum in y-direction:

\[
U \left( \frac{\partial V}{\partial x} \right) + V \left( \frac{\partial V}{\partial y} \right) = -g \left( \frac{\partial \eta}{\partial y} \right) + F_{by} + L_y + R_{by} + R_{xy} \tag{20}
\]

Where:

- \( U \) is the cross shore current averaged against time and depth.
- \( V \) is the long shore current average against time and depth.
- \( F_{bx}, F_{by} \) are the cross shore and longshore components of bottom friction which is a function of bottom roughness along with wave and current velocities.
- \( L_x, L_y \) are the cross shore and longshore components of lateral mixing, the exchange of momentum due to turbulent eddies.
- \( R_{bx}, R_{by} \) are the cross shore and longshore components of wave forcing.
- \( R_{xx}, R_{xy} \) are the cross shore and longshore components of wind forcing.

**Quasi-Steady Current Systems**

There are two primary quasi-steady current systems, the first of which is longshore currents. Longshore currents propagate parallel to the shore in the nearshore zone and are driven by waves approaching the shoreline at an oblique angle. The nearshore current system developed by obliquely incident waves is shown in Figure 2.15.

![Oblique angle of wave approach driving longshore currents](image)

**Figure 2.15:** Current pattern observed in the nearshore region under obliquely incident wave conditions.
The longshore current in Figure 2.15 is generated by changes in the momentum flux of the wave field in the alongshore direction resulting in a transfer of momentum from the wave field to the mean longshore current (Johnson, 2004). Assuming that the effects of wind stress are negligible, incident wave conditions are homogenous in the alongshore direction and that bottom topography is constant, it is possible to determine that the transfer of momentum is balanced by frictional forces between the flow and the seabed, as well as through the exchange of lateral momentum (Longuet-Higgins 1970a, 1970b; cited in Olsson, 2004). This results in the reduction of the nearshore governing equations (Section 2.3.2.2) to Equation 21 which is the balance of wave forcing $R_{by}$ with the cross shore radiation stress gradient $S_{xy}$ and bottom friction. $S_{xy}$ is the radiation stress for obliquely incident waves (Longuet-Higgins 1970a, 1970b; cited in Olsson, 2004) determined for obliquely incident waves using Equation 22.

$$R_{by} = -\frac{1}{\rho d} \frac{\delta S_{xy}}{\delta \xi} \quad (21)$$

$$S_{xy} = \frac{n}{8} \rho g H^2 \cos(\alpha) \sin(\alpha) \quad (22)$$

Rip currents are also classed as quasi-steady currents. Rip currents are a generic name used to describe strong, narrow offshore directed flows that pass through the surf zone often carrying sediment and debris that discolours the water compared to adjacent areas (Komar, 1999; Brander 1998, Short 1985). Rips pose a significant threat to swimmers as they can carry swimmers offshore into deep water at speeds exceeding 2ms$^{-1}$ (Belloti, 2004; Dean & Dalrymple, 2002). Experimental results show that rips occur predominantly in medium to high energy wave environments and are known to vary in intensity, spacing and size in direct proportion with the dominant wave regime (Short, 1985). In these conditions it is observed that rips are a function of the prevailing wave conditions, as well as the direction and rate of change in the dominant wave climate (Short, 1985). However, it is also observed by Brander (1999) that the flow in low energy rip currents is modulated by tidal fluctuations, with maximum flow occurring at low tide and minimums recorded at high tide. Rip currents are formed primarily due to longshore variations in radiation stress, the resulting imbalance between the free surface set-up and the radiation stress induces a region of narrow offshore directed flow. Figure 2.16 represents the generic features driving rip current flow in the nearshore region, resulting in a nearshore circulation cell. Nearshore circulation cells are constrained within the surf zone, however their lengths are

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variable, with the spacing between rip features ranging between one and eight times the width of the surf zone (Inman et al., 1971). Nearshore circulation cells are responsible for a continuous flow of water between the surf zone and the offshore zone and act as distributing mechanisms for contaminants present within the surf zone (Inman et al., 1971).

Figure 2.16: Schematic diagram of a nearshore circulation cell, including rip currents driven by longshore variation in radiation stress.

There are various factors which can induce longshore variation in radiation stress which are summarised in Table 2.4. Whilst it is not appropriate to discuss each of these factors individually, it is prudent to acknowledge that they fall under two broad classifications. Firstly, there are fixed topographic controls such as offshore islands or breakwaters which directly influence the incident radiation stress or direction of radiation stress affecting the beach (Dean and Dalrymple, 2002). Secondly, hydrodynamic interactions between the incident wave field and currents (wave-current interactions) or infragravity features (wave-wave interactions) will induce periodic variations in the longshore wave climate leading to variable radiation stresses (Dean & Dalrymple, 2002; Johnson, 2004). These transient rip formations can occur on topographically homogeneous systems and hence rarely remain stationary with time (Johnson, 2004).
Table 2.4: General rip formation mechanisms (adapted from Dean and Dalrymple (2002) and Horikawa (1988) cited in Johnson (2004)).

<table>
<thead>
<tr>
<th>Forcing Mechanisms</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wave-wave Interactions</strong></td>
<td></td>
</tr>
<tr>
<td>Incident/synchronous edge wave interaction</td>
<td>Bowen (1969); Harris (1967)</td>
</tr>
<tr>
<td>Incident/infragravity edge wave interaction</td>
<td>Bowen and Inman (1969); Sasaki and Horikawa (1974)</td>
</tr>
<tr>
<td>Intersecting wave trains</td>
<td>Dalrymple (1975); Fowler and Dalrymple (1990)</td>
</tr>
<tr>
<td>Incident wave group/edge wave interaction</td>
<td>Symonds and Ranasinghe (2001)</td>
</tr>
<tr>
<td><strong>Wave-Curent Interactions</strong></td>
<td></td>
</tr>
<tr>
<td>Refractive wave/current interaction</td>
<td>Dalrymple and Lozano (1978)</td>
</tr>
<tr>
<td>Dissipative wave/current interaction</td>
<td>Murray and Reydellet (2002)</td>
</tr>
<tr>
<td><strong>Topographic Interactions</strong></td>
<td></td>
</tr>
<tr>
<td>Bottom Topography</td>
<td>Zyserman et al (1990); Sonu (1972); Noda (1972); Sasaki (1974)</td>
</tr>
<tr>
<td>Coastal Boundary - Breakwater</td>
<td>Liu and Mei (1976)</td>
</tr>
<tr>
<td>Coastal Boundary - Islands</td>
<td>Mei and Angelides (1977)</td>
</tr>
<tr>
<td>Barred Coastline</td>
<td>Dalrymple (1978)</td>
</tr>
<tr>
<td>Coupled sediment/water interaction</td>
<td>Hino (1975)</td>
</tr>
</tbody>
</table>

Undertow is another quasi-steady current in the nearshore zone, it occurs because of the nett onshore mass transport induced by wave action described by Equation 9. As there can be no nett onshore flow of water, the mass inflow \( M \) must be transported out of the surf zone by the undertow. This flow is not uniformly distributed with depth due to the decrease in wave-induced stress with depth (Dean and Dalrymple, 2002).

**Variable Currents**

Variable currents are features of nearshore circulation which display flow with frequencies lower than the incident wave climate, but with a higher level of variability than the quasi-steady currents active in areas which are restricted by the incident wave climate and or topography (Johnson, 2004). There are two classes of variable nearshore waves; infragravity waves and shear waves.

Infragravity waves are oscillations in the water level within the surf and swash zones that occur due to long period variations in the wave set-up caused by the passage of wave groups. A variety of energetic infragravity waves exist within the nearshore zone with periods of between 20 and 200 seconds including edge waves and surf beat (Johnson, 2004; Olsson, 2004; Svendsen & Putrev, 1996). Long period infragravity waves generally form standing waves on sloped beaches due to their low wave steepness (Horikawa (ed), 1988). As such, the signal associated with infragravity is often the dominant energy on sheltered beaches with several studies indicating that the dominant component of energy in the swash oscillations is in the period of infragravity variations rather than the sea or swell bands (Wright et al., 1982; Guza &
Surf beat is driven by variations in the height of wave groups incident on the beach. When wave groups of high mean amplitude are incident, the level of set-up on the beach increases, whilst during periods of lower waves the mean set up is lower. This oscillation induces an offshore radiation of forced water level variation at the frequency of the incident wave groups (Dean & Dalrymple, 2002). Similarly, edge-waves are generated through the non-linear interaction of the incident wave field with the edge-wave wave form (Lippman et al., 1997; cited in Johnson, 2004). Edge waves are generated by obliquely incident long period waves and are restricted to the beach; as they move way from the beach they refract back towards it and are again reflected at such an angle that they return to the beach, this process continues as shown in Figure 2.17 (Horikawa (ed), 1988). In the case of leaky mode edge waves the level of refraction is not sufficient to hold the waves to the shoreline and they are able to ‘escape’ offshore. Edge waves are significant sources of energy within the nearshore as they are able to trap the energy of the oscillations with minimal dissipation offshore (Komar, 1998).

![Figure 2.17: Trapped and leaky mode edge waves. Trapped waves are reflected from the beach at such an angle that they are subsequently refracted back onshore, whilst leaky modes are not sufficiently refracted and as such ‘escape’ offshore.](image)

The variations in wave breaking induced by the presence of surf beat or edge waves sets-up a longshore variation in radiation stress and as such forces low frequency motion in the surf zone (Johnson, 2004).
Shear waves are another infragravity effect that can influence the magnitude of longshore currents. Shear waves are low frequency, wave-like oscillations of longshore currents with periods and wavelengths of 100 seconds and 100 metres respectively (Svendsen & Putrev, 1996). They are driven by the incidence of large waves upon the shoreline causing an oscillation in the velocity of flow within the longshore at a low frequency (Dean & Dalrymple, 2002). Shear wave motion relies on the action of cross-shore shear as a restoring force rather than gravity (Bowen & Holman, 1989; Dean & Dalrymple, 2002). This motion occurs in the horizontal plane and causes the longshore current to move back and forth across the surf zone. The total velocity variance in the longshore current due to the action of the shear waves can exceed that due to other infragravity effects such as edge waves or surf beat (Howd et al., 1991; cited in Johnson, 2002). It has also been suggested by Kirby et al. (1998) that resonant interactions may exist between shear waves and the other infragravity effects; however these relationships have not yet been investigated.

2.3.3 Dispersion and Mixing

Mixing and dispersion are key processes within the surf zone and coastal waters. They are critical parameters to consider when investigating the ability of coastal waters to receive and dilute discharged material (List et al., 1990). In the case of the Adelaide coastal waters, the level of mixing and dispersion determines the transport and dilution of contaminants entering the nearshore zone from outlets such as the Patawalonga and Torrens Rivers.

The energy required for driving mixing and dispersive processes in the nearshore region is derived primarily from wave action incident on the shore as well as wind and coastal currents (Inman et al., 1971). Within the surf-zone, waves interact with currents and other waves, which results in two well-defined mechanisms that drive mixing. The first of these is the turbulence of the breaking wave which drives rapid mixing along the path of the wave bore in an onshore direction. Secondly, wave-current interactions drive advective transport in both the alongshore and cross-shore directions forming circulative cells, these interactions are complex and are known to involve low frequency fluctuations (Oltman-Shay et al., 1989) of the current field and circulation through the vertical plane driving horizontal momentum mixing (Svendsen & Putrev, 1994; cited in Takewaka et al., 2003). Circulative cells (Figure 2.16) consist of longshore currents and seaward flowing rips and are responsible for a
continuous interchange of water between the nearshore and offshore regions. As such they are key dispersal mechanisms for material injected into the surf zone. The intensity, frequency and direction of the incident wave climate, as well as the dimensions of the nearshore circulatory cells, have been found to be key variables impacting on the nearshore mixing processes (Inman et al., 1971).

2.3.3.1 **Key Definitions and Concepts**

The terminology used to describe mixing and dispersion can be somewhat convoluted and in many cases in the literature the same term is used to describe quite different phenomena. For consistency and clarification, the key terms used in this document pertaining to mixing and dispersive processes within the surf zone are defined according to Fischer et al. (1979).

- **Mixing**: Any process that leads to one parcel of water becoming intermingled with, or diluted by another, referring specifically to the action of dispersion and diffusion.
- **Dispersion**: The process of scattering particles or a cloud of contaminants through the combined effects of shear and transverse diffusion.
- **Diffusion (Turbulent)**: The random spreading of particles through turbulent motion. Turbulent diffusion is considered to be somewhat analogous to molecular diffusion; however the scales of motion, described by ‘eddy’ diffusion coefficients, are significantly larger.
- **Diffusion (Molecular)**: Refers to the scattering of particles through random molecular motion. This is described by Fick’s Law of diffusion, Equation 23, where \( q \) represents the solute mass flux, \( C \) is the mass concentration of a diffusing solute and \( D \) is the co-efficient of proportionality otherwise known as the molecular diffusivity.

\[
q = -D \frac{\partial C}{\partial x}
\]  

These definitions should be complemented with the following definitions of transport mechanisms, again for the purpose of consistency within this document.

- **Advection**: transport due to an imposed current system, including quasi-steady and variable currents in the nearshore region.
- **Shear**: The advection of fluid at varying velocities at different positions. Shear occurs in changes in current velocity and direction with depth in complex estuarine and coastal flow regimes.
2.3.3.2 Richardson’s Law & The Dispersion Co-efficient

The concept of turbulent relative dispersion was established by Richardson (1926) in his analysis of the observed increase in turbulent diffusivity between molecular scales of motion and general circulation. In his analysis Richardson (1926) considered the separation statistics of a cluster of a large number of marked molecules and argued that the mean square separation attains a limit as the averaging time is increased. He reasoned that this is because only eddies comparable in size with the separation of the particles will be effective in increasing their separation (cited in Sawford, 2001). Using a range of diffusion data obtained from molecular to global scales Richardson (1926) derived Equation 24 describing the regime of relative turbulent diffusion through the relationship of horizontal variance and eddy diffusivity.

\[ \sigma^2 = c_1 \varepsilon t^3 \]  

(24)

Where \( \sigma^2 \) represents the horizontal variance of the marked particles, \( c_1 \) is a numerical constant, \( t \) is the time and \( \varepsilon \) is the rate of energy dissipation. Using Equation 24 it is possible to derive the relationship between the apparent diffusivity and the scale of diffusion in Equation 25 (Fischer et al., 1979).

\[ K_a = c_2 \varepsilon^{\frac{2}{3}} t^{\frac{4}{3}} \]  

(25)

In Equation 26, \( K_a \) is the apparent diffusion co-efficient derived from the variance and defined by Equation 26.

\[ K_a(t) = \left( \frac{1}{2} \right) \left( \frac{\delta \sigma^2(t)}{\delta t} \right) = c(\sigma^2)^{\frac{2}{3}} \]  

(26)

These relationships are derived on the basis that the eddy’s responsible for the horizontal spread of a cluster of particles are locally isotropic and homogenous, thus suggesting that the eddy properties are dependant only on the rate of energy dissipation. However, in the turbulent flow of the surf zone, it is clear that neither homogeneity nor isotropy is maintained.

Whilst, Richardson’s 4/3 power law was initially developed in the description of turbulent diffusivity in the atmosphere, it also forms the basis of turbulent relative dispersion theories in the ocean. Witting (1933) was the first to demonstrate that the effective diffusivity increases with the scale of diffusion in the ocean, whilst
Richardson and Stommel (1948) applied the atmospheric eddy diffusion laws to the sea surface (cited in Sawford, 2001). Richardson’s (1926) developments influenced the work of Kolmogorov (1941) who derived a similar theory for small scale processes. This formed the basis of Okubo’s (1974) analysis of observed oceanic diffusion diagrams. Okubo developed two types of diffusion diagrams, the first representing horizontal variance $\sigma^2$ with time and the other plotting the apparent diffusivity $K_a$ against a length scale of diffusion, nominally $\sigma$ as shown in Figure 2.18. Okubo concluded that the apparent diffusivity increases with the scale of diffusion at a rate fitting the 4/3 law, remaining accurate over a wide range of scales, ranging from 10m to 1000km.

![Figure 2.18: Float dispersion compared to diffusion coefficient (Okubo, 1974). The vertical axis is the apparent diffusivity $K_a$ (cm$^2$s$^{-1}$).](image)

This scale variation is significantly larger than that predicted by Batchelor (1952) and Kolmogorov (1941) and significantly, none of the conditions cited in the derivation of this co-efficient are valid within the surf zone. Namely, within the surf zone
conditions are neither homogeneous nor stationary and a clear boundary exists. However, various other studies of diffusion collated by Okubo (1974), not reliant on such strict conditions, give rise to the same diffusion law (cited in Johnson et al., 2004). Thus, processes other than those described by the classical analysis of Batchelor (1952) may lead to the 4/3 law (Fischer et al., 1979). Scale dependence is observed in the results of Johnson (2004) when compared to those of Rodriguez (1995). At smaller scales the values of $K$ derived compare favourably; however at larger scales, the values of $K$ vary by orders of magnitude. This suggests that caution is required when comparing dispersion values in the nearshore (Johnson, 2004).

The dispersion estimate obtained from the analysis of drifter positions using Equation 24 also includes the effects of shear flow and turbulent diffusion. By removing shear induced spreading, rotation and divergence from the apparent dispersion ($K$) it is possible to estimate the true horizontal turbulent diffusivity (Tseng, 2001).

### 2.4 Studies of Mixing and Dispersion in the Surf Zone

The measurement of spatially variable currents within the nearshore zone is an area of research that has been relatively neglected in the literature with relatively few studies having been conducted in this area. The majority of field investigations have utilised Eulerian measurement techniques involving the deployment of an array of stationary sensors that measure the current properties, from a fixed frame of reference, at a specific location. Whilst the use of Eulerian arrays has been the pre-eminent field investigation approach, the number of sensors required to accurately define spatial scales of motion, has restricted their potential application in the analysis of mixing and dispersion.

Conversely, a minority of field studies have utilised Lagrangian measurement techniques, relying on a moving frame of reference, through which the behaviour and properties of the fluid flow can be tracked with time. Lagrangian experimental approaches provide reliable data pertaining to the spatial structure of current formations, from a small number of instruments (in the case of drifters). As a result Lagrangian methodologies are generally less expensive to deploy, as fewer instruments and consequently less manpower is required to obtain the same data as an Eulerian array. Significantly, for determining the fate of contaminants in the nearshore zone, Lagrangian techniques allow the calculation of diffusion coefficients.
with a greater level of accuracy than fixed current meters (Pal et al., 1998). Johnson (2004) comprehensively addresses a number of studies using Lagrangian measurement techniques. These studies focus primarily on the description and quantification of topographic rip currents and use a variety of tracking techniques compiled in Table 2.5.

Table 2.5 Lagrangian methods employed in tracking currents in the nearshore zone (adapted from Johnson 2004).

<table>
<thead>
<tr>
<th>Lagrangian Field Measurement Technique</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface floats and drogued drifters fixed using a compass from a boat or shore</td>
<td>Shepard et al. (1941); Shepard &amp; Inman, (1950); Sonu, (1972)</td>
</tr>
<tr>
<td>Live' floats, swimmers tracked by theodolite</td>
<td>Short &amp; Hogan, (1994); Brander &amp; Short, (2000)</td>
</tr>
<tr>
<td>Floats and balloons tracked by successive aerial photographs.</td>
<td>Sasaki &amp; Horikawa, (1975, 1978)</td>
</tr>
<tr>
<td>Dye releases tracked by sequential aerial photography and observations</td>
<td>Bowen &amp; Inman (1974); Rodriguez et al. (1995); Takewaka et al. (2003)</td>
</tr>
<tr>
<td>Surface drifters tracked by non-differential GPS technology</td>
<td>Johnson, (2004); Olsson (2004)</td>
</tr>
</tbody>
</table>

The dye diffusion experiments, specifically those conducted by Inman et al. (1971), Bowen & Inman (1974), Rodriguez et al. (1995) and Takewaka et al. (2003), utilised the original measurement technique of dispersion in real surf zones. However, following the concurrent development of surf zone drifters utilising satellite GPS technology by Johnson et al. (2003) and Schmidt et al. (2003), further studies into surf zone mixing and dispersion have been conducted by Johnson (2004) and Olsson (2004).

GPS tracked drifters have also been utilised in larger scale oceanographic deployments. List et al. (1990) carried out investigations into diffusion and dispersion in coastal waters offshore from California using large sea going drogues, whilst Tseng (2004) deployed drifters in the eddy formations formed in the wake of small islands. These studies formed much of the theoretical and analytical foundations for latter dispersion based work carried out in the nearshore region.

### 2.4.1 Dye Diffusion Experiments

Dye diffusion experiments have been used since the late 1950’s to study mixing processes in the open sea (Bowles et al. (1958) cited in Riddle and Lewis, 2000); however, to the author’s knowledge the first field studies into mixing and dispersion within the surf zone were carried out by Inman et al. (1971). These investigations were undertaken at three natural beaches across southern California and northern
Mexico with incident wave climates ranging between 0.3m and 1m at sites in the sheltered Gulf of California to between 1m and 2m at sites exposed to the Pacific Ocean. Rhodamine B dye, a conservative tracer, was injected into the surf zone and water samples were collected at various temporal and spatial intervals. The analysis of the fluorescence of the water samples, with respect to calibrated standards of known concentration allowed the calculation of the effective dilution. Further measurements were taken to obtain information pertaining to the direction and flux of wave energy entering the surf zone, the large scale circulation of the current system and the beach morphology. Through this, Inman et al. (1971) were able to identify and quantify two key mixing mechanisms within the surf zone, each having distinctive length and time scales determined by the incident wave climate and surf zone dimensions. Rapid turbulent mixing in the onshore direction associated with wave breaking and the motion of the wave bore, was described by Equation 27 where; $\varepsilon_x$ is the onshore-offshore diffusivity co-efficient, $H_{rms}$ is the root mean square (rms) breaker height, $X_b$ is the surf zone width and $T$ is the period of the peak of wave energy spectra (Inman et al., 1971). Equation 27 directly relates the incident wave regime to the level of mixing in the onshore-offshore direction (the y axis is denoted as lying parallel to the beach).

$$\varepsilon_x \equiv \frac{(H_{rms})_b X_b}{T} \quad (27)$$

Along the ocean beaches investigated by Inman et al., (1971), the value of the diffusivity co-efficient was found to be in the order of 2-5.9m²s⁻¹ in the cross-shore direction, whilst in the longshore direction it was found to range between 0.13-0.17m²s⁻¹. In the more sheltered beaches of El Moreno, Mexico, the cross-shore diffusivity was found to be significantly lower, ranging between 0.08-0.3m²s⁻¹ in the cross-shore, whilst in the longshore direction diffusivity ranged between 0.03 and 0.08m²s⁻¹.

Inman et al. 1971 were also able to describe advective mixing within the surf zone associated with longshore and rip current systems. Their description is shown in Equation 28 where $N$ is the concentration of dye in the $n^{th}$ cell down current from the point of injection and is a function of the initial tracer concentration $N_0$, the longshore discharge of water between adjacent cells $Q_l$ and the maximum longshore current discharge $Q_m$ (Inman et al., 1971).

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Analysis by Inman et al. (1971) also showed that diffusion patterns could be described approximately by one and two dimensional Fickian diffusion parameters depending on the size of the injected patch and the surf zone width. In its simplest form the eddy diffusivity \( \varepsilon \) is assumed to be constant in any direction, and hence diffusion follows Fick’s Law. However, in large scale oceanic diffusion, Fickian parameters are not effective descriptors, as the flux of a diffusing quantity is dependant primarily on length and time scales of eddies. Inman et al. (1971) found that the diffusive processes within the surf zone were highly organised with length and time scales related to the incident wave climate, Equation 27 and hence can be described by Fickian processes. When the patch size was small compared to the width of the surf zone, the diffusion patterns could be described using the two dimensional Fickian diffusion relationship, Equation 29. In this situation the patch was effectively unbounded and as such diffusion was able to occur both in the longshore and on-offshore planes (y and x respectively). However, when the patch dimensions were of a similar magnitude to the width of the surf zone, the diffusive behaviour was effectively bounded in the on-offshore direction, along the x plane. In this situation only longshore diffusion was possible and was described by Inman et al. (1971) using Equation 30, which is normalised for boundaries at the waterline and the edge of the surf zone through which minimal transport takes place, except via defined rip currents. Eventually, the spread of dye throughout the surf zone means that patches, that were originally two dimensional reach the boundaries and are able to be described by the one dimensional Equation 30. Equations 29 and 30 both describe the concentration of an injected tracer at a point with time; \( A_0 \) represents the total volume of tracer injected whilst \( \varepsilon_x \) and \( \varepsilon_y \) are the diffusivity coefficients in their respective planes. Note that the one dimensional equation, Equation 30, acts only on the y-plane, in the direction of longshore transport.

\[
N'(x, y, t) = \left( \frac{A_0}{4\pi(\varepsilon_x \varepsilon_y)^{1/2}} \right) \exp \left[ \frac{-\left( x^2 \right)}{4\varepsilon_x t} - \frac{-\left( y^2 \right)}{4\varepsilon_y t} \right] \times \left[ \left( \frac{1}{(2\pi)^{1/2}} \right) \times \int_{-a}^{a} \exp \left[ \frac{-\left( x^2 \right)}{4\varepsilon_x t} - \frac{-\left( y^2 \right)}{4\varepsilon_y t} \right] dy \right]^{-1}
\]

(29)

\[
N(y, t) = \left( \frac{A_0}{4\pi a^{1/2}} \right) \times \exp \left[ -\frac{y^2}{4\varepsilon_y t} \right]
\]

(30)
Following from the significant advances of others including Longuet-Higgins (1970 & 1972) and Inman et al. (1971), Bowen and Inman (1974) were able to assign quantitative values to the nearshore mixing due to waves within and offshore of the surf zone as well as through longshore currents. However, rather than deriving the eddy diffusivity co-efficient as shown in Equation 27 and utilised in Equations 29 and 30, Bowen and Inman (1974) utilised the nomenclature $A_H$ to describe the horizontal kinematic eddy viscosity, a value equivalent to $\varepsilon_x$. Offshore of the surf zone, Bowen and Inman (1974) cite the work of Masch (1963) and Thornton (1973) in developing two equations for the kinematic eddy viscosity. The derivation of eddy viscosity by Masch (1963) takes two forms depending on the presence of wind, shown in Equations 31 and 32. The derivation is based on the linear Airy theory and relates the eddy viscosity to the wave amplitude $a$, the wave number $k$, the maximum orbital velocity $u_m$, the wind speed $U$ and gravity. The wave steepness ($ak/\pi$) range under which these equations were evaluated by Masch (1963) is limited, ranging between 0.08 and 0.12. Consequently, Equations 31 and 32 are not directly applicable to realistic coastal situations under which the wave steepness may vary by orders of magnitude.

$$A_H \approx \frac{ak(Uu_m^2 + u_m^4)}{g}$$  \hspace{1cm} (31)

$$A_H \approx \frac{ak u_m^2 (1 + ak)}{g}$$ \hspace{1cm} (32)

Thornton (1970) approached the derivation of $A_H$, outside of the surf zone, from a different perspective to Masch (1963) finding the eddy viscosity to be dependant on the orbital velocity $u$ and the particle displacement $\tau$ as shown in Equation 33.

$$A_H = |u\tau| = \frac{a^2 \sigma}{\pi}$$ \hspace{1cm} (33)

The values of $A_H$ derived from Thornton’s (1970) equation are significantly higher than those derived by Masch (1963) which is due to the fact that Equation 33 is applicable for higher wave steepness such as is encountered close to the edge of the surf zone where more vigorous mixing is expected. From this comparison it can be
seen that deep water results and assumptions are not directly applicable to shallower areas.

Bowen & Inman (1974) also address the quantification of mixing rates in longshore currents and within the surf zone; obtaining the same outcomes as described in Inman et al. (1971). Bowen and Inman (1974) suggested that in the longshore direction, mixing is described by Equation 28 whilst, in the surf zone, mixing is dominated by the incident wave field properties, as described in Equation 27. Also noteworthy is the work of Longuet-Higgins (1970a&b) who suggested that the eddy viscosity in the surf zone is a function of the distance from shore and a characteristic velocity given by the celerity \( \sqrt{gh} \) as shown in Equation 34.

\[ A_H = 0.4 N \sqrt{gh} \]  

(34)

The primary drawback of this approach is that the eddy viscosity is overestimated beyond the wave breaking depth, where eddies induced by the turbulence of the wave motion decrease rapidly.

Following the dye diffusion experiments of the early 1970’s little field work addressing mixing and dispersion in the nearshore zone was undertaken until 1995 when Rodriguez et al. (1995) used a combination of numerical models and field dye diffusion experiments to investigate pollutant dispersal on beaches along the Spanish Mediterranean coastline. The dispersion coefficient value obtained from the numerical model of \( K_h = 0.018 \text{m}^2\text{s}^{-1} \) correlated well with the experimental results of \( K_h = 0.03\pm0.01 \text{m}^2\text{s}^{-1} \), which was obtained by relating the dispersion coefficient to a numerical constant \( \beta \), the water depth and the shear velocity \( u^* \). In this work, Rodriguez et al. (1995) noted the complexity of non-linear turbulence–wave-current interactions and commented that this complexity was the reason why ‘after 20 years of studies, there are no universally accepted “complete” formulations neither for dispersion nor for eddy viscosity’.

Takewaka et al. (2003) conducted dye dispersion experiments in a longshore current driven by an obliquely incident wave field of significant height 0.56m and period 6.5 seconds. The experimental design consisted of a dye discharging apparatus mounted on a pier and an ensemble of photographic and video recording equipment.
suspended from helium filled balloons, at a height of approximately 200m above the sea. This equipment was utilised to obtain imagery of the spatial and temporal variation in the injected dye patch. Through analysis of the imagery Takewaka et al. (2003) were able to qualitatively describe the dye behaviour as resembling dispersion in a shear flow field as described by Fischer et al., 1979 and Svendsen and Putrevu (1994). The patch was advected alongshore with the dominant longshore current, spreading along this axis was due to variations in the velocity field of the longshore current as well as turbulent diffusion. Spreading observed in the cross shore direction was due to turbulent diffusion in the surf zone and cross shore transport. Digital processing techniques were applied to the imagery which allowed the size of the patch to be calculated by setting thresholds for the colouration of individual pixels. Through this process the standard deviation of the patch could be determined in both the x and y directions as shown in Equations 35. In Equation 35 the values of $X_c(t)$ and $Y_c(t)$ are values representative of the average size of the patch, calculated through assigning values of 1 or 0 to each pixel depending on whether it met assigned threshold values and averaging across the entire image.

\[
\sigma_x(t) = \sqrt{\frac{1}{N} \sum \left( (x - X_c(t))^2 \right) g(x, y, t)}
\]

\[
\sigma_y(t) = \sqrt{\frac{1}{N} \sum \left( (y - Y_c(t))^2 \right) g(x, y, t)}
\]

The standard deviations derived in Equation 35 were used to quantitatively verify the physical observations. This allowed the identification of three distinct stages in the evolution of the dye patch. The stage initially following injection was characterised by a consistent, steady increase in both $\sigma_x$ and $\sigma_y$ as the patch deformed from its original circular shape into a stretched somewhat elliptical form. Following this stage the patch underwent rapid deformation in the longshore direction due to the shear effects of the prevailing longshore current, resulting in an increase in $\sigma_y$. Physical observations verify that the increase in $\sigma_y$ was due to shear dispersion in the longshore current as no turbulence was induced by breaking waves across the patch path. The final stage of patch evolution is characterised by the increasing contribution of diffusion in the cross shore direction and an increase in the rate of change of $\sigma_x$. The calculated values of $\sigma_x$ and $\sigma_y$ were plotted against time and used by Takewaka et al., (2003) to determine the dispersion coefficient $K_x$. Takewaka et al. (2003) determined the value of $K_x$ by assuming a Gaussian diffusion process represented in Equation 36

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and neglecting the effects of cross shore flow. It is also possible to assume the vertical flow is absent as no waves were observed breaking across the flow path and as such the effects of wave motion and return could be neglected. By assuming concentration ratios \( C/C_0 \) of 0.1\%, 0.5\% and 1.0\% Takewaka et al. (2003) were able to determine \( K_x \) values 0.01, 0.017 and 0.025 respectively by varying the value of \( K_x \) to make Equation 36 fit the plot of observed \( \sigma_x \) values with time, Figure 2.19.

\[
\sigma_{\text{aw}}(t) = \left\{ \frac{1}{3} \right\} \left[ -4K_x t \log \left( \frac{C}{C_0} \sqrt[4]{\pi K_x t} \right) \right]\]

(36)

The dispersion co-efficient values calculated by Takewaka et al. (2003) correlate relatively consistently with those determined by Riddle and Lewis (2000) who reviewed dispersion data from 25 nearshore and estuarine sites predominantly around the United Kingdom. They found lateral dispersion coefficients ranging between \( 0.003 \text{m}^2\text{s}^{-1} \) and \( 0.42 \text{m}^2\text{s}^{-1} \) with a mean of \( 0.05 \text{m}^2\text{s}^{-1} \), and compared these values to experimental data from the south-east U.S.A and Ireland finding all data sets to be relatively similar. The experimental results addressed by Riddle and Lewis (2000) were not obtained from the surf zone.

### 2.4.2 Drifter Experiments

The use of Lagrangian drifters in measuring mixing and dispersion processes has traditionally been restricted to large-scale offshore and oceanic applications. In particular, List et al. (1990) and Tseng (2001) provide valuable examples of the application of drifter technology to the measurement of dispersion phenomena. List et al. (1990) deployed a number of drogues in coastal waters offshore of southern
California and used their movements in the calculation of transport and dispersing properties over diurnal periods, concurrently pioneering many of the analysis techniques used in this study. The analytical approach employed by List et al. (1990) involved the analysis of the individual drifter co-ordinates at each point in time to determine the average x and y co-ordinates. These co-ordinates comprised the mean location of all the drifters or the ‘centroid’ which was subsequently used in the determination of the cluster variance. By plotting the variance with time it is possible to determine an estimate of the dispersion as described by Equation 26 (Section 2.3.3.2). Tseng (2001) made similar measurements through the deployment of drifters near estuary openings and in the wake of small eddies offshore from southwestern Taiwan. However, Tseng (2001) utilised a slightly different analytical approach, utilising the relationship shown in Equation 37 This relationship differs slightly from the classical relationship (Equation 26) developed by Richardson (1926) and utilised by List et al. (1990), however this difference is mainly superficial as Equation 37 is still derived according to the same principals of turbulent dispersion. Rather the variation is due to a different approach to the derivation of $\sigma^2$ utilised by Tseng (2001) and is inconsequential in terms of the effect on derived values of $K$. This is highlighted by the fact that Tseng (2001) derived $K$ values in the order of $12-15 m^2s^{-1}$ in tidally forced estuarine zones, during periods of strong tidal flow. Tseng (2001) utilised an alternative relationship for the derivation of $K$. The formula is not fundamentally different from the classical relationship derived by Richardson (1926), but does differ ‘cosmetically’ in the utilisation of $\sigma_x$ and $\sigma_y$ rather than a combined $\sigma^2$ derived from the average of the variation in the x and y directions respectively.

$$K = \frac{1}{4} \frac{\partial \sigma_x \sigma_y}{\partial t}$$  \hspace{1cm} (37)

The lack of drifter deployments within the nearshore zone has largely been due to the absence of appropriate technology, dictating that drifters were cumbersome, expensive and somewhat inaccurate over scales of less than 100m. The removal of selective availability from the international global positioning system (GPS), in May of 2000, greatly enhanced the accuracy of the GPS system and cleared the way for the development of small and relatively inexpensive drifters suitable for use in the shallow nearshore region (Johnson et al., 2003). Drifters suitable for use in the nearshore were developed concurrently and independently by Schmidt et al. (2003) and Johnson.
et al. (2003) and as such, only a limited number of experiments have been conducted utilising this technology.

As part of their drifter validation tests Schmidt et al. (2003) conducted synchronized dye and drifter release experiments and were able to display qualitatively that the behaviour of dye patches and drifters within the surf zone are analogous. This was significant as it suggested that the dispersion coefficients obtained from dye diffusion experiments are comparable to coefficients obtained from drifter experiments (Schmidt et al. 2003). Schmidt et al. (2003) validated the velocities obtained from their drifters by comparison with the velocities measured by simultaneously deployed fixed position current meters. These results confirmed a high degree of correlation between the Lagrangian and Eulerian measurements in the longshore direction, obtaining a high correlation of 0.95. However they also demonstrated a very poor correlation in the cross shore domain. This was attributed to the fact that the drifters measure the current structure at the top of the water column, whilst, the fixed current meters obtain data from the sea bed. As such, the Eulerian measurements were likely to have been affected by surf zone phenomena, such as undertow, which, is enhanced with proximity to the bed. The validation processes adopted by Johnson et al. (2003) were similar to those of Schmidt et al. (2003). Johnson et al. (2003) carried out drifter experiments with concurrent Acoustic Doppler Current Profiler (ADCP) deployments within the surf zone. Comparisons were made by collating the data obtained by ADCP and the drifters during periods when their separation was less than 10m. This velocity data was averaged over two peak wave periods, centering on the period of smallest instrument separation. The data obtained through this approach showed a slight, but consistent, underestimation of the depth averaged velocity by the drifters, in both the longshore and cross shore direction. This was the same effect as was noted by Schmidt et al. (2003). Johnson et al. (2003) justify this variation, suggesting that it is to be expected due to the knowledge that surf-zone wave averaged velocities, measured by the drifters, are greater near the surface and hence can be expected to exceed the depth averaged flow.

The most extensive deployments of surf-zone drifters to date have been undertaken by Johnson (2004). Johnson deployed drifters within longshore and rip-current formations along high energy beaches in Perth, Western Australia. In the analysis of transient rip currents, Johnson (2004) addressed a number of factors ranging from
qualitative description of the rip motion and behaviour through to the analysis of dispersion at the rip head. Cluster dispersion analysis was carried out following the methods of List et al. (1990) for a total of four rip events. The total dispersion coefficient was found to range substantially between 1.29 and 3.88m²s⁻¹, which are of similar magnitude to the diffusion rates determined for the surf zone, as determined by Inman et al. (1971). Qualitatively, Johnson (2004) noted the apparent local suppression of horizontal dispersion within the ‘rip neck’, the region of rapid, offshore directed flow through the surf zone. Subsequent rapid expansion at the rates noted was then observed in the ‘rip head’, an area of enhanced local dispersion. Further dispersion analysis carried out by Johnson (2004) involved the plotting of dispersion coefficients against the lengths scale $\sigma$, following from the analysis of Okubo (1974). Through this, Johnson (2004) derived the power laws describing the relationship between the scale of drifter separation and relative dispersion rates. These power laws were found to have exponents ranging between 1.3 and 1.5 within the surf zone and between 1.47 and 1.85 in the rip head outside of the surf zone. These results, particularly within the surf zone, demonstrate the relatively high correlation of the data with the 4/3rds law proposed by Richardson (1926). It also further highlights the enhancement of dispersion in the rip head region.

In the analysis of longshore currents Johnson (2004) utilised simultaneous deployments of ADCP to record current magnitudes and directions, and an InterOcean S4 wave recorder. The presence of the Eulerian recording devices allowed the consideration of the incident wave climate and current field thus providing a reference for the drifter data. Johnson (2004) carried out extensive cluster and drifter trajectory analysis allowing the calculation of dispersion coefficients $K_x$ and $K_y$ of 0.2m²s⁻¹ and 0.3m²s⁻¹ respectively for 10m average separation of the drifters. These results are not directly comparable to those obtained by Takewaka (2003), the only other known longshore dispersion results, because Takewaka (2003) assumed a Fickian diffusion process (Section 2.4.1). However, the values of $K_x$ obtained for a cloud size of 5m, or a 5m drifter separation, of 0.025m²s⁻¹ and 0.039m²s⁻¹ respectively, are consistent. These results are significantly less than the values determined by Johnson (2004) in the rip head. Johnson (2004) also noted the apparent scale dependence of dispersion in the longshore flow field. As with the rip current analysis, Johnson (2004) derived the exponents of the power laws describing the lines of best fit for the relationship between the dispersion coefficients and a length scale of separation. The power law
exponents were found to range significantly, with the total longshore value found to be 1.92 whilst the cross-shore component was calculated as 2.41. The relationships used to derive these values are plotted in Figure 2.20.

Olsson (2004) deployed Lagrangian surf zone drifters in the analysis of eddies formed in the lee of coastal structures, primarily groynes, along the metropolitan coastline of Perth, Western Australia. The primary focus of Olsson’s (2004) work was the qualitative analysis of the spatial structure of the currents in the eddy field, through the tracking of the drifter paths and their respective velocities. This also included the calculation of the dispersion coefficient at the seaward extremity of the offshore eddy flow located near the tip of the groyne structure. The dispersion co-efficient was calculated on a limited number of occasions and ranged markedly between, 0.6$m^2s^{-1}$ and 4.1$m^2s^{-1}$. Olsson (2004) notes that due to the small number of sample points it is not possible to reasonably estimate the dispersion co-efficient representative of the underlying system.
2.5 Adelaide Coastal Waters Study

The calculation of mixing and dispersion rates within Adelaide’s coastal waters is part of a collaborative study into environmental issues being coordinated by the South Australian government. The Adelaide Coastal Waters Study (ACWS) will address various factors affecting all aspects of the coastal region and will extend 20km offshore between Port Gawler and Sellicks Beach (CSIRO, 2004a). This area includes the entire Adelaide metropolitan coastline and as such supports a large, urban population, which in turn applies significant anthropological pressures to the natural system. The key objective of the ACWS is to ‘develop knowledge and tools to enable sustainable management of Adelaide’s coastal waters by identifying causes of ecosystem modifications and quantifying the actions required to halt and reverse the degradation’ (CSIRO, 2004b). The areas of specific focus and research include:

1) The quantification of contaminant inputs from point sources such as stormwater drains and river outflows, submarine groundwater discharges and inputs from atmospheric sources.

2) The assessment of the impact of these inputs on sea-grass ecosystems and other key biota within Adelaide’s coastal waters. This is a key motivation for the study of mixing and dispersion within the ACWS as the impact of coastal discharges on the predominantly offshore seagrass beds is dependant on the efficiency of transport and dispersive mechanisms.

3) Monitoring of marine and coastal features using remote sensing technology and the interpretation of changes since the 1940’s in response to natural and anthropological stimuli. This will focus specifically on changes in the extent of sea-grass beds and morphological variations resulting from sediment supply fluctuations.

4) A complete sediment transport budget will be developed, addressing the sources, sinks and fate of sediments in the coastal littoral zone.

5) Oceanographic studies of currents within the Gulf of St Vincent, using modeling, in-situ observations and satellite imagery. Specifically, this research area addresses coastal and seafloor morphology along with contaminant transport.

6) The development of a cost effective environmental monitoring strategy, addressing all of the key research areas, for implementation and integration with existing monitoring programs.
2.5.1 Motivation for Current Study

The primary motivation for the assessment of mixing and dispersion rates within the study area is to allow the quantification of contaminant transport and dilution. There are multiple contaminant sources into coastal waters including river runoff, submarine groundwater discharge, wastewater discharge and the atmosphere: however in terms of volume the flow of rivers, which includes stormwater runoff is the largest single source (CSIRO, 2004a). The mean average discharges of selected rivers within the Adelaide metropolitan region are collated in Table 2.6, along with their respective catchment areas.

Table 2.6: Mean annual discharge, catchment area and runoff for selected rivers in the ACWS study area (Storm water data audit, v1.3, Draft, 2004)

<table>
<thead>
<tr>
<th>Catchment Area</th>
<th>Mean Discharge (GL)</th>
<th>Catchment Yield (ML/km² = mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gawler River (to Sea)¹</td>
<td>883</td>
<td>10.3</td>
</tr>
<tr>
<td>Smith Creek²</td>
<td>205.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Barker Inlet²</td>
<td>407.8</td>
<td>10.3</td>
</tr>
<tr>
<td>R. Torrens³</td>
<td>218.5</td>
<td>22.4</td>
</tr>
<tr>
<td>Patawalonga³</td>
<td>212.4</td>
<td>19.7</td>
</tr>
<tr>
<td>Holdfast drains²</td>
<td>8.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Field River¹</td>
<td>36.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Christies Creek¹</td>
<td>37.8</td>
<td>8.1</td>
</tr>
<tr>
<td>L. Onkaparinga⁴</td>
<td>138.7</td>
<td>9.5</td>
</tr>
<tr>
<td>O. Estuary²</td>
<td>28.2</td>
<td>5.6</td>
</tr>
<tr>
<td>Southern Creeks⁵</td>
<td>244.9</td>
<td>2.3</td>
</tr>
</tbody>
</table>

1. Annual mean of flows for April 01 to April 03. 2. Estimated from rainfall and volumetric runoff coefficients. 3. Average data for October 94 to November 03. 4. Modelled data for the period October 94 to November 03. 5. Flow in Pedler Creek at Stump Hill Road for April 01 to April 03 multiplied up to total southern creek catchment area. NOTE: Ten year flows are consistent with two year flow period of 2001/3.

Table 2.6 shows that the run-off through a given area is not directly dependant on the catchment area, with larger catchments not necessarily resulting in larger catchment yields. The Torrens River represents a catchment area of 212.4km² below the Kangaroo Creek reservoir and has the highest mean annual flow of 22.4GL. This is more than double that of the Gawler River (10.3GL) which has an effective catchment area of 883km², which is ~4 times larger. This discrepancy arises from the nature of the catchment. Whereas the Gawler catchment is largely rural the Torrens catchment is highly urbanised. Within these urbanised areas, runoff is enhanced due to the existence of extensive and efficient drainage systems as well as large areas of sealed surfaces, such as roads and rooftops, into which water is not able to percolate.

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In addition, the time between rain falling and increases in discharges being observed is longer within rural catchments as the water does not drain as efficiently, the consequence of this is that the discharge observed within urban catchments increases rapidly following rainfall hence inputting a large volume of water within a short period of time. This rapid inflow has the capacity to significantly alter local seawater salinity levels as well as transport large contaminant loads (Steffensen, 1985). In particular, the re-routing of the Torrens River outflow to the coastline through Breakout Creek has created a significant new discharge site where previously no low salinity water had been entering the system.

The water that enters the coastal environment, from these outfalls as well as from wastewater treatment facilities and submarine groundwater discharge, has been found to contain numerous contaminants. These contaminants include nutrients such as nitrogen and phosphorus as well as inorganic substances, suspended sediments and heavy metals such as lead, copper, cadmium, zinc and iron (Steffensen, 1985; Stormwater Data Audit, 2004). Furthermore, samples obtained from rivers within the metropolitan region since 1978 have been found to contain the herbicides Lindane, Dachtal, Simazine and Atrazine as well as the insecticide Dieldrin. These occurrences are summarised in Table 2.7.

The exact concentrations and volumes of stormwater contaminants discharging into coastal waters have never been systematically monitored over significant periods of time. Hence, nett inflows have not been quantified. However, offshore monitoring of water quality indicates that land based discharges have a significant impact (Steffensen, 1985).

Seagrass beds are an important part of the marine ecosystem within the Gulf of St Vincent and have been declining in area rapidly since the 1940’s, with a shift in species composition towards algal seaweed such as *Giffordia*, a known indicator of water quality decline (CSIRO, 2004). The biological impact of the various contaminants present in coastal discharges, is not well understood and is a major focus of the ACWS. By measuring the dominant oceanographic processes, including dispersion, within the Adelaide coastal region, it is possible to quantify the transport of nearshore waters into the offshore region, the seagrass habitat, and hence determine
whether coastal discharges and associated contaminants are a possible cause of seagrass decline.


<table>
<thead>
<tr>
<th></th>
<th>ANZECC (2000) trigger level for protection of 95% of species</th>
<th>Gawler River</th>
<th>Torrens River</th>
<th>Brownhill Creek</th>
<th>Sturt River</th>
<th>Onkaparinga</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1978-83</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample n</td>
<td>4</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Detections</td>
<td>1</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Lindane</td>
<td>0.2</td>
<td>0.01</td>
<td>0.02, 0.16</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dacthal</td>
<td>-</td>
<td>0.01</td>
<td>0.08, 0.08, 0.08, 0.06</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>1996-7</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Insecticides</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sample n</td>
<td>-</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Detections</td>
<td>-</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dieldrin</td>
<td>ID</td>
<td>-</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Herbicides</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sample n</td>
<td>-</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Detections</td>
<td>-</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Simazine</td>
<td>3.2</td>
<td>-</td>
<td>3.6, 2.9</td>
<td>4.9, 3.7, 1.9, 0.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Atrazine</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3 Approach & Methodology

3.1 Lagrangian GPS Drifters

Lagrangian measurements are made utilising a moving reference frame through which the behaviour and properties of individual fluid particles can be tracked with time (Munson et al., 2002). This is in contrast to Eulerian approaches which employ fixed frames of reference to analyse the behaviour of fluid particles and the variation in their properties with time. Lagrangian approaches are far more practical in the analysis of mixing and dispersion across significant spatial scales. This is because Eulerian experimental formats require multiple reference points in order to resolve the spatial scales of motion and hence, the rate of dispersion (Tseng, 2001; Winant, 1983). In the case of Brander (2001) it was necessary to deploy a total of 5 pressure sensors and 9 current meters in order to resolve the flow kinematics of a small, relatively stable, low energy rip. In larger, transient or more spatially variable formations, the use of Eulerian arrays rapidly becomes impractical, due to the high cost of the numerous sensors as well as the manpower required to set-up, maintain and operate extensive instrument arrays. Conversely, Lagrangian drifters are able to provide reliable data pertaining to the structure of current formations from tracking the paths of a relatively small number of floating drifters (Johnson, 2004; Tseng, 2001; List et al. 1990) or by measuring the growth of dye patches (Takewaka, 2003; Rodriguez et al., 1995; Inman et al., 1971). The data obtained is particularly valuable in observing the spatial structure of flow fields and their dynamics and significantly, for determining the fate of pollutants in ecological investigations, allows diffusion coefficients to be determined more accurately than with use of fixed current meters (Pal et al., 1998; cited in Johnson et al., 2003). Traditionally, the use of drifters has been restricted to large scale oceanographic applications (Tseng, 2001; List et al., 1990), however, Johnson et al. (2003) developed drifters suitable for use in the nearshore zone. These drifters provide the benefits attributable to Lagrangian measurement techniques; namely the ability to determine reliable diffusion coefficients and define spatial variability of current systems over a significant scale. Yet, they are more compact and inexpensive than previous ocean going drogues, allowing their deployment by individuals or small groups, directly into the nearshore zone.
3.1.1 Design

The GPS surf zone drifters developed by Johnson et al. (2003) have the primary advantages of being inexpensive, simple to construct and reliable in applications where larger, more sophisticated drifters may not be required, such as the nearshore zone, lakes, estuaries and rivers. The drifter units consist of four primary components, represented in Figure 3.1.

![Figure 3.1 Components of the surf zone drifters developed by Johnson et al. (2003) and utilised in field studies of mixing and dispersion in the nearshore zone.](image)

The main casing of the drifter is made out of 100mm diametre polyvinyl chloride (PVC) pipe of 320mm total length and is able to withstand pressure testing, up to the equivalent of at least 40m of seawater (Johnson et al., 2003). The casing is fitted with a standard screw on ring seal fitting (1a) and a clear Perspex lid with a further o-ring, mounted on the internal frame, which both act to prevent leakage into the casing. The internal frame acts to secure the GPS, the data logger and the battery pack; with the GPS located immediately below the clear Perspex cover and the heavy battery pack, consisting of seven standard alkaline D-cell batteries, located at the base of the drifter to act as ballast. This ensures that the drifters maintain upright stability with almost neutral buoyancy. By maintaining almost neutral buoyancy it is possible to minimise inertial effects and wind forces on the drifter, as only 2cm of the drifter is exposed above the surface of the water in calm conditions (Johnson, 2004). The GPS and data logger are both powered by the battery pack and are configured such that once the power is connected, initialisation and satellite acquisition occurs automatically and
recordings of location, time and date are stored in the data logger at a frequency of 1Hz.

The drifters can be modified through the addition of various drogue configurations for use in both larger scale oceanographic applications (Verspecht, 2002) or in the surf zone (Johnson 2004; Olsson 2004), and at varying water depths (Johnson et al., 2003). The modification for use in the surf zone involves the attachment of parachute drogues to the base of the main casing of the drifter. These parachutes act to prevent the drifter from ‘surfing’ along the wave bore when it is caught in breaking waves. The parachutes are almost neutrally buoyant so a small lead weight is attached to their base in order to orientate them in the water column ensuring that they hang vertically below the main casing and receiver unit. Under calm conditions, or in non-breaking waves, the parachutes are closed and present only their cross-sectional area, thus, they do not significantly influence the drifter trajectory (Johnson et al., 2003). However, under rapid vertical motion such as that experienced when the drifter is lifted and projected towards the shore by the motion of a breaking wave or wave bore, the parachute opens. This dramatically increases the drag on the drogue and has the effect of anchoring the drifter to the orbital velocities below the breaking region (Johnson, 2004). The drogue is also effective in damping vertical and horizontal oscillatory motion in the receiver unit as experienced by non-drogued drifters.

The length of the drogue attachments varies significantly depending on the number of parachutes utilised, however, given the relatively shallow nature of the surf zone it is not unusual for the drogue apparatus to come into contact with the bottom. Johnson (2004) addressed this issue through drag tests in a tow tank and found that the effect of the drogue dragging along the bottom was small, however some measurement error was inevitable. As such the minimum viable depth of operation is the length of the main casing itself, 320mm. Additionally, the initial depth at which contact occurs can be significantly reduced by utilising one parachute arrangement rather than the two originally developed by Johnson et al. (2003). The effect of having fewer parachutes was investigated by Johnson (2004) and was found to be negligible in the measurement of wave averaged velocities as long as at least one parachute was attached.
3.1.2 Accuracy

Whilst the removal of selective availability (SA) has greatly enhanced the accuracy and reliability of non-differential GPS systems, there are still a number of factors that can cause positioning errors. These include limitations in the precision of GPS receivers, satellite clock errors, variation between the known satellite position and actual location, atmospheric effects influencing the speed of light and the reflection of signals off large structures (Hofmann-Wellenhof et al., 1997; cited in Johnson et al., 2003). Some of these effects create errors in the form of ‘noise’, random positioning errors following no particular trends and apparent only for individual readings. Other factors however, have the effect of creating position errors which oscillate with a preferred frequency (Johnson et al., 2003). The key factor when assessing satellite positioning errors for the purpose of surf zone drifter analysis is whether the errors are absolute or relative. Absolute errors have little practical impact, as whilst they do record erroneous locations, the relative difference between these positions is correct and hence does not affect the recorded path of the drifter. Relative errors, which are changes in the position of a stationary receiver relative to an arbitrary datum point, have the potential to seriously disrupt any position, velocity or acceleration calculations performed on the data.

Johnson (2004) addressed the level of relative error affecting the GPS surf zone drifters by conducting a series of stationary tests. GPS units and data loggers were left in open spaces for periods of 45 minutes to obtain data which was then analysed to obtain the standard deviation of both the easting and northing co-ordinates. Eastings were found to have a smaller variation in recorded positions with a standard deviation among the data of 1.3 compared to 1.6m for northings (Johnson et al., 2003). Maximum displacements from the datum point were significantly larger with readings of 4.2m and 5.2m for easting and northings respectively (Johnson et al., 2003). Errors due to the precision of the data loggers were noted with the recording of co-ordinate significant figures only sufficient to ensure accuracy of 0.16m easting and 0.19m northing at a latitude of 32°S. Johnson (2004) shows that non-differential GPS systems are sufficiently accurate to measure movements with frequencies of less than 0.05Hz, a period of 20s. However, it is also noted that this can be improved upon by using differential GPS systems, which allow movements with frequencies as high as 1Hz to be measured (Schmidt et al., 2003; cited in Johnson 2004).
3.2 Eulerian Measurements

Eulerian descriptions of fluid motion are obtained by making the necessary recordings, such as, velocity, direction, pressure and density as functions of time and space. This is in contrast with Lagrangian techniques under which fluid properties are a function of time only (Munson et al., 2002). The relative advantages and drawbacks of both Eulerian and Lagrangian approaches have been discussed previously, where it was demonstrated that within the nearshore zone, Lagrangian drifters provide the most effective tool in the efficient investigation of the spatial structure of currents and associated mixing and dispersion. However, Eulerian measurements provide the advantage of spatially constant measurements of current properties. Consequently, Eulerian measurements were obtained to determine the dominant direction and magnitude of current flow profiles as well as data pertaining to water level variability and as such, the prevailing wave climate, at the selected deployment site. The fact that the spatial domain remains constant during the sampling period, allows the analysis of changes in the current regime with time and hence, the possible factors leading to these variations.

Prior drifter based studies into nearshore currents have also utilised Eulerian measurements, including Olsson (2004) who deployed an ADCP in the wave shadow of Cottesloe groyne to determine comparative flow magnitude profiles and Johnson (2004), who used concurrent drifter and ADCP deployments in the analysis of rip current formations.

3.2.1 Acoustic Doppler Current Profiler

The ‘Aquadopp’ ADCP was utilised in the collection of current and pressure data during the March 2005 deployments. The ADCP was programmed to record current direction and velocity across 10cm cells at a frequency of 1Hz. The cell size refers to the interval over which individual measurements are made, allowing the derivation of complete current profiles through the water column from the seafloor, to the water surface. In the case of a 2m deployment depth, the water column is divided into twenty 10cm cells, each of which is sampled individually. The flow characteristics in each of the cells are measured in terms of the three dimensional components. The easterly, northerly and vertical current magnitudes in metres per second (ms\(^{-1}\)), are then stored as separate output files, which can be analysed individually.
Approach

The ADCP was utilised in the measurement of pressure, also at a frequency of 1Hz. The relationship between pressure and water depth, consequently allows the direct derivation of the water level from the pressure data. The relatively high frequency of measurements allows for the recording of shorter period water level variations in the form of locally generated wind waves (3-5s) as well as longer period swell waves (10-14s) and tidal oscillations. The length of the tidal period (~12hrs) compared to the period of deployment (~6hrs) prevents the complete measurement of the tidal cycle during a single deployment.

3.3 Field Deployment

The experiments were conducted in the nearshore zone along West Beach on the Adelaide metropolitan coastline. This site was selected due to the presence of the artificial waterway ‘Breakout Creek’ which is the outflow point of the Torrens River into the sea. Hence, it is a key location when investigating contaminant inflows and subsequent dilution through mixing and dispersion in the coastal zone. Two approaches were utilised within the experimental process; specifically the deployment of surf-zone drifters which rely on a Lagrangian, moving, frame of reference in order to calculate the dispersion co-efficient as well as the eulerian, fixed frame of reference ADCP which is able to provide data on the current direction and velocity throughout the water column in addition to pressure, depth, variations which indicate the motion of waves and longer period phenomena including tides.

The first step in the deployment of the drifters was to survey the shoreline in the experimental area. To do this, a single drifter was carried around the shoreline, whilst the remaining drifters were left stationary at a central location. This allowed the relatively simple derivation of the shoreline profile, which provides a valuable reference in data analysis. Drifters were then carried by hand offshore from the surf zone, to water depths ranging between ~1.2m and 2m, and released simultaneously as clusters. The drifters were then allowed to float independently until they washed ashore, or reached depths of less than 32cm on sandbars, at which point the main casing started dragging on the seafloor, significantly impeding motion. In some cases drifters moved offshore and had to be retrieved, this was particularly influenced by the wind speed and direction. Once drifters were recovered either onshore or offshore they were removed from circulation, by placing them on the beach, until the next cluster could be initiated. Drifter deployments were carried out in two tranches, in
September 2004 over three consecutive days from the 1st to the 3rd and between the 20th and the 23rd of March 2005. These dates are able to provide a comparison between the level of mixing and dispersion under seasonally variable conditions in winter and summer as well as providing a comparison between times of peak and residual contaminant inflows.

A large number of individual drifter experiments were carried out and it is not practical to describe each individual drift, however, the basic procedures described were utilised consistently through each deployment. The wind, wave and tidal conditions encountered during each of the deployment periods are discussed in the following section.

The ADCP was deployed on three occasions, on the 20th, 21st and 22nd of March 2005. On each occasion the ADCP was deployed in water of around 2m depth, within a channel, on the shoreward side of a major sandbar over which the water depth was reduced to as little as 50cm. The instrument was fastened to a cross-beam structure, facing upwards, to maintain stability and orientation. A buoy, which floated freely at the surface, was attached to this frame structure by rope in order to provide for the easy identification of the ADCP location and subsequent retrieval of the equipment. Generally, the deployment position of the sensors was relatively calm with little wave or current activity evident observed. However, it was noted that during periods of greater wave activity, breaking was induced over the shallow sandbar; the bores of these waves were observed to pass over the ADCP, inducing shoreward currents in the upper levels of the water column.

Figure 3.2 Photographs of the drifter and the ADCP deployment configurations respectively.
3.3.1 September 2004

Due to the necessity of traveling to Adelaide from Perth in order to perform field work, it was not possible to select specific conditions in which to deploy the drifters. Factors such as winds and waves can not be predicted for significant periods in advance and thus, drifters had to be deployed under the prevailing conditions during the pre-determined sampling dates. The average wind conditions recorded during September and the preceding winter months are presented in Table 3.1. The data contained in this table suggests that conditions become windier in late winter and early spring, both in the mornings and afternoon. However, the variation between the morning and afternoon conditions actually decreases over the same period, representing a decrease in the sea breeze activity.

<table>
<thead>
<tr>
<th></th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean 9am Wind Speed (km/hr)</td>
<td>12.6</td>
<td>13.8</td>
<td>16.1</td>
<td>17.6</td>
</tr>
<tr>
<td>Mean 3pm Wind Speed (km/hr)</td>
<td>17.1</td>
<td>18.9</td>
<td>20.6</td>
<td>21</td>
</tr>
</tbody>
</table>

Tidal oscillations during the sampling period can be accurately predicted and form the basis, in the absence of ‘random’ phenomena such as storm surge, of water level oscillations. The water level recordings during the sampling period, from the nearby tidal gauge at Outer Harbour, are represented in Figure 3.3. This shows the high water level variation due to the spring tides during the sampling period. Whilst the sampling was conducted opportunistically, as noted previously, it is fortunate that drifter deployments were conducted across a representative cross section of tidal conditions. As represented in Figure 3.3, deployments were conducted during periods of both rising and falling water levels, thus allowing the comparison of dispersion rates at different periods of the tidal cycle.

The generally gentle slope of Henley beach exacerbates the motion in the position of the mean water level, from a horizontal perspective, through the tidal cycle. On several occasions during the drifter deployments, the shoreline retreat or advance was observed to be in the order of tens of meters. On these occasions, surveys of the shoreline profile were conducted prior to and post drifter deployment in order to quantify the shoreline transgression/regression during the experimental period.
Figure 3.3 Water level variations recorded at the Outer Harbour tidal gauge during the first tranche of sampling in September 2004. The data shows the high ‘spring’ tidal range of ~2m as well as the periods of drifter deployment. It should also be noted that deployments were carried out on both rising and falling tides as well as at the extremes of the tidal range. (Data supplied by Greg Pearce of HydroSurvey Australia (Flinders Ports Pty Ltd)).

1st September 2004
Sampling was conducted on the afternoon of the 1st of September 2004 between approximately 13:30 and 15:30. The wind direction was predominantly from the south west and ranged between velocities of 3.6m s\(^{-1}\) and 5.7m s\(^{-1}\) as shown in Table 3.2 which lists the meteorological recordings of wind speed and direction at the nearby Adelaide airport. Wave conditions were choppy, driven by the relatively strong sea breeze and whilst accurate measurements of wave characteristics including amplitude and period are not available, observations suggest significant wave heights in the order of 0.4m and a significant wave period of 4-6s. Drifters were deployed in several clusters close to shore and were rapidly washed into shallow water resulting in generally short drift times. The direction of the longshore current was northerly. This resulted in successive deployments being made in a northerly progression along the coast, before retrieval and redeployment at the original point. The conditions under which the clusters were released are noted in Table 3.2, this also includes brief comments pertaining to the clusters behaviour and other significant points of interest.
Table 3.2 Summary of drifter deployments on the 1st of September 2004, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Time</th>
<th>Drifters</th>
<th>Shortest Duration [s]</th>
<th>Velocity [m/s]</th>
<th>Direction [°]</th>
<th>Tide [m]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13:30</td>
<td>2,3,4</td>
<td>296</td>
<td>4.61</td>
<td>230</td>
<td>0.62</td>
<td>Deployed ~35m offshore, drifters follow generally NW bearing, except drifter 4 which moves offshore and had to be recovered by hand.</td>
</tr>
<tr>
<td>2</td>
<td>14:00</td>
<td>2,3,4,5</td>
<td>47</td>
<td>3.61</td>
<td>240</td>
<td>0.82</td>
<td>Deployed ~25m offshore, to the north of cluster 1. Short drift terminated by drifters running aground. Drifted ~10m directly north.</td>
</tr>
<tr>
<td>3</td>
<td>14:30</td>
<td>all</td>
<td>49</td>
<td>5.69</td>
<td>220</td>
<td>1.1</td>
<td>Deployed near Cluster 2 start, ~25m offshore. Drifters moved north and onshore up to 50m. Drifter 5 ran aground at an early stage after moving directly onshore after release.</td>
</tr>
<tr>
<td>4</td>
<td>15:00</td>
<td>all</td>
<td>381</td>
<td>4.11</td>
<td>230</td>
<td>1.36</td>
<td>Deployed ~40m offshore and moved north ~55m before retrieval, drifter 3 moved offshore initially before moving back onshore, without interference</td>
</tr>
<tr>
<td>5</td>
<td>15:30</td>
<td>2,3,4,5</td>
<td>166</td>
<td>4.61</td>
<td>220</td>
<td>1.62</td>
<td>Deployed ~30m offshore. Drifters moved north and slightly onshore. Some, particularly drifter 4, followed highly variable, meandering paths.</td>
</tr>
</tbody>
</table>

The deployment period was characterised by a rising tide, Figure 3.3, which resulted in the shoreward retreat of the waterline as represented in Figure 3.4. During the sampling period the shoreline location was observed to regress by between approximately 6 and 12 meters depending on bathymetric features, which affect the slope of the beach face profile.

![Figure 3.4](image-url)
**2nd September 2004**

The drifters were utilised in two separate deployments, the first between 9:00 and 12:00 and the second between 13:30 and 16:00. The conditions during the morning deployment were very calm with little wind and almost no waves present (Figure 3.5). Due to this lack of wind and wave forcing, the motion of the drifters was particularly sluggish and clusters took large amounts of time to disperse relatively short distances.

![Figure 3.5: Photograph of Henley Beach on the morning of September 2nd 2004, noting the calm wind and wave conditions.](image)

Initially, clusters were released immediately offshore from the mouth of Breakout Creek and tended to meander southwards. Subsequent clusters were released progressively further north from the rivermouth, a process that was enhanced by the increasing west-south-westerly winds. These winds consequently instigated a steady increase in the northerly longshore drift. A summary of the individual cluster releases completed during the sampling period is included in Table 3.3.

<table>
<thead>
<tr>
<th>Date: 2/09/2004 Morning</th>
<th>Wind</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date: 2/09/2004 Morning</td>
<td>Wind</td>
<td>Comments</td>
</tr>
<tr>
<td>Clusters</td>
<td>Time</td>
<td>Drifters</td>
</tr>
<tr>
<td>1</td>
<td>9:20</td>
<td>all</td>
</tr>
<tr>
<td>2</td>
<td>9:45</td>
<td>all</td>
</tr>
<tr>
<td>3</td>
<td>10:40</td>
<td>all</td>
</tr>
<tr>
<td>4</td>
<td>11:35</td>
<td>all</td>
</tr>
</tbody>
</table>

**Table 3.3 Summary of drifter deployments on the 2nd of September 2004 (morning), including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).**
The afternoon drifter deployments were associated with vastly different conditions to the morning. The wind was predominantly south-westerly at velocities ranging between 2.6 ms\(^{-1}\) and 4.6 ms\(^{-1}\). The wave conditions were choppy, with significant wave heights observed to be in the order of 0.4 m with an associated period around 3-5 s.

Clusters were deployed up to 100 m offshore, in water depths approaching 2 m, well beyond the surf zone. They were observed to travel significant distances northwards before being washed ashore. It was observed that the velocity of the drifters increased as they moved closer to the shore. A description of each individual drift is summarised in Table 3.4, which also includes specific wind and tidal measurements at the time of the cluster release.

Table 3.4 Summary of drifter deployments on the 2\(^{nd}\) of September 2004 (afternoon), including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Date: 2/09/2004</th>
<th><strong>Wind</strong></th>
<th><strong>Tide</strong></th>
<th><strong>Comments</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>Time</td>
<td>Drifters</td>
<td>Shortest Duration [s]</td>
</tr>
<tr>
<td>1</td>
<td>13:30</td>
<td>2,3,4</td>
<td>1025</td>
</tr>
<tr>
<td>2</td>
<td>14:10</td>
<td>2,3,4</td>
<td>829</td>
</tr>
<tr>
<td>3</td>
<td>15:00</td>
<td>2,3,4</td>
<td>569</td>
</tr>
<tr>
<td>4</td>
<td>15:30</td>
<td>2,3,4</td>
<td>512</td>
</tr>
</tbody>
</table>

Tidal conditions varied significantly between the morning and afternoon deployments. The morning drifter deployments were carried out under falling tidal conditions, with the low tide level at Outer Harbor of 0.179 m, recorded at 12:15, shortly after sampling finished (Hydrosurvey Australia, 2005). Conversely, the afternoon period was characterised by a rapidly rising tide, which had reached a level of 1.63 m by the end of the drifter deployment at 16:00. This was short of the maximum tidal level of 2.116 m, recorded at 17:50 (Hydrosurvey Australia, 2005). The variation in the shoreline positions during the deployment periods are represented schematically in Figure 3.6, which clearly illustrates the interrelationship between the tidal oscillations and shoreline transgression/regression.

In Figure 3.6 it can be seen that the beach profile changes dramatically though the tidal cycle. An overall perspective of the beach profiles measured throughout the day is shown in A, whilst B shows a direct comparison of the shoreward transgression...
over a 70m section of beach. Between 09:00 and 13:30 the tide falls and the mean water level mark moves offshore, whilst subsequently, between 13:30 and 16:00 the shoreline is observed to advance onshore more than 50metres. During periods of low or falling tides (09:00 and 13:30) the shoreline is located up to 70m further offshore than during higher tides. Of particular note is the river outflow clearly shown in A in the 09:00 profile, whilst it is also possible to see the relic discharge channels further to the north in both the 09:00 and 13:30 profiles.

Figure 3.6 Schematic representation of the variation in the shoreline profile through the tidal cycle. The deployment positions of each of the clusters released during the experimental period are also noted as follows: from the morning deployments Cluster 1 (o), Cluster 2 (x), Cluster 3 (٭), Cluster 4 (∆) and in the afternoon, Cluster 1 (◊), Cluster 2 (), Cluster 3 (>), Cluster 3 (>) and Cluster 4 (<).

September 3rd 2004
On the 3rd of September the drifters were deployed in two clusters between 11:00 and 12:00, with drift durations of approximately 20 and 30 minutes respectively. The winds were relatively calm, not exceeding 3.1ms\(^{-1}\) and were predominantly from the west-north-west.

Prior to the commencement of the drifter experiments on the morning of the 3rd, an InterOcean S4 Vector Averaging Current Meter was deployed at a location
approximately 2km offshore from the study site. Consequently, it was recorded that at 11:00 the incident wave regime was approaching from a bearing of 212° (southsouthwesterly) with a significant wave height of 0.64m and a period of 10.6s.

Table 3.5 Summary of drifter deployments on the 3rd of September 2004, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Courtesy of Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Time</th>
<th>Drifters</th>
<th>Shortest Duration [s]</th>
<th>Velocity [m/s]</th>
<th>Direction [°]</th>
<th>Tide [m]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11:20</td>
<td>all</td>
<td>539</td>
<td>1.5</td>
<td>280</td>
<td>0.325</td>
<td>Deployed ~100m from shore, in relatively calm conditions, drifters moved north ~100m before changing direction and moving onshore</td>
</tr>
<tr>
<td>2</td>
<td>12:05</td>
<td>all</td>
<td>701</td>
<td>2.61</td>
<td>300</td>
<td>0.212</td>
<td>Deployed ~80m from shore, drifters moved shoreward following an erratic, meandering path, at low velocity. Drifters recovered from shallow water when casing began dragging.</td>
</tr>
</tbody>
</table>

A mixing zone was evident from shore, with a clearly defined boundary apparent between the murky brown nearshore waters containing the river discharge and the clearer offshore waters. The drifters were deployed at this boundary layer, about 100 meters from the shore and in waters depths close to 2m. Table 3.5 contains descriptions of the two cluster deployments, the first of which was released at the edge of the mixing boundary whilst the second was deployed slightly inside of the boundary.

Figure 3.7 Graphical representation of the shoreline profiles observed on the 3rd September 2004. The large (>50m) and rapid (1.5 hours) transgression in the position of the shoreline is clearly evident between A and B. The points o and x represent the release points of drifts 1 and 2 respectively.
The drifters were deployed during a period of decreasing tides, which fell from 0.427m at 11:00 to 0.196m at 12:30 (HydroSurvey Australia, 2005). This decrease was associated with a shoreline transgression of up to 50m in the areas of shallow sand flat described previously around the river mouth, shown in Figure 3.7.

3.3.2 March 2005

As noted previously, the necessity of traveling interstate to conduct field work, prevented the selection of specific conditions for drifter deployments. As such the ‘summer’ deployments were carried out in early autumn, however, through analysis of the long term weather records it can be seen that the wind conditions, which have the greatest effect on dispersion rates in a sheltered water body such as the Gulf of St Vincent, in March are very similar to those experienced in December, January and February. Average morning and afternoon wind velocities are compiled in Table 3.6.

<table>
<thead>
<tr>
<th></th>
<th>DEC</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean 9am Wind Speed (km/hr)</td>
<td>15.4</td>
<td>13.5</td>
<td>11.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Mean 3pm Wind Speed (km/hr)</td>
<td>23</td>
<td>22.9</td>
<td>21.6</td>
<td>20.5</td>
</tr>
</tbody>
</table>

Table 3.6 Mean wind speeds collected at Adelaide Airport for the period 1955-2004 (Bureau of Meteorology, 2005)

Table 3.6 shows that whilst the afternoon wind speed is lower than that experienced in the summer months, it is still substantially larger than the morning readings and can be interpreted as indicating the presence of an active sea-breeze system. The general similarity of the wind regimes across the four months, also verifies the suitability of using dispersion measurements obtained in March as a proxy for the other months, in the wind dominated Gulf environment.

The March 2005 deployments were carried out during a period of ‘dodge’ tides, described in Section 2.1.3.1 and characterised by minimal tidal oscillations. This is due to the effect of the $M_2$ and $S_2$, primary semi-diurnal solar and lunar tidal constituents, acting in opposition and effectively canceling each other out. At equinoxes, including the vernal equinox which usually occurs around the 21st of March, the luni-solar diurnal component $K_1$ and the principal lunar diurnal component $O_1$ also act in opposition, leading to a period of up to several days during which almost no tidal oscillations are observed (Grzechnik, 2000).
The water level variation observed during the sampling period at the nearby Outer Harbor monitoring station is presented in Figure 3.8. This highlights the low level of tidal variation during the sampling period with the tidal range observed to be in the order of 1m, compared to a maximum of ~2m observed during September. It can also be seen that the mode of the tides is diurnal during the deployment period, with two high tides and two low tides observed during the tidal cycle. The drifters were deployed on a rising tide each day allowing the collection of dispersion data across a wide spectrum of tidal levels. The reduced tidal range during the March deployments resulted in minimal shoreline transgression/regression during the tidal cycle when compared to the September deployments.

![Tidal Oscillations at Outer Harbor 20-23 March 2005](image)

**Figure 3.8 Diurnal tidal regime at Outer Harbor, between the 20th and 23rd of March 2005, noting the small range of the ‘dodge’ tides, focusing around the 19th and 20th.**

The deployment of the drifters was conducted in a manner similar to that previously described during the September experiments. The primary exception being that rather than deploying the drifters in sequence along the beach, resulting in a net northerly progression of drifter deployment sites, drifters were retrieved and redeployed close to the original site. This allowed the comparison of drifter behaviour at a relatively constant location with changing wind, wave and tidal conditions. Whilst the
longshore position of the deployment sites was kept relatively constant (northings) the presence of a substantial sandbar parallel to the shoreline, provided a cross-shore topographic control. Drifters were deployed both within the channel and offshore from the sandbar to determine whether the presence of such a feature had any control over dispersion rates.

**March 20th 2005**

The drifters were deployed in conjunction with the ADCP on the afternoon of the 20th of March 2005 between 12:45 and 16:25. The ADCP was positioned at 1368505, 6092962 in the UTM zone 53, which correlates to about 25m offshore from West Beach, around 200m north of the Breakout Creek Weir. It was deployed in around 2m of water depth, in the channel formed in the lee of a substantial sandbar structure running parallel to the shoreline in a N-S direction. The sandbar was located primarily between 30 and 60m offshore and at its shallowest point reduced the water depth to approximately 0.5m. The location of the ADCP was used as a reference point and drifter clusters were released repeatedly within its general vicinity, varying primarily in the cross-shore direction with deployments both inside and outside of the sandbar structure, as shown in Figure 3.9

![Figure 3.9](image-url)

**Figure 3.9** Graphical representation of the ADCP (o) location compared to the shoreline and each of the cluster release positions. Cluster 1 (+), Cluster 2 (٭), Cluster 3 (Δ), Cluster 4 (◊), Cluster 5 (<), Cluster 6 (>).
The individual drifters behaved in a different manner after each release, owing to the random nature of transport and the dispersive process within the nearshore zone. However, in each deployment the drifter group tended to follow the same general patterns, specifically; moving in a north westerly direction, within the channel and offshore from the sandbar, until reaching waters sufficiently shallow that the parachutes and eventually casing, ran aground and prevented further motion. As soon as drifters were observed to be dragging, they were removed from circulation, and in the case of drifter 6 in cluster 3, the data obtained from the drifter was removed from analysis completely. A summary of the drifts completed is compiled in Table 3.7.

Table 3.7 Summary of drifter deployments on the 20th March 2005, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Date: 20/03/2006</th>
<th>Wind</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>Time</td>
<td>Drifters</td>
</tr>
<tr>
<td>1</td>
<td>12:45</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>13:20</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>13:40</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>15:00</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>15:20</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>15:40</td>
<td>4</td>
</tr>
</tbody>
</table>

The wind conditions during the deployment were relatively constant between 12:30 and 14:00, however after this point they increased markedly, reaching 7.2m/s by 16:30 (Bureau of Meteorology, 2005), resulting in an increase in activity in the nearshore zone, with whitecapping observed from 14:40 onwards. The direction of the wind was relatively consistent, originally blowing from the west-south-west, but switching to a more directly south-westerly bearing by the time maximum wind speeds were observed.

March 21st 2005
The ADCP was deployed inside the sandbar in a water depth of approximately 1.8m at 10:15 on the 21st of March, coinciding with the low tide. Deployment conditions changed markedly during the deployment period. The initial morning conditions were dominated by gentle breezes with highly variable directions, predominantly northerly.
and easterly. No wind generated waves or white capping were noted. These conditions persisted until around midday, when the wind direction switched to a dominantly south south-west bearing and steadily increased in magnitude through to a peak velocity of 8.2m/s at 18:30 (Courtesy of the Bureau of Meteorology, 2005). This behaviour in the dominant wind regime is representative of typical sea-breeze activity. Coinciding with the change in the dominant wind regime, the wave climate altered significantly through the day, from inactive conditions in the morning, under which no wave activity was observed, to an active white-capping and ‘wind wave’ regime typified by short period (2-3s) locally generated waves (.3m-0.5m) breaking near the shoreline as well as on the shallow offshore sand bar. Clusters were released at a variety of locations, including two deployments on the seaward side of the sandbar, up to 100m offshore. These deployment sites are displayed in Figure 3.10. The approximate location of the sandbar is marked and it should be noted that the beach transect profile changes dramatically over this feature; at the ADCP location inside the channel the water depth is ~2m, before decreasing to ~0.3m over the sandbar and increasing to ~ 2m at the deployment site of Drifter 2.

![Figure 3.10 Graphical representation of the ADCP (o) location compared to the shoreline and each of the cluster release positions, taking particular note of the presence of the sandbar, which imposes a topographic control on the spatial distribution of local currents. Cluster 1 (+), Cluster 2 (٭), Cluster 3 (△), Cluster 4 (◊).]
The behaviour of the drifters, summarised in Table 3.8, was heavily influenced by the dominant wind conditions at the time of deployment; as such the morning drifter deployments tended to follow southerly paths, whilst the drifter deployments, coinciding with the increase in the sea breeze, followed northerly paths.

Table 3.8 Summary of drifter deployments on the 21st March 2005, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Time</th>
<th>Drifters</th>
<th>Shortest Duration (s)</th>
<th>Velocity (m/s)</th>
<th>Direction (°)</th>
<th>Tide (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:15</td>
<td>5</td>
<td>1113</td>
<td>1.51</td>
<td>30</td>
<td>0.718</td>
<td>Drifters deployed at the ADCP in calm conditions with only a slight north-westerly breeze. Drifters moved in a southerly direction onshore.</td>
</tr>
<tr>
<td>2</td>
<td>11:26</td>
<td>5</td>
<td>2994</td>
<td>2.05</td>
<td>320</td>
<td>0.674</td>
<td>Drifters deployed offshore from the ADCP in calm. Drifters moved in a southerly direction onshore, skirting around the sandbar before moving more directly onshore.</td>
</tr>
<tr>
<td>3</td>
<td>13:15</td>
<td>5</td>
<td>3349</td>
<td>3.59</td>
<td>280</td>
<td>0.899</td>
<td>Deployed ~80m offshore, drifters moved back onshore and southwards (D6) before running aground. Higher tidal levels allowed the drifters to pass areas (the sandbar) previously too shallow for motion.</td>
</tr>
<tr>
<td>4</td>
<td>15:40</td>
<td>5</td>
<td>1569</td>
<td>7.2</td>
<td>240</td>
<td>1.422</td>
<td>Drifters deployed offshore from the ADCP. A strong sea-breeze (WSW) was blowing, resulting in a direct NW drift pattern for the drifter cluster, before being they were affected by the wave action, which directed the drifter motion more directly onshore through the localised 'surf' zone.</td>
</tr>
</tbody>
</table>

**March 22nd 2005**

Drifters were deployed on the 22nd of March from 10:00 AM; however, due to technical problems associated with the downloading of the data, satisfactory results were only obtained from the second drift of the day, initiated at 11:35, onwards. The drifters were deployed at a number of locations including; the ADCP, offshore of the sandbar and to the north of the ADCP, inside the channel. These deployment positions are indicated in Figure 3.11, which shows their positions relative to the ADCP and the shoreline.

The wind regime was somewhat atypical to the conditions observed on each of the other days during the sampling period. The conditions were characterised by consistent and relatively strong south easterly winds that were maintained and actually intensified throughout the day. These winds resulted in a noticeable level of whitecapping and generated wind waves that appeared to be moving away from the shore. These conditions instigated a noticeable longshore drift that could be observed in the longshore motion of detrital matter, primarily seagrass, in a northerly direction.
Figure 3.11 Graphical representation of the cluster release positions and the ADCP, relative to the shoreline. Cluster 1 (∆), Cluster 2 (٭), Cluster 3 (+), Cluster 4 (○). Note the release position of cluster 4 which was directly offshore from the Torrens River outflow point.

Significantly, the easterly component of the wind influenced the motion of the drifters, as rather than promoting an onshore flux in the surface layer of the water column, a significant offshore drift was generated. This resulted in the drifters being transported in a north easterly direction and necessitated the author swimming significant distances offshore in order to retrieve them. A brief summary of each of the cluster deployments is included in Table 3.9.

Table 3.9 Summary of drifter deployments on the 22nd March 2005, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydro survey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Date: 22/03/2006</th>
<th>Wind</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>Time</td>
<td>Drifters</td>
<td>Shortest Duration (s)</td>
<td>Velocity (m/s)</td>
<td>Direction (°)</td>
<td>Tide (m)</td>
</tr>
<tr>
<td>1</td>
<td>11:35</td>
<td>5</td>
<td>2028</td>
<td>5.14</td>
<td>140</td>
<td>0.475</td>
</tr>
<tr>
<td>2</td>
<td>12:20</td>
<td>5</td>
<td>1443</td>
<td>6.68</td>
<td>150</td>
<td>0.612</td>
</tr>
<tr>
<td>3</td>
<td>2:20</td>
<td>5</td>
<td>1301</td>
<td>7.2</td>
<td>150</td>
<td>1.262</td>
</tr>
<tr>
<td>4</td>
<td>2:45</td>
<td>5</td>
<td>2976</td>
<td>7.2</td>
<td>150</td>
<td>1.39</td>
</tr>
</tbody>
</table>
March 23\textsuperscript{rd} 2005

The ADCP was not utilised on the 23\textsuperscript{rd} of March, as it was unavailable for deployment. Rather, the focus of the experimentation was to obtain multiple samples of dispersion and flow field characteristics over the same section of beach in order to be able to derive an average flow field of the experimental area as conducted by Mariani (2005) and Johnson (2004). This involved repeatedly deploying the drifters at close to the same location, under relatively constant conditions, so as to determine the mean flow characteristics over that area. This also served the purpose of obtaining multiple measures of dispersion rates over the same area, allowing the analysis of the inherent variability in the co-efficient. The cluster deployment positions and a profile of the shoreline are represented in Figure 3.12.

![Figure 3.12 Release positions of the drifter clusters on the 23\textsuperscript{rd} of March, noting the high number of drifts repeated around the co-ordinates (0,0).](image)

The behaviour of the drifters during the various deployments, was very similar. This was not unexpected given the similarity of their deployment locations. This similarity was enhanced by the consistency of the wind conditions during the experimental period. Only a relatively minor intensification in the magnitude of the wind was experienced, from 2.57m/s to 5.17m/s along with a mild deviation in the mean wind direction from an easterly (bearing 110°) at the beginning of the deployments, to a south south-easterly (bearing 160°) at the time the last cluster was released. These

\textit{Approach}
wind conditions, drove drifter motion contiguous with that experienced previously on the 22\textsuperscript{nd}, specifically, northwards longshore drift. Offshore directed drift was also noted; however the path of the drifters was largely confined by the sandbar. Upon reaching the northern extent of this feature it was ensured that they were recovered before being transported any significant distance offshore. A summary of drifter deployments and their behaviour subsequent to release is included in Table 3.10.

Table 3.10 Summary of drifter deployments on the 23\textsuperscript{rd} March 2005, including wind data (courtesy of the Bureau of Meteorology, 2005) and tide data from the nearby gauge at Outer Harbor (Hydrosurvey Australia and Flinders Port Authority, 2005).

<table>
<thead>
<tr>
<th>Date: 23/03/2006</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>Time</td>
</tr>
<tr>
<td>1</td>
<td>9:55</td>
</tr>
<tr>
<td>2</td>
<td>10:57</td>
</tr>
<tr>
<td>3</td>
<td>11:30</td>
</tr>
<tr>
<td>4</td>
<td>11:55</td>
</tr>
<tr>
<td>5</td>
<td>12:20</td>
</tr>
<tr>
<td>6</td>
<td>12:47</td>
</tr>
<tr>
<td>7</td>
<td>1:15</td>
</tr>
</tbody>
</table>

3.4 Data Analysis

A range of analysis techniques were required in order to convert the raw data, from both the ADCP and the drifters, into the desired information. The majority of this processing utilised MATLAB and was concerned predominantly with determining dispersion characteristics from the drifter data and mean current profiles from the ADCP. The methodology involved with this processing is described in the following sections; 3.4.1 and 3.4.2, which focus on the drifter and ADCP data respectively.

3.4.1 Lagrangian Drifters

A substantial amount of data processing and analysis had to be undertaken in order to obtain meaningful results from the drifter experiments. The raw data was downloaded from the individual drifters subsequent to each deployment, or series of deployments. This data was then processed into a useable format and analysed by hand to determine cluster points from which subsequent analysis derived dispersion values.

3.4.1.1 Initial processing

The drifters store data according to the National Marine Electronics Association (NMEA) default format, which includes the location, time and date, at a frequency of 1Hz as seen in Table 3.10. The location is recorded in latitude and longitude
positions, with an accuracy of 0°0.0001”, or approximately 0.16m of easting and 0.19m of northing at a latitude of 32° south (Johnson 2004). Johnson’s (2004) analysis of measurement errors also determined that the standard deviations of the displacement are 1.24m and 1.98m for eastings and northings respectively, whilst over 95% of location fixes fall within circles of radii 2.2m and 3.6m respectively. Johnson (2004) also demonstrated that the non-differential GPS fixing system is sufficient to accurately measure motions with frequencies below 0.05Hz. This is not as high as the differential GPS system utilized by Schmidt et al. (2003) which was accurate for frequencies as high as 1Hz, but it is suitable for use in the measurement of longer period motion in the surf zone.

Table 3.11 Example of the raw data downloaded from the data loggers.

<table>
<thead>
<tr>
<th>Status</th>
<th>Northing Label</th>
<th>Easting Label</th>
<th>Time (s)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>3501.96 S</td>
<td>13834.505 E</td>
<td>24883</td>
<td>10904</td>
</tr>
</tbody>
</table>

The raw recordings from the drifters were downloaded to computer using the software package ‘Data Download Version 5.5.6’. This data was then converted to the Universal Transverse Mercator (UTM) co-ordinate system for all further analysis using a MATLAB script developed by Johnson (2004). UTM co-ordinates project latitude and longitude co-ordinates onto a concentric cylinder in order to minimise distortion in distances experienced in high latitudes, thus allowing the representation of latitude and longitude co-ordinates on a ‘flat’ map. The UTM system divides the earth into 60 zones each 6 degrees of longitude wide. These zones define the reference point for UTM grid coordinates within the zone and extend from a latitude of 80° S to 84° N. UTM grid coordinates within each of the zones are expressed as a distance in metres to the east and a distance in metres to the north. Adelaide is located in Zone 53 and an example of the UTM co-ordinates converted from the raw data is shown in Table 3.12.

Table 3.12 Example of data converted from latitude/longitude co-ordinates to the UTM co-ordinate system.

<table>
<thead>
<tr>
<th>Converted UTM co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easting</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1374218.40</td>
</tr>
</tbody>
</table>

The raw data recorded by the drifters contained a level of scatter, due to limitations in the capacity of the technology as outlined in Section 3.1.2 as well as high frequency oscillations induced by the passage of waves. The wave induced oscillations were largely neutralized by the drifter parachute, however, on some occasions; the drifter was rapidly transported onshore with the wave bore in what is termed a ‘surfing’ event. These effects, acted to introduce short duration scatter into the dataset, which was not indicative of the underlying current properties. As such, it was necessary to
remove the distortion caused by these effects through a smoothing process. Smoothing was applied on the converted UTM co-ordinates using a MATLAB script developed by Johnson (2004). The script required the input of the data to be smoothed as well as a specification of the pass-band filter to be applied. The smoothing program had the effect of removing oscillations in the data set with frequencies higher than the prescribed pass band, which was set at 0.1Hz, in most cases. At a pass-band filter of 0.1Hz the effects of waves with periods of the order of 5-10 seconds (frequencies of 0.2-0.1Hz) were effectively removed from consideration, as were momentary measurement errors derived from the GPS.

In order to perform dispersion calculations the smoothed datasets had to be analysed by hand to determine the location of clusters; points where all of the drifters were at the same location at the same time. This was one of the most time consuming elements of the data analysis. The smoothed data sets for each of the drifters were plotted on the same graph in Microsoft EXCEL, to determine the location of the cluster points. Once these points had been identified, the subsequent drift patterns were analysed to determine the end point of the drift. The end point was usually characterised by a rapid change in velocity and/or direction indicating that the drifter had been retrieved by hand, whilst in some cases the drift plot was compared to the shoreline to determine when the drifter ran aground. Once the beginning and end points of the drift had been located within the full dataset, the data specifically representing the drift period was copied into separate files. The data for each drifter for each cluster was separated in this manner, resulting in a total of 63 individual files for the September deployments alone. The data in these files was in UTM coordinates and as such each point was referenced according to UTM Zone 53. Whilst this was accurate, the values of the co-ordinates were very high, thus, for the sake of simplicity, all of the ‘broken up’ drifter files were re-referenced back to the individual cluster origin (Table 3.13). Essentially, this represented the creation of a new datum point at the point of release for each cluster. These files formed the basis of all further analysis.

Table 3.13 An example of the process involved in the re-referencing of the co-ordinates datum point to the cluster origin. No accuracy is lost in this process.

<table>
<thead>
<tr>
<th>Original co-ordinates - Cluster origin: 1368444, 6092903</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easting (m)</td>
</tr>
<tr>
<td>1368443.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Re-referenced Co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easting (m)</td>
</tr>
<tr>
<td>-0.4</td>
</tr>
</tbody>
</table>
3.4.1.2 The Dispersion Co-efficient

The calculation of the dispersion co-efficient was based on the work of List *et al.* (1990) in the analysis of drifter dispersion in waters offshore from southern California and later utilised by Johnson (2004) and Olsson (2004) in the surf zone. The first step of the analysis is the determination of the centroid of the drifter paths. The location of the centroid at a given time is the instantaneous average of the easting and northing co-ordinates of each of the drifters. This is determined individually for both the x and y co-ordinates using Equation 38.

\[
\bar{x}_i = \frac{1}{N} \sum_j x_{ij} \quad \quad \bar{y}_i = \frac{1}{N} \sum_j y_{ij} \tag{38}
\]

where N is the number of drifters and (x,y) are the co-ordinates of a drifter j at time i. The variance of the drifters is subsequently determined as the squared sum of differences between the centroid and the location of each drifter as described by Equation 39 (List *et al.*, 1990).

\[
\sigma_{x_i}^2 = \frac{1}{N-1} \sum_j (x_{ij} - \bar{x}_i)^2 \quad \sigma_{y_i}^2 = \frac{1}{N-1} \sum_j (y_{ij} - \bar{y}_i)^2 \tag{39}
\]

This result provides the variance in both the x and y co-ordinates, however, the dispersion of the drogue distribution as defined by Okubo (1974) and cited by List *et al.* (1990) is determined as an average of both of these results in Equation 40.

\[
\sigma_i^2 = \frac{\sigma_{x_i}^2 + \sigma_{y_i}^2}{2} \tag{40}
\]

Using \(\sigma_i^2\) it is possible to calculate the relative dispersion coefficient \(K\) (Johnson, 2004; Okubo, 1974) using the relationship below (previously defined in Section 2.3.3.2, Equation 26).

\[
K(t) = \frac{1}{2} \frac{\partial \sigma_i^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma_i^2}{\Delta t} \tag{41}
\]

The preceding calculations were all carried out using a specifically developed MATLAB script which requires only the names of the input files in order to run. The script determines the centroid location, which is then utilised in the calculation of the variance; \(\sigma^2, \sigma_x^2, \sigma_y^2\). These variances are then plotted with time, as shown in Figure 3.13. The gradient of the least squares regression line of best fit is equivalent to the dispersion co-efficient \(K\) as described above in Equation 41 and in Section 2.3.3.2, Equation 26.
Figure 3.13 Calculation of the values of K as the gradient of the least squares line of best fit for the plot of $\sigma^2$ with time. Similar plots were derived for each cluster and are attached in Appendix B.

K was determined using the data from the entire duration of the cluster, as opposed to during periods of rapid dispersion such as was conducted by Johnson (2004) in the analysis of rip head dispersion. The coefficient of determination $r^2$, was also determined for the least squares line of best fit to quantify the accuracy of the relationship between the regression line and the raw data. Values of $K$, $K_x$ and $K_y$ with associated $r^2$ values less than 0.5 were deemed insufficiently representative of the data and were excluded from further analysis. Dispersion co-efficient values that were not removed from consideration in this manner were compared to the average values and were excluded if they differed by a factor of 10 or more. This only occurred in two cases and in both situations the data appeared to have been unduly biased by a short period of rapid dispersion, combined with a relatively short period of deployment. The remaining values were analysed to determine the value of the mean, and subsequently, the 95% confidence intervals.

As noted by List et al. (1990) the relationship between K and $\sigma^2$ is valid only for a large number of drifters and under the assumption that any one cluster is fully representative of an ensemble. Johnson (2004) also notes that a similar approach can be utilised to determine the directionally dependant values, $K_x$ and $K_y$ from $\sigma_x$ and $\sigma_y$ respectively representing the cross shore and longshore components of dispersion respectively.
Values of $K_x$, $K_y$ and $K_z$ were determined for each of 37 clusters by plotting $\sigma^2$, $\sigma^2_x$ and $\sigma^2_y$ against time and finding the gradient of the linear least squares regression line. The resulting graphs are presented in Appendix B.

### 3.4.1.3 Scale dependence

The dispersion coefficients $K_x$, $K_y$ and $K_z$ was calculated for 1m bins of standard deviation $\sigma$ in order to represent the relationship between the rate of dispersion and the size of the cluster. This utilised a MATLAB script which initially determined $\sigma$, the standard deviation of the drifter clusters. Values of the dispersion co-efficient $K$ were then calculated for each 1m increase in $\sigma$, resulting in independent dispersion co-efficient values for each 1m increase in the drifter deviation. $K$ was calculated by determining the amount of time that the value of $\sigma$ remained in the specified 1m range ($\Delta t$) and comparing this with the change in $\sigma^2$ during the period ($\Delta\sigma^2$).

![Diagram](image)

> From $t_1$ to $t_2$, the cluster increases by $\sigma_2 - \sigma_1$ thus representing $\Delta t$ and $\Delta\sigma^2$ respectively. These values are related by:

$$K(t) = \frac{1}{2} \frac{\partial \sigma^2}{\partial t} = \frac{1}{2} \frac{\Delta \sigma^2}{\Delta t}$$

> As such, it is possible to calculate $K$ over the interval, $\sigma_1$ to $\sigma_2$.

> Subsequent iterations for increasing $\sigma$ values allows the calculation of $K_1$-$K_n$ where $n$ is the maximum average deviation of the drifters from the cluster mean.

Figure 3.14 Diagrammatical representation of the methodology involved in calculating $K$ for increasing cluster deviation.

These values were then used to calculate $K$ through the relationship described by Equation 41. This process is represented schematically in Figure 3.14. Identical procedures were also utilised in the cross-shore and longshore directions in the determination of the relationships between $K_x$, $K_y$ and $\sigma_x$, $\sigma_y$ respectively. The resulting graphs are presented in Appendix B. Following the determination of the dispersion coefficients $K$, $K_x$ and $K_y$ for the 1m increments of $\sigma$, $\sigma_x$ and $\sigma_y$, log-log
scale graphs were plotted for each of the clusters. The dispersion coefficients were plotted on the vertical axis against the standard deviation, as shown in Figure 3.15.

Figure 3.15 Example of the graph derived when the dispersion coefficients $K$, $K_x$, and $K_y$ are plotted against 1m increments of $\sigma$, $\sigma_x$, and $\sigma_y$. Similar plots were derived for each cluster and are attached in Appendix B

A linear least square regression line of best fit was determined for the log-log plots; however, as the raw data describes a non-linear function, it was transformed into a linear function using the parameters outlined in Table 3.14. These transform the raw data, which is described by a non-linear relationship, $y = c_1x^{c_2}$, to a format where it can be described by a linear relationship, $v = \alpha u + \beta$. The coefficients of the line of best fit are determined for the transformed data, and are then transformed back to the original format. The coefficients of the lines of best fit represent the relationship between the average deviation of the drifters in the cluster and the rate of dispersion.

Table 3.14. The data transformation used in the fitting of the least squares line of best fit (adapted from Recktenwald, 2000).

<table>
<thead>
<tr>
<th>Non-linear Function of $C_1$ and $C_2$</th>
<th>Transformation to: $v = \alpha u + \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = C_1x^{C_2}$</td>
<td>$\nu = \ln(y)$, $\mu = \ln(x)$, $\beta = \ln(C_1)$, $\alpha = C_2$</td>
</tr>
</tbody>
</table>

Following the determination of the variables in the line of best fit, the values were compiled and analysed. As with the method utilised in the analysis of dispersion coefficients, coefficients of the line of best fit, with associated $r^2$ values less than 0.5 were deemed insufficiently representative of the data and were excluded from further analysis. Co-efficient values that were not removed from consideration in this manner were compared to the average values and were excluded if they differed by a
factor of 10 or more. The remaining values were analysed to determine the value of the mean, and subsequently, the 95% confidence intervals.

3.4.2 Eulerian ADCP Measurements
The ADCP was only deployed on three days, from which only a single full days measurements were obtained. Recordings of the current velocity were derived at a frequency of 1Hz in three dimensions for individual cells positioned at 10cm intervals from the sensor head to the water surface. The velocities recorded in each of the three dimensions (vertical, longshore and cross-shore) were stored in individual data files thereby allowing individual analysis. Pressure data was also recorded at a frequency of 1Hz allowing for the calculation of wave and tide based water level oscillations.

Analysis of current profiles was conducted using MATLAB. The data files were loaded into the program, prior to the initiation of a script developed by the author. The script was then used to conduct a number of relatively simple procedures. Specifically, the mean velocity values in each cell were determined, thus allowing them to be plotted relative to the sea-floor. Such plots were determined in the cross-shore and longshore domains, in conjunction with the derivation of the mean water depth and the depth averaged current velocity. By selecting the relevant data points it was possible to determine velocity profiles for given periods of time, thus allowing the comparison of morning and afternoon conditions.

The ADCP ran out of memory on the 22\textsuperscript{nd} of March, as the storage facility had not been erased prior to deployment. This resulted in an incomplete dataset being recorded, from 10:00 until 12:54, despite the ADCP having been deployed from 10:00 until \sim 16:30.
4 Results and Discussion

4.1 Cluster Dispersion

The value of the dispersion co-efficient $K$ as well as the cross-shore and longshore components $K_x$ and $K_y$ respectively, were determined for each of the 37 drifter clusters released during the September 2004 and March 2005 deployments. The results for each of the deployment periods are presented in Tables 4.1 and 4.2 respectively, allowing the clear representation of seasonal variation in the dispersion characteristics. These tables include the determination of the dispersion coefficients, with $K = 0.11 m^2/s$ within a 95% confidence interval of 0.08, $K_x = 0.23 \pm 0.07 m^2/s$ and $K_y = 0.15 \pm 0.14 m^2/s$ for the September deployments in comparison to $K = 0.12 \pm 0.07 m^2/s$, $K_x = 0.05 \pm 0.02 m^2/s$ and $K_y = 0.19 \pm 0.09 m^2/s$ which were recorded for the March deployments. These values show the inherent variability associated with turbulent dispersion in the nearshore zone as well as the relatively low number of samples.

The values of the dispersion coefficients determined for the nearshore zone at Henley Beach are vastly smaller than the values reported in oceanic diffusion experiments such as those conducted by Tseng (2001) and Proehl et al. (2005). Tseng (2001) recorded dispersion co-efficient values as high as $45 m^2 s^{-1}$, in enhanced flow regimes in the wake formations off islands near the coast of Taiwan, whilst Proehl et al. (2005) determined total dispersion values of up to $131 m^2 s^{-1}$ around the north flank of Georges Bank. These values demonstrate the potential for high dispersion rates within enhanced flow regions of the open ocean; however, they have little relevance to the nearshore zone where the conditions and factors driving dispersion are markedly different. The calculated dispersion coefficients are also significantly lower than the values found by Johnson (2004) in the rip-neck, where total dispersion, $K$, ranged between 1.29 and $3.88 m^2 s^{-1}$. This indicates the less energetic nature of the Adelaide study site as well as the enhancement of dispersion encountered at the rip head, outside of the surf zone, as noted by Johnson (2004), Olsson (2004) and Inman (1971). However, the obtained results do show a greater level of correlation with Johnson’s findings inside the surf zone. Johnson investigated longshore currents inside the surf zone and was able to find dispersion coefficient values of $K_x = 0.2 m^2 s^{-1}$ and $K_y = 0.3 m^2 s^{-1}$, for a 10m separation. This correlation is somewhat surprising, given the difference in the energy levels of the two study sites.
Table 4.1 Dispersion coefficients calculated for each of the drifter clusters released between the 1\textsuperscript{st} and the 3\textsuperscript{rd} of September 2004, data omitted from the calculation of the mean and the confidence intervals is shown.

<table>
<thead>
<tr>
<th>Date</th>
<th>Cluster</th>
<th>Number of Drifters</th>
<th>Shortest Time (s)</th>
<th>Kx</th>
<th>R(^2)</th>
<th>Ky</th>
<th>R(^2)</th>
<th>K</th>
<th>R(^2)</th>
</tr>
</thead>
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<td>-0.01</td>
<td>0.04</td>
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<td>0.56</td>
<td>0.03</td>
<td>0.35</td>
</tr>
<tr>
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<td>Cluster 2</td>
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<td>0.10</td>
<td>0.95</td>
<td>0.14</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Cluster 3</td>
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<td>49</td>
<td>0.10</td>
<td>0.93</td>
<td>0.06</td>
<td>0.98</td>
<td>0.09</td>
<td>0.96</td>
</tr>
<tr>
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<td>381</td>
<td>1.24</td>
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<td>166</td>
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<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.41</td>
</tr>
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<td>0.00</td>
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<td>0.39</td>
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<td>0.31</td>
<td>0.04</td>
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**Mean**

<table>
<thead>
<tr>
<th>Number of Drifters</th>
<th>Kx</th>
<th>R(^2)</th>
<th>Ky</th>
<th>R(^2)</th>
</tr>
</thead>
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<tr>
<td>0.23</td>
<td>0.84</td>
<td>0.15</td>
<td>0.76</td>
<td>0.11</td>
</tr>
<tr>
<td>0.09</td>
<td>0.11</td>
<td>0.20</td>
<td>0.17</td>
<td>0.12</td>
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</tbody>
</table>

**Std Dev**

| 0.04 | 0.15 |

**95% CI**

| 0.02 | 0.08 |

The calculated dispersion coefficients are also significantly lower than the values found by Johnson (2004) in the rip-neck, where total dispersion, K, ranged between 1.29 and 3.88m\(^2\)s\(^{-1}\). This demonstrates the enhancement of dispersion encountered at the rip head, outside of the surf zone, as noted by Johnson (2004), Olsson (2004) and Inman (1971). However, the obtained results do show a greater level of correlation.

Table 4.2 Dispersion coefficients calculated for each of the drifter clusters released between the 20\textsuperscript{th} and the 23\textsuperscript{rd} of March 2005, data omitted from the calculation of the mean and the confidence intervals is highlighted.

<table>
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<th>Date</th>
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<th>Kx</th>
<th>R(^2)</th>
<th>Ky</th>
<th>R(^2)</th>
<th>K</th>
<th>R(^2)</th>
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<tr>
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<td>0.02</td>
<td>0.26</td>
<td>0.05</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**Mean**

| 0.05 | 0.81 | 0.19 | 0.72 | 0.12 | 0.78 |

**Std Dev**

| 0.04 | 0.15 | 0.20 | 0.12 | 0.16 | 0.12 |

**95% C.I.**

| 0.02 | 0.41 | 0.09 | 0.05 | 0.07 | 0.06 |

The calculated dispersion coefficients are also significantly lower than the values found by Johnson (2004) in the rip-neck, where total dispersion, K, ranged between 1.29 and 3.88m\(^2\)s\(^{-1}\). This demonstrates the enhancement of dispersion encountered at the rip head, outside of the surf zone, as noted by Johnson (2004), Olsson (2004) and Inman (1971). However, the obtained results do show a greater level of correlation.
Results and Discussion

with Johnson’s findings inside the surf zone. Johnson investigated longshore currents inside the surf zone and was able to find dispersion coefficient values of $K_x = 0.2 \text{m}^2\text{s}^{-1}$ and $K_y = 0.3 \text{m}^2\text{s}^{-1}$, for a 10m separation. The correlation between these values and the Adelaide results, suggests that similar processes dominate dispersion within the surf zone at each site.

Mariani (2005) measured dispersion coefficients inside the surf zone under relatively high energy conditions, at Floreat Beach, a location similar to that of Johnson (2004), along the exposed Perth coastline. Mariani (2005) determined values of the dispersion co-efficient $K$ ranging between $0.2 \text{m}^2\text{s}^{-1}$ and $1.78 \text{m}^2\text{s}^{-1}$ with an associated mean value of $0.77\pm0.33 \text{m}^2\text{s}^{-1}$, within a 95% confidence interval. In addition the cross-shore and longshore dispersion coefficients were determined; $K_x$ ranged between 0.27 and $2.1 \text{m}^2\text{s}^{-1}$ in the cross-shore plane whilst $K_y$ varied between 0.35 and $3.34 \text{m}^2\text{s}^{-1}$ in the longshore direction. Mariani (2005) noted the variation in the magnitude of the dispersion co-efficient between the cross-shore and the longshore planes. This was attributed to the presence of boundaries in the cross-shore plane, in the form of the breaker line and the shoreline, compared to the almost complete lack of boundaries in the longshore direction. These conditions were enhanced by the prevailing experimental conditions favoured by Mariani (2005) which were strong sea breezes. This introduced a level of bias in the data, as the presence of strong sea breezes has the effect of restricting the width of the surf zone and maintaining a clear boundary at the breaker line preventing the cross-shore spread of wave induced turbulence. This was noted by Inman et al. (1971) and Bowen & Inman (1974) who observed that in dye release experiments, the dispersion appeared to be contained within the surf zone, due to the absence of turbulence seaward of the break point and the advection of offshore water through the breaker line. Turbulent diffusion is the key dispersive mechanism in the nearshore zone and the restriction of its cross-shore distribution, due to the bounding effect of the surf zone, thus acts to restrict the extent of nearshore dispersion (Bowen and Inman, 1974).

Significantly, the relative enhancement of dispersion in the longshore direction is only noted in Adelaide in the results from the March deployments, where sea-breeze conditions similar to those utilized by Mariani (2005) prevail. The values obtained by Mariani (2005) were significantly larger then those observed in Adelaide. This can be attributed to the more energetic nature of Marianis’ (2005) study site, where sampling
was conducted under sea breeze strengths of as high as 18m²s⁻¹ and was often associated with highly energetic wave conditions, leading to increased turbulence within the surf zone.

A better correlation is observed in the results of a dye dispersion experiment and concurrent numerical modeling conducted by Rodriguez et al. (1995) which found dispersion coefficients in the surf zone to be 0.03m²s⁻¹ ± 0.01m²s⁻¹. Whilst this result is smaller than that recorded at Henley Beach it is significant because it was recorded on a geometrically simple linear beach, on the sheltered Spanish Mediterranean coast, a location similar to that of the Adelaide metropolitan coastline. Numerical modeling confirmed the experimental results of Rodriguez et al. (1995) predicting a horizontal eddy diffusivity of $K_h = 0.018$m²s⁻¹, which again, correlates to some extent with the measured dispersion coefficients.

To the authors’ knowledge, the only other direct measurements of dispersion in the surf zone were undertaken by Takewaka et al. (2003). Takewaka et al. (2003) conducted dye diffusion experiments in the surf zone under significant wave height conditions of 0.56m, associated with a peak period of 6.5s and a longshore current of 0.3m/s. This allowed the calculation of cross-shore dispersion values of 0.01, 0.017 and 0.025m²s⁻¹. These values can not be directly compared to the calculated dispersion values, as Takewaka et al. (2003) assumed a Fickian diffusion process, however it can be seen that at scales of 5m Takewaka et al.’s (1995) results are consistent with those of Johnson (2004) who did not assume Fickian diffusion.

Riddle and Lewis (2000) reviewed data from 25 dye dispersion experiments from estuarine and coastal locations and found the lateral dispersion coefficient to range between 0.003 and 0.42m²s⁻¹ with a median value of 0.05m²s⁻¹. Riddle and Lewis (2000) compared their data to similar experiments conducted off the coasts of Ireland and Cape Kennedy in the United States, which returned median dispersion coefficients of 0.18m²s⁻¹ and 1.0m²s⁻¹. The dispersion values calculated in this experiment can thus be seen to fit within the range of dispersion coefficients encountered within the literature, albeit, the bulk of recorded values are calculated from sites offshore from the surf zone.
The comparison of the recorded experimental results with values from the literature thus demonstrates the low rate of dispersion present in Adelaides nearshore waters. It has been established that the experimental results are lower than those obtained in more active, energetic surf zone areas addressed be Mariani (2005) and Johnson (2004) and are also significantly lower then the rates of dispersion quoted in the open ocean by Tseng (2001) and Proehl et al. (2005). They values are also an order of magnitude lower than dispersion coefficient values of 1-5m²/s which were considered representative of the semi-enclosed water body of Port Philip Bay quoted by C. Pattiaratchi. In contrast, the values obtained correlate to reasonable extent with the results reported from other low energy environments, specifically the sheltered Mediterranean coastline, Rodriguez (1995) and to a lesser extent, the values presented by Riddle & Lewis (2000), who addressed locations across a variety of geographical settings and thus reported a wide range of dispersion values. A summary of the dispersion coefficient values reported in the literature and their relationship to the values presented in this paper is presented in Table 4. 3.
Table 4.3 Summary of the various dispersion coefficient values quoted in the literature and a comparison to the values obtained in Adelaides coastal waters.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Location</th>
<th>Comment</th>
<th>Method</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
<th>Kx(m²/s)</th>
<th>Ky(m²/s)</th>
<th>Comparison to Adelaide</th>
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</thead>
<tbody>
<tr>
<td>Johnson (2004)</td>
<td>Surf Zone</td>
<td>Rip neck</td>
<td>Drifters</td>
<td>1.29</td>
<td>3.88</td>
<td>0.63</td>
<td>0.2</td>
<td>0.3</td>
<td>higher</td>
</tr>
<tr>
<td>Johnson (2004)</td>
<td>Surf Zone</td>
<td>Longshore current 10m separation</td>
<td>Drifters</td>
<td>0.2</td>
<td>1.78</td>
<td>0.76</td>
<td>0.3</td>
<td>0.96</td>
<td>close</td>
</tr>
<tr>
<td>Mariani (2005)</td>
<td>Surf Zone</td>
<td>Longshore current (using power law relationship)</td>
<td>Drifters</td>
<td>0.2</td>
<td>1.78</td>
<td>0.76</td>
<td>0.3</td>
<td>0.96</td>
<td>higher</td>
</tr>
<tr>
<td>Rodriguez (1995)</td>
<td>Surf Zone</td>
<td>Low energy mediterranean beach</td>
<td>Dye diffusion</td>
<td>0.018</td>
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<td></td>
<td>1</td>
<td>0.18</td>
<td>lower</td>
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<tr>
<td>Takewaka et al. (2003)</td>
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<td>Fickian assumption (5m separation)</td>
<td>Dye diffusion</td>
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<td>0.025</td>
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<td>Riddle &amp; Lewis (2000)</td>
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<td>Estuaries, bays, offshore, UK</td>
<td>Dye diffusion</td>
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<td>0.42</td>
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</tr>
<tr>
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<td>Nearshore</td>
<td>Cape Kennedy</td>
<td>Dye diffusion</td>
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<td></td>
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<td>1</td>
<td>1</td>
<td>close</td>
</tr>
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<td>Tseng</td>
<td>Oceanic</td>
<td>Island wakes</td>
<td>Drifters</td>
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<td>0.11</td>
<td>higher</td>
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<tr>
<td>Proehl</td>
<td>Oceanic</td>
<td>Georges bank</td>
<td>Modelling</td>
<td>131</td>
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<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
<td>higher</td>
</tr>
<tr>
<td>THIS PAPER</td>
<td>Surf Zone</td>
<td>September</td>
<td>drifters</td>
<td>0.11</td>
<td>0.23</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>higher</td>
</tr>
<tr>
<td></td>
<td></td>
<td>March</td>
<td>drifters</td>
<td>0.12</td>
<td>0.05</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>higher</td>
</tr>
</tbody>
</table>

**Results and Discussion**
4.1.1 Seasonal and daily variations
A significant level of variation in the derived dispersion coefficients can be observed in the results presented in Tables 4.1 and 4.2. The timescale over which these variations occur is significant; with clear trends visible in the seasonal comparisons, as well as shorter period discrepancies observed during single days or over a period of days in the same sampling period. The variability of the derived dispersion coefficients across the different timescales as well as the reasons for these disparities will be addressed in this section.

4.1.1.1 Seasonal Variation
A summarized version of the dispersion coefficients obtained during the September and March deployments respectively is presented in Table 4.4. This represents the relative consistency of the total dispersion coefficient $K$, whilst a large deviation is noted in the cross-shore results and a smaller, yet significant, variation is noted in the longshore direction.

<table>
<thead>
<tr>
<th></th>
<th>$K$</th>
<th>C.I.</th>
<th>$K_x$</th>
<th>C.I.</th>
<th>$K_y$</th>
<th>C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>0.11</td>
<td>0.08</td>
<td>0.23</td>
<td>0.07</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>March</td>
<td>0.12</td>
<td>0.07</td>
<td>0.05</td>
<td>0.02</td>
<td>0.19</td>
<td>0.09</td>
</tr>
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</table>

The factors influencing these deviations include: changes in the dominant wind regime (which indirectly controls the wave conditions), tides and topographic controls.

Changes in the dominant wind regime are likely to have the greatest effect, as the nature of the relatively sheltered study site dictates that the dominant factor influencing turbulence in the nearshore zone, and hence dispersion, is wind generated waves. Waves influence the rate of mixing in the surf zone through a variety of mechanisms, including a combination of mixing generated by the production of turbulence due to breaking wave activity, mixing generated by the oscillatory flow over the bed, and shear dispersion (Pearson et al. 2002). As noted in the Literature Review, Section 2.1.3.4, the Adelaide metropolitan coastline is subjected to an active sea-breeze system during the summer months. This system causes strong south westerly winds to blow during the afternoon, driving the generation of short period, relatively high energy wind waves. The breaking of these waves in the nearshore zone creates turbulence which is the dominant force driving dispersion. However, the influence of the sea-breeze does not extend to the same extent through winter,
providing a major differentiating factor between the wind regimes of the experimental periods.

During the sea breeze several changes in the surf zone are typically induced, including: an increase in the height of incident waves, a decrease in the wave period (or zero-upcrossing period) and an increase in the velocity of the longshore current (Masselink & Pattiaratchi, 1997). These factors combine to produce an increase in the wave energy incident on the generally calm Adelaide coastline, leading to an increase in turbulence in the nearshore zone. Logically, this should lead to an increase in the observed dispersion coefficients and this is true for the longshore direction. However, this is not the case in the cross-shore direction, where the dispersion coefficient is greatly reduced in comparison to the September deployments. This reduction may be attributed to a combination of factors.

The onshore direction of the sea breeze system has the effect of increasing the onshore advective flux, particularly in the surface layers of the water column (Inman et al., 1971). Essentially, water is pushed shoreward through the forcing of the wind and its associated wave regime. This has the effect of constraining the width of the surf zone. As noted by Bowen & Inman (1974), turbulent dispersion is effectively contained within the surf zone due to the barrier created by the breaker line, thus restraining the motion of the drifters to within these boundaries. As the sea breeze has the effect of narrowing the surf zone, whilst simultaneously increasing turbulence and the longshore current it is a reasonable outcome that:

1 Dispersion in the longshore direction, which is effectively unbounded and is enhanced through the higher generation of turbulence and the stronger longshore current, increases, whilst;

2 Dispersion in the cross-shore direction is restrained by the decrease in the width of the surf zone.

Another factor potentially impacting hydrodynamic processes in the nearshore zone and hence dispersion rates is the presence of topographic features. Whilst no beach profiles were obtained, simple observations confirmed the presence of a large shore parallel sandbar approximately 40 metres offshore from the beach during the summer deployments. This influenced the hydrodynamic regime of the experimental area by instigating wave breaking at a point further offshore than would be expected if it were
Results and Discussion

not present. This reduced the amount of wave energy reaching the shoreline which may in turn have influenced the magnitude of wave induced longshore transport and turbulence close to the shore. However, given the observed result that longshore dispersion inside the sandbar is greater when the sandbar is present, this scenario is unlikely to be a dominant process.

Rather, the primary influence of the sandbar is likely to be as a barrier to cross-shore dispersion in the offshore direction, similar to the breaker boundary line described previously. In fact, the presence of the sandbar would complement the effect of the breaker line, as during sea breeze conditions, the two coincide in their location due to wind induced waves breaking at the shallow sandbar. The onshore advective flux associated with wave breaking dominates the water column (Bowen & Inman, 1974), with the shallow depth of the sandbar effectively preventing offshore directed undertow. As such, the sea breeze and the sandbar act in conjunction with each other to create a boundary through which offshore movement is heavily retarded or completely prevented.

Whilst the sea breeze is a daily phenomenon that has a maximum duration in the order of several hours, the formation and duration of sandbars in a relatively low energy environment such as Adelaide is in the order of several weeks or months (Komar, 1976). Thus, whilst the effect of the sea breeze on dispersion is limited in duration to periods where favourable winds prevail, the sandbar forms a semi-permanent feature which has the combined effects of forming a boundary impeding cross shore flow and channeling (concentrating) flow in the longshore direction (Komar, 1976). This is represented through the comparison of morning and afternoon results. The fact that the dispersion in the cross-shore direction is impeded throughout the deployment period, largely regardless of the prevailing conditions, highlights the influence of the topography.

Another significant contrast of note between the two sampling periods was the tidal regime. During the September deployments semidiurnal spring tides of up to 2m were observed, with significant implications for the nearshore beach morphology as noted in Section 3.3.1. However, during the March deployments the tidal regime was characterized by neap conditions, whereby the tidal range initially was close to zero; however, over the course of the deployment period this increased to a range of
approximately 1m over a semi-diurnal period. Tidal oscillations are known to have several key impacts on the nearshore hydrodynamic regime. Specifically, tidal variances have been attributed to increases in rip currents and longshore currents (Simpson et al. 2005; Komar, 1976), particularly around low tide, when water draining from the beach becomes trapped behind topographic features such as shore parallel sandbars. Flow in longshore currents and rips is enhanced as the water moves towards the breaks in the sandbar and then flows rapidly through these features in the offshore direction (Brander, 1999, Komar, 1976). As such it is plausible that the tidal oscillations may have an effect on dispersion in the study area through tidally induced currents producing turbulence and mixing in the water column (Xing & Davies, 2003).

During field experiments, the author spoke to several local residents who offered valuable information pertaining to the long term behaviour of various aspects of the beach including seasonal variations in current patterns due to tidal oscillations. In particular a resident of 40 years described drift netting for mullet during the 1970’s in the nearshore zone, between 50 and 200m from shore. Specifically, the resident recalled watching the net, which was anchored at one end rotate 90° from a position perpendicular to the shore, to a position parallel to the shoreline. This was noted because the conditions under which the movement took place were completely calm, with no wind or waves observed. However, the tide was dropping during this period, suggesting that the tidal outflow was sufficient to generate a longshore current capable of moving the net. Whilst this description provides an interesting story, it is little more than circumstantial evidence.

Unfortunately, the effect of the tidal oscillations cannot be readily obtained from the results presented in this study. This is because data was not collected over the entire tidal cycle, rather, sampling was opportunistic with results obtained from the same time period each day, and hence relatively similar stages of the cycle,. Additionally, the presence of other dominant factors such as highly variable wind and wave conditions as well as topographic controls as discussed previously will tend to mask any values obtained due to tidal oscillations. The magnitude of the dispersion directly induced by tidal processes affecting the nearshore spatial distribution and magnitude of currents is significantly smaller than the processes discussed previously, due to the low energy nature of tidal variations. However, it is also plausible that tidal movements interacting with other features may enhance dispersion. This is
particularly true in the case of topographic features such as sandbars interacting with a low or falling tide. As the water level decreases the number of waves breaking on the sandbar will increase, due to the shallower water. This leads to the definition of a new breaker line which enhances effects on cross-shore and longshore dispersion associated with the boundary.

In order to determine the actual influence of the tides on nearshore dispersion, it would be necessary to deploy the drifters through various stages of the entire tidal oscillation under completely calm conditions. This would ensure that the effects of other forcing factors are removed from the obtained results.

4.1.1.2 Daily Variation (September, 2004)
Significant variation was noted in the values of the dispersion coefficients determined across consecutive days in the same deployment period, as well as under differing conditions through the duration of a single day. In order to determine the influence of the variability in conditions between consecutive deployments, wind directions were taken into account during data processing. Dispersion coefficients determined in the total, cross-shore and longshore directions, for winds with a northerly and a southerly component respectively are shown in Table 4.5. This leads to the derivation of markedly different dispersion coefficient values for the respective prevailing wind conditions. During the September deployments, it was found that $K = 0.16 \text{m}^2\text{s}^{-1}$ under prevailing winds with a southerly component, whilst $K = 0.03 \text{m}^2\text{s}^{-1}$ for winds with a prevailing northerly component. This is a significant variation, which is also seen in the longshore and cross-shore directions; $K_x = 0.18 \text{m}^2\text{s}^{-1}$ and $K_y = 0.09 \text{m}^2\text{s}^{-1}$ for southerly prevailing winds, whilst $K_x = 0.03 \text{m}^2\text{s}^{-1}$ and $K_y = 0.02 \text{m}^2\text{s}^{-1}$ under northerly conditions.

These results may appear to be counter intuitive when one notes that the dominant direction of winds with a southerly component is south westerly. This is congruous to the sea breeze described in the March deployments which was associated with a significant retardation of mixing in the cross-shore direction. This was attributed to the sea breeze’s enhancement of the onshore advective fluxes and the effect of the onshore winds in constraining the width of the surf zone. In this situation however, cross-shore dispersion rates are larger under south westerly conditions. This can be attributed to a combination of two factors, namely the wind direction and velocity.
Table 4.5 Dispersion coefficient values calculated taking into account whether the prevailing winds contained a northerly or southerly bias, during the September 2004 deployments.

<table>
<thead>
<tr>
<th>Date</th>
<th>Cluster</th>
<th>Wind Direction (°)</th>
<th>Wind Velocity (m/s)</th>
<th>Kx</th>
<th>R^2</th>
<th>Ky</th>
<th>R^2</th>
<th>K</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
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<td>1/09/2004</td>
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<td>230</td>
<td>4.61</td>
<td>0.01</td>
<td>0.04</td>
<td>0.07</td>
<td>0.56</td>
<td>0.03</td>
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<td>240</td>
<td>3.61</td>
<td>0.17</td>
<td>0.02</td>
<td>0.10</td>
<td>0.95</td>
<td>0.14</td>
<td>0.95</td>
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<td></td>
<td>Cluster 3</td>
<td>220</td>
<td>5.69</td>
<td>0.10</td>
<td>0.93</td>
<td>0.08</td>
<td>0.98</td>
<td>0.09</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Cluster 4</td>
<td>230</td>
<td>4.11</td>
<td>1.24</td>
<td>0.95</td>
<td>0.09</td>
<td>0.80</td>
<td>0.00</td>
<td>0.96</td>
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<td>Cluster 5</td>
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<td>0.07</td>
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<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.41</td>
</tr>
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<td>2/09/2004 (AM)</td>
<td>Cluster 1</td>
<td>360</td>
<td>1.5</td>
<td>0.00</td>
<td>0.64</td>
<td>0.01</td>
<td>0.67</td>
<td>0.01</td>
<td>0.77</td>
</tr>
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<td>Cluster 2</td>
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<td>0.01</td>
<td>0.80</td>
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<td>0.00</td>
<td>0.00</td>
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<td>0.04</td>
<td>0.80</td>
<td>0.02</td>
<td>0.41</td>
<td>0.03</td>
<td>0.78</td>
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<td>250</td>
<td>4.61</td>
<td>0.10</td>
<td>0.93</td>
<td>0.58</td>
<td>0.84</td>
<td>0.39</td>
<td>0.87</td>
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<tr>
<td>2/09/2004 (PM)</td>
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<td>250</td>
<td>3.61</td>
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<td>0.31</td>
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<td>0.39</td>
<td>0.11</td>
<td>0.55</td>
<td>0.07</td>
<td>0.60</td>
</tr>
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<td>220</td>
<td>2.61</td>
<td>0.24</td>
<td>0.88</td>
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<td>0.05</td>
<td>0.13</td>
<td>0.90</td>
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<td>0.11</td>
<td>0.00</td>
<td>0.19</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>3/09/2004</td>
<td>Cluster 1</td>
<td>250</td>
<td>1.5</td>
<td>0.02</td>
<td>0.41</td>
<td>0.05</td>
<td>0.27</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Cluster 2</td>
<td>300</td>
<td>2.61</td>
<td>0.05</td>
<td>0.71</td>
<td>0.02</td>
<td>0.31</td>
<td>0.04</td>
<td>0.71</td>
</tr>
</tbody>
</table>

| Southerly Component | Mean     | 0.18 | 0.92 | 0.09 | 0.77 | 0.16 | 0.66 |
|                     | Std Dev  | 0.06 | 0.03 | 0.02 | 0.20 | 0.13 | 0.13 |
|                     | 95% CI   | 0.06 | 0.03 | 0.02 | 0.18 | 0.11 | 0.13 |
| Northerly Component | Mean     | 0.03 | 0.74 | 0.02 | 0.42 | 0.03 | 0.65 |
|                     | Std Dev  | 0.03 | 0.08 | 0.02 | 0.18 | 0.01 | 0.21 |
|                     | 95% CI   | 0.02 | 0.08 | 0.02 | 0.18 | 0.01 | 0.21 |

Data excluded due to high deviation from mean
Data excluded due to low R^2

The direction of the winds is a key factor in determining the seeming incongruity in the relationship between the sea breeze restricting dispersion in summer and similar conditions seemingly enhancing dispersion in winter. The key parameter is the level of wind energy that is transferred to waves incident upon the study area. Winds from the south west direction produce waves which strike the Adelaide coastline obliquely, producing conditions optimal for the production of longshore currents (Longuet-Higgins 1970). The production of turbulence in the nearshore surf zone through the action of wave breaking and the longshore transport associated with the south westerly winds ensures that dispersion is relatively active.

In contrast, the prevailing wind direction with a northerly component during the September deployments was north north-easterly. This is almost parallel to the shoreline of the study site and as such, the direction of propagation ensures that wind waves produced under these conditions do not transfer a large amount of energy into the surf zone. The reduced energy transfer into the surf zone implies that relatively less turbulence is induced to drive dispersive processes, when compared to south westerly wind conditions.

The other factor influencing the relative rates of dispersion during the September deployments is the wind velocity. This applies in conjunction with the wind direction...
Results and Discussion

and serves to reinforce the outcomes already obtained. Winds with a southerly component average 4.1m/s during the September deployments, whilst winds from the north average just 1.42m/s. As has already been addressed, the south westerly conditions are optimal for the efficient transfer of wave energy into the surf zone and the promotion of the longshore current. The stronger winds experienced from the south west direction add to this effect, providing a higher amount of wind wave energy to facilitate the induction of turbulence and dispersion within the surf zone.

Conversely, the weak winds associated with the northerly direction provide a restricted amount energy to the water surface leading to limited wave energy being transferred into the surf zone. Of this limited potential supply, only a small proportion is effectively transferred into the surf zone, as the aspect of the beach relative to the winds is almost parallel. With, little turbulence available within the nearshore zone, dispersion rates under northerly wind conditions are low in all directions, as there is no dominant force that has the effect of actively promoting turbulence in the water column, and hence dispersion.

Consequently, it can be concluded that the relative enhancement of the dispersion coefficient under wind conditions with a southerly component is due to a combination of wind velocity and direction. These factors govern the supply of wave energy into the surf zone and hence directly the affect the instigation of turbulence through the action of breaking waves. Turbulence diffusion is the key dispersive mechanism in the nearshore zone and thus under more energetic and turbulent conditions, dispersion is enhanced. This is represented in the dispersion coefficient results calculated for the differing wind conditions. Under the influence of more energetic, southerly winds, associated with the efficient transfer of energy, dispersion rates are higher. In contrast, when low velocity northerly winds dominate and the lower of turbulence in the nearshore zone is impeded, dispersion rates are lower.

4.1.1.3 Daily Variation (March, 2005)

During the March deployments there was a significant variation noted in the prevailing conditions. During the first two days of deployment the prevailing conditions were onshore with a strong sea breeze system operating during the afternoons. However, in the following two days, somewhat atypical conditions prevailed with offshore, easterly, winds dominating throughout the sampling period.
This allows the comparison of the effects of prevailing wind conditions, with easterly and westerly components respectively, on the calculated values of the dispersion coefficient, represented in Table 4.6.

Table 4.6 Dispersion coefficient values calculated taking into account whether the prevailing winds contained an easterly or westerly bias, during the March 2005 deployments.

<table>
<thead>
<tr>
<th>Date</th>
<th>Cluster</th>
<th>Wind Direction (°)</th>
<th>Wind Velocity (m/s)</th>
<th>Kx</th>
<th>R^2</th>
<th>Ky</th>
<th>R^2</th>
<th>K</th>
<th>R^2</th>
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<td>0.04</td>
<td>0.93</td>
<td>0.10</td>
<td>0.66</td>
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<td>0.78</td>
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<td>245</td>
<td>4.37</td>
<td>0.01</td>
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<td>0.04</td>
<td>0.67</td>
<td>0.03</td>
<td>0.73</td>
</tr>
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<td>4.62</td>
<td>0.00</td>
<td>0.19</td>
<td>0.05</td>
<td>0.71</td>
<td>0.03</td>
<td>0.67</td>
</tr>
<tr>
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<td>4</td>
<td>230</td>
<td>5.14</td>
<td>0.01</td>
<td>0.39</td>
<td>0.15</td>
<td>0.60</td>
<td>0.08</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>230</td>
<td>5.14</td>
<td>0.08</td>
<td>0.77</td>
<td>0.11</td>
<td>0.55</td>
<td>0.10</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>220</td>
<td>5.65</td>
<td>0.05</td>
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<td>0.21</td>
<td>0.04</td>
<td>0.66</td>
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<td>21/03/2005</td>
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<td>0.85</td>
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The values contained in Table 4.6 demonstrate a clear relationship between the wind direction and the dispersion rate. The total dispersion coefficient was measured as $K = 0.16 \text{m}^2\text{s}^{-1}$ under easterly conditions, whilst when westerly winds were prevailing $K = 0.08 \text{m}^2\text{s}^{-1}$. Similarly, under winds with an easterly component the longshore dispersion coefficient $K_y = 0.24 \text{m}^2\text{s}^{-1}$, was significantly larger when compared to $K_y = 0.14 \text{m}^2\text{s}^{-1}$ which was derived during periods of prevailing westerly conditions.

For both the total dispersion coefficient $K$ and the longshore dispersion coefficient $K_y$, a significant offset is seen between the easterly and westerly wind components. Specifically, an enhancement in the dispersion coefficient values in the order of 100% is seen in the easterly dominated results, relative to the values calculated under westerly conditions. This is in contrast to the dispersion coefficient values calculated in the cross-shore direction, where $K_x = 0.05 \text{m}^2\text{s}^{-1}$ for both easterly and westerly prevailing wind conditions.

Results and Discussion
In contrast with the results obtained during September, the velocity of the wind does not vary significantly with the dominant direction, with an average velocity of 4.75m/s recorded for winds with an easterly component, compared with an average velocity of 4.65m/s recorded for winds from the west.

The dominant factor in the relationship between wind conditions and dispersive rates is the wind direction. However, in the case of the cross-shore dispersion coefficient, it is clear that there must be different mechanisms influencing the dispersion rate, as clearly opposing wind regimes are associated with identical cross-shore dispersion coefficients. Addressing, the value of the cross-shore dispersion co-efficient demonstrates that under both easterly and westerly wind conditions, dispersion is low. This suggests that, either cross-shore dispersion is being impeded, or, there is only a limited amount of energy available to drive turbulence in the nearshore zone thereby restricting the attainable cross-shore dispersion rates.

In the case of winds with a westerly component, it is unlikely that dispersion rates are limited by the amount of wave energy entering the system. This is because the average wind speed is relatively high, reaching a maximum of 7.2m/s and the direction of average flow is almost directly onshore, in a west south westerly direction. Under these conditions, the generation of wind waves within the Gulf of St Vincent is optimized, leading to the conclusion that the amount of energy available under the westerly prevailing conditions was sufficient to induce turbulence to drive more significant dispersion rates. Rather, the restriction of dispersion is due to the effects of the onshore sea breeze conditions as outlined, in the seasonal comparison of data, in Section 4.1.1.1. That is, the onshore breeze and the associated waves have the effect of constraining the width of the turbulent surf zone in the cross-shore direction, thereby narrowing the domain over which cross-shore dispersion can occur, as the edge of the surf zone turbulence effectively acts as an offshore barrier to dispersion.

Under easterly prevailing winds, the restriction in the width of the surf zone through onshore winds is no longer a plausible cause for the relatively low values of cross-shore dispersion observed. Rather, as the wind blows from a predominantly south south-east direction (bearing 130°) it can be assumed that mixing in the cross-shore direction is low due to a lack of turbulent energy in the surf zone driving dispersion.
As the winds are blowing from the land, they do not create waves that are incident on the coastline within the study site. This ensures that the dispersion coefficients in the cross-shore domain are low when winds with an easterly component are dominant.

It should also be noted that the same topographic control to cross-shore dispersion applies under all wind conditions. Specifically, the presence of the shore parallel sandbar as discussed in Section 4.1.1.1 creates an effective offshore boundary to dispersion which is likely to enhance the effect of the sea-breeze in restricting cross-shore dispersion. However, it is unlikely to influence dispersion coefficients under offshore wind conditions, as energy limitation is the key factor affecting dispersion, not a boundary to cross-shore flow.

The difference in the longshore dispersion coefficients calculated under differing wind regimes can also be justified through the direction of the prevailing wind conditions. Winds with a westerly component were typically almost directly onshore, perpendicular to the coast, with an average bearing of 260°. These conditions are not optimal for the generation of longshore currents as water is pushed directly onshore (as opposed to obliquely incident waves which generate the longshore currents in the direction of the longshore component of the wind, Section 2.3.2.1). As there is no longshore component in the direction of the incident wave, a uni-directional longshore current is unable to develop and the longshore dispersion coefficient remains relatively low as the separation of the drifters is not affected by shear dispersion in the nearshore zone.

In comparison, the average direction of the wind with an easterly component is south south-easterly. These winds blow in a direction which is more parallel to the coast, so whilst it does not generate waves which are incident upon the shoreline, it does generate a flow which moves parallel to the coast and is analogous with the longshore current (Komar, 1976). The longshore current increases the longshore dispersion coefficient through the impact of shear dispersion. Drifters are rapidly transported in the longshore direction as they enter the narrow region of relatively rapid flow typical of the longshore current. This leads to an increase in the longshore separation of the drifters, increasing $K_y$. Due to the offshore orientation of the wind propagation, the longshore current generated is not particularly strong and is not constrained to a
narrow region. Therefore, the effect of shear dispersion associated with the longshore current is relatively minor.

During March, two prevailing wind regimes dominated the deployment period in roughly equal shares. These wind regimes were characterized by significant easterly and westerly directional components respectively. Cross-shore dispersion was low under all conditions, which was attributed to restriction in the width of the surf zone through onshore advective processes during onshore westerly conditions, whilst when offshore easterly winds were dominant the lack of cross-shore dispersion was attributed to a lack of energy driving turbulence and hence dispersion. It is also noted that during the March deployments topographic controls applied due to the presence of an offshore submerged sandbar, which effectively formed a barrier to cross-shore dispersion under all prevailing wind conditions. In the longshore direction, enhancement of dispersion was observed while winds with an easterly component prevailed. This was attributed to the southerly bias in the wind’s direction, which acted to promote longshore currents in the nearshore zone. These longshore currents acted to increase the observed dispersion by providing a mechanism through which shear dispersion was able to influence the separation of the drifters in the longshore direction.

4.1.2 Accuracy of Results

The results presented in the previous sections, whilst as accurate as possible are likely to contain various inaccuracies. These errors can be attributed to a number of factors, some of which are preventable and others which are inherent to the process and hence are difficult to remove. They are best managed through the mitigation of their impacts.

The most easily identified sources of errors in the measurements are due primarily to preventable causes. Specifically, errors in the field were caused when the drifters moved into water that was too shallow and the drifter casing, or the attached drogue came into contact with the bottom. This resulted in an increase on the drag affecting the drifter and a subsequent decrease in its velocity. The effects of the drifter dragging on the bottom were difficult to eliminate from the data as the change in drifter behaviour was subtle, with the variance in drifter behaviour occurring over time, with increasing severity, as the drag increased. The influence of drag on the drifters was
difficult to identify, as it was possible that dispersion could increase, when the main cluster group moved away from the affected drifter or conversely, decrease when the cluster group moved towards an affected drifter. This was often the case in situations where a ‘lead’ drifter would move into shallow water and become stuck whilst the remaining drifter group ‘caught up’. Great efforts were devoted to removal of drag affected data from the analysis, both in the field, where dragging drifters were noted upon collection, and in the data analysis, where decreases in drifter velocity were noted in the proximity of the shoreline and known sandbars. However, it can not be stated definitively that this process has had a 100% rate of success, particularly in situations where more then one drifter was affected. Similarly, other preventable errors, present in the raw data included periods where the drifters were affected by breaking waves, known as surfing, and periods where the drifters were moved by hand. Both of these error sources were relatively rare; due to the low wave energy nature of the study site and the field approach of not moving the drifters by hand until the end of a cluster deployment. Neither of these factors is likely to have significantly affected the processed data, as both affects were typified by short rapid motions, usually associated with an obvious change in direction. The identification and removal of such events was relatively simple.

The more ingrained sources of error in the data stem from the non-preventable effects. From a technological perspective, measurement errors associated with the GPS system were present and they induced significant scatter in the raw data. The removal of these effects is difficult. It is clear that some data points are erroneous; as they are characterised by large deviations (up to 3.5km) in the recorded position, for a short period, before returning to the ‘real’ position. However, at smaller scales, where the deviation is of the order of the actual drifter motion, it becomes difficult to distinguish measurement errors from actual data. This problem was mitigated to a large extent through the process of smoothing, which used a moving average routine to calculate the most likely position of the drifter at each point in time. This process ‘smoothed out’ the effects of rapid short duration motions, creating a path for the drifter more representative of the underlying motion than suggested by the rapid short term deviations. Thus, whilst the effects of GPS positioning errors are not simple to eliminate, their effects can be mitigated in such a way that they have little bearing on the final processed data.
The high variability of the processed results is an area of concern that was mitigated to the greatest extent possible through using a number of procedures as outlined in Section 3.4.1.2. Specifically, a 0.5 cut-off was applied for the value of the coefficient of determination, $r^2$, when calculating the dispersion coefficient from the line of best fit on the graph of variance with time. This ensured that the calculated value of the dispersion coefficient was representative of the underlying data. In addition, results which did comply with the $r^2$ condition but differed from the calculated mean by a factor of 10 or more were removed. This second condition is applied in order to mitigate the inherently erratic nature of turbulent dispersion in the nearshore zone.

Whilst the conditions of homogeneity and isotropy in eddies responsible for turbulent diffusion must be respected (Johnson, 2004) it is also clear that different factors do influence dispersion in the surf zone and over different timescales. The same flow may be regarded as a mean motion at small scales of observation, whilst at larger scales it may be observed to form part of a complex turbulent flow (List et al. 1990). The period and scale of forces affecting the drifters will have an influence on the determined dispersion coefficients and in order to mitigate these effects values which are sufficiently detached from the mean are removed from further analysis.

Whilst these methodologies are effective in reducing the variability of the recorded dispersion coefficients, the size of the 95% confidence intervals relative to the coefficient values indicates the inherently erratic nature of dispersion itself as well as the factors influencing it. This has significant implications when analysing the trends obtained from a relatively small number of points; specifically, the analysis of daily variations in the March and September deployments. Ideally, more data points would have been available, leading to a greater level of confidence in average values upon which assumptions as to the dominant dispersive regime were based. However, it is only possible to work with the data that is available and in some cases this meant that the degree of certainty in the result was compromised to an extent, by assuming that a limited number of data points were accurate and representative of the underlying trends.

In the analysis of dispersion trends with varying wind conditions, it was necessary to attempt to identify some of the causal relationships between observed conditions and the associated dispersion rate. As this was based on a relatively limited number of
data points, it is prudent to note the inherent variability in dispersion rates and acknowledge that this may impact on the interpreted relationships. In the same manner, it is important to acknowledge that whilst the primary factor affecting dispersion at the study site is wind conditions, the system is dynamic and is subjected to ongoing changes in the tide, current and wave regimes which can also have a significant impact on dispersion.

### 4.1.3 Scale Dependence

The relationship between the dispersion coefficient and the scale of the drifter separation was addressed by finding the dispersion coefficient for 1m bins of standard deviation.

The coefficients for the lines of best fit between $K$, $K_x$, and $K_y$ and the length scales $\sigma$, $\sigma_x$, and $\sigma_y$, for each of the cluster releases during September 2004 are shown in Table 4.7. Using this data it was possible to determine the power law relationships for the dispersion coefficient $K$ shown in Equation 42.

$$K = 0.03\sigma^{1.40} \tag{42}$$

Where, $c_1$ (0.03) and $c_2$ (1.40) fall within 95% confidence intervals of ±0.02 and ±0.26 respectively. Likewise, in the cross-shore direction $K_x$ was described by a power law with $c_1 = 0.02\pm 0.01$ and $c_2 = 1.46\pm 0.38$, whilst in the longshore direction, $c_1 = 0.03\pm 0.02$ and $c_2 = 1.35\pm 0.48$.

#### Table 4.7 Coefficients of the least squares lines of best fit, calculated for each of the drifter clusters released between the 1st and 3rd of September 2004, based on the values of $K$ calculated for 1 m bins of standard deviations. Data omitted from the calculation of mean and confidence intervals is highlighted.

| Date       | Run | Drifters | Time (s) | $C_1$ | $C_2$ | $r^2$ | $C_1$ | $C_2$ | $r^2$ | $C_1$ | $C_2$ | $r^2$
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</table>

Data excluded due to high deviation from mean
Data excluded due to low $r^2$
These values are lower than those calculated by Johnson (2004) who, in the investigation of longshore flow, found power law exponents ranging between 1.57 and 2.38 in the cross-shore direction and between 1.91 and 2.41 in the long-shore. The correlation is stronger with Johnson’s (2004) data pertaining to dispersion through the rip head, in which power law exponents of 1.30 and 1.58 were determined in the cross-shore and longshore directions respectively. The correlation is even closer when the data is compared to the results of Mariani (2005) who found the power law exponents of 1.24, 1.36 and 1.33 in the total, cross-shore and longshore directions respectively. Mariani (2005) noted the correlation between his values and the 4/3rds power law derived by Richardson (1926) which relates the dispersion coefficient to the length scale separation of a number of marked particles. Mariani (2005) noted the apparent conflict between the conditions assumed by Richardson (1926), of isotropic, homogenous and unbounded flow and the actual conditions of the surf zone. This was also noted by Johnson (2004), who suggested that nearshore processes are rarely homogenous or isotropic, particularly in the cross-shore direction. Inhomogeneity in the nearshore turbulence means that the dispersion of a pair of particles becomes dependant not just upon their separation but also their orientation and cross-shore position. This inhomogeneity can be attributed to the changing depth profile of the surf zone. The changing depth profile offshore also has the effect of causing water columns to ‘stretch’ in the vertical direction when moving into deeper water in order to maintain continuity, tending to induce negative dispersion in the particles that would normally tend to separate in a disorganised current field (Johnson 2004, List et al. 1990).

The unifying properties of the 4/3rds power law were first addressed by Okubo (1971), who noted that several theories of turbulent dispersion lead to the same 4/3 power law. In particular, Okubo discusses the fact that other theories of turbulent dispersion are able to derive the same 4/3rds relationship, without the strict assumptions of classical analysis conducted by Richardson (1926) and Batchelor (1952). Okubo (1971) demonstrated that this rule holds for a remarkably large range of scales in oceanic dispersion, ranging from 10m up to 1000km (Johnson, 2004) by plotting the dispersion co-efficient K against the scale of diffusion, represented by σ.

The derived power laws match the exponent of Okubo’s (1974) data closely, and as such, the gradients observed in Figure 4.1 correlate closely with the 4/3rds law.
However a significant variation in magnitude is observed between the data range of Okubo (1974) and the derived values. List *et al.* (1990) noted a similar divergence of up to two orders of magnitude. This was attributed by List *et al.* (1990) to the effects of coastal shear acting in addition to turbulent dispersion. Whilst the oceanic scales of coastal shear are not directly comparable to the surf-zone, it is likely that the effects of shear dispersion increase the observed dispersion coefficients.

![Figure 4.1 Comparison of the derived power laws with the data range of Okubo (1974).](image-url)

Shear dispersion in the surf zone may be responsible for the deviation, noted in Figure 4.1, between the observed dispersion values and the effects of pure turbulent dispersion.
dispersion described by Okubo (1974) and the 4/3rds law. This is noted by Tseng (2001) who reasons that it is the apparent dispersion which is derived from Lagrangian modes of measurement, and hence the effect of shear flow must be removed in order to obtain the true turbulent diffusivity.

The coefficients for the lines of best fit between $K$, $K_x$ and $K_y$ and the length scales $\sigma$, $\sigma_x$ and $\sigma_y$, for each of the cluster releases during March 2005 are shown in Table 4.8. The values derived correlate relatively well with the results obtained from the September deployments. The dispersion co-efficient $K$ is described by Equation 43.

$$K = 0.02\sigma^{1.26}$$

The confidence interval for these values is significant, with the 95% confidence interval of the exponent equal to $\pm 0.18$. Similar values were also determined in the cross-shore and longshore directions. In the cross-shore direction, the dispersion coefficient values are described by the power law with $c_1 = 0.02\pm0.01$ and $c_2 = 1.23\pm0.32$, whilst in the longshore domain, $c_1 = 0.02\pm0.01$ and $c_2 = 1.42\pm0.17$.

Table 4.8 Coefficients of the least squares lines of best fit, calculated for each of the drifter clusters released between the 20th and 23rd of March 2005, based on the values of $K$ calculated for 1 m bins of standard deviation. Data omitted from the calculation of mean and confidence intervals is highlighted.

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<td>0.01</td>
<td>0.17</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Data excuded due to low $r^2$

These values are of the same order of magnitude as the values derived during September and correlate well with those of Mariani (2005) who performed field work

Results and Discussion
under similar sea breeze dominated conditions. The observed cross-shore dispersion rates are significantly lower during March, which reduces the overall power law exponent. This was noted by Mariani (2005) who identified a relative enhancement in the longshore power law exponent which he associated with ‘drifters dispersing faster and more consistently’ in the longshore direction.

Comparison with Mariani’s results is significant as it demonstrates a similar trend occurring under sea breeze conditions at two different study sites. Whilst Mariani (2005) was not able to offer an explanation for his observations of the ‘enhancement’ in longshore dispersion, the comparison of results obtained during March and September respectively, offers the insight that the observed deviation is due to restricted cross-shore dispersion rather than enhanced dispersion in the longshore direction.

During the September deployments the power law exponents, describing the relationship between the dispersion co-efficient and the separation scale, were relatively stable in a narrow band between 1.35 and 1.46. In contrast, during March the power law exponents ranged between 1.23 and 1.42, depending on direction. In particular, the cross-shore exponent decreased from 1.46 to 1.23, thus demonstrating that under sea breeze conditions the longshore dispersion coefficient remains relatively unchanged. This can be attributed to the restriction in the width of the turbulent surf zone that is promoted by the action of the sea breeze. The sea breeze through it’s generation of onshore directed wind waves with relatively large magnitudes (for a low energy site, sheltered from large ocean swells) increases onshore advection and acts to restrict the offshore extent of turbulence (Bowen & Inman, 1974). Consequently the scale over which dispersion is able to occur in the cross-shore domain is restricted, thus reducing the value of the power law exponent describing K relative to $\sigma$ in the cross-shore domain.

4.1.4 Implications
The calculated dispersion rates and the factors influencing them, have significant implications for contaminant fate and transport in Adelaide’s coastal waters. As discussed previously, the recorded dispersion rates in the nearshore zone are low when compared to more energetic settings such as the surf zone and the offshore oceanic environment.
This outcome indicates that the dilution of contaminants entering the nearshore zone through the various rivers, storm water and wastewater discharges along the Adelaide metropolitan coastline occurs at a slow rate. It is noted by Johnson (2004) that, currently, there is little understanding of the net flux of material from the surf zone to the immediate offshore region due to horizontal currents, especially on longshore uniform beaches. However, the results obtained suggest that the effective boundary formed by the edge of the turbulent surf zone and the topographic control imposed by the longshore sandbar formation, combine to constrain the offshore extent over which dispersion of contaminants from the nearshore zone is able to occur. This creates a bounded nearshore zone in which dispersion rates are low and through which little matter is transported in the cross-shore direction. Effectively, any contaminants entering the nearshore zone will remain trapped in this narrow region, with the primary transportation occurring in the longshore direction.

4.2 Drifter Paths and Current Velocity
Extensive qualitative descriptions of the drifter behaviour in the nearshore and surf zones subsequent to release as clusters is included in this document, in the Approach section (Section 3.3). For this reason, the analysis of individual cluster deployments will not be addressed in detail in this Section; rather, the focus will be on fundamental variations in drifter behaviour with a specific consideration applied to the factors which instigate the largest variations in drifter velocities and paths.

4.2.1 Direction
Qualitatively, trends in drifter behaviour subsequent to release are highly dependant on prevailing wind conditions. Under prevailing wind conditions with a southerly component drifters move in a northerly direction. Conversely, when there is a northerly component in the prevailing conditions, drifters move towards the south. Likewise, when winds contain an onshore (westerly) component, shoreward motion is enhanced, whilst during offshore conditions, drifters were observed to maintain their offshore position and in some cases, move offshore. Offshore motion was largely restricted to periods where minimal wave energy was incident on the coast, thus restricting the onshore advection associated with wave action which tended to suppress the offshore motion induced purely by the prevailing winds.
These general trends are represented in Figure 4.2 where the plots of the drifter paths under various prevailing wind conditions are compared. Inset A represents the drifter behaviour subsequent to the deployment approximately 50m offshore whilst winds from a bearing of ~30° were prevailing. As can be seen in the path of the individual drifters which are averaged to determine the track of the cluster centroid; the motion of the centroid is almost directly in a south–easterly direction. This can be attributed to the combined influence of the northerly breeze, which promotes the southerly drift and wave activity noted during the deployment which encourages advective onshore transport (Dean & Dalrymple, 2002; Inman et al., 1971).

Inset C of Figure 4.2 represents drifter motion under southerly prevailing conditions. The contrast between Insets A and C is clear, with a directly northwards drifter path tracked during the prevailing southerlies. The cluster was deployed approximately 45m offshore, and at the time of retrieval the centroid position was approximately 25m offshore, thus representing a level of onshore transgression during the deployment. Again, the onshore component of the drifter motion can be attributed to a wave generated onshore mass flux. Similarly, insets B and D represent cluster deployments under westerly and easterly prevailing conditions respectively. Enhanced onshore motion of the drifters is evident in B, where the cluster was released approximately 100m from shore and the drifters were washed ashore (with the exception of drifter 6) with only around 60m of longshore transport. In the case of easterly conditions, represented in Inset D, the drifters were deployed approximately 35m offshore and moved northwards, parallel to the coast before being recovered around 60m offshore. The lack of direct offshore motion under the easterly conditions can be attributed to the constraining effects of the topography. The drifters were released in the channel inside of a major shore-parallel sandbar and were observed to travel in a northerly direction on the shoreward side of this feature for around 100m, before this feature became deeper, resulting in the enhancement of motion in the cross-shore domain. The impact of wave based factors in this deployment was insignificant as no wave activity was observed, thus mitigating the possible influence of surf zone bounding effects.

These observations are unsurprising given the known relationship between wind speed and direction and surface currents, which is particularly enhanced in the absence of significant external perturbations such as currents generated from non-locally
generated waves (Horikawa (Ed.), 1988). This demonstrates the relationship between the prevailing wind conditions and the spatial structure of the nearshore current system, under conditions where wind is the dominant influencing factor.

The directional behaviour of the drifters can be compared to the vertical profile of the current structure measured by ADCP. Consequently, the influence of changes in the wind and wave regime, on the vertical current structure, can also be investigated.

ADCP measurements were collected on the 21st of March 2005 and have been separated into three hour sections, representing morning and afternoon conditions. The variation in the deployment conditions is marked, with the respective average wind speed and directions presented in Table 4.9. This shows the dramatic increase in wind speed and change in direction, to a south westerly bearing, typical of the sea breeze phenomenon.

<table>
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<tr>
<th>Time</th>
<th>Speed (m/s)</th>
<th>Direction (°)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>13:30-16:30</td>
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</table>

The associated changes in the current structure are represented in Figures 4.3 and 4.4, which represent the average current profiles in the longshore and cross-shore directions respectively, under calm, morning conditions and during vigorous sea breeze conditions in the afternoon.

The most marked change in the current profiles is observed in the longshore direction, Figure 4.3. During the morning the wind conditions are relatively calm and from a northerly direction. This induces the weak southerly transport observed in Inset A, where the negative current velocity indicates a southerly direction. Inset A suggests that mixing through the water column is complete, as the entire velocity profile is constant around 6cm/s from the sea-bed to the surface, except for a small section of flow at approximately 1.3m above the seafloor that is typified by lower velocities of around 1-2cm/s.
Figure 4.2 Graphical representation of the general trends exhibited in the drifter motion under northerly (A), westerly (B), southerly (C) and easterly (D) prevailing wind conditions.
The velocity profile changes markedly during the afternoon. Wind speeds were observed to increase by a factor of more than three times. This increase in velocity was associated with a change in course, such that the direction of approach was south westerly at a bearing of 230° resulting in obliquely incident conditions along the north-south aligned coastline. Obliquely incident wind and wave conditions are optimal for the generation of northerly longshore currents (Komar 1976; Horikawa, 1988; Mariani, 2005). The northerly flowing longshore current is clearly observed in the ADCP data, Inset B, where the surface current in a northerly direction is in the order of 10cm/s. The surface enhancement of the longshore current is due to the increased frictional effect of wind close to the surface. In contrast with the morning conditions, the velocity profile of the current decreases rapidly with depth, showing a slight reversal in direction at the sea floor, and a depth averaged current of just 3.5cm/s compared to a surface velocity of 10cm/s.

![Longshore Current Profile, 9:45-12:45, 21/03/05](image1)

![Longshore Current Profile, 1:30PM-16:30, 21/03/05](image2)

Figure 4.3 Longshore ADCP current profiles from the morning (A) and afternoon (B) of the 21/3/05. The green line represents a velocity of 0, whilst the red line indicates the mean depth averaged velocity. The length of the lines indicates the average depth. (Negative velocity indicates southerly currents)

The current profiles correlate strongly with the observed drifter paths which followed southerly paths during the morning and were transported in a northerly direction during the afternoon. This is coincident with the surface currents recorded by the
ADCP, which are the dominant factors influencing drifter motion as the maximum depth of the casing is just 32cm and the total drogue depth is ~60cm.

The cross-shore components of the current profile also demonstrate significant variability due to their relationship to the prevailing wind and wave regime. During the morning, the observed current profile is offshore (westerly) at an average velocity of ~5cm/s (Figure 4.4, Inset A). This velocity is maintained at a relatively constant rate through the profile; however a certain degree of intensification is noted through the center of profile whilst a slight reduction in velocity is noted in the surface layers. This reduction in the offshore current in the surface layers may be attributed to the onshore motion of waves and the friction of the westerly component of the prevailing winds. During the afternoon (Inset B) the average velocity increases to ~7cm/s, attributable to the intensification in observed wind conditions. This induces a greater level of mass transport into the nearshore zone, and hence leads to an increase in the offshore directed flow.

![Cross-shore Current Profile, 9:45-12:45, 21/03/05](image1)

![Cross-shore Current Profile, 1:30PM-16:30, 21/03/05](image2)

**Figure 4.4** Cross-shore ADCP current profiles from the morning (A) and afternoon (B) of the 21/3/05. The green line represents a velocity of 0, whilst the red line indicates the mean depth averaged velocity. The length of the lines indicates the average depth. (Negative velocity indicates westerly currents)
Effectively, the dominant current being measured in the cross-shore direction is the undertow, the return flow resulting from the onshore advection of mass occurring closer onshore due to breaking waves.

The current velocity profiles obtained in these low energy conditions differ significantly from those obtained near an active, relatively high energy surf zone by Johnson (2004), who observed a clear deviation in the vertical profile of the cross-shore flow, with a large onshore component noted in the higher levels of the water column at velocities in the order of 30cm/s, associated with the passage of breaking waves. The undertow is not uniformly distributed with depth due to the decrease in wave-induced stress with depth (Dean and Dalrymple, 2002) and is suppressed underneath the energetic onshore flow created by breaking waves. However in the low energy environment, the passage of wave bores is restricted to low frequency occurrences, with the majority of waves passing the ADCP location without breaking. As such, there is little onshore mass flux through the surface layers of the water column and the offshore directed return flow is able to dominate.

4.2.2 Velocity
The velocity of drifter motions recorded in the nearshore zone is presented in Table 4.10. The values are relatively low with the maximum average speed on a single day of deployment measured as 22cm/s, whilst the minimum average speed was 5cm/s. Maximum momentary velocities were similarly low, with values ranging between 20cm/s and 62cm/s. These values illustrate the relatively low energy nature of the nearshore current regime, when compared to the velocities obtained in a number of drifter experiments including:

- Johnson (2004), who found average longshore velocities of greater then 50cm/s and maximum values in excess of 150cm/s
- Olsson (2004), who found average velocities in nearshore circulative cells located in the lee of coastal structures ranging between 44cm/s and 26cm/s and maximum velocities of 198cm/s
- Mariani (2005), who determined longshore velocities ranging between 30cm/s and 100cm/s depending on the strength of the sea breeze.
Table 4.10 Average wind and drifter velocities.

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<th>Max Velocity (m/s)</th>
<th>Mean Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Sep</td>
<td>5</td>
<td>4.52</td>
<td>228</td>
<td>0.57</td>
<td>0.22</td>
</tr>
<tr>
<td>2-Sep</td>
<td>8</td>
<td>2.69</td>
<td>240</td>
<td>0.61</td>
<td>0.13</td>
</tr>
<tr>
<td>3-Sep</td>
<td>2</td>
<td>2.05</td>
<td>290</td>
<td>0.36</td>
<td>0.14</td>
</tr>
<tr>
<td>20-Mar</td>
<td>6</td>
<td>4.81</td>
<td>235</td>
<td>0.62</td>
<td>0.14</td>
</tr>
<tr>
<td>21-Mar</td>
<td>4</td>
<td>3.58</td>
<td>330</td>
<td>0.20</td>
<td>0.05</td>
</tr>
<tr>
<td>22-Mar</td>
<td>4</td>
<td>6.55</td>
<td>150</td>
<td>0.41</td>
<td>0.17</td>
</tr>
<tr>
<td>23-Mar</td>
<td>7</td>
<td>4.18</td>
<td>135</td>
<td>0.45</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The relatively low magnitude of the nearshore current systems in this study can be attributed to the low incident wave energy at the study site, in contrast to the studies noted above which were all carried out at exposed locations on the Western Australian coastline, with incident significant swell heights ranging up to 1.51m (Olsson, 2004). However, as previously noted the incident swell energy at the sheltered Adelaide study site is low, with the dominant energy source in the nearshore zone being the locally generated short period wind waves. Examination of the data supports this assertion, with a strong correlation observed between the wind speed and direction and the mean current velocities. The correlation is not as strong for the maximum velocities; however, given the momentary nature of these values they can easily be affected by erratic random motions, and as such are intended to act only as a guide to the relative magnitude of the largest currents relative to the mean.

The highest recorded velocities are recorded under relatively strong prevailing winds as demonstrated on the 1st of September where the maximum average drifter velocity was recorded during wind speeds in excess of 4.5m/s. However, the direction of the winds is also important with onshore winds shown to lead to larger velocities in the nearshore zone. The largest average wind velocity recorded over the seven day experimental period was 6.55m/s; however, as the direction of this breeze was south-easterly, the generation of wind waves incident upon the nearshore zone was limited, and thus a relatively low magnitude nearshore current of 17cm/s was recorded by the drifters. In contrast the lowest average wind speed recorded, 2.05m/s, was associated with an average velocity of 14cm/s only 3cm/s less then that recorded under the higher wind speed. However, the direction of propagation was almost directly onshore, ensuring that the maximum level of wave energy was incident upon the shoreline.
The correlation between the ADCP data and the drifter recorded velocities was relatively strong. The average drifter speed recorded on the 21st of September is just 5cm/s, which correlates well with the depth averaged velocities recorded by the ADCP. In the cross-shore direction velocities of 4.8cm/s were recorded in the morning compared to 7.2 cm/s in the afternoon, whilst in the longshore direction the morning depth averaged velocity was 5.7cm/s compared to 3.7cm/s in the afternoon. The drifter velocities were averaged over the entire day, aggregating the variations induced by changes in the prevailing conditions; however given the previously noted reduction in the surface current velocities recorded by the ADCP, the values appear highly congruous. The level of coherency in the comparison of Lagrangian drifter measurements and Eulerian ADCP data was investigated by Olsson (2004), who found that the level of similarity was very strong, with a general underestimation in the order of 5% observed in the Eulerian data. As noted by Olsson (2004) the high correlation of the drifter velocities with the Eulerian data can be attributed in part to the low water depth, whereby the surface current measured by the drifters does not vary significantly from the mean depth averaged current. This is because; given sufficient time, in the shallow water of the surf-zone these currents essentially combine to become a single non-differentiable water body.

It is important to note that the state of the development of the seas is significant as the velocity of the nearshore current systems is dependant on the wave action in the nearshore zone. Winds change direction and intensity more rapidly than can be integrated by the wave regime and hence there is a lag time between the wind speed being recorded and the seas reaching a state of development representative of the conditions. As such, reported current velocities will not always be fully representative of the wind conditions recorded at the same time, which explains some of the seeming contradictions in Table 4.10, where some (20th March) greater wind speeds are associated with current speeds which are lower than those recorded under lower wind speeds (1st September) from the same direction.

4.2.3 Flow fields

Numerous deployments of the drifters from the same location on the 3rd of September provided data suitable for the construction of a velocity field diagram, Figure 4.5, representing the primary characteristics of the flow over a section of the study site. The ensemble plot of all of the drifter paths which were combined in the velocity field
is presented in Inset B. This demonstrates the relatively structured format of the drifter paths, with relatively little variation noticeable in the paths of the 35 individual drifter tracks. The general trend of the flow is northerly, with a limited offshore component attributable to the south easterly winds prevailing at an average velocity of 4.18 m/s.

Inset A represents the average velocity of drifters inside spatial bins of 5m by 10m dimension. As can be seen, the spatial pattern of the current regime is relatively simple, with a clear channel of enhanced flow apparent in a northerly direction. The drifters were initially deployed in around 1.5m of water depth, inshore of a large sandbar formation. The drifter paths can be seen to move inside of this feature, into areas of slightly deeper water whilst progressing in a northerly direction. As the drifters move into the channel, inside the shore parallel sandbar feature, the average velocities are observed to intensify. This is related to the increased water depth allowing a region of enhanced flow to develop, which is clearly evident in the significantly enhanced drifter velocities within the channel formation.

Figure 4.5 Velocity field diagram calculated from the drifter deployments of the 23rd of September. Inset A represents the average velocities and direction for each box on a 5m by 10m grid, where a 1m/s current is equivalent to a distance of 15m and ‘dots’ represent point were no velocities were recorded. Inset B represents the ensemble of all of the individual drifter paths compiled in the calculation of the velocity field. The units of the vertical and horizontal axes are [m].

Results and Discussion
The channel flow can be observed to closely track the shoreline, indicating that the region of enhanced flow is a function of depth, thereby maintaining a close correlation with the offshore depth contours. It can be seen that the magnitude of the observed flows decreases markedly in either direction cross-shore of the peak flow. In both the onshore and offshore directions respectively this decrease in velocity can be attributed to the declining water depth, firstly, moving towards the shoreline, and secondly, moving offshore but into the shallower water associated with the elevated sandbar.

The most prevalent feature of the velocity vectors in Figure 4.5 is the dominance of the longshore component, indicating that the primary direction of drifter motion within the nearshore zone is in the longshore domain. This correlates with the calculated dispersion coefficient values (see Section 4.1) which demonstrate enhanced dispersion in the longshore domain through the effects of shear flow, whilst cross-shore dispersion is impeded through the bounding effects of topographic and hydrodynamic conditions. Figure 4.5 clearly represents this situation, where the dominant flow conditions are longshore in nature whilst drifter motion is extremely limited in the cross-shore dimension.

The spatial structure of the current system represented in Figure 4.5 is relatively simple, presenting a system with a relatively stable current regime dominated by a single primary flow feature. It represents the consistency of the spatial structure of the nearshore currents and as such, it can be interpolated that the underlying dispersive properties are similarly uniform for the given conditions. This is a significant result as it allows the extrapolation of the derived dispersion data to the surrounding Adelaide metropolitan coastline, due to the demonstrated consistency of current structures over a 200m length within the study area.
5 Conclusion

Mixing and dispersion rates in Adelaid's coastal waters were measured using Lagrangian drifters utilising GPS technology and as a result the hydrodynamics of the nearshore region are now better understood. The process of turbulent diffusion responsible for dispersion was found to be driven predominantly by the local meteorological conditions, in particular the summer sea breeze. These conditions directly control the wave energy in the sheltered waters of the Gulf of St Vincent. As such, the dispersive characteristics of the coastal waters generally reflect the prevailing wind regime.

Dispersion rates in this region are low, resulting in the containment of material discharged from terrestrial sources such as rivers and stormwater drains within the nearshore zone. This is enhanced by the bounding effects of the surf zone, whereby dispersion in the cross-shore direction is restricted by the presence of barriers in the form of shoreline and the breaker line. In contrast, transport in the longshore direction is not affected by any substantial boundaries. It can be concluded that contaminants which are discharged from terrestrial sources are largely confined to the nearshore region, where limited mixing does occur. However, the lack of cross-shore dispersion through the surf zone boundary ensures that the transport of contaminants offshore is limited. Thus, coastal discharges are unlikely to significantly affect the health of seagrass beds located kilometers from the coast. This is because the offshore transport mechanisms necessary for bringing the terrestrially sourced contaminants into contact with the seagrass communities do not exist. The longshore flow is the key factor determining the fate and transport of material discharged into the coastal zone.

There are two broad areas in which future research is recommended, namely; further field experiments and numerical modeling. Future field research should address the areas in which conclusive results could not be obtained during through the work conducted in this paper. Specifically, attention should be directed towards the determination of dispersion rates under:

- High energy conditions: All of the deployments in this study were carried out under low energy swell conditions. The primary source of energy was always locally generated waves, thereby the local wind conditions were by definition always coincident with the wave conditions. It is recommended that further deployments be conducted under conditions where, non-locally generated, high
magnitude ‘swell’ waves are coincident with variable local winds and low wind conditions. This will allow the analysis of the effect that wave energy has on local mixing and dispersion rates in separation from the local wind regime. This could not be conducted in this study, due to the low energy prevailing wave conditions in the Gulf of St Vincent and the generally dominant local wind conditions.

- Purely tidal influences: Similarly, whilst it is known that tidal oscillations can induce dispersion in the nearshore zone, the extent of this effect could not be investigated in this study due to the presence of other more dominant factors. It is therefore recommended that dispersion studies investigating the influence of tidal variations be conducted.

A comparison of the derived Lagrangian results with Eulerian measurements is also recommended. This would involve the deployment of an array of Eulerian sensors which would allow the derivation of the spatial structure of the nearshore current system with time. In particular it would allow the analysis of dispersion through the entire water column, in contrast with Lagrangian drifters which only measure the hydrodynamic behaviour of the upper levels of the water column. Such work would also provide a useful validation of the results obtained from this study.

Measurement of offshore dispersion rates should be conducted, from close to the surf zone to well offshore. This would allow the magnitude of dispersion suppression in the surf zone to be addressed. It would also allow the more thorough investigation of the larger scale hydrodynamic regime within the Gulf of St Vincent.

Understanding the overall hydrodynamic regime is the primary aim of the second area of recommended research; numerical modeling. The need for this work has been well flagged throughout this document, as the dispersion coefficient will form a key input parameter for any model of the hydrodynamics within the nearshore zone. A primary focus of this work should be the determination of the fate of contaminants constrained within the nearshore zone and transported along the coast in the longshore current. Such modeling work is planned, with the output providing a key outcome of the Adelaide Coastal Waters Study.
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Appendices

Appendix A

*Drifter Paths and Velocity: Henley Beach, 1/09/04-3/09/04*

This section contains data recorded through field deployments of surf zone GPS drifters at Adelaidess’ Henley Beach, near the outflow of Breakout Creek. The two primary categories of data presented are as follows:

1. The raw drifter paths. The drifters’ movement after their release as a cluster is plotted. Clusters range from three to five drifters and are shown relative to the position of the shoreline, so as to provide a reference to their motion. Each drifter is plotted in a different colour allowing easy identification. Drifter releases are marked by circles ‘o’, whilst the point of drifter retrieval is marked by ‘x’.

2. Velocity plots of the individual drifters are shown*. Parameter’s are noted in each case and refer to the input parameter’s required for the creation of the velocity plot in MATLAB using a script developed by Johnson (2004). Specifically, the required specifications include: ‘gaps’ a measure of the period between which successive velocity values are calculated and ‘scale’ a specification which determines the magnitude of a vector utilised to represent a given velocity. Only the ‘gaps’ parameter is explicitly stated in the heading (in brackets), as the relative magnitude of a 1m/s vector is clearly shown in each individual plot.

In the case of clusters involving five drifters, the velocity profiles of only four of the drifters are represented due to formatting restrictions. In these cases the shortest duration drift is omitted.

Drifter paths and associated velocity plots are not presented for data collected on the 23rd of March 2005. This is because the ensemble drifter plots and velocity field are shown in the results and discussion, Section 4.2.3, thus presenting this information again would be superfluous to requirements.

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References
1/09/04, Cluster 1

September 1st 2004, Cluster 1

- Centroid path
- Drifter 2
- Drifter 3
- Drifter 4
- Shoreline

Drifter 2 (10s)

Drifter 3 (10s)

Drifter 4 (10s)
1/09/04, Cluster 2

September 1st 2004, Cluster 2

Drifter 2 (2s)  

Drifter 3 (2s)  

Drifter 4 (2s)  

Drifter 4 (2s)
Cluster 4, 1/9/04

September 1st 2004, Cluster 3

Drifter 2 (4s)  Drifter 3 (4s)

Drifter 5 (4s)  Drifter 6 (4s)
Cluster 5, 1/9/04

September 1st 2004, Cluster 2

Drifter 2

Drifter 3

Drifter 5

Drifter 6
Cluster 2, 2/9/04 (morning)

September 1st 2004, Cluster 3

Drifter 2 (10s)  Drifter 3 (10s)

Drifter 4 (10s)  Drifter 6 (10s)
Cluster 3, 2/9/04 (morning)

September 1st 2004, Cluster 3

Drifter 2 (10s)      Drifter 3 (10s)

Drifter 4 (10s)      Drifter 6 (10s)
Cluster 1, 2/9/04 (afternoon)

September 2nd (afternoon), 2004, Cluster 1

Drifter 2 (20s)

Drifter 3 (20s)

Drifter 4 (20s)
Cluster 2, 2/9/04

September 2nd (afternoon), 2004, Cluster 2

Drifter 2 (20s)

Drifter 3 (20s)

Drifter 4 (20s)
Cluster 3, 2/9/04

September 2nd (afternoon), 2004, Cluster 3

Drifter 2 (20s) Drifter 3 (20s)

Drifter 4 (20s)
Cluster 4, 3/9/04

September 2nd (afternoon), 2004, Cluster 4

Drifter 2 (10s)  Drifter 3 (10s)  Drifter 4 (10s)
Cluster 1, 3/9/04

September 3rd, 2004, Cluster 1

Drifter 2 (25s)      Drifter 3 (25s)

Drifter 5 (25s)      Drifter 6 (25s)
Cluster 2, 3/9/04

September 3rd, 2004, Cluster 2

Metres [m]

Drifter 2 (10s)        Drifter 3 (10s)

Drifter 5 (10s)        Drifter 6 (10s)
Cluster 1, 20/3/05

March 20th, 2005, Cluster 1

- Centroid path
- Drifter 2
- Drifter 3
- Drifter 4
- Drifter 5
- Drifter 6

**Drifter 2 (10s)**

**Drifter 3 (10s)**

**Drifter 5 (10s)**

**Drifter 6 (10s)**
Cluster 2, 20/3/05

March 20th, 2005, Cluster 2

Centroid path
- Drifter 2
- Drifter 3
- Drifter 4
- Drifter 5
- Drifter 6

Metres [m]

Drifter 2 (10s)

Drifter 3 (10s)

Drifter 4 (10s)

Drifter 5 (10s)
Cluster 3, 20/3/05

Drifter 2 (30s)     Drifter 3 (30s)

Drifter 5 (30s)     Drifter 6 (10s)
Cluster 4, 20/3/05

March 20th, 2005, Cluster 4

- Drifter 2 (10s)
- Drifter 3 (10s)
- Drifter 4 (10s)
- Drifter 6 (10s)
Cluster 5, 20/3/05

March 20th, 2005, Cluster 5

Drifter 2 (30s)

Drifter 3 (30s)

Drifter 6 (30s)
Cluster 6, 20/3/05

March 20th, 2005, Cluster 6

Drifter 2 (10s)  Drifter 3 (10s)

Drifter 4 (10s)  Drifter 6 (10s)
Cluster 1, 21/3/05

March 21st, 2005, Cluster 1

Drifter 2 (10s)      Drifter 3 (10s)

Drifter 4 (10s)      Drifter 6 (10s)
Cluster 3, 21/3/05

March 21st, 2005, Cluster 3

Drifter 2 (10s)  Drifter 3 (10s)

Drifter 5 (10s)  Drifter 6 (10s)

1.0 m/s
Cluster 4, 21/3/05

March 21st, 2005, Cluster 4

Drifter 2 (10s)

Drifter 3 (10s)

Drifter 4 (10s)

Drifter 5 (10s)
Cluster 1, 22/3/05

March 22nd, 2005, Cluster 1

Drifter 2 (10s)

Drifter 3 (10s)

Drifter 4 (10s)

Drifter 5 (10s)
Cluster 2, 22/3/05

March 22nd, 2005, Cluster 2

- Drifter 2 (10s)
- Drifter 3 (10s)
- Drifter 5 (10s)
- Drifter 6 (10s)

1.0 m/s
Cluster 3, 22/3/05

March 22nd, 2005, Cluster 3

Drifter 2 (10s)

Drifter 3 (10s)

Drifter 4 (10s)

Drifter 5 (10s)
Cluster 4, 22/3/05

March 22nd, 2005, Cluster 4

Drifter 2 (10s)      Drifter 3 (10s)

Drifter 5 (10s)      Drifter 6 (10s)
Appendix B

*Calculation of the Dispersion Co-efficients: K, Kₓ and Kᵧ*

&

*Scale dependence: K vs. σ*

1. This appendix contains graphs of variance vs. time for the cluster deployments. The gradients of the plots represent the values of the dispersion coefficients K, Kₓ and Kᵧ.

2. Graphs of K, calculated for 1m bins of standard deviation, are presented. The coefficients of the regression lines of best fit provide the values of the power law exponents in the comparison of the data with the 4/3rds law and Okubo’s data. Thereby, characterising the scale dependence of the dispersion.
1/9/04: Cluster 1;

1/9/04: Cluster 2;

1/9/04: Cluster 3;
1/9/04: Cluster 4;

2/9/04: Cluster 1 (morning);

2/9/04: Cluster 2 (morning);
2/9/04: Cluster 3 (morning);

2/9/04: Cluster 4 (morning);

2/9/04: Cluster 1 (afternoon);
2/9/04: Cluster 2 (afternoon);

2/9/04: Cluster 3 (afternoon);

2/9/04: Cluster 4 (afternoon);
20/3/05: Cluster 1

20/3/05: Cluster 2

20/3/05: Cluster 3
21/3/05: Cluster 4

22/3/05: Cluster 1

22/3/05: Cluster 2