‘Dispersion in Sheltered Coastal Waters of Western Australia’

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Abstract

The dispersion of anthropogenic inputs to sheltered coastal waters along Western Australia is an issue of increasing importance as coastal populations and industries continue to grow. In addition, the dispersal of eggs, larvae and nutrients within the nearshore environment influences where marine flora and fauna settle and flourish. This affects fisheries, recreation and tourism. In response, measurements of dispersion were taken within three sheltered coastal regions of Western Australia: Fays Bay (Rottnest Island), Osprey Bay (Ningaloo Reef) and Koombana Bay (Bunbury).

Water motions were tracked using drifters, which are compact, low cost lagrangian devices that utilise the position fixing technologies of the global positioning system (GPS). Dispersion coefficients were calculated, and the time dependence, scale dependence, diffusion characteristics and the influence of environmental conditions were investigated.

The dispersion coefficients found for the three regions were; 0.05 (±0.02) m²/s (Fays Bay), 0.1 (±0.05) m²/s (Osprey Bay) and 0.4 (±0.2) m²/s (Koombana Bay). Topographical restriction imposed by the surf zone and the shoreline at Fays Bay and Osprey Bay resulted in a lower capacity for dispersion within these regions, particularly in the cross-shore direction. The variance of drifter position at the study sites was shown to grow according to time to the power of 1 to 2. This relationship differs considerably to that predicted by Batchelor (1952) following similarity theory: $\sigma^2 \sim t^3$. However, the scale dependence of dispersion at the study sites correlated strongly with Richardson’s 4/3 power law.

The environmental conditions observed at Fays Bay resulted from two extreme weather patterns possible for the region; the passing of a low pressure event and the dominance of a high pressure system. The dispersion coefficients responded to the varied regimes. High rates of dispersion were associated with low pressure conditions, namely high water levels, large significant wave heights, long mean wave periods, high current velocities and north to north-westerly winds. Conversely, low rates of dispersion were associated with high pressure conditions, namely low water levels, low significant wave heights, short mean wave periods, low current velocities and S-SE winds. In contrast, the environmental conditions observed at Osprey Bay and Koombana Bay were fairly constant; and resulting dispersion coefficients displayed no strong associations with the environmental variables monitored.
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**Glossary**

**Advection:** net drift of particles across a cross-sectional area, representing the net movement of the centre of mass of a portion of fluid or fluid property

**Conservation of Mass:** The total mass of a material volume or system is constant. In mathematical terms, 
$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

**Dispersion:** mixing, spreading or scattering of particles or some other fluid property by the combined effects of shear and transverse (crossways) diffusion

**Eddy:** irregular whirls of random fluid motion that cause velocity shears that enhance mixing

**Ensemble mean velocity:** the arithmetic mean of a number of measurements of a random process, a spatial rather than time average

**Equilibrium range:** A range of eddy scales with properties dependent only on the rate of energy transfer down ($\varepsilon$) and the fluid viscosity ($\nu$)

**Eularian:** Fixed reference frame

**Fickian diffusion:** molecular and diffusion turbulent diffusion; mixing processes that follow Fick’s Law

**Inertial subrange:** A range of eddy scales with properties dependent only on the rate of energy transfer down ($\varepsilon$)

**Isotropic:** independent of orientation

**Lagrangian:** Moving reference frame

**Laminar Flow:** flow which is stable, “smooth” and moves in layers; exhibits low Reynolds numbers; has one or two length and time scales which define its structure; and mixing is slow, caused only by molecular diffusion

**Mixing:** any process that causes one particle of water to be mingled with or diluted by another

**Molecular diffusion:** the mixing, spreading or scattering of particles by random molecular motions under the influence of a concentration gradient

**Reynolds number:** a dimensionless group which describes flow character formed from a characteristic velocity, a characteristic length scale and the kinematic viscosity of the fluid

**Shear:** the advection of fluid at different velocities at different locations within a flow field

**Turbulence:** turbulent flow

**Turbulent Flow:** flow which is unstable, “rough” and moves in three dimensions; exhibits high Reynolds numbers; has a continuous spectrum of space and time scales; and mixing is rapid, caused by molecular diffusion, turbulent diffusion and shearing

**Turbulent diffusion:** the random mixing spreading or scattering of particles by the turbulent motion of eddies
Terms and Abbreviations

\( C \): mass concentration of diffusing solute (kg/m\(^3\))

\( \bar{C} \): time averaged concentration (kg/m\(^3\))

\( D \): molecular diffusion coefficient (m\(^2\)/s)

\( D_{p} \): dominant wave direction, the wave direction with the highest energy integrated over all frequencies (compass bearing in °)

\( D_{Tp} \): main wave direction of the peak wave period, (compass bearing in °)

\( \varepsilon \): rate of energy transfer or dissipation in a fluid (m\(^2\)/s\(^3\))

\( h \): total depth (m)

\( H_{s} \): significant wave height, the mean of the highest 1/3 of waves (m)

\( \eta \): the Kolmogorov scale, the smallest eddy scale in a turbulent flow (m)

\( k \): turbulent or eddy diffusion coefficient, sometimes referred to as the eddy diffusivity, or simply the diffusivity (m\(^2\)/s)

\( K \): dispersion coefficient (m\(^2\)/s)

\( K_{a} \): apparent diffusivity, analogous to the dispersion coefficient (m\(^2\)/s)

\( l \): characteristic length scale (m), or in Richardson’s law the particle separation (m)

\( \mu \): dynamic or absolute viscosity of a fluid (kg/m.s)

\( \nu \): kinematic viscosity of a fluid (m\(^2\)/s)

\( q \): solute mass flux, mass per unit area per unit time (kg/m\(^3\)/s)

\( \hat{q} \): mass flux vector with components \((q_x, q_y, q_z)\) in a Cartesian co-ordinates (kg/m\(^3\)/s)

\( \bar{q} \): time averaged mass flux vector with components \((q_x, q_y, q_z)\) in Cartesian co-ordinates (kg/m\(^3\)/s)

\( r \): radius (m)

\( \rho \): density (kg/m\(^3\))

\( s \): particle separation in Batchelor’s analysis (m)

\( \langle s \rangle \): spatial average particle separation (m)

\( \sigma^2 \): variance of a distribution (m\(^2\))

\( \sigma_{rc}^2 \): variance of a radially symmetric distribution (m\(^2\))

\( \sigma \): standard deviation of a distribution (m)

\( \sigma_{a} \): apparent standard deviation of a distribution (m)

\( t \): time (s)

\( T \): time averaging period (s)

\( T_z \): mean wave period (s)
$T_p$ : peak wave period (s)

$u$ : velocity in the x direction (m/s)

$\bar{u}$ : mean velocity in the x direction, could refer to a spatial (ensemble) or time average velocity (m/s)

$u_x$ : surface current in the x direction (m/s)

$u''$ : turbulent velocity in the x direction (m/s)

$v$ : velocity in the y direction (m/s)

$\bar{v}$ : mean velocity in the y direction, could refer to a spatial (ensemble) or time average velocity (m/s)

$v''$ : turbulent velocity in the y direction (m/s)

$\Omega_z$ : vertical shear ($\partial u / \partial z$) relative to the mean current in a flow (s$^{-1}$)

$x$ : displacement of a particle in the x direction (m)

$\bar{x}$ : ensemble mean displacement of a particle in the x direction (m)

$y$ : displacement of a particle in the y direction (m)

$\bar{y}$ : ensemble mean displacement of a particle in the y direction (m)

$\nabla$ : vector notation indicating a three dimensional situation

ADV: Acoustic Doppler Velocimeter

AIMS: Australian Institute of Marine Science

CALM: Conservation and Land Management

CSIRO: Commonwealth Science and Industrial Research Organisation

GPS: Global Positioning System

UWA: University of Western Australia

WA: Western Australia

WAMSI: Western Australian Marine Science Institution
1 Introduction

For centuries societies have exploited the dispersive capacity of estuaries and the sea to flush away waste products. However, inputs from growing populations and industry along the West Australian (WA) coast threaten to exceed this capacity; and the catch phrase “dilution is the solution to pollution” may no longer apply. The insufficient dilution of anthropogenic inputs to coastal regions can lead to reduced water quality. In turn, this has the potential to harm commercial fisheries, hinder recreational activity, raise human health concerns and threaten ecosystem integrity. The potential for reduced water quality is higher in sheltered coastal waters, which typically display reduced flushing capabilities. Understanding the dispersion characteristics of sheltered coastal regions along the WA coast will enable relevant management bodies to ensure the continuation of adequate water quality in those locations.

Dispersion is also of fundamental importance to natural life in the sea. The dispersal of eggs, larvae and nutrients within the nearshore environment influences where marine flora and fauna settle and flourish. In turn, this can affect human activities such as fisheries, recreation and tourism - all of which are valued highly in WA. Understanding the dispersion characteristics of coastal regions along the WA coast will enable the prediction of egg and larvae distribution for important marine species.

This study aimed to characterise the dispersion features of three key sheltered coastal regions within WA. Key regions were defined as locations which are under current or potential threat from increasing anthropogenic inputs, and are important for fisheries, recreation or tourism. The study sites chosen were Fays Bay, Rottnest Island; Osprey Bay, Ningaloo Reef; and Koombana Bay, Bunbury.

Rottnest Island is a popular WA tourist icon that lies approximately 18 km west of Perth. It is an A Class Reserve, is visited by approximately 500,000 people a year and displays a unique marine ecosystem. It is home to extensive seagrass meadows second only to Shark Bay in species diversity, and the coral at Pocillopora Reef, Parker Point, is considered the southern most tropical coral reef in Australia.

The Ningaloo Reef is the largest fringing coral reef in Australia, extending 260 km along the WA coastline from the North West Cape to Red Bluff. The region supports a highly diverse population of marine life, including species with special conservation significance such as fishes, turtles, whale sharks, dugongs, whales and dolphins. As such, the Ningaloo area
provides for a broad range of recreational activities and nature based tourism, and is currently regarded as the State’s premier marine conservation icon. Unlike the Great Barrier Reef in Queensland, Ningaloo Reef is particularly susceptible to visitor disturbance due to its unique proximity to the coast.

The City of Bunbury is located approximately 180 km south of Perth, and aligns the large coastal embayment of Koombana Bay. Bunbury is the third fastest growing region in Australia, and Koombana Bay encloses the Port of Bunbury: a world wide distribution point for South West industries such as mining, manufacturing and agriculture. In addition, Koombana Bay is a rapidly developing residential and commercial region, and home to an important South West tourist icon, the Bunbury Dolphin Discovery Centre.

The objectives defined to meet the overall aim of the study were to:

- obtain field measurements of dispersion within the small protected region of Fays Bay, the nearshore lagoon of Osprey Bay and the large sheltered embayment of Koombana Bay;
- calculate representative dispersion coefficients for each study site;
- investigate the time and scale dependence of dispersion at each study site;
- isolate the effects of diffusion from the overall dispersion measured at each study site; and
- identify the influence of relevant environmental factors (such as wind, waves and water level) on the dispersion coefficients calculated.

The findings of this study will be useful management tools for the three key WA regions described. In addition, the dispersion coefficients identified for Osprey Bay, Ningaloo Reef will be used in conjunction with wind, wave, tide and current data obtained by the Australian Institute of Marine Science (AIMS) and the Commonwealth Science and Industrial Research Organisation (CSIRO) to validate a numerical model. This model will have the capacity to predict circulation and mixing within a typical section of Ningaloo Reef. The model is to be developed as part of the State funded Ningaloo Research Program, under the Western Australian Marine Science Institution (WAMSI).
2 Literature Review

2.1 Dispersion and Mixing

Mixing is any process that causes one particle of water to be mingled with or diluted by another (Fischer et al. 1979). Diffusion is the mixing, spreading or scattering of particles or some other fluid property by random molecular or turbulent motions (Fischer et al. 1979; Rubin & Atkinson 2001; Lewis 1997). Shear is the advection of fluid at different velocities at different locations within a flow field (Fischer et al. 1979). Dispersion is the mixing, spreading or scattering of particles or some other fluid property by the combined effects of shear and diffusion (Fischer et al. 1979). The terms mixing, dispersion and diffusion are often used interchangeably in the literature because they all cause the spreading of fluid properties. However, it is important to realise that the behaviour of and mechanisms behind these processes are vastly different. Sections 2.1.1 to 2.1.5 outline the background and theories that define these processes.

2.1.1 Mixing and Advection

Mixing is any process that causes one particle of water to be mingled with or diluted by another (Fischer et al. 1979). Both diffusion and dispersion result in fluid mixing. Mixing should not be confused with advection: the net drift of particles across a cross-sectional area (Lewis 1997). Advection usually involves motions associated with mean flow or currents such as in rivers, or in coastal waters due to tides (Fischer et al. 1979; Rubin & Atkinson 2001).

2.1.2 Molecular Diffusion

Diffusion can occur by either molecular or turbulent processes. Molecular diffusion is the mixing, spreading or scattering of particles or some other fluid property by random molecular motions (Brownian motion) under the influence of a concentration gradient (Fischer et al. 1979; Rubin & Atkinson 2001; Lewis 1997). Molecular diffusion occurs according to Fick’s Law, and so is often referred to as Fickian Diffusion (Fischer et al. 1979). Fick’s Law states: the mass flux of one constituent in a fluid relative to another in a given direction is proportional to the gradient of constituent concentration in that direction (Fischer et al. 1979). Figure 2.1 demonstrates this process schematically.
In one dimension ($x$), Fick’s Law can be stated

**Equation 2.1**

$$ q = -D \frac{\partial C}{\partial x} $$

where $q$ (kg/m$^2$/s) is the mass flux, $C$ (kg/m$^2$) is the mass concentration of diffusing particles and $D$ is the molecular diffusion coefficient (m$^2$/s). The negative sign indicates that the process must transport mass from the region of high to low concentration. In three dimensions ($x, y, z$) Fick’s Law can be written in vector notation

**Equation 2.2**

$$ \vec{q} = -D \vec{\nabla} C $$

where $\vec{q}$ is the mass flux vector with components ($q_x, q_y, q_z$) in a Cartesian co-ordinate system (Streeter et al. 1998). Applying conservation of mass another relationship can be derived, which is commonly referred to as the diffusion equation (Fischer et al. 1979). In three dimensions the diffusion equation can be written in vector notation

**Equation 2.3**

$$ \frac{\partial C}{\partial t} = D \nabla^2 C $$

or written out fully

**Equation 2.4**

$$ \frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right) $$

### 2.1.3 Turbulence

In order to adequately describe turbulent diffusion, an understanding of turbulent processes is required.

**Laminar and Turbulent Flow**

Fluid can be defined as to move in one of two regimes; laminar flow or turbulent flow. Laminar and turbulent flows are difficult to define. However, they have a number of clear characteristics which distinguish them from each other:
• laminar flow is stable, “smooth” and moves in layers, as opposed to turbulent flow which is unstable, “rough” and moves in three dimensions;
• laminar flow exhibits low Reynolds numbers (Re), as opposed to turbulent flow which exhibits high Re numbers. The Re number is the dimensionless group

\[
\text{Equation 2.5} \quad \text{Re} = \frac{ul}{\nu}
\]

where \( u \) (m/s) is a characteristic velocity of the flow (e.g. the mean velocity), \( l \) (m) is a characteristic length scale (e.g. the diameter of a pipe carrying flow) and \( \nu \) (m²/s) is the kinematic viscosity of the fluid, \( \nu = \frac{\rho}{\mu} \), where \( \rho \) (kg/m³) is the density and \( \mu \) (Kg/m.s) is the dynamic or absolute viscosity (Streeter et al. 1998);
• laminar flow has one or two length and time scales which define the structure of the flow, whereas turbulent flow is characterised by a continuous spectrum of space and time scales;
• in laminar flow mixing is slow, caused only by molecular diffusion, while in turbulent flow mixing is rapid, caused by molecular diffusion, turbulent diffusion and shearing. This laminar and turbulent character is illustrated in Figure 2.2 a) where a filament of dye is introduced on the centreline at the upstream end of a pipe. In laminar flow the filament makes a streak along the centreline, but in turbulent flow the streak is rapidly spread across the pipe (Fischer et al. 1979);
• laminar flow dissipates little energy, while turbulent flow is strongly dissipative, and decays rapidly without a continuous supply of energy.

Almost all natural flows are turbulent to some extent (Rubin & Atkinson 2001).
Figure 2.2: a) Dye introduced at the upstream end of a pipe in laminar and turbulent flow; and b) Record of longitudinal velocity at the centre of a pipe at large at large and small Reynolds number (Fischer et al. 1979)

*Time-averaged Description of Turbulence*

Osbourne Reynolds (1884) was the first to describe turbulence mathematically (Lewis 1997). Reynolds considered fluid properties of interest as consisting of a time-averaged mean component and a fluctuating component (Rubin & Atkinson 2001). This is indicated in Figure 2.2 b) where the mean centreline velocity in the pipe with turbulent flow ($\bar{u}$) is constant, with random fluctuations ($u'$) occurring above and below. The total resulting velocity at any point in time is

**Equation 2.6**  
$$u = \bar{u} + u'$$

where $\bar{u}$ is defined as the time-average of $u$,

**Equation 2.7**  
$$\bar{u} = \frac{1}{T} \int_0^T u dt$$

and $T$ is the averaging period (Rubin & Atkinson 2001). Also by definition,

**Equation 2.8**  
$$\int_0^T u' dt = 0$$
Time-averages are convenient and easy to use, however, the time averaging period must be chosen carefully to best represent the situation. T should be small compared to the timescale of variation of mean flow properties, but long enough to allow random components. Time-averaged concentrations are used in section 2.1.4 in the mathematical description of turbulent diffusion.

**Statistical Description of Turbulence**

Another method of describing turbulence is by defining the statistical properties of the flow field, such as averages, variances and correlation coefficients. Consider a number of particles released simultaneously. The random displacement $x$ of each particle at time $t$ after it is released can be observed. The displacement $x$ can be considered a random variable with a normal distribution whose statistical properties can be determined if a large number of experiments are carried out (i.e. a large number of particles are released). For example, an ensemble mean velocity $\bar{u}$ is derived in this way

**Equation 2.9**

$$\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i$$

where $N$ is the total number of experiments performed (i.e. the number of particles released simultaneously) and $i$ indicates each experiment. Section 2.1.4 expresses turbulent diffusion with the use of statistics as described here. At this point it should be noted that $\bar{u}$ is used widely in the literature to represent both time and spatial (ensemble) mean velocities, and so will be used to denote both in this dissertation.

**Eddies and Kolmogorov’s Theory of Universal Equilibrium**

One of the most important effects of turbulence is the mixing of fluid properties. Mixing in turbulent flow occurs predominantly through the action of eddies. Eddies are irregular whirls of random fluid motion that enhance mixing (Lewis 1997). The curvatures in the dye observed in the pipe containing turbulent flow (Figure 2.2) are caused by the action of these eddies.

Kolmogorov’s theory of universal equilibrium, or local similarity theory, proposes the behaviour of turbulent eddies in a fluid. The theory suggests that there are a range of eddies present in turbulent flow, with large scales determined by the domain size, down to very small scales (Fischer et al. 1979). Energy cascades from the largest to the smallest scales in the fluid. Inertial forces transfer energy from the larger to smaller scale eddies, and at the smaller scales viscous forces dissipate energy as heat (Lewis 1997). At some point down the cascade, a scale is reached where the eddies are fully three dimensional and isotropic (independent of
orientation) (Lewis 1997). For eddies smaller than this isotropic scale, properties are dependent only on the rate of energy transfer down ($\varepsilon$) and the fluid viscosity ($\nu$). This eddy range is termed the “equilibrium range”. At the larger end of the equilibrium range, viscous dissipation is assumed to be small, thus here turbulence is dependent only on $\varepsilon$. This eddy range is termed the “inertial subrange”. At the smaller end of the equilibrium range, viscous dissipation is considerable, thus here turbulence is again dependent on $\varepsilon$ and $\nu$. This eddy range is termed the “dissipation subrange” or “range of viscous dissipation”. At the bottom of the dissipation subrange is the smallest scale in the flow, the Kolmogorov Scale, $\eta$ (m), which can be described

**Equation 2.10**

$$\eta = \left( \frac{\nu^3}{\varepsilon} \right)^{1/4}$$

where $\nu$ (m$^2$/s) is the kinematic viscosity of the fluid, and $\varepsilon$ (m$^2$/s$^3$) is the rate of energy dissipation in the fluid. These energy ranges are detailed in Figure 2.3.

![Figure 2.3: Kolmogorov’s theoretical equilibrium spectrum (Lewis 1997)](image)

Kolmogorov’s theory of universal equilibrium has been applied widely in ocean studies (Lewis 1997). Both Batchelor (1952) and Okubo (1971, 1974, 1976) have applied Kolmogorov’s theory to derive theoretical explanations of ocean behaviour (see sections 2.1.4, 2.4.1 and 2.4.2).

Eddies of different sizes have different affects on the nature of mixing in a fluid (Lewis 1997). Consider a patch of tracer in a turbulent flow. The patch is affected by three different eddy scales at any instant, as detailed in Figure 2.4. Eddies which are larger than the patch transport the patch without altering its size (Figure 2.4 (a)). This process is termed advection, described in section 2.1.1. Intermediate size eddies cause distortions which increase the boundary of the patch with the surrounding fluid (Figure 2.4 (b)). This is a dispersive effect; dispersion is discussed in detail in section 2.1.5. Finally eddies which are smaller than the
patch are diffusive, smoothing out distortions and irregularities in the patch shape (Figure 2.4 (c)). This is a diffusive effect; turbulent diffusion is discussed in detail in section 2.1.4.

![Figure 2.4: The effect of different eddy scales on transport and spreading of a patch of tracer (Lewis 1997)](image)

### 2.1.4 Turbulent Diffusion

Turbulent diffusion is the random mixing, spreading or scattering of particles or some other fluid property by the turbulent motion of eddies (Fischer et al. 1979; Rubin & Atkinson 2001). Thus turbulent diffusion involves the movement of portions of fluid rather than individual molecules as in molecular diffusion (Rubin & Atkinson 2001). The mathematics describing turbulent diffusion are roughly analogous to molecular diffusion, as both processes are governed by Fick’s Law. As such, both molecular and turbulent diffusion are commonly referred to as Fickian diffusion. However, turbulent diffusion occurs according to eddy diffusion coefficients, which are much larger than molecular diffusion coefficients (Fischer et al. 1979).

The concentration of a constituent at any point in the turbulent fluid will fluctuate with time. Thus the concentration can be averaged over some selected period of time (as described in section 2.1.3), and the resulting mass flux is a mean rate over that time. The mass flux in one dimension due to turbulent diffusion can be stated

**Equation 2.11**

\[ \bar{q}_x = -k_x \frac{\partial \bar{C}}{\partial x} \]

where \( \bar{q}_x \) (kg/m²/s) is the average mass flux in the x direction over a selected time period, \( \bar{C} \) (kg/m²) is the average concentration over a selected time period and \( k_x \) is the turbulent or eddy diffusion coefficient in the x direction (m²/s). In three dimensions, the mass flux can be written

**Equation 2.12**

\[ \bar{q} = -(k_x \frac{\partial \bar{C}}{\partial x} + k_y \frac{\partial \bar{C}}{\partial y} + k_z \frac{\partial \bar{C}}{\partial z}) \]
As for molecular diffusion, conservation of mass can be applied and a diffusion equation derived (Lewis 1997). In three dimensions the turbulent diffusion equation can be written

\[ \frac{DC}{Dt} = \frac{\partial}{\partial x} (k_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z} (k_z \frac{\partial C}{\partial z}) \]

where the diffusion coefficients are allowed to vary in the component directions. With diffusion coefficients constant in time and independent of the spatial coordinates (Lewis 1997), Equation 2.13 reduces to Fick’s equation

\[ \frac{DC}{Dt} = k_x \frac{\partial^2 C}{\partial x^2} + k_y \frac{\partial^2 C}{\partial y^2} + k_z \frac{\partial^2 C}{\partial z^2} \]

Many investigations of dilution in the sea have been based on solutions to Equation 2.13 by making certain simplifying assumptions or applying numerical analysis (Lewis 1997). A common feature of the distributions predicted using these methods is that they are in Gaussian (Normal) form (Lewis 1997), and can therefore be described statistically (as detailed in section 2.1.3). This form assumes that the mass of a diffusing species is constant while the volume increases with time. The concentration distribution in a given direction is assumed to be bell-shaped, and the spread can then be expressed by a variance \( \sigma^2 \)

\[ \sigma^2_x = \frac{\int (x-\mu_x)^2 C(x,t)dx}{\int C(x,t)dx} \]

(Fischer et al. 1979) where \( \mu \) is the location of the centroid of the concentration distribution in the x direction defined by

\[ \mu_x = \frac{\int xC(x,t)dx}{\int C(x,t)dx} \]

and the diffusion coefficient is given by

\[ k_x = \frac{1}{2} \frac{d\sigma_x^2}{dt} \] implying \( \sigma_x^2 = 2k_x t \)

(Lewis 1997; Fischer et al. 1979). The same equations apply in the other coordinate directions (\( y \) and \( z \)).

Richardson’s Law

Richardson (1926) was the first to quantify turbulent diffusivity when he sort to explain the difference between the diffusivity predicted by molecular motions (i.e. molecular diffusion; slow, small scale mixing) and the diffusion observed in the atmosphere (turbulent diffusion; rapid, large scale mixing). He considered the separation of a pair of particles within a cluster
Richardson defined a “distance-neighbour” graph or function, which in current terminology is known as the probability density function (pdf), for the separation of a pair of particles (Sawford 2001). Using a range of data from molecular to global scales Richardson related the turbulent diffusion coefficient calculated by Equation 2.17 to the separation of particles, as shown in Figure 2.5. Richardson concluded that diffusion coefficients varied as

\[ k_x = 0.2l^{4/3} \quad \text{or} \quad k_x = 0.2\sigma^{4/3} \]

where \( l \) was a characteristic length scale for the system under observation, the standard deviation of the particles from their mean position (the mean square displacement of the particles from the centre of mass). Equation 2.18 is commonly known as Richardson’s “four-thirds power law”.

![Figure 2.5: Richardson’s original plot of \( k \) versus particle separation \( l \) (Richardson 1926).](image)

Richardson’s Law was arrived at theoretically by Batchelor (1952). Batchelor extended Richardson’s concept to three dimensions, and used dimensional arguments and Kolmogorov’s universal equilibrium theory (or local similarity theory) for small scale processes (described in section 2.1.3) to determine that rates of spread at different times during the diffusion process (Lewis 1997). Batchelor considered a field of homogenous turbulence. He argued that if the scale of turbulent eddy motion is large compared to the separation between a pair of particles \( s \), then only two length scales are important in defining the statistics of their relative motion. These are the initial separation \( s_0 \) and the Kolmogorov scale \( \eta = (v^3/\varepsilon)^{1/4} \) as defined in Equation 2.10. Similarly, only two timescales...
are important; \( t - t_o \) and the Kolmogorov time-scale \( t_o = (\nu / \varepsilon)^{1/2} \). Dimensional analysis gives

**Equation 2.19**

\[
\frac{d\langle s^2 \rangle}{dt} = \varepsilon \tau^2 f\left(\frac{s_o}{\varepsilon^{1/2} \nu^{3/2}}, \frac{\tau \varepsilon^{1/2}}{\nu^{1/2}}\right)
\]

where \( \tau = t - t_o \) (Fischer et al. 1979). Applying Kolmogorov’s hypothesis that turbulence within the inertial subrange depends only on \( \varepsilon \) (as described in section 2.1.3), and assuming time scales are small but just large enough that the initial separation of the particles \( s_o \) has been essentially “forgotten”, then Equation 2.19 reduces to

**Equation 2.20**

\[
\frac{d\langle s^2 \rangle}{dt} \propto C \varepsilon (t - t_i)^2
\]

where \( t_i \propto \frac{s_o^{2/3}}{\varepsilon^{1/3}} \) and \( C \) is a constant (Fischer et al. 1979). Integrating this gives

**Equation 2.21**

\[
\langle s^2 \rangle \propto t^3
\]

which implies that the mean square separation of particles is proportional to the third power of \( t \), a relationship sometimes referred to as “the third power law of variance”. This in turn implies

**Equation 2.22**

\[
\frac{d\langle s^2 \rangle}{dt} \propto \varepsilon^{1/3} \langle s^2 \rangle^{2/3}
\]

In words, Equation 2.22 states that the rate of increase of the mean square separation of particles is proportional to the mean square separation to the power 2/3 (Fischer et al. 1979). Equation 2.22 is remarkably similar Richardson’s Law. This similarity can be explained as follows. The pdf for the separation of a pair of particles \( (l) \) utilised by Richardson is equivalent to the pdf describing the distance of a particle from the centre of mass of an identical pair (Fischer et al. 1979). Provided that turbulence is homogenous and the initial separation of particles has been forgotten as described above, the description of the mean square separation of particles in an ensemble \( \langle s^2 \rangle \) will be identical, and this description will be the same as the description of the mean square displacement from the centre of mass \( \langle \sigma^2 \rangle \), i.e. \( l \equiv \langle s^2 \rangle \equiv \sigma^2 \). This leads to the proposition that

**Equation 2.23**

\[
k = \alpha (\sigma^2)^{2/3} = \alpha \sigma^{4/3}
\]

For some constant \( \alpha \) which satisfies Equation 2.17 (Fischer et al. 1979), i.e.

**Equation 2.24**

\[
k = \frac{1}{2} \frac{d\sigma^2}{dt} = \alpha (\sigma^2)^{2/3} = \alpha \sigma^{4/3}
\]

Equation 2.24 (commonly referred to as the 4/3 law) is identical to Richardson’s Law (Equation 2.18), when \( \alpha = 0.2 \).
It is interesting to note that Equation 2.24 seems to apply over wide time and length scales, despite the limiting assumptions applied during its derivation. The 4/3 law assumes that time scales are small, and that the scale of turbulence is within the inertial subrange. However, atmospheric data suggests that the law is valid over a much larger scale than the Batchelor-Kolmogorov theory would indicate as viable. Richardson (1926) showed that his law holds for molecular diffusion on a scale of $5 \times 10^{-2}$ cm to cyclonic depressions on a scale of 1000 km. The reasons for this are not clear, however other diffusion theories not so limited in scale give rise to the same law, so it appears that the processes leading to the 4/3 law are feasible (Fischer et al. 1979).

2.1.5 Dispersion

Dispersion is the mixing, spreading or scattering of particles or some other fluid property by the combined effects of shear and diffusion (Fischer et al. 1979). The terms dispersion and diffusion are often used interchangeably in the literature because they both cause the spreading and mixing of fluid properties. However, it is important to realise that the mechanisms behind the two processes are different. Dispersion includes the effects of shear, and as such dispersion coefficients can be very much larger than turbulent diffusion coefficients. Dispersion is sometimes referred to as “effective” diffusion or “apparent” diffusion.

Sir Geoffrey Ingram Taylor was the first to analyse the concept of dispersion when he described the spread of dissolved contaminants in laminar flow through a pipe (Taylor 1953). In his paper Taylor (1953) describes how when a soluble substance is introduced to a pipe containing a fluid flowing with a laminar regime, the substance spreads out under the combined action of molecular diffusion and the variation of the velocity across the pipe, or shear. A year later this concept was extended to cover turbulent flows (Taylor 1954) and has since been applied widely to describe environmental regimes (Fischer et al. 1979). Common to all these flows is that spreading in the direction of flow is caused primarily by the velocity profile in the cross section. Such flows are commonly referred to as “shear flows”.

The concept of vertical shear is illustrated in Figure 2.6 which features a column containing a well mixed tracer in a flowing channel of fluid (Figure 2.6 (a)). Drag on the bottom of the channel (or the “no slip” condition which requires the velocity at the channel boundary to be zero) leads to a linear variation of velocity with depth. This velocity shear causes the column to “tip over” (Figure 2.6 (b)), and vertical mixing above and below leads to the formation of a new mixed column, much wider than the first (Figure 2.6 (c)). In essence, vertical shearing
causes longitudinal dispersion. Longitudinal and transverse shear also cause dispersion, in the transverse and longitudinal directions respectively.

![Figure 2.6: Dilution of a column of tracer produced by combined effects of distortion by linear velocity shear and vertical mixing (Lewis 1997)](image)

The effectiveness of the shear process on the mixing of a tracer as described above depends on the time scale involved, as illustrated in Figure 2.7. Initially, the patch of tracer remains circular as it is spread by turbulent eddies and transported by the mean current (Figure 2.7 (a)) as detailed in section 2.1.3 (Figure 2.4). At intermediate times since the introduction of the tracer vertical shear along the direction of mean flow causes longitudinal dispersion as described in Figure 2.6. Although vertical shear across the direction of mean flow can occur and result in transverse dispersion, the shear in this direction is very much smaller (Lewis 1997). The result is that the tracer is stretched in the direction of mean flow (Figure 2.7 (b)). At longer times since the introduction of the tracer, diffusion by turbulent motions is dominated by transverse and longitudinal shearing, and thus transverse and longitudinal dispersion occurs. The ratios of timescales which control the shear effect have been incorporated into numerous mathematical descriptions of shear dispersion (Lewis 1997).

![Figure 2.7: The increasing significance of longitudinal and lateral shear with time illustrated by a patch of dispersing tracer (Lewis 1997)](image)
Kenneth Bowden applied Taylor’s dispersion theories to the ocean in 1965, simplifying the problem by assuming a bounded flow with shear along the direction of mean flow and steady-state conditions under which the vertical velocity distribution was constant with time (Bowden 1965). Bowden’s total dispersion solution for a linear profile with constant vertical diffusion can be written

\[
K_x = k_x + \frac{u_s^2 h^2}{30k_z}
\]

where \(K_x\) (m\(^2\)/s) is the dispersion coefficient in the x or longitudinal direction, \(k_x\) (m\(^2\)/s) is the longitudinal turbulent diffusion coefficient, \(u_s\) (m/s) is the surface current in the x direction, \(h\) (m) is the total depth and \(k_z\) (m\(^2\)/s) is the vertical turbulent diffusion coefficient (Lewis 1997).

Carter and Okubo (1965) developed a theory for predicting the total dispersion of a tracer patch during a study of the physical processes of dispersion in the Cape Kennedy area of the United States (Lewis 1997). Their theory applied for an unbounded flow with shear along the direction of mean flow and steady-state conditions. A basic mass balance equation was considered

\[
\frac{\partial C}{\partial t} - \frac{\partial}{\partial x} \left( \frac{C}{\Omega_z} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{C}{\Omega_z} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{C}{\Omega_z} \frac{\partial C}{\partial z} \right) = \frac{1}{\Omega_z} \frac{\partial^2 C}{\partial x^2} + k_x \frac{\partial^2 C}{\partial y^2} + k_z \frac{\partial^2 C}{\partial z^2}
\]

where \(\Omega_z\) is the vertical shear (\(\partial u / \partial z\)) relative to the mean flow. It was assumed that the diffusion coefficients in Equation 2.26 described mixing by eddies much smaller than the patch, thus the coefficients could be considered constant with respect to both space and time. Larger scale eddies were assumed to be responsible for the shearing of the patch. These assumptions allowed a solution to Equation 2.26 which gave the horizontal variances

\[
\sigma_{x}^2 = 2k_x t + \frac{1}{6} \Omega_z^2 k_x t^3
\]

\[
\sigma_{y}^2 = 2k_y t
\]

The first terms in both Equation 2.27 and Equation 2.28 indicate how spreading is controlled by turbulent eddies, while the second term in Equation 2.27 indicates the additional spreading in the x direction caused by vertical shear. Note that the second term in Equation 2.27 indicates that \(\sigma_{x}^2 \sim t^3\). In light of this relationship, the universal equilibrium theory or similarity theory applied by Batchelor (1952) (section 2.1.4) is not the only theory which deduces the third power law of variance.

Equation 2.17 can be applied, and it follows that
and therefore the dispersion coefficient can be written

Equation 2.30

\[ K_x = k_x + \frac{1}{4} \Omega_z^2 k_z t^2 \]

Saffman derived a similar dispersion solution for the spread of a semi-bounded patch (Lewis 1997),

Equation 2.31

\[ K_x = k_x + \frac{3}{56} \Omega_z^2 k_z t^2 \]

Carter and Okubo also developed a theory for predicting total dispersion in an unbound tracer patch which considered the effect of lateral shear and assumed no significant velocity variation with depth (Lewis 1997). In this model, the variation of the longitudinal velocity in the transverse or lateral direction \( \frac{\partial u}{\partial y} \) contributed to the longitudinal dispersion. Carter and Okubo assumed that the velocity variations were linear, that \( k_y \) was constant and that the tracer patch was bounded above and below (Lewis 1997). They derived

Equation 2.32

\[ K_x = k_x + \Omega_y^2 k_y t^2 \]

A random walk model is another tool that can be applied to predict dispersion in the ocean. Random walk theory is not based on a conservation of mass equation like those presented above, but rather a model tracks each particle in diffusing cloud. As such, this method requires significant computing power, and has only recently become a feasible method of describing dispersion.

\section*{2.2 Dispersion in the Nearshore Zone}

The nearshore zone (Figure 2.8) is the most dynamic region of the ocean. Within the nearshore region waves shoal, break and travel shoreward as a bore, dissipating energy to the coast (United States Army Corps of Engineers 2002). The breaking waves act to generate various coastal currents; including long-shore currents, cross-shore currents and rip currents. Coastal currents in the nearshore zone can also be wind driven, or generated by tidal motions. The energy provided to the coast by wind, waves and currents drives mixing and dispersion in the nearshore zone (Inman et al. 1971).
When wind blows over the ocean the surface waters are turbulently mixed (Bowen & Inman 1974). In addition, wind activity leads to the creation of surface waves. Surface waves (in the form of both sea and swell) can contribute to mixing in the nearshore zone in three ways.

1. The mixing processes associated with non-breaking wave motion. Here the contribution of non-breaking waves to turbulent mixing may be small compared to that of other processes, such as tidal currents (Bowen & Inman 1974);
2. The rapid mixing of water in the cross-shore direction within the surf zone caused by breaking waves and their bores. Cross-shore diffusion via this mechanism is known to be substantially more effective than diffusion in the longshore direction (Inman et al. 1971); and
3. The large scale mixing due to wave-induced longshore and rip currents. These currents combine to provide an effective advective mechanism within the nearshore zone, commonly referred to as the “nearshore circulation cell” (Bowen & Inman 1974). Water is transported shoreward by breaking waves, flows alongshore and then moves seaward in rip currents, creating a continuous exchange of water between the surf zone and the rest of the nearshore region (Bowen & Inman 1974).

### 2.3 Lagrangian Techniques

Lagrangian techniques involve ocean studies with a moving reference frame. Such studies have been used widely to characterise subsurface and surface flows. In particular, lagrangian techniques are common in studies of ocean dispersion. Some of the first lagrangian studies of subsurface flow involved the use of neutrally buoyant, acoustically tracked floats to measure subsurface currents by John Swallow in the 1950’s (Davis 1991). Swallow floats had an immediate impact on the understanding of the ocean at the time, and provided the first evidence in favour of Stommel’s then-new theory of deep thermohaline circulation (Davis 1991).
Swallow floats were followed by SOFAR floats; large and long range floats developed by Rossby and Webb (1970). These floats were used widely in the 1970s and 1980s, and were the basis for most of what has been learned from floats about the large scale ocean (Davis 1991).

The earliest lagrangian studies of surface flows were performed from anchored ships using visually tracked buoys with drogues (Davis 1991). The invention of radar made it possible to track a set of drifters for days, as done by Reid et al. (1963) to map a coastal eddy, and Parker (1972) to define the cross stream structure of the Gulf Stream (Davis 1991). Since then satellite positioning has revolutionised drifter technology, making the cost-effective long-term global tracking of ocean currents possible e.g. by Doppler based Argo floats.

The most recent lagrangian studies have involved:

- surface floats and balloons tracked by sequential aerial photographs (Sasaki & Horikawa 1975);
- “live floats” where swimmers were tracked by theodolite (Short & Hogan 1994; Brander & Short 2000);
- dye releases tracked by observation and photographs (Bowen & Inman 1974; Rodriguez et al. 1995; Takewaka et al. 2003); and

Results from the most relevant of these studies are discussed in section 2.4 below.

### 2.4 Previous Studies

#### 2.4.1 Okubo (1971; 1974; 1976)

Akira Okubo collated data from a number of instantaneous dye release experiments to determine whether Richardson’s 4/3 law or some other general scaling law could be applied in the ocean (Okubo 1971). Okubo (1971) prepared two kinds of “diffusion diagrams”. He defined a diffusion diagram as “a plot of a characteristic parameter of diffusion against another such parameter”. The first of Okubo’s diffusion diagrams featured the horizontal variance versus diffusion time (Figure 2.9), and the second showed the apparent diffusivity versus the scale of diffusion (Figure 2.10). While Okubo’s paper refers to diffusion, the effect of shears (which must have been present during the experiments) were implicitly regarded by Okubo as part of the influence of eddy size on patch spreading (Lewis 1997), as discussed in
section 2.1.3, Figure 2.4. Thus the apparent diffusivity regarded by Okubo is equivalent to the dispersion, and Okubo’s “diffusion diagrams” are really dispersion diagrams.

Okubo (1971) used data from 20 carefully selected instantaneous dye release experiments, with time scales ranging from 2 hr to 1 month, and length scales ranging from 30 m to 100 km. He assumed that the dye experiments were radially symmetric, thus computed the variance for a radially symmetric distribution (\( \sigma_{rc}^2 \))

**Equation 2.33**
\[
\sigma_{rc}^2 = 2\sigma_x\sigma_y
\]

Okubo (1971) computed the apparent diffusivity (\( K_a \))

**Equation 2.34**
\[
K_a = \frac{\sigma_{rc}^2}{4t}
\]

and arbitrarily defined a length scale (\( l \)) as

**Equation 2.35**
\[
l = 3\sigma_{rc}
\]

Okubo’s diffusion diagrams gave the relations

**Equation 2.36**
\[
\sigma_{rc}^2 = 0.0108t^{2.34}
\]

**Equation 2.37**
\[
K_a = 0.0103l^{1.15}
\]

Equation 2.36 indicates that the variance increased with time at a power between 2 and 3. This result is close to theories derived by Batchelor (1952) and Carter and Okubo (1965), which predict that the variance grows according to \( t^3 \), the third power law of variance (Equation 2.21). Equation 2.37 indicates that the apparent diffusivity grows according to \( l^{1.15} \). This power law is slightly less than that derived by Richardson (1926); \( l^{1.33} \), the 4/3 power law.

Okubo noted that his findings did not rule out the possibility that the third power law of variance and the 4/3 power law of the diffusivity may be valid locally for some time and length scales. To illustrate this Okubo plotted both his data and less recent findings on diffusion diagrams, and fitted the two laws locally, as shown in Figure 2.9 and Figure 2.10.
Figure 2.9: Okubo’s (1971) “diffusion diagram” for variance versus diffusion time, with the third power law of variance fitted locally.
As shown by Richardson in the atmosphere, Okubo (1971) demonstrated that the 4/3 law is valid over a much larger scale than the Batchelor-Kolmogorov theory would indicate as viable. The data utilised by Okubo spanned large time (2 hrs to 1 month) and length (30 m to 100 km) scales, in which conditions would not be isotropic and homogeneous. Hence it is surprising that the data follows a single law very similar to that found by Richardson (1926) and derived by Batchelor (1952) under these assumptions.

Okubo (1971;9174) defined the following equations, which reflect Batchelor’s (1952) application of similarity theory as described in section 2.1.3 (i.e. assuming that eddies responsible for horizontal spreading are locally isotropic and homogeneous, lying in the inertial subrange)
The simplifying assumptions made in Okubo’s work should be remembered when regarding his findings. Okubo assumed radial symmetry, and dispersion patterns are never radial; the variance of a non-symmetric patch will be larger. Okubo’s definition of the length scale was arbitrary ($l = 3\sigma_r$), and little comparison was made to environmental parameters such as wind speed and wave size. Finally the effects of shearing were not addressed; shears were implicitly regarded as part of the influence of eddy size on patch spreading (Lewis 1997).

Okubo addresses one of these simplifications, the arbitrary definition of the length scale, in a paper discussing the application of his work in the numerical modelling of oceanic dispersion (Okubo 1974). Okubo proposes a more accurate formula for use in the numerical modelling of a radially symmetric patch

Equation 2.39  
$$K(r) = 0.0680r^{1.15}$$

where $r$ is the radius and $K$ is the dispersion coefficient.

### 2.4.2 Okubo and Ebbesmeyer (1976)

Okubo and Ebbesmeyer (1976) provided an analytical method by which shear-induced spreading, rotation and divergence could be removed from apparent diffusion or dispersion ($K$) experienced by a set of drogues to determine true horizontal turbulent diffusivity ($k$). The observation of the $x$, $y$ coordinates of $n$ number of drogues are used to calculate the speeds $u$, $v$ of each drogue simultaneously at $t$ times. The speeds of each drogue are then expanded in a Taylor series about the centroid located at $\bar{x}(t)$, $\bar{y}(t)$ as shown below.

Equation 2.40  
$$u_i(t) = \bar{u}(t) + \frac{\partial \bar{u}(t)}{\partial x} [x_i(t) - \bar{x}(t)] + \frac{\partial \bar{u}(t)}{\partial y} [y_i(t) - \bar{y}(t)] + u_i'' (t)$$  
$$v_i(t) = \bar{v}(t) + \frac{\partial \bar{v}(t)}{\partial x} [x_i(t) - \bar{x}(t)] + \frac{\partial \bar{v}(t)}{\partial y} [y_i(t) - \bar{y}(t)] + v_i'' (t)$$

where $\frac{\partial \bar{u}(t)}{\partial x}$, $\frac{\partial \bar{u}(t)}{\partial y}$, $\frac{\partial \bar{v}(t)}{\partial x}$ and $\frac{\partial \bar{v}(t)}{\partial y}$ are linear velocity gradients at the centroid and $u_i''$ and $v_i''$ are the turbulent speeds. Okubo and Ebbesmeyer (1976) then apply Equation 2.38 b) derived by Okubo (1971). It is assumed that $\varepsilon$ is equal to $\sigma_u$, $\sigma_v$ (the standard deviations of the turbulent speeds) and $l$ is equal to $\sigma_x$, $\sigma_y$ (the standard deviations of the drogue positions) so that the turbulent diffusivity can be estimated by

Equation 2.41  
$$a) \ k_x = c \sigma_x \sigma_u \quad \text{and} \quad b) \ k_y = c \sigma_y \sigma_v$$
where c is an unknown constant of order 0.1-1. It should be noted that four is the minimum requirement for the number of drogues to determine the velocity gradients, centroid speeds and turbulent velocities using linear regression procedures with sufficient statistics (Okubo & Ebbesmeyer 1976).

The Taylor series applied assume that velocity gradients are uniform within the group of drogues and that second and higher order terms are considered as turbulence. This simplification views oceanic turbulence in two major parts; the large scale eddies that appear as shears of the mean velocity (the “dispersive eddies” featured in Figure 2.4 b)), and the small scale eddies responsible for eddy diffusion (the “diffusive eddies” featured in Figure 2.4 c)). In the real ocean, oceanic turbulence contains a wide variety of eddies, and is therefore not easily separable in this way. As a group of drogues continues to spread, the division between shear and turbulent diffusion changes, and what is considered turbulence includes larger and larger scales. This means the resulting true horizontal diffusivity will change with scale, and therefore cannot really be considered a “true” diffusivity at all. While the method described by Okubo and Ebbesmeyer (1976) is useful, it should be remembered that the separation provided is based on the time and length scales applied.

2.4.3 List et al. (1990)

List et al. (1990) performed drogue studies in the coastal waters of southern California. Up to six drogues were released and tracked for 36 hrs, with positions fixed (accurate to 1 m) every 30-40 min. From this data, List et al. (1990) determined estimates of drogue dispersion.

List et al.’s (1990) calculation of the dispersion coefficients began with the determination of the position of the centroid of the set of n drogues at time t. The variances in the x, y and overall directions were resolved and Equation 2.17 was applied to determine the relative dispersion coefficients, as shown in Equation 2.42 below.

\[
\begin{align*}
K_x(t) &= \frac{1}{2} \frac{\partial \sigma_x(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma_x(t)^2}{\Delta t} \\
K_y(t) &= \frac{1}{2} \frac{\partial \sigma_y(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma_y(t)^2}{\Delta t} \\
K(t) &= \frac{1}{2} \frac{\partial \sigma(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma(t)^2}{\Delta t}
\end{align*}
\]

It should be noted that the relationship between \( K(t) \) and \( \sigma(t) \) in Equation 2.42 is strictly only valid for a large number of drogues, and under the assumption that any drogue set is
representative of an ensemble and can therefore be described statistically (see section 2.1.3). In addition, statistical descriptions as described require random variables, and since mixing in the coastal zone is not an entirely random process (shear effects are non-random), it should be recognised that $K(t)$ calculated in this way is not a true statistical measure of ensemble behaviour. As a result, $K(t)$ determined for a single, relatively small group of drogues ($n \geq 4$) deployed in the coastal zone is likely to become negative at times (List et al. 1990).

List et al. (1990) found dispersion coefficients ranging from -5 to 55 m²/s and increasing with scale as shown in Figure 2.11. They found that their data exhibited the same trends as Okubo’s (1971) data, but with somewhat larger values of the dispersion coefficient thought to indicate the influence of energetic flows associated with coastal shear. List et al. (1990) compared their data with Okubo’s (1974) data, and found that while their results agreed with Richardson’s 4/3 law they show a wide divergence in magnitude. List et al. (1990) again attributed this observation to increased shear on the coast.

![Figure 2.11: Dispersion coefficients (presented in cm²/s x 10⁵) determined by List et al. (1990) during April (winter) 1985 in the coastal waters of southern California](image)

List et al. (1990) followed the Okubo and Ebbesmeyer (1976) method for removing shear-induced spreading, rotation and divergence from drogue observations (using $c = 1$ and a timescale of 30-40 min), and found turbulent diffusivities ranging from 0-30 m²/s (Figure 2.12). The turbulent diffusivities determined were small for scales below 1 km, but rapidly accelerated at larger scales, as shown in Figure 2.12. List et al. (1990) also followed a method for calculating turbulent diffusivities suggested by Yanagi et al. (1982), and a newly proposed method in which the effects of advection and diffusion are solved separately for a number of time steps. All three methods identified the same broad trends.
2.4.4 Riddle and Lewis (2000)

Riddle and Lewis (2000) compiled data from 285 dye dispersion experiments performed within estuaries, lochs and coastal waters mainly within the UK between 1968 and 1996. Dispersion coefficients were calculated by one of two methods. The first method involved plotting the patch width variances, applying linear regression and using the gradient $b$ to determine $K$ in accordance with Equation 2.17, as shown below.

Equation 2.43

$$K = \frac{1}{2} b$$

The second method involved the use of a site specific random walk model.

In the studies described, shear was shown to be the dominant dispersive factor. As such, Riddle and Lewis (2000) assumed that the measured lateral dispersion coefficients were equivalent to the spreading due to velocity shear, i.e. turbulent diffusion was assumed to be negligible.

Riddle and Lewis (2000) identified dispersion coefficients ranging from 0.002 m$^2$/s in the weak tidal current of Loch Ryan in Scotland to 31.1 m$^2$/s in the strong tidal flow of the East Solent in the south of England. These results encompass the dispersion coefficients reported for the coast of Ireland by Elliot et al. (1997), which ranged between 0.02 to 0.4 m$^2$/s.
2.4.5 Tseng 2002

Tseng (2002) conducted three experiments with surface drifters in the coastal waters of southwestern Taiwan. In each experiment four or five drifters were tracked simultaneously for 18-26 hours with positions fixed every 20-30 minutes. The dispersion coefficient was defined as

\[
K = \frac{1}{4} \frac{d\sigma_x \sigma_y}{dt}
\]

where the value of \( K \) was estimated from the average slope of \( \sigma_x \sigma_y \) with respect to time by linear regression of the latter stage of the experiment, as shown in Figure 2.13.

Tseng’s (2002) results showed two stages or regimes within the experiments performed: a coherent regime at the beginning when the drifters remained clustered, and a rapid dispersion regime where separation grew to the order of kilometres (Figure 2.13). Tseng (2002) found dispersion coefficients of 12.5 m²/s and 14.5 m²/s for the two experiments conducted in an estuary zone (TW1 and TW2) and 45 m²/s for the experiment conducted further offshore and in the vicinity of a small island (KH) (Figure 2.13). The lower rate of dispersion observed in experiments TW1 and TW2 was attributed to a moderate tidal current, while the high rate of dispersion identified for experiment KH was explained by island trapping: the enhanced mixing and transport processes associated with instabilities in the wake of an island (Tseng 2002).
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Figure 2.13: Variance (solid circle) $\sigma_x, \sigma_y$ of drifter positions vs. time for the experiments of (a) TW1, (b) KH and (c) TW2 performed by Tseng (2002). The solid line is a least square fit for the latter stage of each experiment (Tseng 2002)

Tseng (2002) separated the effects of shear-induced spreading, rotation and divergence from his drogue data to reveal turbulent diffusivities as done by Okubo and Ebbesmeyer (1976), Yanagi et al. (1982) and List et al. (1990). He found that $k$ values computed via the Yanagi et al. (1982) and List et al. (1990) methods were roughly the same magnitude (0.22-0.64 m$^2$/s and 0.34-0.92 m$^2$/s respectively), while values computed using the Okubo and Ebbesmeyer (1976) method (using $c = 0.1$ and a timescale of 20-30 min) were somewhat larger (2.36-4.86 m$^2$/s, Figure 2.14). However, as found by List et al. (1990), general trends in variation identified by the three methods were “remarkably consistent” (Tseng 2002, pp. 99).
Figure 2.14: Diffusivities obtained by Tseng (2002) using the method of Okubo and Ebbesmeyer (1976) vs. time for the experiments of (a) TW1, (b) KH and (c) TW2. The bars indicate a 95% confidence interval, and the values of $k$ are calculated from the mean in the latter stage of each experiment (Tseng 2002)

2.4.6 Takewara et al. (2003)

Takewara et al. (2003) performed dye dispersion experiments at a sandy beach in Hasaki, Japan. Dye was placed in a wave reforming zone which lay between an offshore bar where limited breaking occurred, and the final surf zone where all passing waves broke. The movement of the dye within the surf zone was tracked by a moored video. Takewara et al. (2003) assumed that Gaussian diffusion processes (i.e. processes resulting in a Normal distribution) operated in the cross-shore direction, and determined a cross-shore dispersion coefficient according to

Equation 2.45:

$$\sigma_{ss}(t) = \left\{ \frac{1}{3} - 4K_x t \log \left( \frac{C}{C_0} \sqrt{4\pi K_x t} \right) \right\}^{1/2}$$
where \( C/C_0 \) was chosen to be 0.1%, 0.5% and 1%, and the apparent standard deviation in the cross-shore direction \( (\sigma_{xa}(t)) \) and the cross-shore dispersion coefficient \( (K_x) \) were varied to best fit the experimental results as shown in Figure 2.15 below. The resulting coefficients were 0.01, 0.017 and 0.025 m\(^2\)/s.

It is important to note that Takewara et al. (2003) assumed Gaussian diffusion processes (i.e. random turbulent diffusion processes) in an instance where shear effects were probably present. Takewara et al. (2003) noted that there was almost no wave breaking in the experimental region, and as such it is suitable to assume that no vertical circulation due to wave breaking or associated return flow was present. In addition, considerable error would have been associated with the estimation of \( \sigma_x(t) \), \( \sigma_y(t) \) and \( C/C_0 \) from the moored video. This should be remembered when considering Takewara et al.’s (2003) study.

\[ \text{Figure 2.15: Cross-shore diffusivities estimated by Takewara et al. (2003) for } C/C_0 = 0.01 \text{ and } K_x = 0.025 \text{ m}^2/\text{s} \]

### 2.4.7 Spydell et al. (2006)

Spydell et al. (2006) studied surf zone dispersion using drifters at a sandy beach in San Diego, California. They calculated dispersion in a similar manner to List et al. (1990) (section 2.4.3), but applied a factor of \( \frac{1}{4} \) rather than \( \frac{1}{2} \) during the determination of \( K \) from \( \partial \sigma(t)^2 / \partial t \) (as done by Tseng (2002)) to provide equivalence between relative and absolute dispersion (Spydell et al. 2006).
Spydell et al. (2006) established dispersion coefficients ranging from 0.1-1 m/s², and found that larger waves and stronger longshore currents corresponded to larger coefficients. They observed that the variance of drifter position grew according to $t^{3/2}$ and that dispersion increased with scale, following $\sigma^{2/3}$. These findings differ from the two dimensional inertial subrange scalings $\sigma^2 \sim t^3$ and $K \sim \sigma^{4/3}$ (Richardson’s Law) derived by Batchelor (1952). Spydell et al. (2006) suggested that the eddy field responsible for the dispersion measured at their site was not a classical two dimensional inertial subrange field, but a vorticity dominated field with length scales 5-50 m.

### 2.4.8 The University of Western Australia

A number of dispersion experiments utilising surface drifters tracked by non-differential GPS (GPS surf zone drifters) have been performed at the University of Western Australia (UWA). These studies were undertaken by Verspecht (2002), Johnson (2004) / Johnson & Pattiaratchi (2004), Mariani (2004), Olsson (2004) and Jones (2005). All utilised the methods proposed by List et al. (1990) for the calculation of dispersion, and identified an overall dispersion coefficient by applying linear regression, similar to that undertaken by Riddle and Lewis (2000).

Verspecht (2002) investigated the surface dynamics of ocean fronts at the entrance to Exmouth Gulf on the North West Cape. Dispersion coefficients were found to range from 1–100 m/s² and the slope of dispersion ($K$) versus length scale ($2\sigma$) (as shown by a dispersion diagram) was found to agreed with Richardson’s 4/3 power law.

Johnson & Pattiaratchi (2004) / Johnson (2004) and Mariani (2004) performed field investigations of dispersion at two Perth metropolitan beaches; Scarborough and Floreat. Johnson & Pattiaratchi (2004) found dispersion coefficients within the head region of transient rips on Scarborough Beach ranging from 1.3–3.9 m/s. Johnson (2004) determined an average cross-shore dispersion coefficient ($K_x$) of 0.2 m/s² and an average longshore dispersion coefficient ($K_y$) of 0.3 m/s² for within longshore currents at Scarborough Beach. At Floreat Beach, Mariani (2004) found dispersion coefficients within the surf zone ranging from 0.2–1.8 m/s², with a mean of 0.76 m/s². All three studies determined dispersion values ($K$) for 1m bins of standard deviation ($\sigma$), and produced plots featuring these parameters (dispersion diagrams) to indicate the scale dependence of the dispersion. Johnson & Pattiaratchi (2004) and Johnson (2004) identified power laws with exponents slightly larger...
than 4/3 (Richardson’s 4/3 power law), while Mariani (2004) identified power laws with exponents very similar to 4/3.

Olsson (2004) investigated dispersion in the head of a topographically induced rip current in the lee of Cottesloe Groyne, Perth. He identified dispersion coefficients ranging from 0.6–4.1 m/s².

Jones (2005) took field measurements of dispersion at Henley Beach, Adelaide, and found a mean dispersion coefficient for within the surf zone of 0.1 m/s². Jones also determined dispersion values (K) for 1m bins of standard deviation (σ), and found that dispersion rates at Henley Beach correlated strongly with Richardson’s 4/3 power law. A comparison with results obtained by Okubo (1974) indicated an order of magnitude offset, which Jones (2005) attributed to the effects of increased shear dispersion close to the coast.

2.5 Study Regions

2.5.1 Fays Bay, Rottnest Island

As described in section 1, Rottnest Island is an A Class Reserve which contains the terrestrial component of the Island itself (11 km long and 4.5 km wide) and approximately 3810 hectares of surrounding sea (Rottnest Island Authority 2002). Rottnest Island displays a unique marine ecosystem, supporting very different species to that of the adjacent mainland. Extensive seagrass meadows occur around the Island, second only to Shark Bay in species diversity (Rottnest Island Authority 2005). Approximately 400 species of fish and 20 species of coral occur within the Reserve, and the coral at Pocillopora Reef, Parker Point, is considered the southern most tropical coral reef in Australia (Rottnest Island Authority 2002). Rottnest Island is home to 135 species of tropical fish as compared to 11 species recorded off the metropolitan coastline (Rottnest Island Authority 2005). A major factor influencing this diversity is the position of the Island in the path of the Leeuwin Current.

Climate and winds

The Rottnest Island climate is Mediterranean, with hot dry summers and mild wet winters (Hopkin 2001). Summer weather patterns at Rottnest are dominated by high pressure systems (summer anticyclones) typically associated with southerly winds that strengthen in the afternoon, as shown in the wind roses featured in Figure 2.16. Winter weather is characterised by high pressure systems (winter anticyclones) which are periodically displaced by low pressure systems (mid-latitude depressions) (Hopkin 2001). These cold fronts are
associated with strong north-westerly winds, turning westerly and then south-westerly (Fahrner & Pattiaratchi 1994).

![Wind roses for Rottnest Island](image)

Figure 2.16: a) 9 am and b) 3 pm wind roses for Rottnest Island, based on data collected on the Island from November 1987 to October 2006 (provided by the Bureau of Meteorology, 2006)

**Waves**

The waters around Rottnest Island are influenced by oceanic swells and locally generated wind waves (Hopkin 2001). The oceanic swells are generally formed in the Southern and South Indian Ocean, with significant wave heights of about 0.5 m all year round (Lemm et al. 1999). Daily sea breezes generate moderate south-westerly seas in summer, with significant wave heights of 1-2 m, and periods of less than 8 s (Lemm et al. 1999). Winter storms generate heavy north-westerly seas and swell, with significant wave heights of 1.5-2.5 m, and periods of greater than 8 s (Lemm et al. 1999).
Tides
Rottnest Island is a micro-tidal environment. It experiences predominantly diurnal tides, and has a spring tidal range of 0.4 m and a lowest astronomical tidal range of 1.1 m (Hopkin 2001).

Currents
Two ocean currents influence the ocean environment of Rottnest Island; the Leeuwin Current and the Capes Current. The Leeuwin Current is a south-flowing band of relatively warm, low salinity, low nutrient water, driven by a density gradient along the WA coastline (Hopkin 2001). It originates in the tropics off the NW of Western Australia, and hugs the coast until Cape Leeuwin, where it turns east and disperses in a series of eddies (Hopkin 2001). The Leeuwin Current is less than 100km wide and 300m deep (Pattiaratchi & Buchan 1991), with a maximum surface velocity of 1m/s (Hopkin 2001). The Leeuwin Current is highly seasonal. Strongest flows occur during autumn and winter, while during summer and spring the current is weakened and pushed seaward by the northward flowing Capes Current. The Capes Current is a relatively cool north-moving current that flows inshore of the Leeuwin Current during summer months in response to predominant southerly winds (Taylor & Pearce 1999). It is narrow, approximately 20 km long, and records monthly mean current speeds of 5-10 cm/s (Hopkin 2001). The Capes Current is associated with the upwelling of cool, nutrient rich water from below the Leeuwin Current.

Study site - Fays Bay
The field site on Rottnest Island was Fays Bay; a small, north-east facing bay on the north side of Rottnest Island. Fays Bay is protected by a section of offshore reefs, shown in Figure 2.17. Fays Bay is also fully sheltered from prevailing wind and wave action from the south and south-west, and partly sheltered from north-westerly winter storms. There is a narrow channel (about 2 m wide) between the headland and the offshore reef system that connects the western side of Fays Bay to the open ocean, and a wide channel (about 50 m) leaves the eastern side of the bay (see Figure 2.17). Water depth within the channels ranges from 1.5-3 m. There is also a large rock section in the centre of the Bay and a broad shallow zone (0-1 m deep) extending inshore from the rock section.
Previous study within Fays Bay by UWA’s 2004 and 2005 Marine Science classes indicates that current velocities within the Bay are largely driven by water level. At low water the offshore reef system is exposed, waves are prevented from breaking and surging into the Bay and resulting current velocities in the channels are low. However, at high water waves break on the offshore reefs and drive water into the Bay, resulting in high current velocities in the channels. Figure 2.18 below indicates this process.

Figure 2.18: a) shows the relative energy of the frequency of oscillation (Hz) against Julian Day of the year and b) shows the water level (m) against Julian Day of the year. Note that there is minimal wave action (0.06-0.1 Hz high energy band) during low tide.
2.5.2 Osprey Bay, Ningaloo Reef

As described in section 1, Ningaloo Reef is the largest fringing coral reef in Australia (Commonwealth of Australia 2002). The region supports a highly diverse population of marine life, including species with special conservation significance such as fishes, turtles, whale sharks, dugongs, whales and dolphins. As such, the Ningaloo area provides for a broad range of recreational activities and nature based tourism, and is currently regarded as the State’s premier marine conservation icon (Marine Parks and Reserves Authority & Conservation and Land Management 2005). The Ningaloo Marine Park was established in 1987 to conserve a portion of the unique region, and on 30 November 2004 the Park boundary was amended to include the entire Ningaloo Reef (Marine Parks and Reserves Authority & Conservation and Land Management 2005).

Ningaloo exhibits the typical features of a fringing reef; a reef crest, a reef flat and a lagoon. Waves break as they reach the shallow reef crest, and a surf bore dissipates along the reef flat. The reef flat deepens into a lagoon, which varies from 200 m to 7 km in width, with an average depth of 2-4 m (Marine Parks and Reserves Authority & Conservation and Land Management 2005). Gaps regularly intercept the main reef line providing for a series of reef segments. Taylor and Pearce (1999) observed currents along the reef and found that surf coming over the reef brings a turbid, green-coloured rush if water into the lagoon. This water is transported parallel to the reef front, moves out through the major gaps in the reef and finally turns in the direction of the prevailing longshore current. This form of circulation is commonly referred to as a nearshore circulation cell (see section 2.2).

Climate and winds

The climate along Ningaloo Reef is arid-tropical; characterised by low rainfall, high evaporation rates, relatively high temperatures and seasonal tropical cyclones (Commonwealth of Australia 2002). Wind conditions generally involve prevailing south-easterly trade winds during the night and morning which are replaced by stronger south-westerly sea-breezes in the afternoon (Taylor & Pearce 1999). A strong and persistent southerly wind blows between September and March, and by April the prevailing wind swings more to the east (particularly in the morning). This delays the onset of the south-westerly sea-breeze and often results in a period of calm conditions in the middle of the day. The mean wind speed in summer is approximately 30 km/hr, falling to about 11 km/hr in winter due to the more variable nature of wind direction in that season (Taylor & Pearce 1999; Commonwealth of Australia 2002).
Waves
South to south-westerly driven swell waves prevail throughout the year with a mean annual height of about 1.5 m (Fitzpatrick & Penrose 2002; Marine Parks and Reserves Authority & Conservation and Land Management 2005). Wind-driven (sea) waves have a mean annual height of about 1.2 m, and total waves have a mean annual height of about 2 m, regularly reaching 3.5-4.0 m in winter and 3 m in summer (Marine Parks and Reserves Authority & Conservation and Land Management 2005).

Tides
Ningaloo Reef is located just north of the WA coast’s major tidal transition zone, which separates the South Western Australian tidal zone (diurnal and micro-tidal) and the North Western tidal zone (semi-diurnal and macro-tidal). As such, the tides in the area are mixed, predominantly semi-diurnal, with a maximum range of approximately 2 m (Marine Parks and Reserves Authority & Conservation and Land Management 2005).

Currents
Currents within the region can be influenced by waves, wind, tides or oceanic drift. Prevailing winds are known to drive strong northerly currents in the nearshore region (Marine Parks and Reserves Authority & Conservation and Land Management 2005). Wave-induced currents strongly influenced by tidal changes are also thought to dominate (Fitzpatrick & Penrose 2002) after (D’Adamo & Simpson 2001).

There are two main oceanic drift currents that affect the Ningaloo region; the Leeuwin Current (described in section 2.5.1) and the Ningaloo Current. The Leeuwin Current is imperative to the existence and survival of the Ningaloo Reef, bringing tropical species from the north and providing adequate temperatures for tropical marine life (Commonwealth of Australia 2002). From spring to mid-autumn the cool, north-moving Ningaloo Current flows inshore of the Leeuwin. The Ningaloo Current is driven by the predominant southerly winds, and is thought to be associated with the upwelling of cool, nutrient rich water from the below the Leeuwin Current (Commonwealth of Australia 2002). Study by Taylor and Pearce (1999) suggests that the Ningaloo Current determines the dispersal of coral larvae following the autumn mass spawning, and plays an important part in retaining planktonic biomass within the Ningaloo ecosystem.
Study site – Sandy and Osprey Bay

The field site at Ningaloo was located in the vicinity of two well known Ningaloo bays; Sandy Bay and Osprey Bay (Figure 2.19). For simplicity, this region will be referred to as Osprey Bay. The site contains a reef segment with a gap in the main reef line, allowing for the removal of turbid waters pumped over the reef during wave breaking as described by Taylor and Pearce (1999). The main reef line is orientated to the north-north-east, so prevailing winds and waves arrive approximately parallel. North of the gap the reef flat leads to a wide and shallow lagoon (approximately 2 m deep). To the south of the gap a wide reef flat sits offshore of a narrow lagoon with a deep channel (4-5 m deep) in the centre.

Figure 2.19: Aerial photograph of the Ningaloo Reef study site. Note the reef crest, reef flat, the gap in the fringing coral reef and the northern and southern lagoons (provided by CALM, 2006)
2.5.3 Koombana Bay, Bunbury

The City of Bunbury is the regional capital of the South West of WA. As described in section 1, Bunbury is situated about 180 km south of Perth, and is the third fastest growing region in Australia (Australia’s South West Inc. 2005). The State Government has recently pegged the region to grow as a major contributor to WA’s economy, and to become a major alternative investment and residential destination to the metropolitan area (South West Development Commission 2006). The City of Bunbury aligns Koombana Bay, a large sheltered coastal embayment.

Koombana Bay encloses the Port of Bunbury; a world wide distribution point for South West industries such as mining, manufacturing and agriculture. Major commodities exported from the Port of Bunbury include alumina, mineral sands, woodchips, caustic soda and silica sand (Bunbury Port Authority 2006). In addition to shipping services, Koombana Bay is now a rapidly developing residential and commercial region. Recently the Bunbury Area Strategy project (funded by the State and Federal governments under the Commonwealth Better Cities program) relocated major pieces of industrial infrastructure on the south-western shore of Koombana Bay, including oil tanks, a waste water treatment plant, transportation and storage facilities, to make way for the multi-award winning residential and commercial development of Marlston Hill. Following the success of Marlston Hill, the State Government now intends to transform the Bunbury Outer Harbour (which is situated on the north-western shore of Koombana Bay) from an ageing industrial site into a world-class waterside development (South West Development Commission 2006).

Koombana Bay is also home to a major South West tourism icon, the Bunbury Dolphin Discovery Centre. The Centre caters for shore and boat-based interaction (including snorkelling) with the wild Bottlenose dolphins that frequent the Bay area, and provides an avenue for education, conservation and research into these popular marine mammals and their environment.

Climate and winds

The climate of Bunbury is similar to that described for Rottnest Island in section 2.5.1. The predominant wind direction is south-westerly, and the mean wind speed is approximately 10 km/hr (Bunbury Port Authority 2006). The strongest winds in the morning are generally easterlies, while the strongest winds in the afternoon are generally westerlies. This is displayed in the wind roses featured in Figure 2.20 below.
Waves
The historical wave climate measured just off the Bunbury Peninsula (at the Bunbury Port Authority Beacon No.3) indicates a mean significant wave height of 3 m, and a mean wave period of 10 s for the region (Bunbury Port Authority 2006).

Tides
Bunbury is a micro-tidal environment, and experiences predominantly diurnal tides. It has a spring tidal range of 0.5 m, a lowest astronomic tide range of 0.1 m and a highest astronomic tide of 1.4 m. Mean sea level at Bunbury is 0.7 m (Bunbury Port Authority 2006).
Currents
As for Rottnest Island, the Leeuwin Current and the Capes Current influence the ocean current patterns of the greater Bunbury region. Water circulation in Koombana Bay is thought to be wind driven in summer, and drogues have indicated mean summer current speeds of 0.03 m/s (Hearn et al. 1985). In addition, a tidally induced jet is known to flow from a man-made connection to the Leschenault Inlet on the eastern side of the Bay called The Cut (Figure 2.21). The mean current speed recorded during summer observations of the jet was approximately 0.04 m/s.

Study site - Koombana Bay
Koombana Bay is a large coastal embayment partially enclosed by the Bunbury Peninsula and Point Casuarina (Figure 2.21). The region is sheltered from prevailing wind and wave action from the south and south-west, and partly sheltered from north-westerly winter storms. Natural depths within the Koombana Bay range to 10 m, although a deep shipping channel runs through the centre of the Bay to the Inner harbour located in the south-east corner of the region. The Outer harbour runs along the western side of Koombana Bay.

Figure 2.21: Map featuring the study site, Koombana Bay. The approximate location of Marlston Hill and the Dolphin Discovery Centre are indicated by the red box and red dot respectively. Note also the location of The Cut, the Outer harbour and the Inner harbour
3 Methods

The following section details the sampling and analysis methods applied during this study.

3.1 Sampling

Lagrangian measurements of water motion were taken within the nearshore region of the study sites using GPS surf zone drifters. This is described in sections 3.1.1 to 3.1.3. Data indicating the environmental conditions at the three sites investigated were acquired from various sources, detailed in section 3.1.4.

3.1.1 Features of the GPS surf zone drifters

GPS surf zone drifters (drifters) are compact, low cost lagrangian devices developed by Johnson et al. (2003) that utilise the position fixing technologies of the global positioning system (GPS). GPS is a worldwide radionavigation system that employs an array of satellites to infer the position of a receiver (Hofmann-Wellenhof et al. 1997). Originally, high precision GPS was restricted to military use. However, since the removal of the “selective availability” of GPS in 2000, features of the order of 10 m can now be resolved (Johnson et al. 2003).

Drifter Design

The drifters have five primary components (illustrated in Figure 3.1):

1. Outer casing – a 100 mm diameter polyvinyl chloride (PVC) sewerage pipe with standard end fittings for a total length of 320 mm. The casing is fixed with a screw on ring seal fitting that secures the Perspex cover of the inner instrument frame. This construction is capable of withstanding pressures associated with depths of up to 40 m below sea level;
2. Inner instrument frame – a frame designed to secure the receiver-antenna system and data logger. It includes a clear Perspex cover which allows GPS transmission and an o-ring to prevent leakage;
3. Receiver-antenna system (GPS) – a Garmin GPS 36 integrated receiver–antenna, which is a standard marine unit;
4. Data logger - a DGPS-XM Data Logger from R.I. Keskull (Sydney, Australia), wired directly to the GPS 36 output through an RS232 connector. The data logger stores position, time, and date at a default setting of 1 Hz. It can store 95 200 points, equivalent to 26 h of continuous operation on the default setting, or equivalent to 260 hr on an optional operating mode of 0.1 Hz. A light-emitting diode (LED) display
on the logger indicates the status of the device (power on/off, whether good data are being received, low memory, full memory, and low battery power); and

5. Power source - seven standard alkaline D-cell batteries provide sufficient power for 40 hrs of continuous use at 1 Hz. They are located in a unit at the base of the drifter to act as ballast and provide upright stability. The power on/off is a reed switch latch relay that is activated with a small magnet (Johnson et al. 2003).

Figure 3.1: A Johnson et al. (2003) GPS surf zone drifter. The photograph shows the casing, battery pack, and internal frame with GPS receiver–antenna and data logger attached. Note that the duct tape around the casing is simply to attach the flag wire which carries a small ribbon to aid visibility; it has no other structural purpose

To reduce wind-induced slippage and drag the drifters are designed to be almost neutrally buoyant; only the upper surface covering the internal GPS antenna sits above the water (Johnson 2004). Due to the low profile of the drifter in the surf zone, drifters sometimes become submerged e.g. by breaking waves. This can result in a gap in the GPS data collected, however, even in strongly breaking waves data recovery is over 99 % and gaps are rarely more than 10 s (Johnson 2004).

To reduce wave-induced drag and the “surfing” movement of the drogue in breaking waves a soft parachute drogue made from Dacron sailcloth and a small lead weight is attached below
the outer casing (Johnson et al. 2003). In non-breaking waves the parachute is closed, however, in breaking waves the parachute opens and serves to anchor the drifter to the orbital velocities below the breaking region, thus preventing surfing (Johnson 2004). One or more drogues can be attached below the drifter, depending on the depth of the water column, (Figure 3.2). Only one drogue was utilised during this study.

In a shallow surf zone, the drogue may touch the seabed. Johnson (2004) investigated the effect of bottom drag on drifter motion in a tow tank. He found this effect to be small, although measurement errors were deemed to be inevitable when the drogue was in contact with the bottom.

The weights attached to the parachute allow the drogue to hang vertically below the main unit in the water column. In addition, the drogue and weight together act to stabilise the main drifter unit and prevent it from rolling excessively (Johnson et al. 2003). A wire and small ribbon are attached above the main unit to improve visibility (Figure 3.1). This attachment induces no observable wind slip (Johnson 2004).

Figure 3.2: Drifter with one parachute drogue attached to stabilise the drifter and prevent “surfing” (Johnson et al. 2003)

*Non-differential GPS Position Error*

Errors in the positions reported by the non-differential GPS utilised by the drifters can be caused by:
Dispersion in Sheltered Coastal Waters of Western Australia  
Eve Hollingsworth

- precision limits in the GPS receiver;
- satellite clock error;
- errors in the “known” satellite positions;
- atmospheric effects on the speed of light; and
- multipath reflection of signals off large obstacles (Johnson et al. 2003) after (Hofmann-Wellenhof et al. 1997).

Error can be absolute or relative. Absolute position errors are unimportant in the context of dispersion calculations. However, relative errors could contaminate velocity calculations. Johnson (2004) investigated the absolute and relative error of the drifters by performing a series of stationary tests, where drifters were left in a fixed location for 45 min. Absolute errors of approximately 0.16 m of easting and 0.19 m of northing were determined. Relative errors were defined through standard deviations and maximum displacements. The standard deviation of position from the mean was found to be 1.3 m in the easting direction and 1.6 m in the northing direction (Johnson et al. 2003). In addition, the maximum displacements from the mean position in the easting and northing directions were found to be 4.2 and 5.2 m respectively (Johnson et al. 2003).

Drifter Dynamics

Johnson (2004) modelled the dynamics of a surf zone drifter numerically, and compared the wave-averaged lagrangian velocities of the drifter with a eularian (fixed reference frame) depth and wave-averaged velocity. He found error between the two velocity measures that did not show a linear relationship with the variation of the parameters (current speed, wave height etc.), illustrating the complex nature of drifter dynamics. Examination revealed three sources of this error:

1. Surfing: the waves dragged the drifter shoreward faster than the orbital velocities. This effect increased with wave height.
2. Vertical sampling bias: the drifter tended to “over sample” the undertow due to the presence of the parachute, so that the drifter moved more quickly offshore than eularian measurements would predict. This effect increased with the number of parachutes used.
3. Horizontal wave motion sampling bias: in the model used, onshore currents led to longer wave troughs and shorter wave crests, while offshore currents lead to shorter wave troughs and longer wave crests. Thus in onshore currents the drifter spent more time in the troughs and moved offshore, and in offshore currents the drifter spent more
time in the crests and moved onshore. In contrast, the current variations described above had no effect on the eularian current velocity.

Two of the errors identified by Johnson (2004) through numerical modelling were minimised by the nature of this study. Firstly, due to the protected aspect of the environments characterised, the drifters were rarely under the influence of an energetic surf zone. In fact, the drifters only entered the surf zone on one sampling occasion at Osprey Bay, Ningaloo Reef. As a result errors due to “surfing” were limited. Secondly, only one parachute was utilised throughout the course of the study, and thus errors due to vertical sampling bias were minimised.

Field Validation

Direct field validation of lagrangian drifter performance against eularian current meter measurements is difficult; the high speed nature of surf zone currents means that fixed current meters and the moving drifters quickly separate. Johnson (2004) attempted the field validation of his drifters by repeated deployment of a drifter in close proximity to a moored Acoustic Doppler Current Profiler (ADCP). He found that the best fit agreement was remarkably good, even in the cross shore direction where the influence of wave breaking may be expected to be unacceptably large (Johnson 2004). It was noted however, that drifter velocities tended to be smaller than the depth-averaged flow velocities (Johnson 2004; Johnson & Pattiaratchi 2004).

Field tests of surf zone drifter performance by Schmidt et al. (2006) involving simultaneous drifter and dye release experiments showed promising similarities. In every case the drifter moved offshore or onshore with the seaward edge of the dye, and remained in or near the area of highest dye concentration (Spydell et al. 2006).

Limitations

At this point it is important to note that drifters do not measure dispersion in the same way as a dye tracer (Johnson & Pattiaratchi 2004). Drifters are a connected body and therefore cannot be sheared and mixed vertically (resulting in longitudinal dispersion) as described in section 2.1.5, Figure 2.6. As such, drifter dispersion measurements may not be comparable to dye dispersion measurements in regions where shear is a dominant dispersive mechanism. However, drifters do respond to transverse and longitudinal shear (as discussed in section 2.1.5).
3.1.2 Deployment of the GPS surf zone drifters

Drifters were deployed at each of the study sites detailed in section 2.5. Prior to deployment, the drifter batteries were tested for functionality and the o-rings were cleaned, checked for cracks and greased to ensure watertight conditions within the unit. Drifters were assembled and switched on, and the time of activation was recorded. For each experiment or “run”, drifters were transported to the desired release point, and deployed in a cluster formation, as illustrated in Figure 3.3. The time of deployment was recorded, and care was taken to ensure that the parachutes were not tangled at the time of release. Deployment details for each study site are given below. At the end of each day the drifters were switched off and the data loggers removed and stored safely.

Figure 3.3: Photograph of drifters deployed at Osprey Bay just after release in a cluster formation

Fays Bay, Rottnest Island

Drifter experiments were performed within Fays Bay over two days in September 2004 (20th September 2004 and 23rd September 2004). The studies were carried out by a group of students from the UWA 2004 Marine Science 304 class. Five drifters (d2-d6) were swum out to various release points within the Bay, deployed, and retrieved when they drifted out of the Bay or too close to rocks. Each drifter run took about 20 mins. Drifter experiment details are included in Table 3.1 below. Drifters were also used to map the position of the shoreline, a rock in the centre of the Bay and the location of the outer reef.
Table 3.1: Drifter run details for the Rottnest study site, 20th and 23rd September 2004

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>Time at Release</th>
<th>Time at Retrieval</th>
<th>Total Drift Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20th September 2004</td>
<td>14:52</td>
<td>15:09</td>
<td>17min</td>
</tr>
<tr>
<td>2</td>
<td>20th September 2004</td>
<td>15:24</td>
<td>15:36</td>
<td>12min</td>
</tr>
<tr>
<td>3</td>
<td>23rd September 2004</td>
<td>10:54</td>
<td>11:05</td>
<td>11min</td>
</tr>
<tr>
<td>4</td>
<td>23rd September 2004</td>
<td>11:19</td>
<td>12:10</td>
<td>51min</td>
</tr>
<tr>
<td>5</td>
<td>23rd September 2004</td>
<td>13:45</td>
<td>13:59</td>
<td>14min</td>
</tr>
</tbody>
</table>

Osprey Bay, Ningaloo Reef

Drifter experiments were performed within Osprey Bay over three days during April 2006 (20th April 2006, 21st April 2006 and 22nd April 2006). Four drifters (d3-d6) were transported in a small zodiac provided by CSIRO, and deployed from two locations within the lagoon, just in front of the surf zone. These release points were in line with two instruments moored by AIMS and CSIRO for the Ningaloo Research Programme; North ADV2 and South ADV2. The drifters were allowed to float independently for approximately two hours before they were retrieved. Drifter experiment details are included in Table 3.2 below.

Table 3.2: Drifter run details for the Ningaloo study site, 20th, 21st and 22nd April 2006

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>Time at Release</th>
<th>Time at Retrieval</th>
<th>Total Drift Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20th April 2006</td>
<td>09:58</td>
<td>12:07</td>
<td>2hr 9min</td>
</tr>
<tr>
<td>2</td>
<td>20th April 2006</td>
<td>13:42</td>
<td>15:28</td>
<td>1hr 46min</td>
</tr>
<tr>
<td>3</td>
<td>21st April 2006</td>
<td>13:36</td>
<td>15:56</td>
<td>2hr 20min</td>
</tr>
<tr>
<td>4</td>
<td>22nd April 2006</td>
<td>09:23</td>
<td>11:27</td>
<td>2hr 4min</td>
</tr>
</tbody>
</table>

Koombana Bay, Bunbury

Drifter experiments were performed within Koombana Bay over two days in September 2006 (17th September 2006, and 18th September 2006). Four drifters (d1, d3, d4 and d8) were transported to various release points within the Bay in a small aluminium dinghy. On 17th September 2006 two experiments (about 2 hours duration each) were carried out in the centre of the Bay. Due to rough weather conditions on 18th September 2006, experiments on this date were performed in a sheltered section of the Bay close to the shore (about 1. Drifter experiment details are included in Table 3.3 below. Drifters were also used to map the position of the shoreline.
Table 3.3: Drifter run details for the Bunbury study site, 17th and 18th September 2006

<table>
<thead>
<tr>
<th>Run</th>
<th>Date</th>
<th>Time at Release</th>
<th>Time at Retrieval</th>
<th>Total Drift Time</th>
</tr>
</thead>
<tbody>
<tr>
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<td>17th September 2006</td>
<td>10:43</td>
<td>12:40</td>
<td>1hr 57min</td>
</tr>
<tr>
<td>2</td>
<td>17th September 2006</td>
<td>13:45</td>
<td>15:52</td>
<td>2hr 7min</td>
</tr>
<tr>
<td>3</td>
<td>18th September 2006</td>
<td>11:33</td>
<td>12:31</td>
<td>58min</td>
</tr>
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<td>4</td>
<td>18th September 2006</td>
<td>12:41</td>
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<td>55min</td>
</tr>
<tr>
<td>5</td>
<td>18th September 2006</td>
<td>14:31</td>
<td>15:31</td>
<td>1hr 0min</td>
</tr>
<tr>
<td>6</td>
<td>18th September 2006</td>
<td>15:53</td>
<td>16:33</td>
<td>40min</td>
</tr>
</tbody>
</table>

### 3.1.3 Data download from the GPS surf zone drifters

As described in section 3.1.1, the drifter data logger stores position (in geographic coordinates - latitude and longitude), time, and date. The software package “Data Download Version 5.5.6” was used to download this information following each day of study at the various field sites.

### 3.1.4 Environmental conditions

As described in section 2.2, wind causes the turbulent mixing of surface waters. Consequently wind was identified as a possible driving force for dispersion at all three of the sites investigated. Wind data recorded at the Rottnest Island Meteorological Station by the Australian Bureau of Meteorology (BoM) were obtained for Fays Bay. Wind data applicable to Osprey Bay were recorded at the Milyaring Visitor Centre (located approximately 40 km north of the study site) by AIMS. Wind data recorded at Carey Park, Bunbury by the BoM were obtained for Koombana Bay.

As described in section 2.5.1, circulation within Fays Bay is known to be driven by water level. Currents can provide impetus for dispersion in the nearshore zone (section 2.2), and as a result water level was identified as a possible driving mechanism for dispersion at this site. Water level data were obtained via a single point Acoustic Doppler Velocimeter (ADV, described below and featured in Figure 3.4) deployed by the UWA 2004 Marine Science 304 class. This ADV was mounted on a stainless steel frame, and set to burst sample every hour at a frequency of 2 Hz. Wave action along the offshore reef system could also influence water movement within Fays Bay. As such, wave data collected by the Rottnest Island Wave Buoy over the study period were obtained from the Department for Planning and Infrastructure (DPI). The observations made by this buoy cannot be applied directly to determine wave heights within Fays Bay. However, the data indicates the relative magnitude of wave activity within the region over the period of study.
As described in section 2.5.2, nearshore circulation cells driven by wave pumping over the reef line are thought to dominate water motions along Ningaloo Reef. Nearshore circulation cells are known to cause large scale mixing and advection within the nearshore zone (section 2.2), and as such wave action was identified as a possible driving force for dispersion at this site. Directional wave data were obtained via a profiling ADV deployed within the gap in the main reef line by AIMS and CSIRO (referred to as the Inner Channel Nortek). This ADV was mounted on a stainless steel frame, and set to burst sample every 2 hrs at a frequency of 2 Hz.

Wave action within Koombana Bay is minimal, hence wave climate is unlikely to drive dispersion in this region. It is possible water level variations affect dispersion rates within the Bay, and as such water level data recorded at the Bunbury Inner tide gauge (located within the Inner harbour, see Figure 2.21) over the study period were obtained from the DPI.

*Acoustic Doppler Velocimeter (ADV)*

An ADV is an instrument that utilises the Doppler Effect to determine vector averaged current speeds. An ADV emits constant frequency acoustic pulses into the water column in three different directions (Nortek AS 2006). As the sound waves travel, they ricochet off particles suspended in the moving water and reflect back to the instrument. The difference in frequency between the waves the ADV sends out and the waves it receives is called the Doppler shift, and the ADV uses this shift to calculate how fast the particles (and therefore the water around them) are moving (Nortek AS 2006). An ADV can also sample diagnostic data between the mean current data, which can be used to infer wave characteristics (Nortek AS 2006). An ADV can be single point; measuring current velocities at a single point within the water column (as deployed within Fays Bay, Figure 3.4), or profiling; measuring current profiles throughout the water column (as deployed within Osprey Bay).
3.2 Analysis

The data presented in this dissertation were analysed with the use of the mathematical software package MATLAB R2006a and Microsoft EXCEL. The methods of analysis of lagrangian drifter data are featured in sections 3.2.1 to 3.2.9. The methods of analysis of eularian wind, water level and wave data are covered in section 3.2.10.

3.2.1 Coordinate conversion

As described in sections 3.1.1 and 3.1.3, the drifters store position data in geographic coordinates (latitude and longitude), which incorporate the round nature of the earth. These coordinates are stored with reference to the Geocentric Datum of Australia 1994 (GDA94), a reference system directly compatible with GPS (Geoscience Australia 2006a). To simplify the calculation of drifter dispersion, these geographical coordinates were converted to Cartesian coordinates (eastings and northings) which gave a “flat map” of each region in units of meters. These flat maps are known as the Map Grid of Australia 1994 (MGA94).

The conversion was done via the use of a model that describes the shape of the earth (an ellipsoid), and projection formulae - mathematical equations that “cut and stretch” geographical positions onto a plane (Geoscience Australia 2006a). The Universal Transverse Mercator (UTM) projection formulae - in particular Redfearn’s Formulae - and the Geodetic
Reference System 1980 (GRS80) ellipsoid (which is generally considered the same as the World Geodetic System 1984 (WGS84) ellipsoid) were used to project the geographical coordinates onto the MGA94. Redfearn’s formulae are accurate to better than 1 mm in any zone of Australia (Geoscience Australia 2006a).

The MGA94 maps are divided into zones (Geoscience Australia 2006a). The zone of each study region was determined through the use of the Geoscience Australia Geographic to Grid converter (Geoscience Australia 2006b). The zone was then added to a series of MATLAB scripts developed specifically for the conversion described above by Johnson (2002b). The raw drifter data were processed using this script, and the conversion results validated against the grid coordinates provided by the Geoscience Australia converter.

3.2.2 Smoothing

As described in section 3.1.1, drifter data can contain small sources of error such as incidents of “surfing” and high frequency GPS positioning error (Johnson 2004). This error was removed from the raw data by the application of a filter or smoothing process, which removed any oscillations in the data set with a frequency higher 0.1 Hz. For example, say the drifters “surfed” waves with typical periods of 5-10 s. These periods equate to frequencies of 0.2-0.1 Hz respectively, and as such the data corresponding to these motions would be removed by the 0.1 Hz filter, leaving a wave averaged signal (Johnson 2004). As for the coordinate conversion, the series of MATLAB scripts used to filter the raw drifter data were developed by Johnson (2002b) specifically for this purpose.

3.2.3 Run separation

Following coordinate conversion and smoothing the data were separated into the runs performed at each study site. The time of release and retrieval recorded in the field were used to locate the appropriate data for each run, and then the time of release was validated by plotting the drifter coordinates at this time on a chart in Microsoft EXCEL. The run data from each drifter were combined and stored in a single file. The first 10 seconds of run 1, 20th April 2006, Osprey Bay, has been included in Table 3.4 below to illustrate the format applied.
Table 3.4: The first 10 seconds of Run 1, 20\textsuperscript{th} April 2006, Osprey Bay, included to illustrate the format applied to the drifter data collected for each run at each study site

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Drifter 3 Eastings (m)</th>
<th>Northings (m)</th>
<th>Drifter 4 Eastings (m)</th>
<th>Northings (m)</th>
<th>Drifter 5 Eastings (m)</th>
<th>Northings (m)</th>
<th>Drifter 6 Eastings (m)</th>
<th>Northings (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>791224.8</td>
<td>7537427.1</td>
<td>791225.4</td>
<td>7537429.7</td>
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</tr>
<tr>
<td>2</td>
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<td>791225.0</td>
<td>7537429.7</td>
<td>791223.0</td>
<td>7537429.5</td>
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<td>791224.8</td>
<td>7537429.5</td>
<td>791222.4</td>
<td>7537429.0</td>
<td>791221.9</td>
<td>7537429.2</td>
</tr>
<tr>
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<td>7537427.1</td>
<td>791224.7</td>
<td>7537429.5</td>
<td>791222.4</td>
<td>7537429.0</td>
<td>791221.9</td>
<td>7537429.2</td>
</tr>
<tr>
<td>7</td>
<td>791224.8</td>
<td>7537425.2</td>
<td>791224.5</td>
<td>7537429.5</td>
<td>791222.3</td>
<td>7537428.8</td>
<td>791221.7</td>
<td>7537429.0</td>
</tr>
<tr>
<td>8</td>
<td>791224.7</td>
<td>7537423.4</td>
<td>791224.3</td>
<td>7537429.5</td>
<td>791222.2</td>
<td>7537428.6</td>
<td>791221.7</td>
<td>7537429.0</td>
</tr>
<tr>
<td>9</td>
<td>791224.7</td>
<td>7537423.4</td>
<td>791224.3</td>
<td>7537429.3</td>
<td>791222.1</td>
<td>7537428.4</td>
<td>791221.6</td>
<td>7537428.8</td>
</tr>
<tr>
<td>10</td>
<td>791224.7</td>
<td>7537423.4</td>
<td>791224.3</td>
<td>7537429.3</td>
<td>791222.1</td>
<td>7537428.6</td>
<td>791221.7</td>
<td>7537428.8</td>
</tr>
</tbody>
</table>
3.2.4 Trajectories

The drifter trajectories for each run at Fays and Koombana Bay were plotted on the maps of the regions obtained by the drifters during the study periods. The position of the moored ADV at Fays Bay was also plotted. The drifter trajectories for each run at Osprey Bay were plotted on a geo-referenced tagged image file format (tiff) satellite photograph of the study site (provided by CALM, 2006) with the aid the MATLAB Mapping toolbox. The position of the moored ADV’s North ADV2, South ADV2 and the Inner Channel Nortek were also plotted.

3.2.5 Velocities

Drifter velocities in the $x$ and $y$ directions for each run were calculated as the time derivative of the drifter position each second according to:

$$u(t) = \frac{\partial x(t)}{\partial t} \quad v(t) = \frac{\partial y(t)}{\partial t}$$

This was done utilising the MATLAB function Gradient, which returns the numerical gradient of an array with the spacing between points (in this case $\Delta t = \partial t$) assumed to be one. The overall magnitude of the velocity at each time was then computed

$$velocity = \sqrt{u^2 + v^2}$$

Mean velocities and the associated 95% confidence intervals for each drifter and overall were also determined.

3.2.6 Dispersion

The dispersion coefficients for each run were calculated according to the method outlined by List et al. (1990), which utilises the statistical relationship outlined in Equation 2.17 (see section 2.4.3), and follows the original work of Okubo (1971; 1974). This method has since been applied by Riddle and Lewis (2000), Verspecht (2003), Johnson (2004), Olsson (2004), Mariani (2004) and Jones (2005). The position of the centroid of the set of $n$ drifters at time $t$ in both the $x$ and $y$ directions were determined for each run as follows:

$$\bar{x}(t) = \frac{1}{n} \sum_{i=1}^{n} x_i(t) \quad \bar{y}(t) = \frac{1}{n} \sum_{i=1}^{n} y_i(t)$$

The variances in the $x$, $y$ and overall directions were resolved

$$\sigma_x(t)^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i(t) - \bar{x}(t))^2$$
\[
\sigma_y(t)^2 = \frac{1}{n-1} \sum_{i=1}^{n} (y_i(t) - \bar{y}(t))^2 \\
\sigma(t)^2 = \frac{\sigma_x(t)^2 + \sigma_y(t)^2}{2}
\]

and then plotted against time. The gradients \((b_x, b_y, \text{ and } b)\) of the least squares regression fits between the variances and time were determined, and then substituted as \(\Delta \sigma_x(t)/\Delta t\), \(\Delta \sigma_y(t)/\Delta t\) and \(\Delta \sigma(t)/\Delta t\) in Equation 2.42 (section 2.4.3) to determine the dispersion coefficients, as done by Riddle and Lewis (2000) (Equation 2.43, section 2.4.4). Equation 2.42 and Equation 2.43 are repeated here for convenience.

**Equation 2.42**
\[
K_x(t) = \frac{1}{2} \frac{\partial \sigma_x(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma_x(t)^2}{\Delta t} \\
K_y(t) = \frac{1}{2} \frac{\partial \sigma_y(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma_y(t)^2}{\Delta t} \\
K(t) = \frac{1}{2} \frac{\partial \sigma(t)^2}{\partial t} \approx \frac{1}{2} \frac{\Delta \sigma(t)^2}{\Delta t}
\]

**Equation 2.43**
\[
K_x = \frac{1}{2} b_x \quad K_y = \frac{1}{2} b_y \quad K = \frac{1}{2} b
\]

The mean dispersion coefficients \((K_x, K_y, \text{ and } K)\) and the associated 95% confidence intervals were determined for each of the three study sites. The correlation coefficients \((R_x, R_y, \text{ and } R)\) between the actual variances and the variances predicted by the least squares fits for each run were determined using the MATLAB function Corrcoef. The coefficients of determination \((R_x^2, R_y^2 \text{ and } R^2)\) were calculated as the square of the correlation coefficients. Data from any run with a coefficient of correlation less than 0.5 were excluded from the calculation of the mean. This was because a coefficient of this magnitude implies that less than 50% of the fluctuations in variance can be explained by the time, and therefore the regression can not be deemed representative.

At this point it is important to re-iterate that the relationship between \(K(t)\) and \(\sigma(t)\) is strictly only valid for a large number of drogues, moving randomly, and under the assumption that any drogue set is representative of an ensemble, as described in section 2.4.3. The abovementioned restrictions were not met by this study, which involved the deployment of a single, relatively small group of drogues \((n = 4)\) in the nearshore zone. However, the List et
al. (1990) method for calculating the dispersion coefficient as applied in this study gives an effective and relatively simple to calculate approximation to the true values of dispersion.

### 3.2.7 Time dependence

A dispersion diagram featuring the variance of drifter position and the time of drifting (as produced by Okubo (1971) and featured in Figure 2.9) was constructed for each run. This was done by plotting log-log graphs of $\sigma_x^2$, $\sigma_y^2$ and $\sigma^2$ against time and fitting least squares regression lines to the data. The coefficients of the linear fits on the log-log plots gave exponential relationships referred to in this study as “time power laws”. The process of conversion from a linear to exponential relationship is detailed in Figure 3.5 below.

![Figure 3.5: Schematic showing the conversion process from a logarithmic linear relationship to an exponential relationship between variance and time](image)

The mean coefficients ($a_x, a_y, a$ and $b_x, b_y, b$) and their associated 95% confidence intervals were determined for each of the study sites. As done in section 3.2.6, correlation coefficients and coefficients of determination were calculated, and the data from any run with a coefficient of correlation less than 0.5 were excluded from the calculation of the mean.

### 3.2.8 Scale dependence

A dispersion diagram featuring the dispersion coefficient and the standard deviation of drifter position (as produced by Okubo (1971) and featured in Figure 2.10) was constructed for each run. The approach involved determining the dispersion coefficients corresponding to 1 m intervals of standard deviation, as done by Johnson (2004), Mariani (2004) and Jones (2005). First the square roots of the variances (determined as described in section 3.2.6) were taken to derive the standard deviations:

**Equation 3.5**: $\sigma_x(t) = \sqrt{\sigma_x(t)^2}, \sigma_y(t) = \sqrt{\sigma_y(t)^2}, \sigma(t) = \sqrt{\sigma(t)^2}$

The data were then grouped into bins according to standard deviation, i.e. bin 1 included all the data with $\sigma(t) = 0$ to $1$, bin 2 included all the data with $\sigma(t) = 1$ to $2$, and so on until the...
maximum standard deviation was reached. The change in variance and the change in time within each bin was determined and used to calculate the dispersion coefficient for each bin using Equation 2.42. A schematic detailing this process is featured in Figure 3.6.

\[
K_{0-1} = \frac{\sigma^2_1 - \sigma^2_0}{t_1 - t_0}
\]
\[
K_{1-2} = \frac{\sigma^2_2 - \sigma^2_1}{t_2 - t_1}
\]
\[
K_{2-3} = \frac{\sigma^2_3 - \sigma^2_2}{t_3 - t_2}
\]

Figure 3.6: Schematic illustrating the calculation of the dispersion coefficient for 1m intervals (or bins) of standard deviation

Log-log graphs of \(K_x\), \(K_y\) and \(K\) against \(\sigma_x\), \(\sigma_y\) and \(\sigma\) were plotted and least squares regression lines fitted to the data. The coefficients of the linear fits on the log-log plots gave exponential relationships (via the linear → exponential conversion process indicated in Figure 3.5) referred to in this study as “scale power laws”.

The mean coefficients \((c_x, c_y, c\) and \(d_x, d_y, d)\) and their associated and 95 % confidence intervals were determined for each of the study sites. As done in section 3.2.6 and 3.2.7, correlation coefficients and coefficients of determination were calculated, and the data from any run with a coefficient of correlation less than 0.5 were excluded from the calculation of the mean.

### 3.2.9 Turbulence and Diffusivity

Shear-induced spreading, rotation and divergence were removed from the dispersion measured by the drifters to determine the turbulent diffusivity \((k)\) via the Okubo and Ebbesmeyer (1976) method. The \(x\), \(y\) coordinates of the drifters were used to calculate the speeds \(u, v\) of \(n\) drogues simultaneously at \(t\) times:

**Equation 3.6**

\[
x_i(t), y_i(t)
\]
\[
u_i(t), v_i(t)
\]

where \(i = 1,2,3,...n\) and \(t = 1,2,3,...t\) The speeds of each drogue were then expanded in a Taylor series about the centroid located at \(\bar{x}(t), \bar{y}(t)\), as shown in Equation 2.40 (section 2.4.2) and repeated here for convenience.
$u_i(t) = \bar{u}(t) + \frac{\partial \bar{u}(t)}{\partial x} \left[ x_i(t) - \bar{x}(t) \right] + \frac{\partial \bar{u}(t)}{\partial y} \left[ y_i(t) - \bar{y}(t) \right] + u''_i(t)$

$v_i(t) = \bar{v}(t) + \frac{\partial \bar{v}(t)}{\partial x} \left[ x_i(t) - \bar{x}(t) \right] + \frac{\partial \bar{v}(t)}{\partial y} \left[ y_i(t) - \bar{y}(t) \right] + v''_i(t)$

where $\frac{\partial \bar{u}(t)}{\partial x}$, $\frac{\partial \bar{v}(t)}{\partial y}$, $\frac{\partial \bar{v}(t)}{\partial x}$ and $\frac{\partial \bar{v}(t)}{\partial x}$ are linear velocity gradients at the centroid and $u''_i$ and $v''_i$ are the turbulent speeds. The standard deviations of the turbulent speeds were computed as shown below:

\[
\sigma_u(t) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} u_i^2(t)} \quad \text{and} \quad \sigma_v(t) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} v_i^2(t)}
\]

Sanderson et al. (2000) have shown that to achieve unbiased estimates of $\sigma_u$ and $\sigma_v$, n-3 degrees of freedom should be applied within Equation 3.7, rather than n-1. However, for comparability with previous findings, n-1 was retained in this calculation. Equation 2.38 was applied, assuming that $\varepsilon$ is equal to $\sigma_u$, $\sigma_v$, and $l$ is equal to $\sigma_x$, $\sigma_y$ so that the turbulent diffusivity in the $x$ and $y$ were estimated by Equation 2.41 (section 2.4.2) repeated here for convenience:

\[
\begin{align*}
a) \quad k_x &= c \sigma_x \sigma_u \\
b) \quad k_y &= c \sigma_y \sigma_v
\end{align*}
\]

where $c$ is an unknown constant of proportionality. Okubo and Ebbesmeyer (1976) suggested that $c$ should be of order 1. However, Ozmidov (1960) argued that $c$ should be of order 0.1. When Tseng (2002) applied $c = 0.1$ to determine $k$ within coastal waters near Taiwan, he found that this overestimated the diffusivity in comparison to other methods, suggesting that $c$ could be even smaller than 0.1. A constant of proportionality of 0.1 was applied during this study. The turbulent diffusivity in the overall direction was calculated as

\[
k = \frac{k_x + k_y}{2}
\]

As outlined in section 2.4.2, the Taylor series used in this method assumes that velocity gradients are uniform within the group of drifters and that second and higher order terms are considered as turbulence. Hence as the group of drogues continues to spread, the division between shear and turbulent diffusion changes, and what is considered turbulence includes larger and larger scales. This means that the horizontal diffusivity calculated via this method changes with time scale. An appropriate timescale was defined to be approximately 10% of the total time of drifting, and this timescale was applied for each run at each site.
Dispersion coefficients were also calculated (using the same timescale, approximately 10% of the total time of drifting) by applying Equation 2.42 as done by List et al. (1990). It should be remembered that $K(t)$ calculated in this way is not a true statistic measure of ensemble behaviour, and can therefore become negative at times (see section 2.4.3 and 3.2.6).

Following this, any “spikes” in the diffusivities calculated were removed. A spike was defined to be any occasion where the diffusivity was markedly greater than both the other diffusivities and the largest dispersion coefficient calculated for that run. As diffusion is a component of the overall dispersion, spikes in the diffusion imply a situation that is impossible, and must therefore be disregarded. The presence of these impossibilities would suggest that the statistical and theoretical assumptions applied by the Okubo and Ebbesmeyer’s (1976) technique for the isolation of diffusion effects from the overall dispersion are not entirely valid.

### 3.2.10 Environmental conditions

Most of the environmental conditions data provided required no further analysis. It was simply plotted against time, and the duration of each drifter run was identified. The exception was wave data collected by the ADV profiler deployed within Osprey Bay. This data were extracted using a series of MATLAB M-files written by C. Pattiaratchi (pers comm. 2006) and Johnson (2002c). These scripts applied high pass filters to the raw data using Fourier techniques. Cut-off frequencies of 0.005 for long term trends, 0.05 Hz for infragravity waves, 0.15 Hz for swell waves and 0.5 Hz for wind waves (sea) were used. The scripts then determined various wave parameters from the filtered data using the zero-down-crossing-approach (recommended by the International Association of Hydraulic Research), including the significant wave height ($H_s$, the mean of the highest 1/3 of waves) and the mean wave period ($T_z$). Wave direction data were determined through the use of a series of MATLAB M-files produced by Johnson (2002a). These files perform a full directional wave spectrum analysis using algorithms developed by Hashimoto (1997). The outputs included the peak wave period ($T_p$), the main direction of the peak wave period ($D_{T_p}$) and the dominant wave direction ($D_p$); the direction with the highest energy integrated over all frequencies.

Significant wave height, mean wave period and dominant wave direction were plotted against time, and the duration of each drifter run was identified. Three-dimensional surface plots of dominant wave directions, wave frequencies ($1/T_p$) and wave spectral densities for the time periods corresponding to each run were also developed.
4 Results

Results of the investigations undertaken at the three study sites are presented below. Data for Fays Bay, Rottnest Island are presented in section 4.1, data for Osprey Bay, Ningaloo Reef are presented in section 4.2 and data for Koombana Bay, Bunbury are presented in section 4.3.

4.1 Fays Bay, Rottnest Island

4.1.1 Trajectories and velocities

The trajectories plotted for drifter runs 1-5 at Fays Bay are included in Appendix A. An example plot, run 2, is featured in Figure 4.1 below. Table 4.1 indicates the mean velocities for each run. For run 1 (which lasted 17 min on the afternoon of 20th September 2004) the drifters were released within the channel just next to the moored ADV. They travelled in a south to south-easterly direction towards the eastern corner of the Bay, with a mean velocity of 0.153 m/s. For run 2 (which lasted 12 min on the afternoon of 20th September 2004) the drifters were released within the channel just off the western headland (Figure 4.1). They moved quickly across the Bay (with a mean velocity of 0.246 m/s) following the contours of the main channel.

Figure 4.1: Drifter trajectory for run 2, Fays Bay, 20th September 2004. The solid black line indicates the position of the shoreline and the rock section in the centre of the Bay, the dotted black line indicates the position of the offshore reef system, the black cross indicates the position of the moored ADV and the coloured lines represent the drifter tracks.
For run 3 (the shortest run for this study site, lasting 11 min on the morning of 23\textsuperscript{rd} September 2004), the drifters were again released within the channel next to the moored ADV. However, this time the drifters travelled in a north-westerly direction at an average velocity of 0.076 m/s and were washed up on the western headland. For run 4 (the longest run for this study site, lasting 51 min at noon on the 23\textsuperscript{rd} September 2004) the drifters were released just off the eastern headland. All but one of the drifters meandered slowly in a westerly direction. The exception moved to the west and then to the north, ending up on the offshore reef. The mean velocity for run 4 was 0.065 m/s. For run 5 (lasting 14 min on the afternoon of 23\textsuperscript{rd} September 2004) the drifters were again released from within the channel next to the moored ADV. This time the drifters moved in a north to north-easterly direction, and all ended up on the offshore reef (Figure 4.1). The mean velocity for run 5 was 0.064 m/s.

Table 4.1: Mean velocities (Mean) and their associated 95% confidence intervals (95 % CI) calculated for Fays Bay, reported in m/s. The number of samples taken during each run (n) is also indicated

<table>
<thead>
<tr>
<th>(m/s)</th>
<th>Run 1 (n = 1041)</th>
<th>Run 2 (n = 736)</th>
<th>Run 3 (n = 676)</th>
<th>Run 4 (n = 3021)</th>
<th>Run 5 (n = 801)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% CI</td>
<td>Mean</td>
<td>95% CI</td>
<td>Mean</td>
</tr>
<tr>
<td>d2</td>
<td>0.161</td>
<td>0.008</td>
<td>0.234</td>
<td>0.010</td>
<td>0.087</td>
</tr>
<tr>
<td>d3</td>
<td>0.151</td>
<td>0.008</td>
<td>0.224</td>
<td>0.011</td>
<td>0.079</td>
</tr>
<tr>
<td>d4</td>
<td>0.150</td>
<td>0.005</td>
<td>0.274</td>
<td>0.011</td>
<td>0.082</td>
</tr>
<tr>
<td>d5</td>
<td>0.148</td>
<td>0.006</td>
<td>0.288</td>
<td>0.021</td>
<td>0.069</td>
</tr>
<tr>
<td>d6</td>
<td>0.158</td>
<td>0.005</td>
<td>0.209</td>
<td>0.008</td>
<td>0.064</td>
</tr>
<tr>
<td>Overall</td>
<td>0.153</td>
<td>0.003</td>
<td>0.246</td>
<td>0.006</td>
<td>0.076</td>
</tr>
</tbody>
</table>

4.1.2 Environmental Conditions

Synoptics

Synoptic charts for each day of study at Fays Bay are included in Figure 4.2 below. They indicate the presence of a low pressure system crossing the west coast on 20\textsuperscript{th} September 2004, and a high pressure system influencing the south west region on 23\textsuperscript{rd} September 2004.
Results 61

**Figure 4.2:** Synoptic charts at 2 pm local time for a) 20th September 2004, featuring a low pressure system approaching the south west coast and b) 23rd September 2004 featuring a high pressure system across the south west

**Wind**

During the morning (6 am-12 noon) of 20th September 2004, wind speeds at Rottnest Island ranged from 7-15 km/hr (Figure 4.3a), and the predominant wind direction was northerly (Figure 4.4a). Wind speeds dropped slightly in the afternoon, and gradually swung to the west. During both run 1 and run 2 the mean wind speed was 8.3 km/hr (± a 95% confidence interval of 1.3 km/hr).

Between 6 and 10 am on 23rd September 2004 east to south-easterly winds ranged from 9-13 km/hr (Figure 4.3b and Figure 4.4b). The wind direction swung to the south at 11 am, and wind speed increased steadily throughout the afternoon to reach 22 km/hr at 5 pm. During run 3 the mean wind speed was 12.3 km/hr (±1.3 km/hr), during run 4 the mean wind speed was 13.5 km/hr (±1.0 km/hr) and during run 5 the mean wind speed was 17 km/hr (±0.0 km/hr).
Figure 4.3: Wind speeds at Rottnest Island during the study periods a) 20th September 2004 and b) 23rd September 2004. The duration of each run is indicated.

Figure 4.4: Wind directions at Rottnest Island during the study periods a) 20th September 2004 and b) 23rd September 2004. The duration of each run is indicated.
Waves

On 20th September 2006, significant wave heights (Hs) measured off Rottnest Island ranged from 2.71-3.55 m (Figure 4.5a) and mean wave periods (Tz) ranged from 9.54-11.27 s (Figure 4.5b). Significant wave heights and mean wave periods on 23rd September 2006 were considerably lower, ranging from 1.58-2.16 m and 6.67-9.50 s respectively (Figure 4.5b).

![Significant Wave Height (Hs)](image1)

![Mean Wave Period (Tz)](image2)

Figure 4.5: a) Significant wave heights and b) Mean wave period (Tz) measured off Rottnest Island on 20th September 2004 and 23rd September 2004. The duration of each run is indicated

Water level

Water levels measured within Fays Bay decreased over the four day period of 20th September 2004 to 23rd September 2004 (Figure 4.6). The water level recorded on 20th September 2004 rose from a minimum observed at noon just before deployment of the ADV, to a maximum reported at midnight 6 hrs later. As such, run 1 and run 2 were performed during at water levels of 2.07 m and 2.11 m respectively, on the start of the flood tide. The water level recorded on 23rd September 2004 fell from a maximum observed at approximately 2:30 am, to a minimum recorded at the time of retrieval of the ADV. As such,
run 3, run 4 and run 5 occurred on the ebb tide, with run 3 performed at a water level of 1.98 m, run 4 performed at a water level of 1.89 m and run 5 performed at a water level of 1.67 m.

![Figure 4.6: Water levels measured within Fays Bay during over the study period 20th September 2004 (Julian Day 264) to 23rd September 2004 (Julian Day 267). The duration of each run is indicated](image)

### 4.1.3 Dispersion

The plots used to calculate the dispersion coefficients for each run at Fays Bay are included in Appendix A. An example plot, run 1, is featured in Figure 4.7 below. The dispersion coefficients $K$, $K_x$ and $K_y$ calculated for each of the five drifter runs performed at Fays Bay are featured in Table 4.2 below. The mean dispersion coefficients were found to be $K = 0.05 \text{ m}^2/\text{s}$ (± a 95% confidence interval of 0.02), $K_x = 0.08 \text{ m}^2/\text{s}$ (±0.05) and $K_y = 0.03 \text{ m}^2/\text{s}$ (±0.04).

#### Table 4.2: The dispersion coefficients ($K_x$, $K_y$ and $K$) and their associated coefficients of determination ($R_x^2$, $R_y^2$ and $R^2$) calculated for Fays Bay, reported in m$^2$/s

<table>
<thead>
<tr>
<th></th>
<th>$K_x$</th>
<th>$R_x^2$</th>
<th>$K_y$</th>
<th>$R_y^2$</th>
<th>$K$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.127</td>
<td>0.941</td>
<td>0.004</td>
<td>0.137</td>
<td>0.065</td>
<td>0.943</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.103</td>
<td>0.540</td>
<td>0.026</td>
<td>0.329</td>
<td>0.065</td>
<td>0.661</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.014</td>
<td>0.738</td>
<td>0.019</td>
<td>0.695</td>
<td>0.016</td>
<td>0.906</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.002</td>
<td>0.020</td>
<td>0.066</td>
<td>0.846</td>
<td>0.034</td>
<td>0.920</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.094</td>
<td>0.957</td>
<td>0.008</td>
<td>0.442</td>
<td>0.051</td>
<td>0.937</td>
</tr>
<tr>
<td>Mean</td>
<td>0.08</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.97</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.93</td>
</tr>
</tbody>
</table>

*Note: Entries shaded in yellow were not included in the average due to low correlation*
The dispersion coefficients calculated for the runs performed on the afternoon of 20th September 2004 (run 1 and 2) were higher than those determined for the runs performed on 23rd September 2004 (run 3, 4 and 5) (Table 4.2). The lowest dispersion coefficient was calculated for run 3, which was also the shortest run performed at Fays Bay in terms of both time and distance.

The dispersion coefficients for the x direction ($K_x$) were an order of magnitude higher than the dispersion coefficients for the y direction ($K_y$) on 20th September 2004 (Figure 4.1, Table 4.2). However, the data for the dispersion coefficients in the y direction were poorly correlated ($R^2 < 0.5$), and as such these coefficients were not included in the overall mean. Considerable dispersion in the x direction was also observed during run 5, shown clearly by the east-west spread of the drifters (see Appendix A).

**Figure 4.7: Plot used to calculate the dispersion coefficients for run 1, Fays Bay, 20th September 2004**

### 4.1.4 Time Dependence

The log-log plots indicating the time dependence of the dispersion (dispersion diagrams) for each run at Fays Bay are included in Appendix A. An example plot, run 5, is featured in Figure 4.8 below. The time dependence coefficients ($a_x$, $a_y$, $a$ and $b_x$, $b_y$, $b$) calculated for each of the five drifter runs performed at Fays Bay are featured in Table 4.3 below. The mean time dependence coefficients gave the time power laws:

\[
\begin{align*}
\sigma^2 &= 0.2 \ t^{1.0} \\
\sigma_x^2 &= 0.1 \ t^{1.0} \\
\sigma_y^2 &= 0.3 \ t^{1.1}
\end{align*}
\]
Table 4.3: The time dependence coefficients ($a_x$, $a_y$, $a$, $b_x$, $b_y$, $b$) and their associated coefficients of determination ($R_{x^2}$, $R_{y^2}$ and $R^2$) calculated for Fays Bay, reported in $m^2$

<table>
<thead>
<tr>
<th>(m²)</th>
<th>$a_x$</th>
<th>$b_x$</th>
<th>$R_{x^2}$</th>
<th>$a_y$</th>
<th>$b_y$</th>
<th>$R_{y^2}$</th>
<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.009</td>
<td>1.416</td>
<td>0.751</td>
<td>3.118</td>
<td>0.185</td>
<td>0.077</td>
<td>0.076</td>
<td>1.004</td>
<td>0.668</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.361</td>
<td>0.763</td>
<td>0.443</td>
<td>0.751</td>
<td>0.647</td>
<td>0.640</td>
<td>0.573</td>
<td>0.708</td>
<td>0.659</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.500</td>
<td>0.565</td>
<td>0.614</td>
<td>0.146</td>
<td>0.659</td>
<td>0.458</td>
<td>0.293</td>
<td>0.619</td>
<td>0.678</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.030</td>
<td>0.896</td>
<td>0.522</td>
<td>0.001</td>
<td>1.515</td>
<td>0.789</td>
<td>0.003</td>
<td>1.363</td>
<td>0.887</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.037</td>
<td>1.209</td>
<td>0.869</td>
<td>0.012</td>
<td>1.036</td>
<td>0.782</td>
<td>0.023</td>
<td>1.191</td>
<td>0.877</td>
</tr>
<tr>
<td>Mean</td>
<td>0.1</td>
<td>1.0</td>
<td>0.3</td>
<td>1.1</td>
<td>0.752</td>
<td>0.657</td>
<td>0.2</td>
<td>1.0</td>
<td>0.88</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in average due to low correlation

The log-log plots of time dependence (Appendix A) indicate that the variance of drifter position was fairly constant for the first 40-100 s of drift time. Following this the variance increased exponentially, but with many small peaks and troughs. This general trend was displayed well during run 5, as shown by Figure 4.8 below. The main exception was run 3, where the increase in variance with time was minimal.

Figure 4.8: Log-log plot of the variance against time (a dispersion diagram) indicating the time dependence of dispersion for run 5, Fays Bay, 23rd September 2004

### 4.1.5 Scale Dependence

The log-log plots indicating the scale dependence of the dispersion (dispersion diagrams) for each run at Fays Bay are included in Appendix A. An example plot, run 4, is featured in
Figure 4.9 below. The scale dependence coefficients \((c_x, c_y, c, d_x, d_y, d)\) calculated for each of the five drifter runs performed at Fays Bay are featured in Table 4.4 below. The mean scale dependence coefficients gave the scale power laws:

\[
K = 0.009 \sigma^{1.4} \\
K_x = 0.014 \sigma^{1.5} \\
K_y = 0.006 \sigma^{1.7}
\]

Table 4.4: The scale dependence coefficients \((c_x, c_y, c, d_x, d_y, d)\) and their associated coefficients of determination \((R_x^2, R_y^2, R^2)\) calculated for Fays Bay, reported in \(\text{m}^2/\text{s}\)

<table>
<thead>
<tr>
<th></th>
<th>(c_x)</th>
<th>(d_x)</th>
<th>(R_x^2)</th>
<th>(c_y)</th>
<th>(d_y)</th>
<th>(R_y^2)</th>
<th>(c)</th>
<th>(d)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.018</td>
<td>1.319</td>
<td>0.602</td>
<td>0.021</td>
<td>0.073</td>
<td>0.027</td>
<td>0.013</td>
<td>1.235</td>
<td>0.558</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.004</td>
<td>2.311</td>
<td>0.766</td>
<td>0.110</td>
<td>0.084</td>
<td>0.011</td>
<td>0.006</td>
<td>1.915</td>
<td>0.703</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.014</td>
<td>1.241</td>
<td>0.924</td>
<td>0.002</td>
<td>2.766</td>
<td>0.680</td>
<td>0.024</td>
<td>0.198</td>
<td>0.388</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.008</td>
<td>0.773</td>
<td>0.338</td>
<td>0.009</td>
<td>1.265</td>
<td>0.598</td>
<td>0.008</td>
<td>1.061</td>
<td>0.745</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.019</td>
<td>1.175</td>
<td>0.506</td>
<td>0.007</td>
<td>1.068</td>
<td>0.976</td>
<td>0.015</td>
<td>1.148</td>
<td>0.496</td>
</tr>
<tr>
<td>Mean</td>
<td>0.014</td>
<td>1.5</td>
<td></td>
<td>0.006</td>
<td>1.7</td>
<td></td>
<td>0.009</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
<td>0.004</td>
<td>1.1</td>
<td></td>
<td>0.004</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in the average due to low correlation

Generally the dispersion coefficients for each run increased exponentially with length scale (i.e. standard deviation). A good example is run 4, as featured in Figure 4.9. The largest increase in dispersion with scale was observed for run 2. Little or no increase in dispersion with scale was observed in the y direction for run 1 or run 2, or in the overall direction for run 3.

![Figure 4.9: Log-log plot of the dispersion coefficients against the standard deviation (a dispersion diagram) indicating the scale dependence of dispersion for run 4, Fays Bay, 23rd September 2004](image-url)
4.1.6 Turbulence and Diffusivity

Plots featuring the variation in both dispersion and diffusion with time for each of the five runs performed at Fays Bay run are included in Appendix A. An example plot, run 5, is featured in Figure 4.10 below. Generally the diffusion coefficients were less than the dispersion coefficients calculated for each run. The exceptions were run 2 and run 4, where the diffusion coefficients were consistently greater than the dispersion coefficients. As discussed in section 3.2.9, diffusion is a component of the overall dispersion observed within a water body. Therefore, these results imply a situation that is impossible and must be disregarded. Further discussion of these discrepancies is featured in section 5.4.

The rates of diffusion identified for Fays Bay ranged from 0.007-0.235 m$^2$/s. The highest rates of dispersion and diffusion were recorded for run 1, while the lowest rates were observed for run 3. $K_x$ and $K_y$ were generally out of phase, i.e. when $K_x$ increased $K_y$ decreased and vice versa. In contrast, trends in $k_x$ were mostly the same as trends in $k_y$. Various peaks in both the dispersion and diffusion plots were evident.

![Figure 4.10: Plots featuring the rate of a) dispersion and b) diffusion against time for run 5 at Fays Bay](image_url)
4.2 Osprey Bay, Ningaloo Reef

4.2.1 Trajectories and velocities

The trajectories plotted for drifter runs 1-4 at Osprey Bay are included in Appendix B. An example plot, run 2, is featured in Figure 4.11 below. Table 4.5 indicates the mean velocities for each run. For run 1 (which lasted 2 hr and 9 min on the morning of 20\textsuperscript{th} April 2006) the drifters were released from just in front of the moored instrument South ADV2, which was situated on the shoreward boundary of the surf zone, in the centre of the southern lagoon. The drifters travelled shoreward (in an easterly direction) for approximately 500 m over the shallow reef flats and the deeper section of the lagoon. They then turned to the south as they neared the shallower inshore section of the lagoon. The mean velocity for run 1 was 0.235 m/s.

For run 2 (Figure 4.11), which was performed in the afternoon of 20\textsuperscript{th} April 2006 (and which lasted 1 hr and 46 min), the drifters were released from just in front of the moored instrument North ADV2, which was situated on the shoreward boundary of the surf zone in the centre of the northern lagoon. The drifters travelled shoreward (in a south-easterly direction) over the reef flat, and then moved to the south roughly parallel to the coast. Once reaching the gap in the main reef line the drifters began to move offshore through the channel. The mean velocity for run 2 was the highest recorded for the study site at 0.287 m/s.
For run 3 (2 hr and 20 min on the afternoon of 21st April 2006), the drifters were again released from just in front of South ADV2. This time they drifted shoreward and slightly to the north, with the lowest average velocity for the study site of 0.191 m/s. For run 4 (2 hr and 4 min on the morning of 22nd April 2006), the drifters were again released from just in front of North ADV2. As for run 2, the drifters moved shoreward over the reef flat, turned south in the lagoon and headed towards the gap in the reef. The mean velocity for run 4 was 0.231 m/s.
Table 4.5: Mean velocities (Mean) and their associated 95% confidence intervals (95 % CI) calculated for Osprey Bay, reported in m/s. The number of samples taken during each run (n) is also indicated.

<table>
<thead>
<tr>
<th>(m/s)</th>
<th>Run 1 n = 7741</th>
<th>Run 2 n = 6361</th>
<th>Run 3 n = 8401</th>
<th>Run 4 n = 7441</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean 95 % CI</td>
<td>Mean 95 % CI</td>
<td>Mean 95 % CI</td>
<td>Mean 95 % CI</td>
</tr>
<tr>
<td>d3</td>
<td>0.271 0.010</td>
<td>0.325 0.011</td>
<td>0.219 0.009</td>
<td>0.252 0.010</td>
</tr>
<tr>
<td>d4</td>
<td>0.244 0.004</td>
<td>0.282 0.005</td>
<td>0.194 0.004</td>
<td>0.250 0.008</td>
</tr>
<tr>
<td>d5</td>
<td>0.235 0.004</td>
<td>0.271 0.004</td>
<td>0.192 0.004</td>
<td>0.227 0.004</td>
</tr>
<tr>
<td>d6</td>
<td>0.189 0.003</td>
<td>0.269 0.004</td>
<td>0.158 0.003</td>
<td>0.193 0.003</td>
</tr>
<tr>
<td>Overall</td>
<td>0.235 0.003</td>
<td>0.287 0.003</td>
<td>0.191 0.003</td>
<td>0.231 0.003</td>
</tr>
</tbody>
</table>

### 4.2.2 Environmental Conditions

#### Wind

During the early morning (6-9 am) of 20th April 2006, wind speeds at the Milyaring Visitor Centre ranged from 1-8 km/hr (Figure 4.12a), and the wind direction swung from the south to the north and then to the west, indicating the onset of the sea breeze by 9 am (Figure 4.13a). From 9 am to 4 pm wind speeds increased to 18 km/hr, while wind direction remained westerly. During run 1 the mean wind speed was 10.2 km/hr (± a 95% confidence interval of 2.5 km/hr). During run 2 the mean wind speed was 15.2 km/hr (±2.3 km/hr).

From 6 am to midday on 21st April 2006 easterly (offshore) winds varied from 6-20 km/hr (Figure 4.12b). At 1 pm the wind swung to the north-west (Figure 4.13b), and over the next few hours wind speeds ranged between 15 and 20 km/hr while direction remained fairly constant. During run 3 the mean wind speed was 17.0 km/hr (±1.9 km/hr).

The wind direction was south-westerly throughout the day on 22nd April 2006, with the exception of an hour mid-morning when it swung to the south-east (Figure 4.13c). From 6 am to 9 am wind speeds ranged from 5-10 km/hr (Figure 4.12c). Over the next few hours the velocities increased to reach 16 km/hr by 11 am. During run 4 the mean wind speed was 8.4 km/hr (±3.4 km/hr).
a) 20th April 2006

b) 21st April 2006

c) 22nd April 2006

Figure 4.12: Wind speeds at the Milyaring Visitor Centre during the study periods a) 20th April 2006, b) 21st April 2006 and c) 22nd April 2006. The duration of each run is indicated.
Figure 4.13: Wind directions at the Milyaring Visitor Centre during the study periods a) 20th April 2006, b) 21st April 2006 and c) 22nd April 2006. The duration of each run is indicated.
Waves

On 20th April 2006, significant wave heights (Hs) within Osprey Bay ranged from 0.56-0.77 m (Figure 4.14a) and mean wave periods (Tz) ranged from 10.13-11.74 s (Figure 4.14b). During run 1 a long mean wave period (11.59 s) and the highest significant wave height for the three day period were recorded. During run 2 the longest mean wave period for the day and a high significant wave height (0.68 m) were recorded.

On 21st April 2006, the significant wave height was generally lower, ranging from 0.53-0.72 m (Figure 4.14a). The mean wave period was similar to that reported for 20th April 2006, ranging from 10.02-12.04 s (Figure 4.14b). During run 3 the lowest significant wave height and the lowest mean wave period for the day were recorded.

Significant wave heights on 22nd April 2006 were the lowest recorded for the three day study period, ranging from 0.40-0.61 m (Figure 4.14a). Mean wave periods on 22nd April 2006 were highly variable; both the longest (12.09 s) and the shortest (9.37 s) mean wave period for the three day study period were recorded (Figure 4.14b). Mean wave periods were high during the very early morning (12-4 am) and generally decreased throughout the day to reach a minimum at approximately 10 pm. During run 4 the lowest significant wave height of the four runs (0.49 m) and a typical mean wave period (11.10 s) were recorded.
Results

Figure 4.14: a) Significant wave heights and b) Mean wave period (Tz) measured within Osprey Bay on 20th April 2006, 21st April 2006 and 22nd April 2006. The duration of each run is indicated.

The mean dominant wave direction recorded for 20th April 2006 within Osprey Bay was 108 ° (± a 95% confidence interval of 4) indicating that the governing wave action was from the west. The mean dominant wave direction recorded for 21st April 2006 was 106 ° (± 3 °), indicating that the governing wave action was again from the west. The mean dominant wave direction recorded for 22nd April 2006 was more variable than reported for the previous two days, ranging from 94 ° (from the west) to 123 ° (from the north-west) with a mean of 109 ° (± 5 °). A plot featuring the typical dominant wave direction observed over the three day study period is featured in Figure 4.15.
4.2.3 Dispersion

The plots used to calculate the dispersion coefficients for each run at Osprey Bay are included in Appendix B. An example plot, run 4, is featured in Figure 4.16 below. The dispersion coefficients $K$, $K_x$ and $K_y$ calculated for each of the four drifter runs performed at Osprey Bay are featured in Table 4.6 below. The mean dispersion coefficients were found to be $K = 0.10$ m$^2$/s ($\pm$ a 95% confidence interval of 0.05), $K_x = 0.08$ m$^2$/s ($\pm 0.07$) and $K_y = 0.15$ m$^2$/s ($\pm 0.07$).

Table 4.6: The dispersion coefficients ($K_x$, $K_y$ and $K$) and their associated coefficients of determination ($R_x^2$, $R_y^2$ and $R^2$) calculated for Osprey Bay, reported in m$^2$/s

<table>
<thead>
<tr>
<th></th>
<th>$K_x$</th>
<th>$R_x^2$</th>
<th>$K_y$</th>
<th>$R_y^2$</th>
<th>$K$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.003</td>
<td>0.005</td>
<td>0.085</td>
<td>0.784</td>
<td>0.044</td>
<td>0.620</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.119</td>
<td>0.650</td>
<td>0.026</td>
<td>0.516</td>
<td>0.072</td>
<td>0.710</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.066</td>
<td>0.454</td>
<td>0.211</td>
<td>0.927</td>
<td>0.138</td>
<td>0.932</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.045</td>
<td>0.745</td>
<td>0.162</td>
<td>0.883</td>
<td>0.162</td>
<td>0.806</td>
</tr>
<tr>
<td>Mean</td>
<td>0.08</td>
<td>0.15</td>
<td>0.10</td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>0.07</td>
<td>0.07</td>
<td>0.05</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in the average due to low correlation

The dispersion coefficients for the two runs performed on 20$^{th}$ April 2006 were lower than the coefficients for run 3 (21$^{st}$ April 2006) and run 4 (22$^{nd}$ April 2006). The lowest coefficient was recorded for run 1, and the highest coefficient was recorded for run 4 (Figure 4.16).
The dispersion coefficients in the y direction were generally larger than the dispersion coefficients in the x direction (Figure 4.16), although it should be noted that the dispersion coefficients in the x direction for run 1 and run 3 were not included in the overall mean due to low correlation (as described in section 3.2.6). The exception to this trend was run 2, where the dispersion in the x direction was an order of magnitude higher than the dispersion in the y direction.

Figure 4.16: Plot used to calculate the dispersion coefficients for run 4, Osprey Bay, 20th September 2006

4.2.4 Time Dependence

The log-log plots indicating the time dependence of the dispersion (dispersion diagrams) for each run at Osprey Bay are included in Appendix B. An example plot, run 3, is featured in Figure 4.17 below. The time dependence coefficients \(a_x, a_y, a\) and \(b_x, b_y, b\) calculated for each of the four drifter runs performed at Osprey Bay are featured in Table 4.7 below. The mean time dependence coefficients gave the time power laws:

\[
\sigma^2 = 0.005 \, t^{1.4} \\
\sigma_x^2 = 0.01 \, t^{1.4} \\
\sigma_y^2 = 0.02 \, t^{1.6}
\]
Table 4.7: The time dependence coefficients (a\textsubscript{x}, a\textsubscript{y}, a, b\textsubscript{x}, b\textsubscript{y}, b) and their associated coefficients of determination (R\textsubscript{x}\textsuperscript{2}, R\textsubscript{y}\textsuperscript{2} and R\textsuperscript{2}) calculated for Osprey Bay, reported in m\textsuperscript{2}.

<table>
<thead>
<tr>
<th>Run</th>
<th>a\textsubscript{x}</th>
<th>b\textsubscript{x}</th>
<th>R\textsubscript{x}\textsuperscript{2}</th>
<th>a\textsubscript{y}</th>
<th>b\textsubscript{y}</th>
<th>R\textsubscript{y}\textsuperscript{2}</th>
<th>a</th>
<th>b</th>
<th>R\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.915</td>
<td>0.608</td>
<td>0.345</td>
<td>0.000</td>
<td>1.862</td>
<td>0.771</td>
<td>0.011</td>
<td>1.226</td>
<td>0.789</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.001</td>
<td>1.543</td>
<td>0.570</td>
<td>0.065</td>
<td>0.961</td>
<td>0.565</td>
<td>0.006</td>
<td>1.285</td>
<td>0.692</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.003</td>
<td>1.433</td>
<td>0.762</td>
<td>0.000</td>
<td>1.707</td>
<td>0.829</td>
<td>0.001</td>
<td>1.585</td>
<td>0.862</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.021</td>
<td>1.124</td>
<td>0.689</td>
<td>0.000</td>
<td>1.834</td>
<td>0.803</td>
<td>0.001</td>
<td>1.542</td>
<td>0.784</td>
</tr>
<tr>
<td>Mean</td>
<td>0.01</td>
<td>1.4</td>
<td>0.02</td>
<td>1.6</td>
<td>0.005</td>
<td>1.4</td>
<td>0.005</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>0.01</td>
<td>0.2</td>
<td>0.03</td>
<td>0.4</td>
<td>0.005</td>
<td>0.2</td>
<td>0.005</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in average due to low correlation.

The log-log plots of time dependence (Appendix B) indicate that as a general rule the variance of drifter position was fairly constant for the first 40 s of drift time. Following this the variance increased exponentially, but with many small peaks and troughs. The log-log plots also indicate a relatively large peak in variance at about 100 s, and a relatively large trough in variance at about 130 s. These broad trends were illustrated well during run 3, as shown by Figure 4.17 below. The exception was run 1, which did not display the features described. Run 1 also showed the smallest time dependence of the four experiments.

Figure 4.17: Log-log plot of the variance against time (a dispersion diagram) indicating the time dependence of dispersion for run 3, Osprey Bay, 21\textsuperscript{st} April 2006

4.2.5 Scale Dependence

The log-log plots indicating the scale dependence of the dispersion (dispersion diagrams) for each run at Osprey Bay are included in Appendix B. An example plot, run 4, is featured in
Figure 4.18 below. The scale dependence coefficients (c_x, c_y, c and d_x, d_y, d) calculated for each of the four drifter runs performed at Osprey Bay are featured in Table 4.8 below. The mean scale dependence coefficients gave the scale power laws:

\[ K = 0.006 \sigma^{1.3} \]
\[ K_x = 0.005 \sigma^{1.4} \]
\[ K_y = 0.006 \sigma^{1.4} \]

Table 4.8: The scale dependence coefficients (c_x, c_y, c and d_x, d_y, d) and their associated coefficients of determination (R_x^2, R_y^2 and R^2) calculated for Osprey Bay, reported in m^2/s

<table>
<thead>
<tr>
<th></th>
<th>c_x</th>
<th>d_x</th>
<th>R_x^2</th>
<th>c_y</th>
<th>d_y</th>
<th>R_y^2</th>
<th>c</th>
<th>d</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.009</td>
<td>1.032</td>
<td>0.340</td>
<td>0.010</td>
<td>1.113</td>
<td>0.547</td>
<td>0.014</td>
<td>0.837</td>
<td>0.363</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.004</td>
<td>1.660</td>
<td>0.622</td>
<td>0.002</td>
<td>1.681</td>
<td>0.605</td>
<td>0.004</td>
<td>1.458</td>
<td>0.734</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.014</td>
<td>0.949</td>
<td>0.445</td>
<td>0.004</td>
<td>1.455</td>
<td>0.713</td>
<td>0.010</td>
<td>1.112</td>
<td>0.556</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.005</td>
<td>1.206</td>
<td>0.650</td>
<td>0.007</td>
<td>1.359</td>
<td>0.736</td>
<td>0.005</td>
<td>1.413</td>
<td>0.687</td>
</tr>
<tr>
<td>Mean</td>
<td>0.005</td>
<td>1.4</td>
<td>0.650</td>
<td>0.007</td>
<td>1.359</td>
<td>0.736</td>
<td>0.005</td>
<td>1.413</td>
<td>0.687</td>
</tr>
<tr>
<td>St Dev</td>
<td>0.001</td>
<td>0.3</td>
<td>0.003</td>
<td>0.2</td>
<td>0.003</td>
<td>0.2</td>
<td>0.003</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>0.001</td>
<td>0.4</td>
<td>0.003</td>
<td>0.2</td>
<td>0.003</td>
<td>0.2</td>
<td>0.004</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in the average due to low correlation

The dispersion coefficients for each run increased exponentially with length scale (i.e. standard deviation), as shown in Figure 4.18. The largest increase in dispersion with scale was observed for run 2, while the smallest increase was observed for run 1.
4.2.6 Turbulence and Diffusivity

Plots featuring the variation in both dispersion and diffusion with time for each of the four runs performed at Osprey Bay run are included in Appendix B. An example plot, run 4, is featured in Figure 4.19 below. The diffusion coefficients were consistently less than the dispersion coefficients calculated for each run.

The rates of diffusion identified for Osprey Bay ranged from 0.002-0.575 m$^2$/s. The highest rates of dispersion and diffusion were recorded for run 4, while the lowest were recorded for run 1. As found for Fays Bay, $K_x$ and $K_y$ were generally out of phase while trends in $k_x$ were mostly the same as trends in $k_y$ (see Figure 4.19). Several distinct peaks in the rate of dispersion and or diffusion were observed during the runs performed:

- the rate of dispersion during run 2 showed a trough at 60 min and a peak at 70-80 min. The resultant rate of diffusion was low, although it increased slightly after 60 min;
- the rate of diffusion during run 3 featured clearly defined peaks at 40, 60 and 80 min. A similar peak was observed at 60 min in the run 3 dispersion plot; and
- during run 4 both the rate of dispersion and diffusion increased rapidly following about 90 min. The rate of diffusion also showed a marked peak at 60 min (Figure 4.19).

![Figure 4.19: Plots featuring the rate of a) dispersion and b) diffusion a time for run 4 at Osprey Bay](image-url)
4.3 Koombana Bay, Bunbury

4.3.1 Trajectories and velocities

The trajectories plotted for drifter runs 1-6 at Koombana Bay are included in Appendix C. An example plot, run 2, is featured in below. Table 4.9 indicates the mean velocities for each run. For run 1 (which lasted 1 hr and 57 min on the morning of 17th September 2006) the drifters were released from the centre of Koombana Bay, just to the east of the main shipping channel. From there the drifters travelled approximately 800 m directly toward the eastern shore. The mean velocity for run 1 was 0.154 m/s. For run 2 (2 hr and 7 min on the afternoon of 17th September 2006) the drifters were released from the western side of Koombana Bay, just east of the Casuarina Boat Harbour boundary. They travelled approximately 800 m in a south-easterly direction towards the centre of the Bay (Figure 4.20). The mean velocity for run 2 was 0.123 m/s.

Figure 4.20: Drifter trajectory for run 2, Koombana Bay, 17th September 2006. The solid black line indicates the position of the shoreline and the coloured lines represent the drifter tracks.
For run 3 and 4 (58 and 55 min respectively during midday on 18th September 2006) the drifters were released within a sheltered section in the south-west corner of the Bay. They travelled approximately 400 m in a north-easterly direction before retrieval. The mean velocities for the two runs were 0.151 m/s and 0.170 m/s respectively.

For run 5 and 6 (1 hr and 40 min respectively during the afternoon of 18th September 2006) the drifters were again released within the sheltered section in the south-west corner of the Bay. As before, they travelled approximately 400 m in a north-easterly direction. However, on these occasions there was considerable spread in the drifter position, with one drifter travelling in an almost easterly direction during run 5. The mean velocities for the two runs were 0.155 m/s and 0.176 m/s respectively.
Table 4.9: Mean velocities (Mean) and their associated 95% confidence intervals (95 % CI) calculated for Koombana Bay, reported in m/s. The number of samples taken during each run (n) is also indicated.

<table>
<thead>
<tr>
<th>(m/s)</th>
<th>Run 1 n = 7021</th>
<th>Run 2 n = 7611</th>
<th>Run 3 n = 3481</th>
<th>Run 4 n = 3301</th>
<th>Run 5 n = 3611</th>
<th>Run 6 n = 2401</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95 % CI</td>
<td>Mean</td>
<td>95 % CI</td>
<td>Mean</td>
<td>95 % CI</td>
</tr>
<tr>
<td>d1</td>
<td>0.150 0.002</td>
<td>0.108 0.001</td>
<td>0.108 0.003</td>
<td>0.163 0.003</td>
<td>0.148 0.003</td>
<td>0.173 0.003</td>
</tr>
<tr>
<td>d3</td>
<td>0.151 0.002</td>
<td>0.112 0.002</td>
<td>0.112 0.003</td>
<td>0.166 0.003</td>
<td>0.152 0.003</td>
<td>0.177 0.004</td>
</tr>
<tr>
<td>d4</td>
<td>0.155 0.002</td>
<td>0.133 0.002</td>
<td>0.133 0.003</td>
<td>0.180 0.003</td>
<td>0.165 0.003</td>
<td>0.171 0.004</td>
</tr>
<tr>
<td>d8</td>
<td>0.161 0.002</td>
<td>0.140 0.001</td>
<td>0.140 0.003</td>
<td>0.170 0.003</td>
<td>0.156 0.003</td>
<td>0.185 0.004</td>
</tr>
<tr>
<td>Overall</td>
<td>0.154 0.001</td>
<td>0.123 0.001</td>
<td>0.151 0.001</td>
<td>0.170 0.002</td>
<td>0.155 0.001</td>
<td>0.176 0.002</td>
</tr>
</tbody>
</table>
4.3.2 Environmental Conditions

Synoptics

Synoptic charts for each day of study at Koombana Bay are included in Figure 4.2 below. They indicate the presence of a low pressure system approaching the coast on 17th September 2006, and crossing the coast on 18th September 2006.

Figure 4.21: Synoptic charts at 2 pm local time for a) 17th September 2006, featuring a low pressure system approaching the south west coast and b) 18th September 2006 featuring a low pressure system crossing the south west coast

Wind

During the early morning (6-9 am) of 17th September 2006, wind speeds at Carey Park, Bunbury ranged from 11-15 km/hr (Figure 4.22a), and the wind direction was westerly (Figure 4.23a). Wind speeds increased to about 18 km/hr by early afternoon, and reached a maximum of 26 km/hr by 5 pm (Figure 4.22a). Wind direction swung gradually to the north-west during the morning, and remained in that direction for the remainder of the day (Figure 4.23a). During Run 1 the mean wind speed was 18.3 km/hr (± a 95% confidence interval of 1.9 km/hr). During Run 2 the mean wind speed was 18.5 km/hr (±2.3 km/hr).

Winds speeds increased throughout the early morning of 18th September 2006, to reach 35 km/hr by 10 am (Figure 4.22b). The wind direction during this period was a consistent westerly (Figure 4.23b). Wind speeds dropped throughout the afternoon and evening, and the wind direction swung 270° (i.e. to the south, east and then north by midnight) (Figure 4.22b).
and Figure 4.23b). The mean speeds during the four runs performed on 18th September 2006 were

- Run 3: 28.7 km/hr (± a 95% confidence interval of 6.6 km/hr)
- Run 4: 27.7 km/hr (±6.2 km/hr)
- Run 5: 28.7 km/hr (±1.3 km/hr)
- Run 6: 26.7 km/hr (±4.7 km/hr)

**a) 17th September 2006**

![Wind Speed Chart 17th September 2006](image)

**b) 18th September 2006**

![Wind Speed Chart 18th September 2006](image)

Figure 4.22: Wind speeds at Carey Park, Bunbury during the study periods a) 17th September 2006 and b) 18th September 2006. The duration of each run is indicated
Figure 4.23: Wind directions at Carey Park, Bunbury during the study periods a) 17th September 2006 and b) 18th September 2006. The duration of each run is indicated.

Water level
The water level recorded within the Bunbury Inner harbour on 17th September 2006 dropped from a maximum observed during the early hours of the morning to a minimum reported mid-afternoon (Figure 4.24a). As such, run 1 was performed on the ebb tide and run 2 on the turn of the tide an hour later. The water level recorded on 18th September 2006 followed a similar trend (Figure 4.24b). However, the peak water level was higher; the minimum water level was lower; and the rate of change between the two was faster. Run 3 and run 4 occurred on the ebb tide, and run 5 and 6 were performed on the turn of the tide mid-afternoon.
Figure 4.24: Water levels measured within the Bunbury Inner harbour during the study periods a) 17th September 2006 and b) 18th September 2006. The duration of each run is indicated

4.3.3 Dispersion

The plots used to calculate the dispersion coefficients for each run at Koombana Bay are included in Appendix C. An example plot, run 5, is featured in Figure 4.25 below. The dispersion coefficients $K$, $K_x$ and $K_y$ calculated for each of the six drifter runs performed at Koombana Bay are featured in Table 4.10 below. The mean dispersion coefficients were found to be $K = 0.4 \text{ m}^2/\text{s}$ ($\pm$ a 95% confidence interval of 0.2), $K_x = 0.5 \text{ m}^2/\text{s}$ ($\pm$0.2) and $K_y = 0.6 \text{ m}^2/\text{s}$ ($\pm$0.7).
Table 4.10: The dispersion coefficients ($K_x$, $K_y$ and $K$) and their associated coefficients of determination ($R_x^2$, $R_y^2$ and $R^2$) calculated for Koombana Bay, reported in m$^2$/s

<table>
<thead>
<tr>
<th>(m$^2$/s)</th>
<th>$K_x$</th>
<th>$R_x^2$</th>
<th>$K_y$</th>
<th>$R_y^2$</th>
<th>$K$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.133</td>
<td>0.917</td>
<td>0.099</td>
<td>0.822</td>
<td>0.116</td>
<td>0.892</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.743</td>
<td>0.963</td>
<td>0.113</td>
<td>0.790</td>
<td>0.428</td>
<td>0.952</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.736</td>
<td>0.704</td>
<td>0.085</td>
<td>0.331</td>
<td>0.410</td>
<td>0.837</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.349</td>
<td>0.900</td>
<td>0.054</td>
<td>0.272</td>
<td>0.201</td>
<td>0.946</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.325</td>
<td>0.900</td>
<td>1.607</td>
<td>0.951</td>
<td>0.966</td>
<td>0.946</td>
</tr>
<tr>
<td>Run 6</td>
<td>0.486</td>
<td>0.796</td>
<td>0.434</td>
<td>0.855</td>
<td>0.460</td>
<td>0.834</td>
</tr>
<tr>
<td>Mean</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.2</td>
<td>0.7</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in the average due to low correlation

The smallest dispersion coefficient was observed for run 1 (17th September 2006), while the largest dispersion coefficient was recorded for run 5 (18th September 2006, Figure 4.25). Dispersion coefficients for the x direction were often larger than dispersion coefficients in the y direction. However, during run 5 the dispersion in the y direction was markedly higher than the dispersion in the x direction, and dispersion in the x and y directions were similar for run 6 (Figure 4.25).

Figure 4.25: Plot used to calculate the dispersion coefficients for run 5, Koombana Bay, 18th September 2006
4.3.4 Time Dependence

The log-log plots indicating the time dependence of the dispersion (dispersion diagrams) for each run at Koombana Bay are included in Appendix C. An example plot, run 2, is featured in Figure 4.26 below. The time dependence coefficients ($a_x, a_y, a$ and $b_x, b_y, b$) calculated for each of the six drifter runs performed at Koombana Bay are featured in Table 4.11 below. The mean time dependence coefficients gave the time power laws:

$$\sigma^2 = 0.001 t^{1.8}$$
$$\sigma_x^2 = 0.001 t^{1.9}$$
$$\sigma_y^2 = 0.007 t^{1.7}$$

Table 4.11: The time dependence coefficients ($a_x, a_y, a$ and $b_x, b_y, b$) and their associated coefficients of determination ($R_x^2, R_y^2$ and $R^2$) calculated for Koombana Bay, reported in $m^2$

<table>
<thead>
<tr>
<th>(m$^2$)</th>
<th>$a_x$</th>
<th>$b_x$</th>
<th>$R_x^2$</th>
<th>$a_y$</th>
<th>$b_y$</th>
<th>$R_y^2$</th>
<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>4.74E-05</td>
<td>1.948</td>
<td>0.928</td>
<td>4.72E-03</td>
<td>1.392</td>
<td>0.965</td>
<td>9.93E-04</td>
<td>1.585</td>
<td>0.973</td>
</tr>
<tr>
<td>Run 2</td>
<td>5.47E-03</td>
<td>1.634</td>
<td>0.976</td>
<td>2.39E-05</td>
<td>2.001</td>
<td>0.934</td>
<td>2.45E-03</td>
<td>1.659</td>
<td>0.977</td>
</tr>
<tr>
<td>Run 3</td>
<td>1.36E-04</td>
<td>2.016</td>
<td>0.823</td>
<td>1.33E-02</td>
<td>1.408</td>
<td>0.820</td>
<td>1.30E-03</td>
<td>1.756</td>
<td>0.976</td>
</tr>
<tr>
<td>Run 4</td>
<td>4.43E-04</td>
<td>1.867</td>
<td>0.949</td>
<td>2.34E-02</td>
<td>1.240</td>
<td>0.839</td>
<td>2.03E-03</td>
<td>1.637</td>
<td>0.957</td>
</tr>
<tr>
<td>Run 5</td>
<td>2.37E-03</td>
<td>1.650</td>
<td>0.974</td>
<td>1.23E-04</td>
<td>2.237</td>
<td>0.967</td>
<td>3.17E-04</td>
<td>2.051</td>
<td>0.975</td>
</tr>
<tr>
<td>Run 6</td>
<td>1.14E-05</td>
<td>2.377</td>
<td>0.870</td>
<td>8.74E-04</td>
<td>1.845</td>
<td>0.952</td>
<td>2.70E-04</td>
<td>1.985</td>
<td>0.939</td>
</tr>
<tr>
<td>Mean</td>
<td>0.001</td>
<td>1.9</td>
<td>0.007</td>
<td>0.007</td>
<td>1.7</td>
<td>0.001</td>
<td>0.3</td>
<td>0.001</td>
<td>0.2</td>
</tr>
<tr>
<td>95% CI</td>
<td>0.002</td>
<td>0.2</td>
<td>0.008</td>
<td>0.3</td>
<td>0.3</td>
<td>0.001</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The log-log plots of time dependence (Appendix C) indicate that the variance of drifter position was fairly constant for the first 50-100 s of drift time. Following this the variance increased exponentially, with few peaks or troughs. This general trend was displayed well during run 5, as shown by Figure 4.26 below.
4.3.5 Scale Dependence

The log-log plots indicating the scale dependence of the dispersion (dispersion diagrams) for each run at Koombana Bay are included in Appendix C. An example plot, run 6, is featured in Figure 4.27 below. The scale dependence coefficients ($c_x$, $c_y$, $c$ and $d_x$, $d_y$, $d$) calculated for each of the six drifter runs performed at Koombana Bay are featured in Table 4.12 below. The mean scale dependence coefficients gave the scale power laws:

$$K = 0.018 \sigma^{1.2}$$

$$K_x = 0.016 \sigma^{1.3}$$

$$K_y = 0.018 \sigma^{1.2}$$

Table 4.12: The scale dependence coefficients ($c_x$, $c_y$, $c$ and $d_x$, $d_y$, $d$) and their associated coefficients of determination ($R_x^2$, $R_y^2$ and $R^2$) calculated for Koombana Bay, reported in m$^2$/s

<table>
<thead>
<tr>
<th>Run</th>
<th>$c_x$</th>
<th>$d_x$</th>
<th>$R_x^2$</th>
<th>$c_y$</th>
<th>$d_y$</th>
<th>$R_y^2$</th>
<th>$c$</th>
<th>$d$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.008</td>
<td>1.167</td>
<td>0.746</td>
<td>0.010</td>
<td>1.093</td>
<td>0.748</td>
<td>0.009</td>
<td>1.108</td>
<td>0.874</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.027</td>
<td>1.054</td>
<td>0.734</td>
<td>0.005</td>
<td>1.389</td>
<td>0.696</td>
<td>0.021</td>
<td>1.049</td>
<td>0.763</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.009</td>
<td>1.589</td>
<td>0.818</td>
<td>0.050</td>
<td>0.697</td>
<td>0.347</td>
<td>0.012</td>
<td>1.361</td>
<td>0.805</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.017</td>
<td>1.242</td>
<td>0.726</td>
<td>0.022</td>
<td>0.931</td>
<td>0.514</td>
<td>0.020</td>
<td>1.094</td>
<td>0.677</td>
</tr>
<tr>
<td>Run 5</td>
<td>0.022</td>
<td>1.072</td>
<td>0.792</td>
<td>0.035</td>
<td>1.136</td>
<td>0.795</td>
<td>0.031</td>
<td>1.102</td>
<td>0.827</td>
</tr>
<tr>
<td>Run 6</td>
<td>0.012</td>
<td>1.487</td>
<td>0.815</td>
<td>0.018</td>
<td>1.316</td>
<td>0.799</td>
<td>0.013</td>
<td>1.403</td>
<td>0.909</td>
</tr>
<tr>
<td>Mean</td>
<td>0.016</td>
<td>1.3</td>
<td>0.018</td>
<td>1.2</td>
<td>0.018</td>
<td>1.2</td>
<td>0.007</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>95% CI</td>
<td>0.006</td>
<td>0.2</td>
<td>0.010</td>
<td>0.2</td>
<td>0.007</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Entries shaded in yellow were not included in the average due to low correlation.
The dispersion coefficients for each run increased exponentially with length scale (i.e. standard deviation). A good example is run 6, as featured in Figure 4.27. The largest increase in dispersion with scale was observed for run 6 (Figure 4.27) and for run 3 in the x and overall directions (Table 4.12). Only a small increase in dispersion with scale was observed in the y direction for run 3.

![Log-log plot of the dispersion coefficients against the standard deviation](image)

**Figure 4.27:** Log-log plot of the dispersion coefficients against the standard deviation (a dispersion diagram) indicating the scale dependence of dispersion for run 6, Koombana Bay, 18th September 2006

### 4.3.6 Turbulence and Diffusivity

Plots featuring the variation in both dispersion and diffusion with time for each of the six runs performed at Koombana Bay run are included in Appendix C. An example plot, run 6, is featured in Figure 4.28 below. The diffusion coefficients were consistently less than the dispersion coefficients calculated for each run.

The rates of diffusion identified for Koombana Bay ranged from 0.005-1.029 m$^2$/s. The highest values of dispersion and diffusion were recorded for run 5, while the lowest were recorded for run 1. As observed for Fays Bay and Osprey Bay, $K_x$ and $K_y$ were generally out of phase while trends in $k_x$ were mostly the same as trends in $k_y$ (see Figure 4.19). Various peaks and troughs in the rate of dispersion and diffusion were observed during run 1 and run 2, although the overall trend was increasing. An increase in the rate of dispersion and diffusion was generally observed at about 40 min during runs 3 to 6. This feature is also demonstrated in Figure 4.19.
Figure 4.28: Plots featuring the rate of a) dispersion and b) diffusion against time for run 6 at Koombana Bay.
5 Discussion

In the following section the results obtained for each study site are discussed. In section 5.1 the environmental conditions observed at the three regions are compared with the dispersion coefficients calculated. In section 5.2 the dispersion coefficients identified during this study are compared with the findings of other relevant studies. Similarly, in section 5.3 the time and scale dependence of dispersion observed during this study is compared with that of other relevant studies. Finally the diffusivities identified for each study site are discussed in section 5.4.

5.1 Environmental Conditions

Fays Bay

The environmental conditions observed at Fays Bay on the 20th September 2004 were associated with the passing of a low pressure system. Conversely, the conditions observed at Fays Bay on 23rd September 2004 were associated with a typical winter anticyclone, or high pressure system. As such, the conditions provided for study were good examples of the two extreme weather options for the region.

The highest rates of dispersion at Fays Bay were observed for the longer distance runs on 20th September 2004, which generally occurred in conjunction with high current velocities, high water levels, large significant wave heights, long mean wave periods, and north to north-westerly winds (i.e. onshore conditions). Conversely, the lowest rates of dispersion were observed for the shorter distance runs on 23rd September 2004, which generally occurred in conjunction with lower current velocities, lower water levels, lower significant wave heights, shorter mean wave periods and S-SE winds (i.e. offshore conditions). The exception was run 5, 23rd September 2006, which reported a relatively high rate of dispersion despite its short trajectory and the environmental conditions described.

The dispersion rate observed at Fays Bay increased as the water level fell, wind speed increased and wind direction swung to the south on 23rd September 2004. Current velocities remained similar throughout the day, suggesting that the increase in dispersion may have been driven by direct wind mixing rather than wind or tide driven currents (as described in section 2.2). However, Fays Bay is largely protected from southerly winds. Correlation does not prove cause, and as such the increase in dispersion observed most probably resulted from some other means such as natural variation.
Osprey Bay

Environmental conditions at Osprey Bay over the three day study period were atypical of the Ningaloo region. Wind speeds were less than average, and the wave heights observed were substantially less than the mean annual wave height of 2 m. Wave direction was from mainly from the west, rather than the predominant south to south-westerly driven swell waves.

There was no clear trend in the wind speed, wind direction, wave direction or current velocity associated with the dispersion recorded within Osprey Bay over the study period. However, these variables did not change substantially over the interval observed, with the exception of wind direction. The highest rates of dispersion were recorded in conjunction with the lowest wave activity observed, and vice versa. Wave energy is commonly thought to drive dispersion in the nearshore zone, as found by Spydell et al. (2006), but these results suggest differently. Lower wave action is known to result in slower cross shore and longshore currents within such regions (C. Pattiaratchi pers comm. 2006). Under these conditions the drifters would experience less focused advection, and possibly have more capacity to disperse. However, no clear trend in current velocity and dispersion was identified. The drop in wave activity associated with the increase in dispersion was marginal, so it is likely that the increase in dispersion resulted from some other means such as natural variation.

As described above, wave heights observed over the study period were lower than average for the region. Possibly if measurements of dispersion were taken in the other extreme of wave activity (i.e. during wave heights larger than average for the region), a trend between wave magnitudes, current velocity and dispersion may be identified. At this point it should be noted that if wave energy is a contributing factor to dispersion within Osprey Bay as suspected, then the estimates of dispersion identified may not be typical. This should be remembered when comparing the mean rate of dispersion identified for Osprey Bay with other estimates of dispersion.

Koombana Bay

Environmental conditions at Koombana Bay over the two day study period were associated with the passing of a low pressure system, featuring strong winds and possibly elevated water levels resulting from storm surge. As such, the weather observed represents one of the two extreme weather options for the region.

There was no clear trend in wind speed, wind direction, current velocity or water level associated with the dispersion recorded at Koombana Bay over the period of study. However,
as described above, only one extreme example of conditions was observed. It is likely that dispersion coefficients obtained during calmer weather (i.e. during the dominance of a high pressure system) would be considerably different. For example, with conditions of light or no winds; wind mixing, wind driven currents and the resulting dispersion are likely to be minimal. Trends between the wind speed and direction and the rate of dispersion observed across the two extreme weather options would likely be identified.

At this point it should be noted that because the conditions observed at Koombana Bay over the study period are considered extreme, the dispersion coefficients identified are also likely to be extreme. This should be remembered when comparing the mean rate of dispersion identified for Koombana Bay with other estimates of dispersion.

### 5.2 Dispersion coefficients

The mean rate of dispersion at Fays Bay (0.05 m$^2$/s) was half the mean rate of dispersion at Osprey Bay (0.1 m$^2$/s). Both of these were substantially lower than the mean rate of dispersion observed at Koombana Bay (0.4 m$^2$/s). In addition, at both Fays Bay and Osprey Bay the longshore dispersion was generally larger than the cross-shore dispersion observed over the study periods. These variations can be at least partially explained by the topographical restrictions present at both regions. At Fays Bay these restrictions include the surf zone (associated with the offshore reefs), and the shallow inside zone of the Bay (Figure 2.17). At Osprey Bay the limitations are the surf zone (associated with the reef crest and flat) and the shoreline (Figure 2.19). These features form boundaries that reduce the capacity for dispersion within these regions, most noticeably in the cross-shore direction. The shoreline is the only boundary present at Koombana Bay (Figure 2.21), and as such this site displays an elevated rate of dispersion, with similar mean dispersion coefficients in the x and y direction. The main exception to this trend was run 2 at Osprey Bay, which exhibited a relatively large rate of dispersion in the cross-shore direction, and a relatively small rate of dispersion in the longshore direction. This can be rationalised by the fact that during this experiment the drifters moved out through the gap in the main reef line and became restricted in the longshore rather than cross-shore direction (Figure 4.11).

Several studies have documented reduced rates of cross-shore dispersion in response to the imposed boundary of a surf zone as observed for Fays and Osprey Bay. Inman et al. (1971) describe that dye released within a surf zone is rapidly mixed in the cross-shore direction until it completely fills the region. Following this however, the dispersion appears to be contained within the surf zone, partially due to the absence of turbulence outside the break point (Inman
et al. 1971), but most probably due to the advection of offshore water through the breaker line (Bowen & Inman 1974). Reduced dispersion in the cross-shore direction of the surf zone has more recently been observed by Johnson (2004), Mariani (2004) and Jones (2005). Johnson (2004) reported a mean cross-shore dispersion coefficient of 0.2 m²/s in comparison to a mean longshore dispersion coefficient of 0.3 m²/s for drifter experiments performed at Scarborough Beach. Mariani (2004) identified cross-shore dispersion coefficients for similar investigations at Floreat Beach ranging from 0.3-2.1 m²/s, as opposed to longshore dispersion coefficients ranging from 0.40-3.3 m²/s. Jones (2005) determined cross-shore rates of dispersion for Henley Beach using surf zone drifters that ranged from 0-0.24 m²/s compared with longshore dispersion rates of 0-0.83 m²/s. Although the drifter experiments performed at Fays Bay and Osprey Bay during this study occur in front of rather than within the surf zone, the restriction in the cross-shore direction still applies.

The relatively low values of dispersion reported for Fays Bay can also be rationalised by the small length scale of the experiments performed. Fays Bay is small, measuring approximately 100 m from headland to headland. As such the drifters could not travel far before leaving the Bay, getting stuck on the bottom or drifting too close to the rocks. The scope for dispersion was therefore greatly reduced at Fays Bay in comparison to the Osprey Bay study site (which was about 3.5 km long and 1 km wide) and Koombana Bay (about 1.5 km long and 2 km wide). The relatively high rates of dispersion reported for Koombana Bay could also be due to the extreme conditions observed during the study period. Further investigation would be required to test this hypothesis.

Table 5.1 below summarises relevant measurements of dispersion taken to date. The mean coefficients determined during this study fall within the broad range identified by Riddle & Lewis (2000). This is as expected because these values were derived from a wide variety of ocean environments, ranging from weak tidal currents of low energy lochs to strong tidal flows along the coast. The mean coefficients determined during this study are markedly smaller than the coefficients determined by Tseng (2002) and Verspecht (2002). This is also as expected, because these values were derived in the open ocean, in energetic (rather than sheltered) regions, unbounded by topographical restrictions associated with the coast. In addition, Tseng’s (2002) values were derived via linear regression of the latter stage of the experiments performed, where rates of dispersion were the highest.

The mean dispersion rates measured during this study are larger than those predicted by Takewara et al. (2003) from dye dispersion experiments at a sandy beach in Hasaki, Japan. It
is counter-intuitive for the dispersion in the sheltered regions studied here to be greater than the dispersion witnessed at the mildly energetic sandy beach studied by Takewara et al. (2003). In addition, drifters cannot be sheared and mixed vertically (resulting in longitudinal dispersion) and are only responsive to transverse and longitudinal shear. This would suggest that rates of dispersion observed with drifters would be less than analogous rates of dispersion observed with dye. This renders the difference in results observed by this study and those found by Takewara et al. (2002) even more unexpected. However, as described in section 2.4.6, considerable errors were associated with Takewara et al.’s (2003) determination of the dispersion coefficient from the moored video used.

The mean coefficients determined during this study are smaller than those identified by Johnson & Pattiaratchi (2004) and Olsson (2004) for within a rip head. This is unsurprising, as both Johnson & Pattiaratchi (2004) and Inman et al. (1971) observed lower rates of dispersion prior to and following rip head expansion, indicating that dispersion is magnified within the rip head. Run 2 at Osprey Bay (Figure 4.11, when the drifters moved offshore through the gap in the main reef line) was the only run that encountered a rip system during this study. However, the drifters were collected before they reached the rip head, so no significant enhancement was observed.

The mean dispersion rates measured during this study are smaller than those measured by Mariani (2004) within the surf zone of Floreat Beach. The mean coefficients determined for Fays Bay and Osprey Bay are also smaller than the coefficients determined for within the surf zone of Scarborough Beach by Johnson (2004). This result is as expected because these beaches are more energetic than the protected regions investigated during this study. The mean coefficients for Koombana Bay are comparable with Johnson’s (2004) results. Although it may seem counter-intuitive that this sheltered embayment would result in a higher rate of dispersion than a surf zone, the surf zone is bounded by the breakers and the shoreline, and thus the capacity for dispersion in the cross-shore direction is reduced. As described above, dispersion within Koombana Bay is bounded only by the shoreline.

The mean coefficients determined during this study are comparable with those found by Jones (2005) for Henley Beach, Adelaide. Henley Beach is a low energy sandy beach, with a mean annual incident wave height of less than 0.5 m (Jones 2005). As such, it is logical that dispersion estimates for Henley Beach would be similar to those for the sheltered sites surveyed during this study.
Table 5.1: Summary of relevant measurements of dispersion taken to date; detailing the author, dispersion coefficient range and/or mean value, method used and study location

<table>
<thead>
<tr>
<th>Author</th>
<th>$K_{\text{range}}$ (m$^2$/s)</th>
<th>$K_{\text{mean}}$ (m$^2$/s)</th>
<th>Method</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>List et al. (1999)</td>
<td>-5 - 55</td>
<td>-</td>
<td>Radar tracked drogues</td>
<td>Coastal waters, southern California</td>
</tr>
<tr>
<td>Riddle &amp; Lewis (2000)</td>
<td>0.002 - 31.1</td>
<td>-</td>
<td>Dye dispersion</td>
<td>Estuaries, lochs and coastal waters, UK</td>
</tr>
<tr>
<td>Tseng (2002)</td>
<td>-</td>
<td>12.5</td>
<td>GPS/ARGOS surface drifters</td>
<td>An estuary zone and an island wake, south-western Taiwan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verspecht (2002)</td>
<td>1 - 100</td>
<td>-</td>
<td>GPS surf zone drifters</td>
<td>Exmouth Gulf, North West Cape, WA</td>
</tr>
<tr>
<td>Takewara et al. (2003)</td>
<td>0.01 - 0.03</td>
<td>-</td>
<td>Dye dispersion</td>
<td>A sandy beach, Hasaki, Japan</td>
</tr>
<tr>
<td>Mariani (2004)</td>
<td>0.2 - 1.8</td>
<td>0.8</td>
<td>GPS surf zone drifters</td>
<td>Floreat Beach, Perth, WA</td>
</tr>
<tr>
<td>Olsson (2004)</td>
<td>0.6 - 4.1</td>
<td>-</td>
<td>GPS surf zone drifters</td>
<td>Cottesloe Beach, Perth, WA</td>
</tr>
<tr>
<td>Johnson (2004)</td>
<td>-</td>
<td>0.2 ($K_x$)</td>
<td>GPS surf zone drifters</td>
<td>Scarborough Beach, Perth, WA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3 ($K_y$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Johnson &amp; Pattiaratchi (2004)</td>
<td>1.3 - 3.9</td>
<td>-</td>
<td>GPS surf zone drifters</td>
<td>Scarborough Beach, Perth, WA</td>
</tr>
<tr>
<td>Jones (2005)</td>
<td>0.01 - 0.7</td>
<td>0.1</td>
<td>GPS surf zone drifters</td>
<td>Henley Beach, Adelaide, SA</td>
</tr>
<tr>
<td>Sydell et al. (2006)</td>
<td>0.1 - 1</td>
<td>-</td>
<td>GPS surf zone drifters</td>
<td>A sandy beach, San Diego, California</td>
</tr>
<tr>
<td>This study</td>
<td>0.02 – 0.07</td>
<td>0.05</td>
<td>GPS surf zone drifters</td>
<td>Fays Bay, Rottnest Island</td>
</tr>
<tr>
<td>This study</td>
<td>0.04 – 0.2</td>
<td>0.1</td>
<td>GPS surf zone drifters</td>
<td>Osprey Bay, Ningaloo</td>
</tr>
<tr>
<td>This study</td>
<td>0.1 – 1.0</td>
<td>0.4</td>
<td>GPS surf zone drifters</td>
<td>Koombana Bay, Bunbury</td>
</tr>
</tbody>
</table>
5.3 Time and scale dependence

Generally both the time and scale dependence of dispersion at Fays Bay displayed a clear power law relationship, with the variance of drifter position and dispersion growing according to $t^{1.0}$ and $\sigma^{1.4}$ respectively. The main exception was run 3, where the dispersion showed little time or scale dependence. This can be explained by the fact that during run 3 the drifters were washed up on the western headland only meters from their release point in the western channel. As such, run 3 was the shortest experiment performed in terms of both time and length scale and recorded the smallest rate of dispersion. The time and scale dependence of dispersion at Osprey Bay also displayed a clear power law relationship, with the variance of drifter position and dispersion growing according to $t^{1.4}$ and $\sigma^{1.3}$ respectively. Run 1 exhibited the lowest time and scale dependence of dispersion, correlating with the smallest dispersion coefficient calculated for the study site. As observed for both Fays Bay and Osprey Bay, the time and scale dependence of dispersion at Koombana Bay displayed a clear power law relationship, with the variance of drifter position and dispersion growing according to $t^{1.8}$ and $\sigma^{1.2}$ respectively.

Okubo collated data for a number of instantaneous dye release experiments performed in the open ocean (see section 2.4.1) and found that the variance of drifter position varied according to $\sigma^2 \sim t^{2.3}$, a time power law markedly larger than indicated by this study. Spydell et al. (2006) also investigated the time dependence of dispersion during their study of a sandy beach in San Diego (see section 2.4.7) and found that the variance of drifter position grew according to $\sigma^2 \sim t^{1.5}$. This finding is similar to the time power law identified for Osprey Bay, which was in between the time power laws found for Fays Bay and Koombana Bay.

Batchelor (1952) derived a theoretical relationship between variance and time through considering a field of homogenous turbulence and applying local similarity theory, as described in section 2.1.4. He found the correlation $\sigma^2 \sim t^3$, or the third power law of time. A plot of the time dependence observed at the three study sites in comparison to the third power law of time is featured in Figure 5.1. The range of the $\sigma^2 \sim t^3$ law presented corresponds to the results of Okubo (1971; 1974) for the third power law of variance fitted locally, as described in section 2.4.1 and shown in Figure 2.9. Figure 5.1 shows that the findings of this study differ markedly from those predicted by Batchelor’s (1952) theory. The results of Spydell et al. (2006) also differ substantially. Spydell et al. (2006) rationalise this by suggesting that the eddy field responsible for the dispersion measured at their site was not a classical two dimensional inertial subrange field (with an energy cascade as described in
section 2.1.3), and as such Batchelor’s derivation is inapplicable (see section 2.4.7). However, the similarity theory used by Batchelor (1952) is not the only theory which deduces the third power law of variance. In the case of a uniform vertical shear in the horizontal current, the longitudinal variance has been shown to be proportional to $\Omega^2 k_z t^3$ (see section 2.1.5, Equation 2.27).

![Figure 5.1: Plot featuring the time dependence observed at the three study sites in comparison with the third power law of variance fitted locally by Okubo (1974)](image)

Table 5.2 below summarises relevant measurements of scale dependence taken to date. Most of the power laws indicated in Table 5.2, including those obtained during this study, are remarkably similar to that proposed by Richardson (1926), developed theoretically by Batchelor (1952) and supported by Okubo (1971; 1974) - the 4/3 power law. As described in section 2.4.1, the data analysed by Okubo spanned large time (2 hrs to 1 month) and length (30 m to 100 km) scales. The data presented in Table 5.2 also spans a variety of time and lengths scales. On broad scales ocean conditions will not be isotropic and homogeneous. Hence, it is surprising that all these data follow a single law very similar to that found by Richardson (1926) and derived by Batchelor (1952) under the assumption of isotropy and homogeneity.
A plot of the scale dependence observed at the three study sites in comparison with the 4/3 power law is featured in Figure 5.2. The range of the $K \sim \sigma^{4/3}$ law presented corresponds to the results of Okubo (1971; 1974) for the 4/3 power law fitted locally, as described in section 2.4.1 and shown in Figure 2.10. The plot shows that the results of this study correlate strongly with the 4/3 law. However, the scale dependence observed for Fays Bay and Koombana Bay is slightly offset from Okubo’s (1971; 1974) findings, due to higher $y$ intercepts. Larger offsets were observed by List et al. (1990) and Jones (2005). List et al. (1990) observed an offset of two orders of magnitude, while Jones observed an offset of a single order of magnitude. Both offsets were attributed to increased shear dispersion close to the coast (as described in sections 2.4.3 and 2.4.8). If this rationale is applicable, the slight offset recorded during this study suggests that the contribution of shear towards the overall dispersion was less than observed during the studies by List et al. (1990) and Jones (2005).
5.4 Diffusivity

As described in section 4.1.6, the diffusion coefficients calculated for run 2 and run 4 at Fays Bay were consistently greater than the dispersion coefficients, implying a situation that is impossible, and as such must be disregarded. These findings suggest that the statistical and theoretical assumptions applied by the Okubo and Ebbesmeyer (1976) technique for the isolation of diffusion effects from the overall dispersion are not valid for the run’s in question. The reasons for this are unclear, as the method gave realistic results for the other runs performed at this study site.

The rates of diffusion reflected the rates of dispersion observed at Fays Bay; low values of dispersion were associated with low diffusivities (run 3), and high values of dispersion were associated with high diffusivities (run 1 and run 5). This suggests that diffusion was an important component of the dispersion measured at Fays Bay.

As found for Fays Bay, at Osprey Bay the rates of diffusion generally reflected the rates of dispersion observed, suggesting that diffusion was an important component of the overall dispersion. In addition, many of the features observed in the rates of dispersion and diffusion recorded for each run at Osprey Bay corresponded to particular features of the study site. The increase in diffusion after 60 min and the peak in dispersion at 70-80 min observed for run 2 corresponded to the drifters reaching the gap in the main reef line, as shown in Figure 5.3.
The dispersion and diffusion in the cross-shore direction experienced the greatest increase, as the drifters were no longer restricted by the surf zone. The peaks observed in the diffusion at 60 and 80 min for run 3 corresponded to the drifters crossing the edge of the reef flat and entering the deepest section of the southern lagoon respectively. The peak observed in the diffusion at 60 min for run 4 corresponded to when the drifters turned into the south flowing longshore current. Finally the increase in both dispersion and diffusion following 90 min of drift time during run 4 corresponded to when the drifters neared the gap in the main reef line. It is likely that the hydrodynamic regime alters at these distinct locations, causing the observed increase in the dispersion and diffusion.

The rates of diffusion reflected the rates of dispersion observed at Koombana Bay during run 1 and run 2 on 17th September 2006. However, this trend was not observed for the remaining runs on 18th September 2006: runs 3 to 6 performed within the sheltered south-west corner of the Bay. For these runs dispersion increased with drift time, while diffusion remained relatively constant until about 40 min. The constant scale of diffusion suggests that shear was an important component of the dispersion observed at Koombana Bay on 18th September 2006. It is likely that wind driven currents developed with the passing of the
low pressure system, resulting transverse and longitudinal shear. The 40 min time scale corresponds to the approximate time taken for the drifters to travel across this protected region and enter the main section of Koombana Bay. As described for Osprey Bay, hydrodynamics probably alter at this point, resulting in the observed increase in diffusion.

The range of diffusivity calculated for Fays Bay (0.007-0.235 m²/s) was approximately half the range of diffusivity for Osprey Bay (0.002-0.575 m²/s). In turn, the range of diffusivity calculated for Osprey Bay was approximately half the range of diffusivity for Koombana Bay (0.005-1.029 m²/s). This trend is similar to that observed for the mean rates of dispersion determined for the three study sites. However, the mean dispersion at Koombana Bay (0.1 m²/s) was four times that observed at Osprey Bay (0.4 m²/s). This discrepancy supports the idea that shear effects were important at Koombana Bay.

The rates of dispersion observed in the x and y directions (Kx and Ky) at each of three study sites were generally out of phase. A similar phenomenon was observed by List et al. (1990), during their drogue study within coastal waters of southern California. List et al. (1990) attributed this feature to drogue set rotation, where offshore drogues moved faster than inshore drogues in response to faster offshore currents. As a result $\sigma_x^2$ and $\sigma_y^2$ increased and decreased alternately; and Kx and Ky were alternately positive and negative. A similar process occurs at the sites investigated here, although the forcing mechanism (current variation) was not necessarily provided by faster offshore currents. The diffusion coefficients identified did not display this trend, because current variation results in mixing due to shear.
6 Conclusions

The dispersion features of three key sheltered coastal regions of WA were characterised through the use of lagrangian drifters. The regions surveyed were Fays Bay, Rottnest Island; Osprey Bay, Ningaloo Reef; and Koombana Bay, Bunbury. The mean dispersion coefficients identified were \(0.05 (±0.02) \text{ m}^2/\text{s}\), \(0.1 (±0.05) \text{ m}^2/\text{s}\), and \(0.4 (±0.2) \text{ m}^2/\text{s}\) respectively. Topographical restriction imposed by the surf zone and the shoreline at Fays Bay and Osprey Bay resulted in a lower capacity for dispersion within these regions, particularly in the cross-shore direction. In addition, the relatively low dispersion values observed within Fays Bay are thought to be due to the reduced scale of this study site in comparison to the others.

The time dependence of dispersion at the study sites indicates that the variance of drifter position grew according to time to the power of 1-2. This relationship differs considerably to that predicted by Batchelor (1952) following similarity theory: \(\sigma^2 \sim t^3\). However, other studies of this nature have identified time power laws of less than that predicted by theory, including Okubo (1971;1974) and Spydell (2006).

The scale dependence of dispersion at the study sites indicates that dispersion grows according to standard deviation to the power of about 1.3. As such, the findings of this study support Richardson’s 4/3 power law.

The environmental conditions observed at Fays Bay resulted from the two extreme weather patterns possible for the region. The first day of study was influenced by the passing of a low pressure system, which produced high water levels, large significant wave heights, long mean wave periods, high current velocities and north to north-westerly winds. The resulting rates of dispersion were relatively high. The second day of study was influenced by a high pressure system, which produced lower water levels, lower significant wave heights, shorter mean wave periods, lower current velocities and south to south-easterly winds. The resulting rates of dispersion were relatively low. In contrast, the environmental conditions observed at Osprey Bay and Koombana Bay were fairly constant. Osprey Bay was influenced by low wind speeds and low wave activity, and conditions at Koombana Bay were dominated by the passing of a strong low pressure system. The resulting dispersion coefficients showed no clear associations with environmental variables monitored, although slightly higher rates of dispersion were observed in conjunction with lower wave heights at Osprey Bay.
7 Recommendations

It is recommended that the outcomes of this study be applied by relevant bodies to aid in the appropriate management of these important WA regions. More specifically, it is recommended that the dispersion coefficients identified during this study be incorporated into the numerical model planned for Ningaloo Reef as part of the Ningaloo Research Program. Model results will predict both the dispersal of contaminants entering the nearshore environment, and the transport of eggs and larvae following the spawning of important marine species. Hydrodynamic models for Rottnest Island and Koombana Bay, utilising the dispersion values determined during this study, would also contribute greatly to the successful management of these regions.

The outcomes of this study highlight areas in which future research would be highly beneficial. It is recommended that the dispersion experiments undertaken at Osprey Bay and Koombana Bay be repeated under appreciably different environmental conditions. Namely, measurements of dispersion should be taken within Osprey Bay during a period of high wind and wave activity, and within Koombana Bay during the dominance of a high pressure system. It is likely that the results of such study would indicate clear relationships between environmental conditions and the rates of dispersion observed.

It is also recommended that dispersion be investigated within another key sheltered coastal region of WA; Cockburn Sound. Cockburn Sound is the most intensively used marine embayment in Western Australia. The Sound is used for recreation, fishing and aquaculture, as an outer harbour for the Fremantle/Perth area, as a site for industries requiring access to port facilities, and as a naval base. These varied uses have led to cumulative pressures and impacts on the health of Cockburn Sound. The results of a complete characterisation of the dispersion features of the Sound could be incorporated into hydrodynamic models for the region, which are currently based on assumed dispersion coefficients.

Further research could also involve dye dispersion experiments performed simultaneously with GPS surf zone drifter deployment. This would enable a direct comparison of the two methods most commonly used for measuring dispersion. In addition, analogous experiments involving the use of drifters with one and then numerous parachute drogues (to span the depth of the water column) would indicate the influence of this feature on dispersion estimates obtained.
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Appendix A - Fays Bay
Drifter Trajectories: the solid black line indicates the position of the shoreline and the rock in the centre of the Bay, the dotted black line indicates the position of the offshore reef system, the black cross indicates the position of the moored ADV and the coloured lines represent the drifter tracks.
Dispersion Plots: plots of the variance of drifter position against time, where the lines of best fit can be used to determine the dispersion coefficients.
Time Dependence Plots: log-log plots of the variance of drifter position against time, where the lines of best fit give the time power laws.
Scale Dependence Plots: log-log plots of the dispersion coefficients against the standard deviation of drifter position, where the lines of best fit give the scale power laws
Diffusivity plots: plots featuring the rate of dispersion ($K$) and the associated rate of diffusion ($k$) against time.
Run 5

**Graph 1:**
- **K (m²/s)**
- **Kx**
- **Ky**

**Graph 2:**
- **k (m²/s)**
- **kx**
- **ky**

**Axes:**
- **Time (min)**
- **K (m²/s)**
- **k (m²/s)**
Appendix B - Osprey Bay
Drifter Trajectories: the yellow crosses indicate the position of the moored instruments (North ADV2, South ADV2 and the Inner Channel Nortek) and the coloured lines represent the drifter tracks.
Dispersion Plots: plots of the variance of drifter position against time, where the lines of best fit can be used to determine the dispersion coefficients.
Time Dependence Plots: log-log plots of the variance of drifter position against time, where the lines of best fit give the time power laws.
Scale Dependence Plots: log-log plots of the dispersion coefficients against the standard deviation of drifter position, where the lines of best fit give the scale power laws.
Diffusivity plots: plots featuring the rate of dispersion ($K$) and the associated rate of diffusion ($k$) against time.
Drifter Trajectories: the solid black line indicates the position of the shoreline and the coloured lines represent the drifter tracks.
Dispersion Plots: plots of the variance of drifter position against time, where the lines of best fit can be used to determine the dispersion coefficients.
Time Dependence Plots: log-log plots of the variance of drifter position against time, where the lines of best fit give the time power laws
Scale Dependence Plots: log-log plots of the dispersion coefficients against the standard deviation of drifter position, where the lines of best fit give the scale power laws.
Diffusivity plots: plots featuring the rate of dispersion ($K$) and the associated rate of diffusion ($k$) against time.