The University of Western Australia

‘Oceanographic studies around the North West Cape, Western Australia’

Florence Verspecht

“This thesis is submitted in partial fulfillment for the degree of Bachelor of Engineering from the Department of Environmental Engineering, at the University of Western Australia.”

November 2002

Acknowledgements

Throughout this year there have been many people who have generously given their time, thoughts, support and help and without them this thesis would have been much harder to complete.

The first thank you goes to my supervisor Professor Charitha Pattiaratchi. He has guided, helped and advised on many aspects of this study and was always ready with ideas and answers to my list of questions.

To the Australian Institute of Marine Science for the use of the data and the experience of working aboard the RV Cape Ferguson, it was quite an adventure. Also to David Johnson of CWR for lending your nifty drifters for the trip, they were a pleasure to use.

Special thanks to Dave and to Karen for editing and to Bernie for the groovy bathymetry. Your time and efforts are truly appreciated.

Finally, I'd like to thank my parents for your devoted support, love and attention throughout the year. I don't think anyone else would have been so excited about tidal fronts, yet you both listened and were involved with everything. Patrish, your prayers were appreciated. Thank you for all the fun and laughs we had this year and for your help in so many ways. Last, but definitely not least, thank you Trinnie for the motivation you gave when I was stuck and the love and understanding when I was stressed. It has been a fantastic year.

Abstract

Oceanographic studies were conducted on an expedition around the North West Cape, Western Australia aboard the AIMS research vessel Cape Ferguson. A conductivity-temperature-depth profiler was used to complete a transect through the entrance of the Gulf to define the density, temperature, salinity, chlorophyll *a* and irradiance. The profiler was also moored to the research vessel to examine the water structure in that position with time. Eulerian measurements were obtained using an InterOcean S4 vector averaging current meter and an acoustic Doppler current profiler. Lagrangian studies were conducted around the Cape investigating convergence through the use of drogued-drifters. The drifter results were plotted as current speeds, analysed for dispersion as a cluster and the difference between surface and deep drogue movement was investigated. The results of the dispersion calculations were compared to the results of the oceanic diffusion studies of Okubo (1974).

The oceanographic picture that emerges around the arid North West Cape is of a region dominated by strong localised tidal currents. The deeper waters outside the Gulf are stratified in temperature while the waters inside the Gulf are vertically well mixed, more turbid and higher in chlorophyll *a*. The strong current system into the Gulf drives the mixing between the stratified water mass and the vertically mixed waters enhancing the productivity at the entrance. The frontal system manifests as surface expressions around Point Murat, along the boundary of the two water masses where the tidal currents are strongest and this slick of plankton attracts higher order species to the front feeding on the abundant prey.

The dispersion coefficients are found to be low, but are considered acceptable, as this range is used in numerical models. Secondary circulation is observed to push the surface waters offshore causing the deeper waters to move towards the coast as a replacement, hence upwelling colder, nutrient rich water at the tips of the Cape. This transverse velocity is approximately 37.9% of the streamwise velocity and the flow regime is a balance between inertia and centrifugal forces. Instabilities are present in the wake of the headland at Point Murat during the strongest tides. This is evident from the drifters and from calculation of the Island Wake Parameter. The region around Point Murat is considered most sensitive due to these eddy-like rotations and the accumulation of particles, therefore numerical modeling is suggested as a further investigation into the dynamics of the circulation around the North West Cape.

Table of Contents

1.0 Introduction

This research is focused on the oceanography around the North West Cape of Western Australia, in the entrance to Exmouth Gulf. The continental shelf in this area is very close to the land. At the entrance to the Gulf the shelf and Gulf water masses converge and are mixed through the action of strong localised tidal currents through the entrance channel. The result of this is the formation of tidal fronts, areas of enhanced biological productivity that attract fish and other higher order biota. The hypothesis presented proposes that the frontal systems investigated around the North West Cape are important in the scope of the physical and biological oceanographic processes around the mouth of the Gulf, and that they must be considered in future environmental management programs. A thorough study is made of the physical processes including circulation and mixing, and water properties. These results are then correlated with previous biological studies of the region.

The Ningaloo Marine Park includes the entrance to Exmouth Gulf and plays host to a plethora of marine life, boasting some of the most exquisite and beautiful creatures in the sea. Although it is dived year round, the reef particularly attracts divers seasonally around April to May for the annual aggregation of the largest fish in the world, the whale shark. The biology of these creatures is little understood, so it will be important for biological researchers to match any physical oceanographic information such as is presented here, to what they know of the sharks. Dolphins and turtles are also abundant near the reef, and are sighted daily when working around the Cape. Pods of dolphins were seen, especially around Point Murat where the fronts formed, feeding off the fish. Therefore it is imperative for the conservation of these marine mammals that more knowledge is gained of the circulation, development and movement of frontal systems in the area.

Environmental management programs (EMP's) for economic, social and scientific proposals are required in both the government and private sector and rely directly on the information gained from research conducted in a specific region. It is essential that marine studies be conducted in the sensitive and relatively pristine environment of the Ningaloo Marine Park so that a broader insight into the physical processes controlling the ecology of the region is acquired. An objective of this study is to create an increased awareness that anthropogenic activities affecting the water quality will also affect the marine fauna and hence jeopardise the resources of the Gulf in terms of tourism, recreational and commercial fisheries. With an understanding of the physical oceanographic processes occurring in the mouth of the Gulf, including the mechanisms generating and maintaining frontal systems, authorities will have the power to protect this fragile marine environment from the harmful influences that come with the pressure of increased development in tourism and industry. The Ningaloo Marine Park is without doubt one of Western Australia's greatest environmental assets, and it is for this reason that a study is undertaken here and that the results are conveyed to parties involved in the protection and environmental management of the park.

Historically, there is no extensive data set on the region encompassing the entrance to the Gulf. Therefore it is necessary for data such as this to be collected for use with numerical models of oil spill trajectories, the fate of contaminants and the transport of drilling muds and solids. Hydrodynamic numerical models are used in risk and impact assessments that are required during the planning stages of potentially hazardous activities. Frontal systems around the Cape directly affect the transport and fate of contaminants and pollutants from the land and around Point Murat. A goal of this study is to quantify the fronts and describe their structure and position. This will permit future prediction of where the fronts will form and when they will occur during the tidal cycle, thus allowing management of the area in terms of shipping routes, boating, waste disposal and mining.

Article 61 of the United Nations Convention on the Law of the Sea (UNCLOS) has been signed by Australia and is implemented through the action plan of Agenda 21. It imposes obligations for Australia to promote sustainability through the regulation of fish catches and prevention of over-exploitation, suggesting efforts be made for the advancement of scientific marine research and the exchange of this information (Commonwealth of Australia 1995) which is cited in Gordon (2000). In response to this agreement, competent organisations including the Australian Institute of Marine Science (AIMS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) embarked upon long-term research projects that would fulfill these objectives. The North West Shelf of Australia is one particular area where these institutions focused their attention through the implementation of a four year North West Shelf Joint Environmental Management Study (NWSJEMS), initiated in 1998. A continuation of this project is progressing on the shelf by way of fine-scale modeling and intensive site-specific investigations.

A review of the North West Shelf studies (Heyward, Revill & Sherwood 2000) notes that there are gaps in our understanding of the role of tidal mixing in the plankton dynamics of the nearshore, and refers to the work of Tranter & Leech (1984) on the fronts in the Port Hedland region. The review discusses gaps in the oceanography of the region and the lack of attention given to the roles of tidal forcing and wind forcing in the nearshore habitats, factors that are important for the understanding of nutrient inputs and transport of larvae in these shallow water communities. The research presented here aims to clarify the dynamics of the tidal fronts around the North West Cape and relate this to the relevant biology in an attempt to partially bridge the gap that Heyward, Revill & Sherwood (2000) identify.

This study has been completed in collaboration with the Australian Institute of Marine Science as part of its ongoing research project on the North West Shelf. Research began in 1993 on the physical oceanography of the shelf and in 1997 a multi-disciplinary investigation started on the biological oceanography of the region focusing on the North West Cape vicinity. The investigation near the North West Cape aims to assist in the management and planning of tourism development and the prawn industry of the Gulf. The data used for this study was collected aboard the AIMS research vessel, the RV. Cape Ferguson, and the research presented here will benefit the physical oceanography group in their study of the circulation processes. AIMS will incorporate the results of this study into their long-term project to further investigate the links between the physical and biological processes in the mouth of the Gulf. Interest in the outcomes of this study have also been shown by parties investigating the tidal regime in the region and by those involved in the management of the Ningaloo Marine Park. A promising sign that the project completed here will be beneficial to the broader scientific research community.

2.0 Literature Review

2.1 PHYSICAL SETTING

2.1.1 Study Area

Exmouth Gulf lies 22°0'S, 114°24'E on the remote coast of Western Australia. It composes of part of the North West Shelf region, occupying an area of approximately 2500km^2 (Figure 1). The majority of the Gulf is extremely shallow with an average depth of only 10m. The Gulf ends abruptly as the continental shelf in the region is quite close to the land. The 200m depth contour is approximately 10km from the northern end of the Ningaloo Reef (Hearn & Parker 1988; cited in D'Adamo & Simpson 2001). The entire Gulf entrance is approximately 45km wide, laterally, from the rocky Cape Range Peninsula (North West Cape) at Point Murat across to the eastern boundary. The deepest region is a 13.5km wide entrance channel, between the North West Cape and the Muiron Islands, of approximately 20m depth. This channel will be the focus of the study, as the strong localised tidal currents and tidal flushing that it experiences play a significant role in the formation and development of the surface aggregations observed. The eastern part of the entrance to Exmouth Gulf is much shallower and is dotted by small islands and bounded by extensive mud and salt flats with fringing mangroves. This part of the Gulf is extremely difficult to access from land due to the mudflats and shallowness, and as a result much of it is unsurveyed.

The town of Exmouth, 13m above sea level, is situated inside the Gulf at 21°56'S, 114°09'E and has a population of only 2285 residents[1]. More than 244 000 tourists visit the region each year[2], predominantly between April and September, making this an important and substantial part of the population. Tourists are attracted to the area for its deep-sea fishing, diving on the reefs and experiences with whale sharks that frequent the region from late March to the beginning of winter.

Point Murat Navy Pier was built in 1964; a construction of steel pylons consisting of the 49.7m long main Pier with two 'breasting dolphins' each connected by a catwalk (25.5m

[1] Bureau of Statistics. Estimated resident population at June 2001 (preliminary). http://www.abs.gov.au

[2] Bureau of Tourism Research. Domestic and international tourist averages for 1998. http://www.btr.gov.au

across) and also two 'mooring dolphins' out 100m either side of the Pier. Although the Pier is primarily used for Navy purposes, it is sometimes used to service survey vessels and rig tenders. There is a pipeline that runs along the side of the Pier, used prior to 1992 for transferring black oil shipments but has since been changed to high grade diesel used for military purposes (T. Inman, Navy Environmental Officer, pers. comm.). McIlwain & Halford (2001) completed a quantitative assessment of the fish and benthic assemblages under and around the Pier, to build on and compare the results to a similar investigation in 1996 (Halford & McIlwain 1996; cited in McIlwain & Halford 2001). The Pier attracts a large number of fish, sponge and coral life on its pylons due to the nutrient input from the strong localised currents through the channel. Even a whale shark was spotted in 1998 feeding near the Navy Pier (S. Parker, Exmouth Diving Centre, pers. comm.) and a pod of dolphins was seen on the north side of the Pier during the field work.

The Cape Range National Park covers the majority of the Cape Range Peninsula and offers a variety of habitats from a desert-line plateau to coastal plains, mangrove swamps and a lagoon that lies between the shore and the Ningaloo reef. The park is popular[3] for hiking through the eucalypt woodlands and spinifex plains, climbing down into the gorges, enjoying the white sandy beaches and snorkeling on the ancient fossil reefs. The area is diverse due to several factors; it is at a latitude where the tropical and temperate zones meet, the Leeuwin Current brings tropical waters from the Indo-Pacific and the cape separates the turbid Gulf waters from the clear marine waters.

Mangroves fringe the mainland coastline and host a unique ecosystem in the nearshore zone, providing a major habitat for birds and marine organisms. Relative to the wet tropics, the diversity of mangroves in this region is low with only five species present while the birds, crustaceans and molluscs that reside in this habitat are highly diverse (IMCRA 1997; cited in Heyward, Revill & Sherwood 2000). The mangroves are also important as nursery grounds for the maturation of juvenile prawns moving out into the Gulf (Dr M. Kangas, Department of Fisheries, pers. comm.). Intertidal and supra-tidal salt and mudflats also flank the inner coast of the Gulf adjacent to the fringing mangroves. This shallow-sea environment is not well documented due to the difficulty of sampling in the area, access being a problem both by land and by sea.

[3] Walkabout (Exmouth). Tourism information site. http://www.walkabout.com.au

Coral reefs line the North West Cape on both sides, this being quite unique in itself as it is the only western coastline in the world with extensive reefs (Taylor & Pearce 1999). Reefs are generally not found around the rest of the world on western coasts due to Ekman transport and its consequent upwelling and primary productivity. Western Australia is special by virtue of the Leeuwin current, forming in the Indonesian waters, flowing poleward along the coast and carrying warm tropical waters and spawn. Ningaloo Reef is on the west of the North West Cape and is the longest fringing coral reef in Australia, approximately 260km in length from Point Murat to Gnarraloo Bay in the south. The main reef flat is on average 2.5km from the coast and is discontinuous with deep channels between segments. A review of the oceanography of the reef and its adjacent waters concluded that the lagoonal waters from the reef were predominantly circulated and transported by waves, tides and winds with a system of wave-pumping over the reef tract driving the nearshore waters generally northward (D’Adamo & Simpson 2001).

The Muiron Islands (21°40’S, 114°20’E) lie in a north-east orientation, two elongated segments that together are roughly 8km long and 1.5km wide. The Islands are Western Australia’s second-largest nesting grounds for loggerhead turtles between late spring and early autumn (Prince 1993, cited in Preen et al, 1997). This consideration was the focus of a recommendation by the Marine Parks and Reserves Selection Working Group (1994), cited in Heyward, Revill & Sherwood (2000), that the eastern side of the Gulf be reserved as a marine protected area but as yet the Muiron Islands have no conservation status. The waters around the Muiron Islands are also a known fishing site and occasionally the people fishing will spot a whale shark feeding nearby (S. Parker, Exmouth Diving Centre, pers. comm.).

Ningaloo Reef, Bundegi Reef and the entrance to Exmouth Gulf (the study area) are all inside the Ningaloo Marine Park, which is one of Western Australia’s six Marine Parks (CALM 1998). Marine Parks are important in the prevention of coastal problems seen in many other parts of the world and work to keep the marine environment as pristine as possible. There are four statutory management zones inside Marine Parks all subject to different scientific, recreational and commercial uses designed to minimise environmental damage and separate incompatible activities. Sanctuary zones are solely for nature conservation and low-impact recreation and tourism, Recreation zones provide for conservation and recreation including recreational fishing (subject to bag limits), Special Purpose zones are for particular priority use or issue and General Use zones are the areas not included in the above three categories. The Ningaloo Marine Park is divided into these categories.

Petroleum exploration drilling was proposed to the Environmental Protection Authority (EPA) in 1991 and this request was assessed with regards to environmental consequence, public opinion and Marine Park regulations (EPA 1991a; EPA 1991b). Of concern was the possibility of an oil spill, the fate and transport of drill cuttings, domestic wastes and dispersants and the subsequent impact on the environment and its inhabitants. The Ningaloo Marine Park and mouth have high conservation status whereas inside the Exmouth Gulf there is no special conservation status. The EPA conclusion therefore was to adhere to government policy and prohibit drilling in these zones of the Marine Park. Exploration outside these sensitive areas however, was approved. Petroleum drilling and production are excluded from Sanctuary, Recreation and certain Special Purpose zones in Marine Parks and in 1994 the Government of Western Australia announced that there would be no drilling for petroleum exploration and production in Ningaloo Marine Park (CALM 1998).

The field study was conducted around Point Murat, therefore the study area will only incorporate the channel entrance to the Gulf adjacent to Point Murat, not the Gulf itself or Ningaloo Reef. This area was chosen for its interesting circulation dynamics and the manifestation of tidal fronts during particular periods of the tidal cycle. The region was exceptional for conducting fieldwork with its abundance of marine life, picturesque backdrop and unbeatable climate.

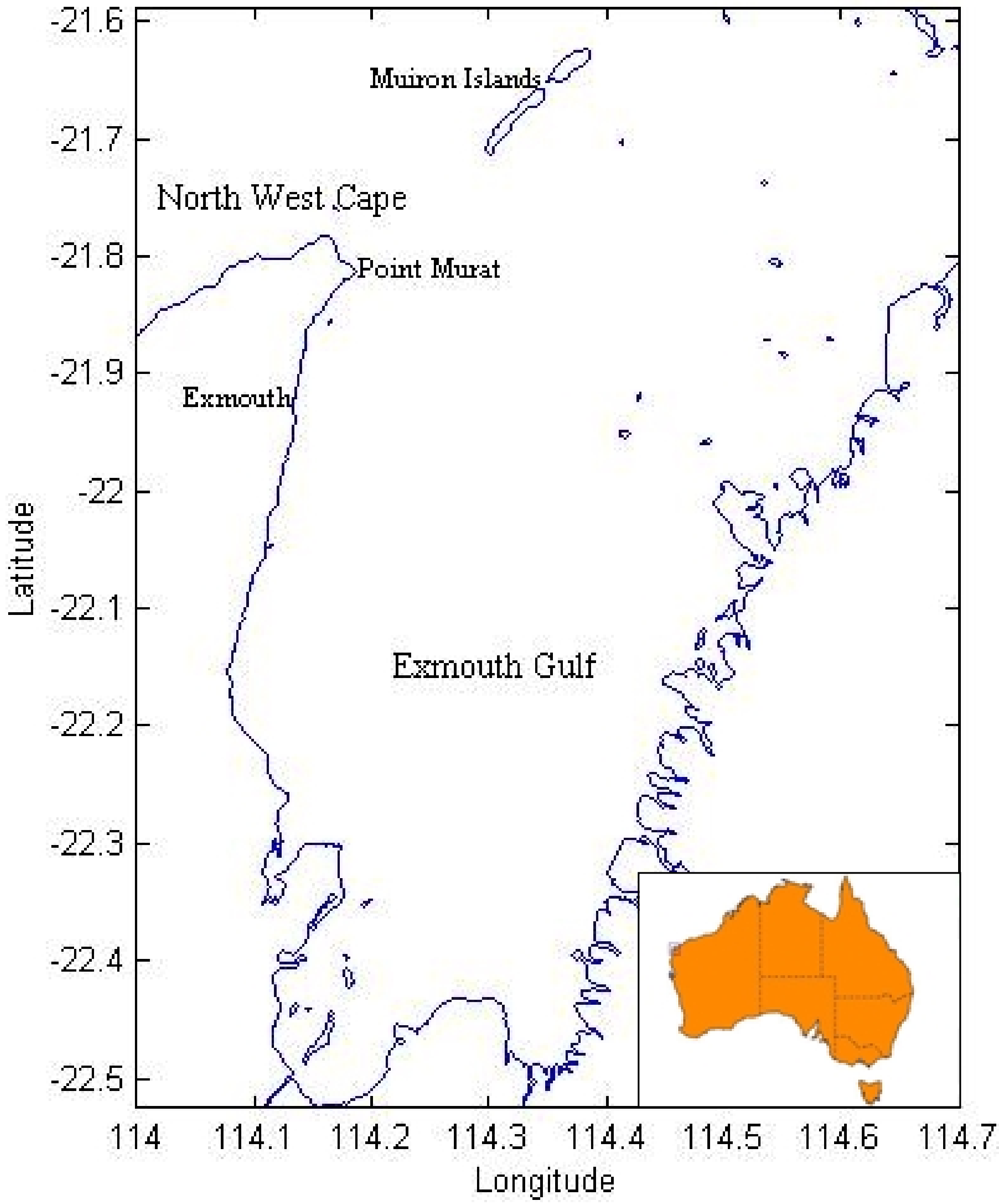


Figure 1. Exmouth Gulf and approaches

2.1.2 Biodiversity, Ecology and Fisheries

The North West Cape region is most famous for its biodiversity and abundant marine life living within the various habitats (Preen et al, 1997). This biodiversity was recognised in a review of the literature on the North West Shelf (Heyward, Revill & Sherwood 2000) where it was noted that species richness is an aspect well documented for the region, showing high diversity and endemism, especially in the invertebrates.

Research by Hallegraeff and co-workers on the North West Shelf (cited in Heyward, Revill & Sherwood 2000) shows there is a relatively high diversity of phytoplankton groups including diatoms, coccolithophorids and dinoflagellates. During the warmer months blooms of *Trichodesmium* occur in the region, these have been observed particularly on the frontal systems around Point Murat. Fine scale primary and secondary productivity has been studied around the North West Cape and Muiron Islands by AIMS but the results of this expedition are as yet unpublished. Tranter & Leech (1987), cited in Heyward, Revill & Sherwood (2000), studied the enhanced production at the interface between the stabilised waters and vertically mixed waters either side of Port Hedland. These frontal systems show identical characteristics to the fronts observed at Point Murat, a standing crop of phytoplankton at the base of the thermocline or bottom of the mixed layer. Heyward, Revill & Sherwood (2000) remarks that the role of tidal mixing remains unclear and that there is need for more research in this field.

The Ningaloo Marine Park is a well-known seasonal aggregation ground for the world's largest living fish, the whale shark (*Riniodon typus*) which appears on the reef shortly after the coral has spawned and zooplankton have consequently multiplied (Taylor 1996). Whale sharks are typically between 4 – 10m in length with a broad flattened head, large mouth and a 'checkerboard' pattern of light spots and stripes on a dark background (Compagno 1984; Last & Stevens 1994) quoted in Colman (1997). Whale sharks filter-feed on planktonic and nektonic prey (such as krill and copepods) as well as small schooling fish and the odd jellyfish. Little is known of the reproduction, development, growth and ageing of these creatures although they have been studied in the Ningaloo Marine Park since 1982 (Taylor 1994). Correlations have been found between their occurrence and the physical and biological oceanography of the region, relating their arrival at the reef with the Southern Oscillation Index and the Leeuwin Current (Wilson et al, 2001). The sharks are normally found on the west side of the North West Cape though they have been sighted throughout the Gulf at various times of the year. Around the winter months divers also frequently spot manta rays (*Manta birostris*) near the reef.

In the particularly clear waters of the Ningaloo Marine Park there is an abundance of four species of sea turtles. Loggerhead turtles (*Caretta caretta*) predominantly use the Muiron Islands as a rookery (nesting ground) while the endangered green turtles and hawksbill turtles (*Eretmochelys imbricata*) use the islands and coastal beaches adjacent to the Ningaloo Reef during the summer months for nesting. These turtle species are less prevalent within Exmouth Gulf due to the higher turbidity of the waters.

The islands around the North West Cape are also an important breeding ground for the bird species that inhabit the Marine Park. Over 25 species of birds that visit the park are listed on the international agreements aimed at the protection of migratory birds. These birds are attracted to the mudflats and mangroves for nesting and breeding with an abundant supply of food source in the offshore waters of Ningaloo Reef. Many birds were seen on the frontal systems around Point Murat, mostly bridled terns (*Sterna anaetheta*) which are found in the warmer seas (Leach 1950), and whose breeding colonies are the Ashburton, Anchor, Flat and Round Islands nearby the North West Cape (Associate Professor R. Wooller, Biological Sciences, pers. comm.).

There is a substantial dugong population (*Dugong dugon*) of approximately 2000 individuals that move between the Ningaloo Reef and Exmouth Gulf through the Marine Park, which is a significant density when compared to other habitats in northern Australia (Preen et al, 1997). Bottlenose dolphins (*Tursiops truncatus*) are common in the Gulf and Marine Park and another species of dolphin (*Sousa chinensis*) has also been sighted. Pods of dolphins were observed throughout the fieldwork around the cape, especially in an eddy adjacent to the Point Murat Navy Pier. Whales are also a common addition to the marine mammals that frequent the area, migrating past the coast from June and returning with calves a few months later. During the winter a group of humpback whales (*Megaptera novaeangliae*) stay off the north west coast (Jenner & Jenner 1995, cited in Heyward, Revill & Sherwood 2000).

The Ningaloo Reef is remarkably diverse and plays host to more than 200 coral species, 600 molluscs species and 500 fish species from the lagoonal inhabitants to the pelagic fishes such as spanish mackerel, cobia and tuna behind the reef front. In the study area, under the Point Murat Navy Pier, hard corals, coralline algae, barnacles, hydroids, soft coral and sponges were found (McIlwain & Halford 2001) with a diverse range of benthic species dwelling on or near them. Many types of sponges were recorded in the video analysis of the pylons under the Pier including species from the *Acanthella*, *Haliclona*, *Jaspis*, *Clavularia* sponges and Gorgonian fans. Hard corals were common with species representatives of the *Montipora*, *Acropora*, and *Favites* corals. *Goniastrea australensis*, *Turbinaria reniformis*, *Pocillopora verrucosa*, and *Pocillopora damicornis* were also present. Nudibranchs, sea stars, sea cucumbers and ascidians were recorded as other benthic species in the study.

Four major species of prawns are caught in Exmouth Gulf; western king prawns (*Penaeus latisulcatus*), brown tiger prawns (*Penaeus esculentus*), endeavour prawns (*Metapenaeus endeavouri*) and banana prawns (*Penaeus merguiensis*). The Exmouth Gulf prawn trawling, approximately a $10 million industry, began in 1963 and has seen annual variations in the catch due to climatic influences such as cyclone events. In 2000, a lower than average season, the total annual prawn landings were 565 tonnes and the king and tiger prawn stocks were fully exploited (State of the Fisheries 2001). Forty years of research and monitoring have been conducted in the Gulf as well as voluntary logbook information from the fishers. The juvenile prawns are predominantly found on the shallow sandy substrates of the mudflats and mangroves in the south-east of the Gulf. They migrate towards the middle of the Gulf when they attain maturity to be recruited into the adult habitat (Dr M. Kangas, pers. comm.). Western king prawns are the dominant target of the fisheries in the Gulf and are found in the northwestern sectors of the Gulf (State of the Fisheries 2001), trawled from late March to early November. Tiger prawns are caught further into the Gulf, south of the king prawn grounds. The by-catch of this prawn fishery are predominantly coral prawns, squid and blue swimmer crabs. There is no significant prawn-fishing region in the area near Point Murat or between the Cape and the Muiron Islands and there is a voluntary closure area (or ‘industry closure’) from 21°47’S, 114°13’E to the coast where the trawlers have decided not to fish.

This is a move designed to protect the sensitive areas close to shore and develop better public relations with the recreational fishers in the area.

2.1.3 Meteorology

The ocean's circulation and properties are ultimately linked to the radiation of the sun, manifested in the form of wind stress, heating and cooling and evaporation and precipitation which in turn affects the atmosphere (Tomczak & Godfrey 1994). The sun's energy is radiated back from the ocean as net long-wave radiation (in the infrared part of the spectrum), evaporation (about 60%) and sensible heat loss (or convection and conduction) which accounts for around 7% of the total (Drake et al, 1978). In the tropics, that is around the equator from 20°N to 20°S, where the earth receives the most solar radiation, the ocean gains heat. The reverse occurs in temperate and polar regions above and below these latitudes. According to diffusion laws, the water must flow from warmer regions to colder and colder waters must flow to warmer. Exmouth Gulf is located 2° below the boundary where these tropical and temperate waters meet.

To the west of the Australian coast lies the Indian Ocean where the northern half is dominated by a monsoonal climate whose effects even reach the southern subtropics. 'Monsoon' is translated from Arabic as seasonally reversing winds, which is exactly the case in the Indian Ocean during the monsoons. During the Winter Monsoon (northern hemisphere December to March) the climate is characterised by dry northeasterly winds over the Asian land mass and south-westerly winds over the North West Shelf (Tomczak & Godfrey 1994). This reverses completely during the Summer Monsoon (June-September) when the winds blow from the south-west and due west, offshore over the North West Shelf. Between 10°S and 40°S (the Subtropical Convergence Zone) is the southern half of the Indian Ocean, which experiences subtropical highs around 25°S - 30°S that form from July-August (winter) and during the summer experiences these highs further south around 35°S.

Tropical cyclones and their accompanying high seas, high tides and variable winds are an integral part of the meteorology of the Indian Ocean and an important climatic effect to be considered for Exmouth Gulf. The cyclones are created from November to April in the centre of the ocean and move along a path that eventually reaches the cyclone belt of Australia and Exmouth Gulf, which experiences an average of 1.2 cyclones annually. The most recent of these destructive events has been the severe tropical cyclone *Vance*, Category 5, which passed across Exmouth Gulf during the morning of the 22nd March 1999. At 11.50am that day at

Learmonth Meteorological Office the highest ever wind speed on mainland Australia was recorded, a wind gust speed of 267 km/h that devastated the town of Exmouth. Cyclones not only affect the constructions on land, but also cause havoc on seagrasses and other soft-sediment benthic inhabitants.

El Nino is the name given to a climatic effect that occurs at irregular intervals every few years, causing disastrous floods, droughts and climatic extremes as well as consequences for the Peruvian fisheries who experience massive plankton and fish kills and the collapse of their industry (Ingmanson & Wallace 1985). El Nino can be measured through the 'Southern Oscillation Index' (SOI) which is derived from observations of air pressure at sea level for Cape Town, Bombay, Djakarta, Darwin, Adelaide, Apia, Honolulu and Santiago de Chile (Tomczak & Godfrey 1994). Darwin and Tahiti are more commonly used for simplicity, where Darwin shows an inverse effect of low air pressure when the SOI is high, accounting for the low pressure system that covers Australia, south-east Asia and India, central and south Africa and South America during these events. During the reversal of the Southern Oscillation from positive to negative, the areas of high pressure systems become low pressure systems and the lows become highs. This reversal is known as an ENSO event (El Nino and Southern Oscillation), where the weather patterns are altered globally and the trade winds and equatorial currents flow west to east rather than east to west. Upwelling is prevented along the west coasts of North and South America due to the build up of water in the east and this is the cause of the collapse of the fisheries. During an El Nino year Australia is also affected through drought and the predominant current off the coast of Western Australia, the Leeuwin Current, is weaker.

Wind stress must be considered when discussing ocean's surface circulation as the surface currents in the top few hundred metres of depth are driven by momentum imparted to them by the wind. The energy of the wind causes friction and sets the ocean's surface layer into motion, approximately a quadratic function of the wind speed

$$|\tau| = C_d \rho_a U^2$$

where τ is the wind stress on the surface layer, ρ_a is the air density, C_d is the dimensionless drag coefficient and U is the wind speed 10m above sea level (Tomczak & Godfrey 1994). W. Walfrid Ekman described the direction of the motion in response to this wind stress as an 'Ekman Spiral', where the surface water moves at 45° to the direction of the wind (to left in the southern hemisphere and right in the northern hemisphere) and the velocity becomes progressively weaker. This rotation occurs due to the Coriolis effect (section 2.1.4). Approximately at 100m, the velocity of the motion is 4% of the velocity at the surface and is rotated 180° from the direction of the wind. The wind has negligible effects on the movement of the water below this depth. The net mass transport is termed 'Ekman transport' and it is perpendicular to the direction of the wind, again, to the left in the southern hemisphere and to the right in the northern hemisphere. This causes the movement of the water away from the coast and the upwelling of nutrients from the colder deep water on the coasts of most western continents.

Exmouth Gulf is an extremely arid region, void of any significant freshwater influx through precipitation or river inflow. The only riverine system flowing into the Gulf is the Ashburton River with it's mouth at 21°42'S, 114°55'E, this being so far east that it has no influence on the processes at Point Murat. On average, the Gulf receives only about 300mm of rain annually, comparable to other semi-arid regions such as Shark Bay, which is further south on the West Australian coast and receives 200 – 400mm annually. The significance of this is that there is no notable freshwater influx in the Gulf entering over the denser seawater to cause stratification. Solar heating would be the cause of any observed vertical stratification seen here. The Gulf has an air temperature range of approximately 13 - 43°C and a mean range of 21.5 - 29°C.

Winds are predominantly westerly, southwesterly and southerly from August through April while they are southerly and easterly during the winter months from May through July. Taylor & Pearce (1999) describe the wind pattern around the Cape in their investigation of the Ningaloo Reef currents, with south-easterly trade winds during the night and stronger south-westerly sea-breezes in the afternoon for much of the year. The summer mean wind speeds are between 7 and 9m/s and in winter this is weaker, only 3m/s with the wind coming from variable directions. The peak wind speeds are in the order of 14m/s for all months. From their observations, there is a strong southerly wind that blows throughout the spring and summer that becomes an easterly by April with calm conditions. This means that generally during the summer the wind blows parallel to the orientation of the North West Cape, along-shore, for much of the day and during the winter months the direction of the wind is more perpendicular to the North West Cape. According to Ekman transport, the water should be moving away from the coast and upwelling should occur, but this is not the case on the Western Australian coast during the winter months because the Leeuwin Current overpowers the Ekman transport (section 2.1.4).

During the time frame of this field study (13 – 16th March 2002) only 0.8mm of rain precipitated and the temperature range was high, varying from 28°C – 37.2°C. The wind directions were typical of the region, southerly and west southwesterly, with calm to moderate magnitudes of 10 – 20 km/h.

2.1.4 Research and Legislation

The North West Shelf Joint Environmental Management Study (NWSJEMS) was initiated by the Western Australian Department of Environmental Protection, aiming to ensure the support of sound environmental planning, management and decision-making involving the region of the North West Shelf in both the public and private sectors. The $2.7m project began in January 1998 and was implemented for four years resulting in an enormous amount of data and information. A review of the research to date is given in Heyward, Revill & Sherwood (2000) who summarise the outcomes and identify gaps in the understanding and research of the region. The review reports on the lack of management plans, tools and models for the region, the gap in oceanographic investigations studying the circulation of the shelf, the extent of nutrient enrichment close to the shelf break and various gaps in the knowledge of the biota. Their recommendations for future work focus on the management of data, in both its exchanges between the private and public researchers and the development of computer based models. Particular models are suggested, including finer spatial scale circulation and oceanographic models, sedimentary and bathymetric models, population dynamics and ecological models and models that use data about the existing and proposed pressures on the region.

The Australian Institute of Marine Science (AIMS) established a project entitled 'Biological Oceanography of the North West Shelf' in 1997 including aspects of the physical oceanography, primary and bacterial production, secondary production and Ichthyoplankon, nekton, whale sharks and euphausiids. The main aims of their study are to investigate the impact of upwelling and other oceanographic processes on pelagic production and in this to resolve the quantities and fates of upwelled nutrients. They focus on krill resources and look at how inter-annual variations in the primary production influence these krill and prawns. The study also aims to pursue the area of zooplankton dynamics, distribution and abundance. Five years later AIMS are furthering their studies on the North West Cape focussing on food webs and linking oceanographic processes, the krill production and whale shark abundance.

In October 1998 to March 1999 AIMS conducted a study that included the region from Thevenard Island in the north down to Ningaloo Reef, encompassing the entrance to Exmouth Gulf. Their research involved both physical oceanographic work as well as looking at the biological aspects of the region through ocean colour and fisheries dispersal. A data report written by AIMS (Steinberg et al, unpubl.) focuses only on the physical oceanographic aspects concerning tidal, surface and internal circulation and its energy budget, forcing factors, transport and mixing processes. Through this, the objective was to determine the physical processes that affect the biological productivity of the region. The report is a summary of the data collected between 1998 and 1999 and includes technical information on the acoustic Doppler current profilers, weather stations, tide gauges, InterOcean S4 vector averaging current meters, thermistor strings, benthic acoustic releases and thermistor dataloggers.

McIlwain & Halford (2001) conducted a quantitative assessment of the fish and benthic assemblages associated under the Navy Pier, an investigation that was produced for the Royal Australian Navy due to the lack of knowledge that there was about the marine communities associated with the Pier. The objectives of their study were to make a comparison of the present coverage of marine fauna and fish diversity with those recorded in the only other study that focused on the Pier, an investigation by Bowman, Bishop and Gorham (1993). The report included a section concerning the conservation significance of the Pier, highlighting the uniqueness of such a variety of large fish from many families. Their suggestion is to rename the area in terms of its sanctuary status to a higher level of protection, thus helping to ensure continuing biodiversity and abundance of the fish and invertebrate life under and near the Pier. A future management plan is advised for monitoring every 3 to 5 years under the Pier and the establishment of communication with the local dive operators who currently use the Pier. This investigation also recommends that research be conducted under the Pier to analyse the benthic communities for heavy metal contamination.

A review of the oceanography of the Ningaloo Marine Park and the adjacent waters (D'Adamo & Simpson 2001) summarises the physical processes, particularly of the lagoonal waters, on the reef but also describes the factors that affect the entirety of the region. The report was prepared as a contribution towards a review of the management plan of the Marine Park. The physical characteristics of the Ningaloo Marine Park are described in three distinct parts, the northern sector, central sector and southern sector. Meteorology is considered in terms of the wind regime, precipitation and evaporation with references to studies by Taylor & Pearce (1999) who identified the Ningaloo Current and Hearn et al. (1986) who investigated the oceanographic processes on the Ningaloo coral reef. The discussion considers the effects of tides and external influences, such as tsunamis and cyclones that change the water level. It outlines measurements by Buchan & Stroud (1993) of the wave regime in the north and draws on research conducted by WNI Science and Engineering who described the swell and sea waves 25km north west of the North West Cape. Regional currents such as the Leeuwin Current and Ningaloo Current are defined and their effects for the Ningaloo Marine Park are generalised in terms of advection and upwelling. The report focuses on the lagoonal circulation and mixing on the Ningaloo reef and presents an overview of the research work that has been conducted in this area.

A summary of international conventions, Commonwealth and State legislation regarding the North West Shelf is presented in a report (Gordon 2000) that was prepared for the North West Shelf Joint Environmental Management Study. Objectives of the report were to provide a complete summary of the legislative and management framework and to evaluate the existing framework, addressing its deficiencies. The report provides a short background into the North West Shelf study and outlines the legal and constitutional framework of Australia's marine areas, defining the various zones; State Coastal Waters, Territorial Seas, Contiguous Zone, Exclusive Economic Zone and the Australian Fishing Zone. The report is essentially a compilation covering legislation, policies and instruments governing marine resource allocation, use, conservation and environmental protection. International, Commonwealth and State legislation are covered, as are national, state and regional initiatives in policies, strategies and other instruments.

2.2 HYDRODYNAMICS

2.2.1 Physical Oceanography

Ocean surface currents are attributed to the friction of the wind on the sea surface (section 2.1.3) while deeper currents are the result of density gradients. Net ocean circulation is a balance of various forces acting together, the pressure gradient, Coriolis force and frictional forces, each dominate for different situations. A pressure gradient exists due to the build up of water in the centres of ocean basins due to the Ekman transport and density differences. Due to gravity, the water flows from the high to the low pressure, therefore a pressure gradient is apparent in the oceans. 'Coriolis force' is a term used to describe the apparent deflection of a particle from an observer on the surface of the earth. In the southern hemisphere, objects will appear to move to the left while in the northern hemisphere they appear to move right. This motion (or force) is apparent because the observer is moving with the earth while the object, which is not directly attached to the surface, will move only on its own path. Thus it seems that the object is deflected. The water particles in the ocean are not attached to the earth, so the Coriolis force affects their motion according to the following equation

$$f = 2\Omega V \sin\phi$$

where f is the Coriolis parameter in force per unit mass, Ω is the angular velocity of the earth (2π radians per 24 hours), V is the velocity of the object relative to the earth and ϕ is the latitude (McCormick & Thiruvathukal 1981). 'Geostrophic balance' is the balance between the Coriolis force and pressure gradient, and geostrophic flow is therefore the corresponding flow, moving along isobars (across the slope, not down it). Adding to geostrophic flow is the effect of the Ekman transport (section 2.1.3), caused by the frictional force of the wind shear over the surface layer of the ocean imparting momentum and causing surface layer currents.

Circulation in the Indian Ocean is governed by the monsoon systems that drive the currents, consequently changing direction with the change from the Winter Monsoon to the Summer Monsoon. This change in current direction takes effect in the northern half of the Indian Ocean, above approximately 10°S. Circulation in the southern half of the Indian Ocean is an anticyclonic gyre, flowing west at 10°S with the South Equatorial Current and east at 40°S with the West Wind Drift at the Subtropical convergence zone (Pickard 1979). The northern limit of this gyre, the South Equatorial Current, originates between the Australian continent and the islands of Indonesia and reaches velocities of over 1 knot. There is a variation in the South Equatorial Current seasonally due to the change between highs and lows over Australia. The current flows at 40 Sv during the summer and increases to 54 Sv (where 1 Sv = 10^6 m^3/s).

Although the circulation off the coast of Western Australia is anticyclonic and there is a movement of water towards the equator, this is only a weak current, the West Australian Current, and is not the predominant current. Adjacent to the coast of Western Australia flows the warm, low salinity, nutrient-poor Leeuwin Current, carrying tropical waters from the northwest shelf of Australia down past Cape Leeuwin and east towards the Great Australian Bight (Cresswell & Golding 1980). The current moves poleward against the prevailing equator-ward wind, contradictory to any other eastern boundary current in the world, while the undercurrent is equatorward. The Leeuwin Current is caused by a steric height difference of 0.5m along the Western Australian coast, and because there is no opportunity for the water to move to the east due to geostrophy, the only option left is to flow south, down the pressure gradient. This flow of the Leeuwin Current is so strong that it overrides the equatorward winds that drive an equatorward current, and the onshore geostrophic flow overrides the Ekman transport (Tomczak & Godfrey 1994). The Leeuwin Current flow is estimated at approximately 5 Sv transport and 0.1 – 0.2 m/s velocity. During the autumn and winter from March to August the Leeuwin Current is strongest while in the spring and summer, September to January, it flows weakest. As the current passes down the coast, warm-core cyclonic eddies are formed and meander seaward away from it (Pearce & Griffiths 1991), accounting for the productivity of the Western Rock Lobster fishery in Western Australia.

From late summer to early autumn there is a current that flows predominantly northward past the Ningaloo Reef on the western side of the North West Cape. Taylor & Pearce (1999) first described the current through direct observation, aerial surveys and a current drogue. Evidence from sea surface temperatures (SST) show that the Ningaloo Current is in fact the dominant current for the reef and surrounds from September to mid-April, pushing colder water up past the reef to the tip of the North West Cape. According to Taylor & Pearce (1999), many of their images showed this counter-current continuing eastwards past the North West Cape and Muiron Islands. The current is driven by strong south-southwesterly winds that prevail during that time of year and push the Leeuwin Current further offshore. The Ningaloo current is a likely source of nutrients to the Ningaloo reef and may also be the cause of enhanced planktonic biomass due to its recirculation and hence an explanation for the seasonal aggregation of the whale sharks in the area (Taylor & Pearce 1999). The Ningaloo Current is thought to also affect the mass coral spawning dispersion and retention through recirculation on the reef. These mass spawning events occur in March and April and are associated with large amounts of protein released into the reef, causing an increase in the abundance of zooplankton, another source of prey for whale sharks. The cause of the daytime swarming of the zooplankton *Pseudeuphausia latifrons*, an attraction for whale sharks around the Ningaloo Reef, was not identified (Wilson, Pauly & Meekan 2001) and although hydrodynamics were suggested, the Ningaloo Current was not mentioned as a possible cause.

Taylor & Pearce (1999) observed that the opposing Leeuwin and Ningaloo currents create a recirculation in the area and that the entrance to Exmouth Gulf is tidally driven with strong influences produced by the ebb and flow of tides in the Gulf. Massel (unpublished) referred to in Ayukai & Miller (1998) describes the circulation of the deeper part of the western side of the Gulf as well flushed through tidal mixing and attributes the excess phytoplankton production of the north western region to this. The shallow south and eastern sides of the Gulf experience low flushing and high evaporation and this causes the water mass to be trapped.

2.2.2 Properties of Seawater

Seawater is composed of a variety of constituents including chloride, sodium, sulfate, magnesium, calcium, potassium, bicarbonate, bromide, boric acid, strontium and fluoride accounting for 34.482‰ (parts per thousand) with chloride and sodium the most important constituents. These constituents combine as the salinity of the water and it is measured through the water’s electrical conductivity. A solution with particular concentration of ions will conduct a particular amount of electricity and this is how the salinity of the water is calculated. Salinity is low in waters that have high precipitation, fresh water runoff or melting ice while salinity is higher where there is high evaporation, freezing or dissolving of salt. The Indian Ocean is characterised by a triangle of low salinity water between 30-35‰ that occupies the northeast of the ocean from the Bay of Bengal down to the northwest of Australia. This low salinity water originates from the high freshwater input that comes from the great rivers draining from the Himalayas including the Ganges, Bramaputra and Irrawaddy. The higher salinity of the rest of the Indian Ocean is due to the arid nature of the

bordering continents, the lack of precipitation and river runoff, where salinity reaches 35.5-36.5‰ (Tchernia 1980).
The ocean absorbs an enormous amount of heat through incoming solar radiation from the sun and this warms the surface layer. Water is slow in heating and cooling due to its high specific heat and in the ocean the warming process is more effective than cooling, therefore the surface layer of the ocean stays warm. Sea surface temperature (SST) is often analysed through satellite images that can detect the differences in temperature in the ocean. The sharp change in temperature when analysing a vertical *in situ* temperature section is termed the 'thermocline' and shows the depth at which the surface layer of warm water overlies the deeper cold water. This gradient in temperature often inhibits the productivity of deeper layers since the warm surface layer, that has high incident light, becomes quickly depleted of nutrients and the bottom layer, that has plentiful nutrients but not enough light, cannot mix through the obstruction of the thermocline. Where there exists a thermocline the region is 'stratified' and throughout the ocean there is notable stratification of the deep waters. In the Indian Ocean the northern half (above 10°S) displays temperatures around 28°C. Maximums occur with the transition from the Winter Monsoon to the Summer Monsoon in spring. The temperatures fall to 25-27°C with the development of the southwesterly winds of the Summer Monsoon due to advection of the upwelled water (Tomczak & Godfrey 1994).

The density of seawater is a function of the temperature, salinity and pressure of the water and it is measured as the mass per unit volume, in kg/m^3. The density of seawater ranges between the values 1021.00kg/cm^3 at the surface and 1070.00kg/cm^3 at 10 000m depth (Pickard 1979) therefore the convention is to subtract 1000 from the real density and quote only the last four digits. So the ocean densities according to convention lie between 21.00 and 70.00 and these values are termed sigma *t* or σ_t (Ingmanson & Wallace 1994). Lighter waters in the ocean overly the denser water, this being a simple law of physics, but this distribution is not always uniform throughout the seas. The gradient from light water to denser water is termed a pycnocline, in the same way that a gradient in the temperature is a thermocline. Deep currents are studied with a knowledge of the density because waters will move towards equilibrium and sink to lower levels until they are at a density equal to their own and will then travel along these layers.

Light is one of the major factors, along with nutrients and temperature, affecting primary productivity in the ocean. Light reaches the sea surface in the spectral range of 290–3000nm but the light that is used in photosynthesis is between 350–750nm, which is in the UV to red regions. The availability of light depends on a number of environmental conditions. Some of these are the absorption of the UV light by ozone, oxygen, water and carbon dioxide, absorption by clouds, waves and rough seas, suspended materials due to river discharge and scattering and reflection of light off the sea surface. Of course the light availability also changes with the time of day and the season (the elevation of the sun). Beer's Law describes the total amount of light entering the water column from the surface and penetrating to a depth z

$$I_z = I_0 e^{-kz}$$

where I_z is the intensity of the light at depth, I_0 is the intensity of the light at the surface, and k is the extinction coefficient of the water (Valiela 1995). Photosynthesis is directly dependent on the intensity of the incident light as the phytoplankton can utilise the light to a maximum value (P_{max}) after which they are unable to take on any more light. Different phytoplankton are able to use a variety of ranges of wavelengths and different amounts of light at various depths. Phytoplankton are generally found between 25 and 150m water depth due to the harmful effects of the UV rays near the surface.

The colour that an observer sees when they look at the ocean are the wavelengths of light being reflected, other wavelengths are being absorbed by the pigments in the chlorophyll of phytoplankton. If the ocean looks blue-green, the red and yellow wavelengths are being absorbed and the blue, violet and green wavelengths are being reflected back to the observer's eye. The productive green waters of the Baltic Sea are an example where red and yellow wavelengths are absorbed and green is reflected. 'Gelbstoff' or dissolved yellow substances from land runoff, detritus and marine humic substances absorbs the blue and green wavelengths, therefore making the water look brown and shifting the euphotic zone (where light can be utilised by phytoplankton) to a shallower depth. Lake Burley Griffin in Australia is an example of a turbid yellow-brown water mass. The Sargasso Sea is the most transparent of the seas, with low productivity (oligotrophic) and little organic matter entering via rivers it has the clearest, bluest waters with light penetrating to 150m (Clayton & King 1990).

Chlorophyll *a* is a pigment used by photosynthetic phytoplankton to perform photosynthesis, and in the ocean this is predominantly the conversion of carbon dioxide through the use of light (*hv*) to compounds with the empirical formula $n(CH_2O)$ and oxygen (Barnes & Hughes 1988).

$$CO_2 + 2H_2O \xrightarrow{hv} CH_2O + O_2 + H_2O$$

In regions where there is no oxygen this reaction involves the introduction of hydrogen into the carbon dioxide molecule using compounds such as hydrogen sulfide. In the following equation H_2X represents the reactant hydrogen donor.

$$CO_2 + 2H_2X \xrightarrow{hv} CH_2O + 2X + H_2O$$

The chlorophyll content of a water sample is an ideal measure of the photosynthesis or primary productivity occurring in the water column giving a picture of the distribution of phytoplankton through the transect or body of water being studied. This can be compared with satellite observations of chlorophyll, measured through an image of sea surface colour that shows the regions high in primary productivity.

McKinnon & Ayukai (1996) who studied the copepod egg production and food resources in Exmouth Gulf found that temperature decreased with distance into the Gulf while the salinity increased and that the Gulf therefore acted as a negative estuarine system. Their study was based around the southeastern side of the Gulf but they included a site at Exmouth and one at Peak Island, which is north east of the Muiron Islands, on the outskirts of the Gulf. The results of chlorophyll *a* measurements showed the values within the Gulf were approximately the same as outside (comparing the Peak Island site with the rest of the Gulf). In their discussion Exmouth Gulf is described as well mixed and generally unstratified due to the tidal currents, shallow waters and wind effects. A study by Ayukai & Miller (1998) investigating the phytoplankton biomass, production and grazing mortality in Exmouth Gulf found there was a pattern of high chlorophyll *a* concentration and patches with high phosphate and nitrate plus nitrite near the mouth compared to the inner part of the Gulf. They observed the colour of the water to change from clear blue offshore water to yellow-green turbid Gulf water as they traveled from the northern entrance of the Gulf to the south. This colour change is attributed to an increase in fine suspended sediments and various forms of detritus in the centre to southern Gulf. Chlorophyll *a* images studied by AIMS[4] show high turbidity within Exmouth Gulf and high chlorophyll *a* near the Ningaloo Reef to low values into the deeper waters of the Indian Ocean.

2.2.3 Wave Regime

Waves possess kinetic energy in the form of the orbital motion of the particles and potential energy through the displacement of the wave above sea level (Ingmanson & Wallace 1985). Wind is the major cause of waves although submarine earthquakes, submarine landslides, submarine volcanic eruptions, landslides into the sea, ships and tidal forces are also causes of waves. Wave period is the time for one wave to pass a specific point (wave frequency is the inverse of this), wave amplitude is the height of the wave above or below sea level and wavelength is the distance between equal points on adjacent waves. Waves are classified into categories according to their period and in order of increasing period, the shortest waves are capillary waves with a period of less than 0.1s and these are observed on larger waves as ripples, while waves with periods greater than capillary waves are termed gravity waves. Wind waves are caused by the action of the wind shear on the surface of the water and have periods between 1 and 30s, increasing in height with an increase in wind velocity.

The wave conditions depend on a number of factors including the fetch length (area over which the wind blows), the duration that the wind blows, the wind speed, the bathymetry and distance from the storm area. The velocities of the waves increase with increasing duration, fetch length and wind speed and decreasing distance from the storm (wind) area (McCormick & Thiruvathukal 1981). Sea waves are the choppy waves with short periods, formed in the vicinity of a storm or by local winds, while swells are waves that can be seen on even a calm day, away from the wind and these have longer periods and a smoother appearance. In deep water, swells can travel thousands of kilometers away from a storm system without imparting significant energy, moving more rapidly than waves with shorter wavelengths. Waves can further be classified as ‘shallow-water’ waves and ‘deep-water’ waves according to the relation of their wavelength to the water depth (not the absolute water depth). Shallow-water waves are those that have a wavelength at least twenty times the water depth and to find the velocity, the following equation is used

[4] http://www.aims.gov.au/pages/research/bonws/bonws-09.html

$$C_s = (gh)^{\frac{1}{2}} = 3.1h^{\frac{1}{2}}\ ms^{-1}$$

where C_s is the velocity of the shallow-water wave and h is the depth in meters. For deep-water waves where the wavelength must be four times the water depth, the velocity is calculated as follows

$$C_d = \frac{gT}{2\pi} = 1.55T\ ms^{-1}$$

where C_d is the velocity of the deep-water wave and T is the period in seconds. Waves that are in between these categories are more complex to calculate. As waves travel to the shore the water depth changes and therefore the deep-water waves (only governed by their period) become shallow-water waves (only governed by the water depth). The consequence of this is a 'piling up' of water near the shore and as the wave becomes unstable it is caused to break approximately when its depth is $1\frac{1}{3}$ times its height. Shelf waves are waves that have amplitudes of typically 0.2m and periods of several days. Low pressure systems and fronts travelling across the coast create these shelf waves and they are maintained by wave refraction travelling along the margin of the continental shelf, where the shelf changes from a plain to a slope.

Internal waves are waves formed at the boundary of waters with two different densities. The waves are caused in the surface of the denser layer through forces such as surface waves, tides, earthquakes, ships' propellers and tidal currents (Ingmanson & Wallace 1985). The periods of these internal waves range from a few minutes to a few days with heights of up to 100m and speeds approximately an eighth of surface waves. The velocity of internal waves is calculated by the following equation

$$C = \sqrt{\frac{gd_2d_1}{d}\left(\frac{\rho_2 - \rho_1}{\rho_2}\right)}$$

where d_1 is the depth of the surface layer with density ρ_1 and d_2 is the depth of the deeper layer with density ρ_2 and d is the total depth of the two layers. Parallel slicks of still water accompany the internal waves and these can be seen on the surface. Internal waves are linked to biological productivity in areas of their occurrence due to the mixing they cause between two layers of water normally separated by a density gradient and therefore the upwelling of nutrient-rich bottom waters with nutrient-depleted surface waters.

Tsunamis, or seismic sea waves, are caused by a vertical displacement of the sea floor, where the downward movement of the sediment causes a drop in the sea level and the generation of a pulse. These vertical movements are caused by earthquakes, underwater avalanches or landslides, explosions from volcanoes or by resonance in submarine trenches (Ingmanson & Wallace 1985). In the deep water of the ocean, around 4000m, the height of these tsunamis is small but their wavelength is extremely long, around 120km. This causes them to behave like shallow-water waves and in the open ocean they can attain speeds of up to 200m/s. As the tsunami reaches the shore where the depth decreases and the slope is steep, the water builds up and by 50m depth their velocity has slowed to 22m/s. Therefore tsunamis are not noticeable in deep waters but cause the loss of lives and millions of dollars damage to coastlines. Tsunami heights can be over 30m when they reach the shore but thankfully can now be reasonably well predicted and warning systems are in place. Although tsunamis are more frequent in the Pacific Ocean, they do occur in the Indian Ocean and Pattiaratchi & Woo (2000), cited in D’Adamo & Simpson (2001) studied their frequency. There were found to be only 45 tsunami events in the Indian Ocean since 49 BC to the north of Australia while only three were found to occur on the northern Australian coastline. The effects of these tsunamis were felt between Exmouth and Broome with heights of up to 6m (4m along the North West Cape) leaving debris and damage to the Marine Park.

Seiches are standing waves, not progressive waves and are important in closed and semi-enclosed basins, bays, marginal seas and Gulfs. Seiches develop due to a prevalent strong wind in one direction over the basin or an imbalance in barometric pressure at opposite ends (Ingmanson & Wallace 1985). A standing wave is characterised by nodes and anti-nodes, where nodes are the points that are stationary on the wave and anti-nodes are the maximum and minimum heights of the water. The physics of a standing wave involves the wave entering the basin, reflecting from the basin end and returning in exactly the opposite formation that it arrived, creating the situation that the water oscillates back and forth with nodes of no movement in between anti-nodes of maximum and minimum height. Seiches do not cause great damage to shorelines as progressive waves can do; they only really become important for the more enclosed bays and harbours that have a seiche period close to that of the local swell and natural forcing functions (Drake et al, 1978).

Another phenomenon effecting the coastal environment are storm surges that are caused by the build-up of water against the coast due to heavy winds from storms or tropical cyclones. The effect of this rise in the sea level is most disastrous for enclosed and semi-enclosed basins, Gulfs and bays and this is enhanced by high tides (especially at new and full moon) that amplify the surge. The result of storm surges are the flooding of the coastline and damage of structures erected near the coast and often the surges arrive in combination with strong winds and rains making evacuation measures quite difficult (McCormick & Thiruvathukal 1981). Tropical cyclones along the northern coast are associated with the largest storm surges in Australia and have their greatest impact when coincident with the spring high tide.

D'Adamo & Simpson (2001) conducted a review of the oceanography of the Ningaloo Reef and adjacent waters and described the wave regime in their report. They use reviews by Hearn et al. (1986), Scott (1997) and personal communication with WNI Science and Engineering to describe the swell and wave climate. In summary they concluded that the swell was predominantly from the southwest in the winter and from the south in the summer where height and direction of the swell was taken 200km North West of the Cape on the Exmouth Plateau. The Southern Ocean generates long-period swell with periods between 12-20s that arrive from the south-southwest all year. Deeper waters off the North West Cape are dominated by a south west swell with period of 14-22s and a mean annual height of 1.5m, that is slightly larger in winter than in summer. The wave climate studied by Scott (1997) showed that the waves are strongly dependent on the weather conditions with the highest waves resulting from summer cyclones, displaying heights of over 10m and periods between 8-13s in extremes. Waves that are generated by tropical cyclones from the monsoons have a tendency to arrive from the north-northeast as this is where the cyclone path generally is and waves propagate radially from the centre of a cyclone. Sea waves with periods of 2-8s have a mean height of 1.2m and are significantly larger in the summer as opposed to the winter. The total wave regime where sea waves and swell are combined is measured to be more severe off the North West Cape than any other place on the North West Shelf. These waves reach a total height of 3.5-4m in summer and 3m in winter and have an overall annual mean of 2m.

2.2.4 Tidal Regime

To understand the processes controlling frontal systems at the mouth of Exmouth Gulf, the focus of this study, it is essential to examine the effects of the tidal regime in the region as it is a significant factor in formation of the observed fronts. Tides are vertical and horizontal movements of the ocean, generated through the gravitational attraction of the moon and the sun to Earth. In the words of Jimi Hendrix (1997) it is '…the sweet love between the moon and the deep blue sea.' The theory of the gravitational attraction of one body mass to another was first proposed by Sir Isaac Newton in 1687 where the gravitational attraction is directly proportional to mass, but inversely proportional to the square of the distance between the bodies. The moon and earth are both revolving around a common centre of mass (contrary to the idea that the moon revolves around the earth). Considering only the effect of the moon and neglecting the effect of the sun, there are two forces interacting; the gravitational attraction of the moon to the earth (Newton's theory) and the centrifugal force due to the two bodies revolving around each other (Ingmanson & Wallace 1985). The centrifugal force is likened to the motion of rotating a ball on a string, the force holding the ball out from the string is the centrifugal force. If the gravitational attraction and the centrifugal force were not in equilibrium with each other, the earth would crash into the moon or it would fly off into space. Tides are the result of a slight imbalance in these forces that is; there is no place on earth where the two forces are exactly equal on a particle, so tides are the sum of the differences. On the moon-side of the earth the gravitational attraction on water particles is greater than the centrifugal force while on the opposite side of the earth the centrifugal force becomes greater than the gravitational attraction. Tides not only affect the water particles in the ocean, they affect every body of water, the continents and even a person's weight will change a few grams between high and low tide. Although the sun is millions of times greater than the earth, its effects are only 46% of the effects of the moon because the moon is 387 times closer, so essentially the same two forces apply for the sun but only to about half the extent.

These two forces would ideally cause two tides a day, in a period of 24 hours and 50 minutes and this is termed 'diurnal'. When there is only one tide in 24 hours and 50 minutes the tide is 'semi-diurnal' and when the number of tides is a combination of diurnal and semi-diurnal the tide is 'mixed'. The elliptical orbit of the moon around the earth (where its closest point, perigee is 384404km and its furthest point, apogee is 406700km) accounts for tides being 50.47 minutes later each day in semi-diurnal tides. Due to the angle of the moon to the earth, which can be up to 35° either side of the equator, the two high tides and two low tides experienced each day are of unequal height and this is termed the ‘diurnal inequality’. At the equator the high and low tides are of the same height. A fortnightly inequality in tidal amplitude is caused by the position of these astronomical forces. When the moon and the sun are aligned, the lunar and solar forces act together causing higher tides called ‘spring tides’. This occurs when there is a new moon (the sun and moon are on the same side of the earth) and when there is a full moon (the sun and moon are on opposing sides). Alternatively, lower tides called ‘neap tides’ are caused when the sun and moon are perpendicular to one another, when there is a half moon (the moon is on either side of the earth). This lunar cycle of spring and neap tides is approximately 29 days long with the springs lasting from day 1 to day 7_, neaps from day 7_ to 15, springs from day 15 to 22 and neaps from day 22 to 29.

The continents of the earth act as barriers to this movement of the ocean and result in predictable but non-uniform tides around the world, each composed of a mixture of various ‘sinusoidal tidal constituents’. These constituents are semi-diurnal and diurnal with periods of approximately 12 hours and 24 hours, respectively, and the amplitude of the tide varies according to the importance of each constituent. The four most important constituents, or harmonic constants, are the lunar semi-diurnal (M_2), the solar semi-diurnal (S_2), the luni-solar diurnal (K_1) and the principal lunar diurnal (O_1) constituents with periods of 12.42hr, 12.00hr, 23.93hr and 25.82hr respectively. The M_2 constituent is approximately twice the amplitude of the other three (Mann & Lazier 1996). The tidal range is another way of describing the tide and it is categorised as microtidal (a range less than 2m), mesotidal (a range of 2 – 4m) or macrotidal (a range greater than 4m), where the range is the difference between the amplitude of spring and neap tides. All three of these categories occur on the coast of Western Australia.

A summary is presented in Table 1 of the harmonic constants and tide levels for Point Murat, the closest geographical port to the mouth of the Gulf (Willis 2002). D'Adamo & Simpson (2001) describe the area as a transition zone between two tidal zones, the diurnal micro-tidal of the southwest of Western Australia and the semi-diurnal macro-tidal of the northwest. This results in a mixed tide that is predominantly semi-diurnal with two high tides and two low tides per day and a tidal range of approximately 2.5m at most during the spring tides, the lower limit of the macro-tidal range. Simpson & Masini (1986) describe the tides at Point Murat as semi-diurnal, with diurnal inequalities and mesotidal. The effects felt from onshore and offshore winds, cyclones and tsunamis amplify the tidal range.

Table 1. Tidal constituents and tide levels at Point Murat (21°49' S, 114°9' E)

Harmonic Constants H (amplitude) in m g (phase) in degrees		**Tidal Levels** reference to lowest astronomical tide (LAT) in m	
Z0 LAT (m)	1.19	**HAT** highest astronomical tide	2.5
M2 lunar semi-diurnal	0.494 314.0	**MHWS** mean high water springs	2.0
S2 solar semi-diurnal	0.268 26.5	**MHWN** mean high water neaps	1.4
K1 luni-solar diurnal	0.183 302.0	**MSL** mean sea level	1.2
O1 principal lunar diurnal	0.128 281.0	**MLWN** mean low water neaps	1.0
Mean time difference TZ –0800 (WST)	+0008	**MLWS** mean low water springs	0.4

Tidal currents on a global scale are created through the movement of the 'tidal wave' (the tides moving around the oceans), where continents, topography, Coriolis and inertial forces are important (Ingmanson & Wallace 1985). This tidal wave separates within each basin and the waves circulate about an amphidromic point where there is little or no tidal change. The Coriolis force affects tidal currents in the open ocean by causing a rotation anti-clockwise in the southern hemisphere and clockwise in the northern hemisphere. Tidal currents in large open ocean basins will complete one entire rotation throughout a tidal cycle.

On a smaller scale, tidal currents are also generated inside embayments, harbours, bays, estuaries and Gulfs due to the restriction imposed by the coastline. The embayment shape, river flow, channel depth and shape and friction affect these currents and they are prone to changing direction constantly. A flood tide describes the motion of the water entering the bay, the shift from low tide to high tide. The ebb tide describes the water leaving the bay, that is the shift from high tide to low tide. In between these tides is a period of 'slack' when the tide is changing. Tidal currents are not necessarily in the same direction as the associated ebb or flood tide, they may be at right angles to one another or even in the same direction. The weakest tidal currents are observed in shallow waters while the strongest are seen in the deeper waters. It is possible to estimate tidal currents in the same way that it is possible to predict the tides.

2.2.5 Tidal Front Systems

A tidal front has been described as a form of 'ergocline'; an area of enhanced biomass attributable to the local physical hydrodynamic processes (Legendre, Demers & Lefaivre 1986). Tidal fronts are recognised by their smooth slick of water amidst waves and surface turbulence. Aggregations of plankton, larvae, eggs and debris are often found on the surface while predators such as fish and higher order biota are found above and beneath the front.

Frontal systems represent the boundary where two water masses of different hydrodynamic properties converge. In summer, there is a stratified regime on the deeper side of the front where there exists a density gradient with lighter surface water overlying heavier, deep water. The shallower side of the front exhibits vertically well-mixed conditions throughout. The density stratification develops either through the heating of the surface water or through differential salinity input into the basin, both resulting in the same effect. A simplified representation of the three-dimensional structure of a frontal system has been adapted from Simpson (1981) in Figure 2 to demonstrate the processes of convergence and upwelling that occur. The figure shows the stratified side of the frontal system to the right with warm surface waters overlying deep cold waters. The left of the figure shows the vertically mixed water mass. At the boundary between these two water masses, the frontal boundary forms exhibiting eddies, upwelling and convergence (as shown by the arrows) and often a velocity along the stratified side of V_R. Loder et al. (1993) summarises this frontal system as consisting of five predominant features; an along front jet (not seen at all frontal sites), a surface convergence zone, variations over the tidal cycle in structure and position, internal waves and strong spatial and temporal variations in small scale turbulence.

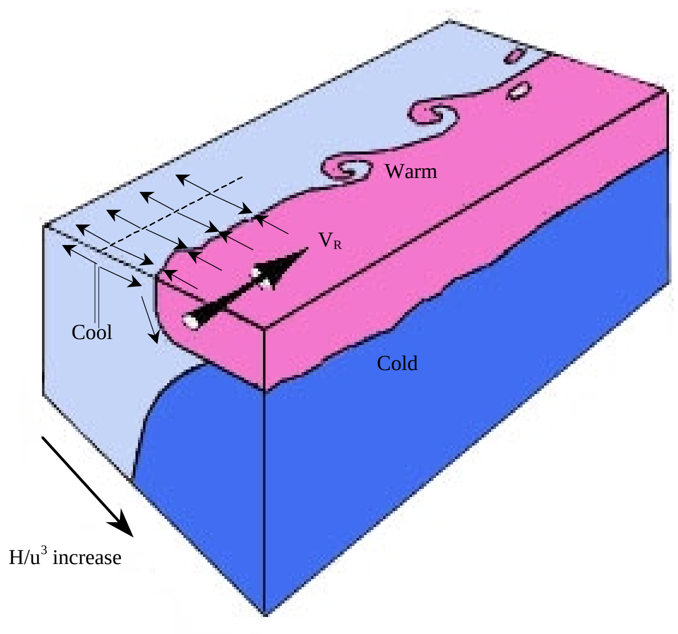


Figure 2. Schematic diagram of frontal structure (taken from Simpson 1981)

Possibly the first ever recorded tidal front is cited in the bible, in Lake Galilee during the spring of AD.34 while the disciples were fishing. According to Bowman & Esaias (1977) an interpretation of the passage is that they were trawling on the biologically poor side of a frontal system. When Jesus stood on the shore he could see the smooth line of the front in the morning light, an observation the fishermen in the boat could not make. Having told them to change sides and fish from starboard, the disciples hauled in as many fish as they could carry from inside the front.

> ‘Simon Peter said to the others, “I am going fishing.” “We will come with you,” they told him. So they went out in a boat, but all that night they did not catch a thing. As the sun was rising, Jesus stood at the water’s edge, but the disciples did not know that it was Jesus. Then he asked them, “Young men, haven’t you caught anything?” “Not a thing,” they answered. He said to them, “Throw your net out on the right side of the boat, and you will catch some.” So they threw the net out and could not pull it back in because they had caught so many fish.’
>
> [5]John 21.1-6

Tidal fronts have been observed and recorded in waters all over the world since the middle of the nineteenth century. They have been extensively documented in areas such as the Irish Sea (Simpson & Hunter 1974), the English Channel (Pingree, Forster & Morrison 1974), Georges Bank in the Gulf of Maine (Lough & Manning 2001) and Dogger Bank in the North Sea (Munk & Neilsen 1994).

Energetics

In the development of tidal fronts, competition exists between the buoyancy forces attempting to stabilise the water column and the vertical mixing forces disrupting the process. Solar energy input acts as a stabilising buoyancy force due to the heating of only the surface layer of water, causing a distinct temperature gradient (thermocline) in areas where the depth of the water column is greater than the depth of the heated surface layer. This stratification may also be caused by freshwater influx due to riverine influences or precipitation, manifesting a gradient in salinity (halocline) in the water column where the less dense freshwater overlies denser salt water. Vertical mixing forces that work to oppose this stratification include

[5] From the ‘Good News Bible: Catholic Study Edition’

stirring due to the wind shear acting over the surface and the incursion and excursion of the tide. Often during the summer months the energy input through heating is sufficient to create a seasonal thermocline where the buoyancy generated is greater than can be dissipated by the effects of the wind and tide and the depth is too significant for top to bottom mixing.

As the tide flows over the continental shelf it exerts frictional stresses on the bottom, the turbulent kinetic energy (TKE) that induces vertical mixing through the water column. This TKE increases with the strength of the tidal current, a variation that occurs during the tidal cycle. As the current speeds increase from neap tides to spring tides, the erosion of stratification increases due to the higher tidal dissipation, while the reverse occurs with the transition from spring tides to neap tides. This variation in mixing regime divides the water into stratified and well-mixed regions during the summer, separated at the boundary by a tidal front.

This boundary advances into deeper water with increased action from the wind or tide, especially in the transition from neap tides to spring tides, subsequently increasing the area of vertically well-mixed water and decreasing the area of stratified water (Pingree 1975). The reverse occurs in the transition from spring tides to neap tides when the tidal currents decrease in speed creating less TKE and consequently the boundary retreats, increasing the area of stratification whilst decreasing the area of vertically well-mixed water. Pingree (1975) expressed this idea as the local flux Richardson number (R_f), a ratio that depends upon the height above the bottom. The TKE production near the bottom is much larger than the potential energy production, therefore R_f goes towards zero. Near the surface, the potential energy input is much greater than the TKE production and therefore R_f becomes larger.

$$R_f = \frac{Potential\ energy\ production\ rate}{Turbulent\ kinetic\ energy\ production\ rate} < 1$$

The newly stratified water, with nutrient levels of the mixed water, was proposed by Pingree et al. (1975) to be a possible mechanism for the high plankton density observed at fronts. Maguer et al. (2000) studied a shallow water tidal front on the Armorican shelf in north-west Europe and found that the high total nitrogen uptake suggested *in situ* growth rather than physical processes. This *in situ* growth is becoming better understood than the other mechanism, whose role is still questionable, involving the advection that occurs as a result of circulation and convergent flow at the front. The nutrient levels of the original stratified water are depleted throughout the spring by the biological productivity in the surface layer, while the thermocline traps the nutrient rich water underneath away from the incident light. Nutrient levels of the mixed water are continuously replenished, as there is no obstruction to their transport through the water column. The nutrients could be transported vertically from below the thermocline or horizontally across from the mixed region to account for the enhanced production at the front. Savidge (1976) conducted a study in the Celtic and Western Irish seas where water from either side of the front was taken and mixed, the results showing a marked increase in photosynthesis due to the 'complementation' of nutrients. There has been considerable debate in the literature over the theories on systems by which this nutrient transfer could occur. Pingree & Griffiths (1978) suggested baroclinic instability, eddy formations at the front, as the predominant mechanism for cross-frontal exchange, and Simpson & Bowers (1981) further discussed this possibility. Three decades after the first significant development in frontal studies (Simpson & Hunter 1974), questions still remain as to the mechanisms for cross-frontal exchange.

Simpson, Allen & Morris (1978) proposed an index of stratification (*V*) relative to the mixed state to represent the condition of the water column where ρ is density and h is the depth of the water. When $V = 0$ the system is well-mixed and as V becomes more negative, the water becomes more stratified. Tidal stirring and wind mixing bring about vertical mixing, positive changes in V, while surface heating has the opposite effect and brings about stratification, negative changes in V.

$$V = \langle V \rangle h = \int_{-h}^{0} (\rho - \langle \rho \rangle) gz dz \qquad \langle \rho \rangle = \frac{1}{h} \int_{-h}^{0} \rho dz$$

The overall potential energy balance is composed of a heating term, tidal stirring term and a wind mixing term, assuming isotropy, homogeneity and only local processes are important. In the heating term, $\dot{Q}$ is the rate of heat input, c is the specific heat and α is the volume expansion coefficient. In the mixing terms, ρ and ρ_s are the water and air densities, U_b is the near bottom velocity, W_s is the wind speed near the sea surface, k_b and k_s are drag coefficients, and ε and δ are the efficiencies of the tide and wind mixing respectively.

$$\frac{dV}{dt} = \frac{-\alpha g \dot{Q} h}{2c} + \frac{4}{3\pi}\varepsilon k_b \rho U_b^{\ 3} + \delta k_s \rho_s \overline{W_s^{\ 3}}$$

The point where *dV/dt* becomes zero defines the frontal position (Simpson 1981), and when the tide-mixing term predominates the wind term may be eliminated, so the equation simplifies to

$$\frac{3\pi\alpha g}{8\varepsilon k_b \rho c}\left(\frac{\dot{Q}h}{U_b^{\ 3}}\right) = 1$$

The parameters α, g, c, and ρ in this equation are constant and $\dot{Q}$ can also be regarded as constant by making the assumptions that the area and time of interest are limited. Provided ε and k_b are also constant, the position of the front may be determined by a critical value of h/u^3 (Simpson & Hunter 1974), which they found to be between 65 - 100. In areas of stratification, h/u^3 is larger, while in well-mixed conditions it is smaller. This measure of frontal location has been used since its proposition for almost all frontal studies, to reveal the location of the boundary between the mixed and stratified regimes. Pingree & Griffiths (1978) used a numerical model to derive the Simpson-Hunter equation and presented it as a stratification parameter with the critical value of 1.5.

$$S = \log_{10}\left[\frac{h}{C_D \left\langle |u|^3 \right\rangle}\right]$$

Biological Aspects

The enhanced phytoplankton at the boundary of the two water masses forms a basis for successively higher trophic levels that feed on those below. These phytoplankton bands at frontal systems are recognised by the chlorophyll *a* signature that features in remote sensing ocean colour images (Le Fevre et al, 1983). A generalised representation of the distribution of phytoplankton assemblages in frontal regions is presented in Demers et al. (1986). They show the dominance of diatoms in the well-mixed side, dinoflagellates and small diatoms in the frontal zone, micro-flagellates and large diatoms in the surface layer of the stratified region and dinoflagellates of decreasing sizes towards the bottom of the stratified water.

Zooplankton fit into the 'tidal mixing paradigm' (Peterson 1986) as the second trophic level in the frontal ecosystem. Mechanisms for their existence at the front are still not clear and, like phytoplankton, could be due to passive advection or higher population growth due to increased phytoplankton biomass. Studies show that tidal fronts often act as nursery sites for larval fish, offering unique opportunities of protection, high food availability and optimal temperature while they are entrained in the convergent waters (Lough & Manning 2001; Townsend et al, 1986). Fish larvae graze predominantly on zooplankton, namely the copepods that are consuming phytoplankton at the frontal zone.

Higher order predators in turn target the swarms of zooplankton and abundant fish around the front. Basking sharks (*Cetorhinus maximus*), the world's second largest fish species, have particular behavioural traits associated with the small-scale frontal systems off the southwest coast of England. The sharks aggregate at the front to feed on the calanoid copepod *Calanus helgolandicus* during the summer by selectively foraging the densest most energy rich patches (Sims, Fox & Merrett 1997; Sims & Quayle 1998). The basking shark displays an annual social courtship-like behaviour, using the front as a place to establish contact with the other sex and eventually move to the depths below the front and mate (Sims et al, 2000). Right whales (*Eubalaena glacialis*) are also found feeding on copepod patches (*Calanus finmarchicus*) in the great South Channel off New England, near the tidal front at the entrance to the channel (Wishner et al, 1988). These whales have been observed to literally 'skim-feed' at the surface, like "tractors mowing a lawn".

Seabirds and diving birds are also prevalent at the front, often revealing the location of the system to the marine researcher by plummeting into the frontal water in pursuit of their meal (Durazo et al, 1998). Diving birds such as auklets tend to feed on zooplankton, larval fish and invertebrates (Hunt et al, 1998) while seabirds such as murres prefer the juvenile fish (Kinder et al, 1983). Puffins, shearwaters and terns have also been sited and noted as frontal feeders (Pingree, Forster & Morrison 1974).

Several other higher order predators such as dolphins, humpback whales, turtles, sharks and other fishes are frequently observed making use of the abundant food at tidal fronts (see Le Fevre 1986 for a review). Bowman & Esaias (1977) highlight the importance of studying tidal fronts so that protected species such as the basking shark and other higher order predators are not at risk from fisheries exploitation, commercial shipping, leisure and ecosystem vessels. Pollutants and rubbish aggregate and concentrate at a tidal front, hence there is a higher uptake of heavy metals, PCB's and other contaminants into the food chain. Tidal fronts must therefore be considered when designing sewage outfall into the water column, routes for oil carrying vessels (in case of spills) and discharge points for municipal, industrial and radioactive effluent.

Irish Sea

The Irish Sea fronts between Ireland and Wales have been studied intensively since Simpson (1971) first described the stratified temperature structure through physical oceanographic profiling of the region. The system was studied further and three years later the 'Simpson-Hunter' stratification parameter was constructed for defining the position of a front (Simpson & Hunter 1974), becoming a basis for all future frontal studies. Savidge (1976) identified bands of chlorophyll through continuous surface monitoring in the vicinity of the Irish Sea fronts and linked this phenomenon with the sharp density gradients that had been previously documented. Simpson, Hughes & Morris (1977) tested the validity of the stratification parameter through the use of a large volume of data and found that, although there was some qualitative support for the model, a lot of scatter was still seen. This was attributed to the variations in wind, wave and heat input. A two-dimensional numerical model was applied to the Irish frontal systems by James (1978) showing how the density structure of the front itself may cause the upwelling and convergence resulting in the enhanced chlorophyll at the front. Simpson & Bowers (1981) then constructed a simplified model that described the influence of wind and tidal stirring on stratification and included a feedback component that reduced the efficiency of the mixing with increased stratification and this model was compared with direct observations. An investigation into the seasonal distribution of bacteria and zooplankton on the Irish Sea fronts was made by Fogg et al. (1985) confirming the general pattern of a shallow-sea tidal mixing front. The chlorophyll *a* distribution at the fronts was found by Fogg et al. (1985) to be similar to other fronts studied around the British Isles but they did not propose a new model for the processes leading to the chlorophyll maximum at the front.

Pingree, Forster & Morrison (1974) who focused their study on the channel between Guernsey and Jersey first recorded turbulent convergent tidal fronts in the English Channel (fronts also occur in mid channel and in the south-west of England off Plymouth). They describe their measurements of temperature, salinity and currents and list the observations of species found on the frontal system and offer explanations for the dynamics of the front. In the following year, Pingree (1975) describes the advance and retreat of the thermocline on the continental shelf in the western approaches to the English Channel, near Ushant Island west of France. The study indicated a connection between it and the seasonal phytoplankton growth. The importance of tidal streams is discussed in terms of the turbulent kinetic energy produced and its control on the development of the thermocline. Le Fevre et al. (1983) analysed complex patterns around western approaches to the English Channel from satellite images. They found the bright patterns to be on the stratified side of the thermal front and concluded through spectral signature analysis that it was phytoplankton they observed. With the development of more advanced oceanographic instrumentation, comparisons were made between *in situ* data and high-resolution radiometric data (Morin, Wafar & Le Corre 1993), showing a strong correlation. It was then possible to use satellite-derived nitrate images to assess the productivity of the Ushant thermal front over the large area in a short period of time. The English Channel fronts were also studied for their attraction of basking sharks, the second largest fish species. The sharks occur near Plymouth off south-west England and are attracted to forage on the zooplankton abundance at the front (Sims, Fox & Merrett 1997). Sims & Quayle (1998) found that the sharks were selective and choose only the richest patches of zooplankton, moving with the patches that are carried by tidal currents. Annually, the basking sharks are found to show courtship-like behaviour near the frontal system (Sims et al, 2000), but retreat to the depths to mate.

Clyde Sea

The Clyde Sea, which lies on the west coast of Scotland, is a different frontal system, driven by a salinity and temperature gradient. The River Clyde and other river systems are a source of freshwater into the sea and due to a sill at the entrance that joins it to the North Channel and prevents the water leaving, the Clyde Sea is stratified (Simpson & Rippeth 1993; Kasai, Rippeth & Simpson 1999). The characteristics of this frontal system are comparable to a solely temperature driven stratification; there is upwelling on the mixed side during spring tides, an along-front residual current is observed and the front moves back and forth, oscillating with the tides. The Clyde Sea front was investigated using conductivity-temperature-depth measurements, a ship-borne acoustic Doppler current profiler and a fixed mooring with temperature, salinity and velocity sensors.

Early work on the continental shelf of the British Isles was that of Fearnhead (1975), a student under the guidance of Dr J. H. Simpson, who used a stratification parameter based upon the tidal power required to mix a stratified body of water to define the boundaries between well-mixed and stratified waters. Observations were used to verify the work and predictions of the positions of fronts around the British Isles were made. The work to date of Simpson, Allen & Morris (1978) and Pingree & Griffiths (1978) on the British Isles was summarised in their contributions at the Chapman Conference on Oceanic Fronts in 1977. Simpson, Allen & Morris (1978) discuss their research into the validity of the 'Simpson-Hunter' stratification parameter and their model of the upwelling and convergence at the front. Pingree & Griffiths (1978) describe their numerical model, used to compare the positions defined by the 'Simpson-Hunter' stratification parameter, to infrared satellite images and *in situ* measurements of the sea surface temperatures. Simpson & Bowers (1979) clarify the adjustments of fronts on the continental shelf of the British Isles through analysis of infrared imagery and conclude there is a consistency in the position and discuss a 'feedback process' where mixing fails once the stratification is established. A review of the results to date about tidal fronts around the British Isles and their existence and behaviour in relation to the mean circulation is given in Simpson (1981), a comprehensive overview of what was known about the mechanisms controlling the circulation in a frontal system.

North Sea

Frontal research in the North Sea on Dogger Bank began in 1970. With the advances in technology different approaches were used to study the fronts and hence more became known of the circulation and dynamics around the fronts. Hill et al. (1993) uses a high frequency ocean surface current radar, a ship-borne acoustic Doppler current profiler, a towed undulating conductivity-temperature-depth profiler and Decca-Argos drifting buoys to describe the North Sea frontal system. Pedersen (1994) clarifies the neap-spring adjustment of frontal position and explains the small adjustments of the location of the front in the North Sea through the incorporation of wind stirring into the model, achieving improved results on previous studies (Simpson & Hunter 1974; Simpson & Bowers 1981). Munk & Nielsen (1994), who studied the trophodynamics of plankton on Dogger Bank, described the distribution of plankton in relation to the front and the impact of predatory larval fish on these plankton. The oceanographic and biological knowledge was then merged (Richardson & Pedersen 1998) to estimate new production in the North Sea where 40% of this production was found to be associated with the frontal system.

Georges Bank

Research on Georges Bank off Cape Cod in the Gulf of Maine on the east coast of central North America, has followed a similar sequence to the studies conducted around the British Isles. Loder & Wright (1985) built on previous work of a depth-dependent tidal rectification model and frontal model to make predictions of the circulation on the northwestern sides of Georges Bank. Their studies found that there was a reduction in currents during the summer due to the decrease in wind stress and consequently stratification developed. Work has particularly focused on this area with respect to the appearance of right whales (*Eubalaena glacialis*) in the Great South Channel, south-east of the bank feeding on the copepod patches that form a surface layer near the front (Wishner et al, 1988). The circulation and hydrodynamics of the Georges Bank tidal fronts were further investigated in Loder et al. (1993), a summary of the research to date and description of the mechanisms involved. They list particular features of the Georges Bank system that are consistent with other frontal systems. Yoshida & Oakey (1996) investigated the northern sides of the bank with more advanced instrumentation including conductivity-temperature-depth, acoustic Doppler current profiler, and EPSONDE measurements. They described the frontal system in terms of its vertical mixing structure and identified particular interesting features of the mixing processes on the bank.

Franks (1997) investigated the biological processes at frontal system boundaries and used Georges Bank to demonstrate the results. A cross-frontal structure of temperature, phytoplankton biomass and cross-frontal velocities for a ‘no mixed-layer’ model and a ‘mixed-layer’ model was developed for Georges Bank and the performance of each was compared. Houghton & Ho (2001) investigated the Lagrangian flow through the Georges Bank front by injecting Fluorescein (a fluorescent dye) into the bottom mixed layer of the front and monitoring the results. Through the differential warming of the dye in different parts of the front, they found that the vigorous vertical mixing of the tidal front inhibits the horizontal transfer of heat. Mavor & Bisagni (2001) studied the seasonal variability of the fronts on Georges Bank through analysis of sea-surface temperatures, comparing seasonal positions of the fronts to historical data of stratification in the area and to the Simpson-Hunter stratification parameter. The front has also been used to model the entrainment and retention of fish larvae (Lough & Manning 2001) using conductivity-temperature-depth measurements, acoustic Doppler current profiler measurements and a satellite-tracked drifter. The model simulations suggested possibilities for the movement and distribution of the larvae.

3.0 Approach

3.1 SAMPLING TECHNIQUES

3.1.1 Expedition

The fieldwork for this study was conducted aboard the RV Cape Ferguson, a 23.9m scientific research vessel owned by the Australian Institute of Marine Science (AIMS). The vessel consisted of a main deck, raised deck, below main deck and wheelhouse, and had a rotating crew of skipper, first mate, engineer and cook aboard. The author joined a team of research scientists including two physical oceanographers (one appointed as cruise leader) and two oceanographic technicians from AIMS that stayed aboard the RV Cape Ferguson for the duration of the fieldwork, the 8^{th} – 17^{th} March 2002. The details of each day of the expedition are summarised below.

Friday 8^{th} March

Upon arrival in Exmouth on a flight from Perth, preparation was started for the deployment of moorings scheduled for the following days. Anti-fouling paint was applied to the buoy packs and instrumentation as a protective layer against the biological growth that is inevitable in the ocean. Concrete was mixed for weighting the anchors on the bottom of the moorings and this was left to set overnight. The RV Cape Ferguson was equipped with a crane for the manipulation of this heavy instrumentation and was operated by the engineer on board.

Saturday 9^{th} March

Mooring deployment began on the 9^{th} of March with long chains weighed down by concrete anchors that were hoisted over the back deck of the RV Cape Ferguson and dropped into the water. Instruments (including the acoustic Doppler current profilers) were fixed with buoy packs on the chain at particular depths where the buoy packs caused the chain to stay upright in the water column. These instruments were to stay in the water for 55 days and would be retrieved on the following AIMS physical oceanography expedition into the Gulf.

Sunday 10^{th} March

The deployments of the moorings continued on the 10^{th} of March. While out at the mooring sites, two conductivity-temperature-depth profiles were taken in the deeper waters north of the North West Cape.

Monday 11th March

Current meters were installed the Mildura wreck (northern tip of the North West Cape) and midway between the Mildura wreck and Point Murat at the anchorage of the RV Cape Ferguson. A visit was made to the Naval Communication Station Harold E Holt to obtain permission to install a tide gauge and a time-lapse camera on the Navy Pier. The Conservation and Land Management (CALM) office was also visited to explain the purpose of the research being conducted by AIMS in Exmouth.

Tuesday 12th March

Two acoustic Doppler current meters were installed under the Navy Pier by the AIMS scientific divers, one of which would be left for three days, the other for 49 days. During the evening 11 conductivity-temperature-depth profiles were taken on a transect from the deeper waters north of the entrance through to just south of the Muiron Islands.

Wednesday 13th March

On the 13th of March the surface drogued-drifters and deep drogued-drifter were assembled and tested, confirming from the preliminary data that the GPS in the drifters was accurate. The drifter work was conducted on the highest tides of the day, early in the morning and late in the afternoon. The drifters were taken out in the inflatable zodiac and deployed at various positions around the frontal system.

Thursday 14th March

A current meter was installed near Bundegi Reef and a time-lapse camera was positioned on the Navy Pier. Conductivity-temperature-depth profiles were made throughout the day by leaving the instrument in the water off the starboard side of the RV Cape Ferguson. This was done to obtain a profile of the incursion and excursion of the surface water mass.

Friday 15th March

One of the two acoustic Doppler current profilers was retrieved from its position under the Navy Pier and the data that it had recorded in this time was checked. Work with the surface drogued-drifters and the deep drogued-drifter continued around the North West Cape and especially around Point Murat. Deployments of the drifters were again early morning and late afternoon at the high tides.

Saturday 16th March

After the last drifter work had been completed by noon, the vessel was unloaded and the instrumentation was packed. A journalist, who stayed aboard for the ten days, posted each day's proceedings onto the World Wide Web covering the entire expedition. http://www.aims.gov.au/pages/about/communications/journal/mariners-journal-00.html

3.1.2 Quasi-Lagrangian Drifters

Lagrangian measurements involve the tracking of individual fluid particles, a moving reference frame, and describe the changes in the fluid properties that are associated with the fluid particles with respect to time while Eulerian methods find the change in fluid properties from a fixed reference. Lagrangian measurements of fluid motion are more useful than Eulerian measurements when considering the fate and dispersion of contaminants and particles in the ocean environment because numerous Eulerian current profilers would be needed to produce the same result as only a few Lagrangian drifters. Davis (1991) reviews the use of drifters in oceanographic studies and summarises the development from the early experiments involving visually tracked devices such as floating paper or bottles to the advanced radio-navigation of the global positioning system (GPS) utilised in this study. Drifters were used in the frontal studies conducted by Loder et al. (1993) and Lough & Manning (2001) who studied the near-surface Lagrangian circulation and convergence on the Georges Bank front. Hill et al. (1993) used Decca-Argos drifter buoys on the North Sea frontal systems while Farmer et al. (1994) utilised a self-contained Acoustic Drifter in Haro Strait. The drifters used for this frontal system research will be referred to as 'quasi-Lagrangian' due to their finite size, wind slippage and drag (Murthy 1975 cited in Johnson et al, 2001) causing them to behave slightly differently to what is observed in water particles.

A set of four compact GPS drifters was used to investigate the surface dynamics around the fronts in the entrance to Exmouth Gulf, designed and constructed by David Johnson[6] and loaned for the duration of the fieldwork (Johnson et al, 2001). Each drifter recorded its time and position (to the nearest 0.001 minute) every 9 seconds when turned on and stored up to 95200 data points (26 hours of continuous use). The design of the drifters is compact and low-cost and is constructed of components that are easily replaceable and repairable with an

[6] Centre for Water Research, The University of Western Australia.

outer casing of 100mm PVC sewage pipe, a ring cap to seal the pipe and flag wire to help with retrieval (Figure 3a). The internal frame holds the GPS receiver, the datalogger and a reed switch and the pipe is weighted with a battery pack of seven standard alkaline D-cell batteries. The drifters stay upright in the water column due to the battery pack weight and are neutrally buoyant having only their Perspex lid and flag out of the water. This minimises the effect of the wind directly, as there is no great surface area out of the water.

The wind does however have an effect in the surface layer of the water column causing wind waves and slippage on the instrument, therefore the four surface drifters were ‘drogued’ with a construction that had been used by AIMS in previous drifter work. AIMS scientific technicians had constructed each drogue from a 1m long 50mm PVC pipe that was weighted to stay upright in the water column and buoyed for stability to float just beneath the surface (Figure 3b). The result was that the only part of the water column essentially being studied was the surface 1m of water. The drogues each had two 60cm plastic rods that were crossed at the top of the PVC pipe and another two rods that crossed at the bottom, fitting through holes bored in the appropriate places. The bottom and top rods supported four coloured plastic sails between them allowing the drogue to stay stable in the water column and minimising wind drag. A cylindrical radar reflector was constructed of light aluminium and was fastened to a plastic pole attached to the centre pipe for retrieval by the ship’s radar. A bright red flag was also added to the pole for easy visual detection during the day and a flashing light was attached for the evening sampling.

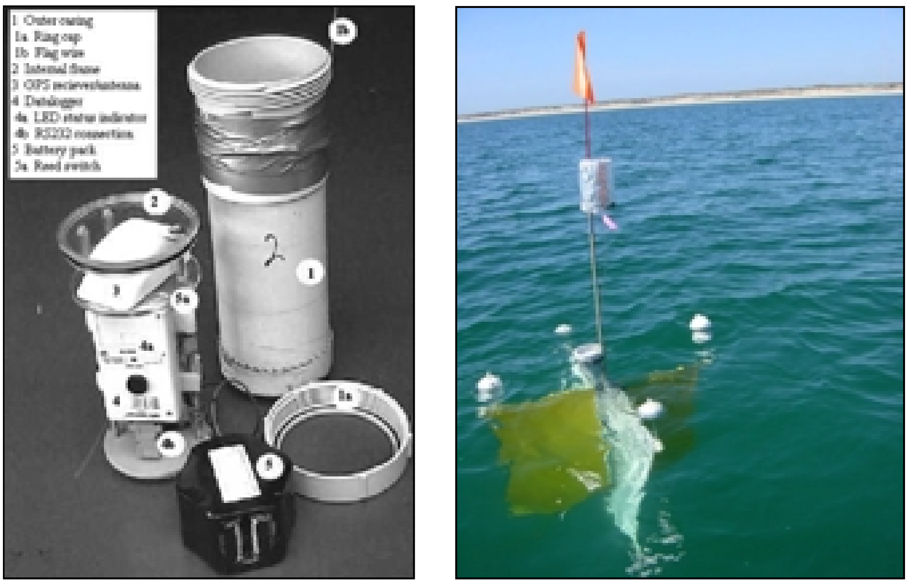


Figure 3. (a) Drifter components (b) Drogue in water at Point Murat, North West Cape

A fifth drifter was assembled slightly differently to investigate shear in the water column and consisted of two parts. The top part was a skeleton drifter constructed precisely as the drogues previously described minus the sails and bottom two rods. Tethered to this surface drifter by a 3m rope was a deep drogue that consisted of only the weighted centre PVC pipe, bottom and top crossed rods with floats and the sails. This deep drogue stayed between three and four meters in the water column. A Garmin eTrex hand-held GPS was fastened to the surface skeleton drifter so that its position was also recorded (every 10s) and later mapped.

An inflatable zodiac was used to deploy the drifters, monitor their movement and reposition them throughout the fieldwork to the locations of interest around the North West Cape, all this being recorded in field notes that were used later to edit the data. A second Garmin eTrex was utilised to run along the front in the zodiac and record its shape and position at various times during the fieldwork for reference with the drifter results. Several problems were encountered during the sampling including the loss of the drifters for an hour on Friday 15th and subsequently finding the deep drogue entangled with one of the surface drogues, possibly on a reef or rock outcropping. On the same day one of the surface drifters flashed a warning of 'low battery' but on inspection it was found to be wired incorrectly and could not be used for the remaining fieldwork.

Current Speed

The drifters were taken out at different times and locations during the tidal cycle from the 14th to the 16th of March to investigate the dynamics of the currents around the North West Cape. The purpose of deploying the drifters in different locations throughout the three days to calculate the current speeds was to obtain a picture of the mean flow using the Lagrangian method. Drifters were always placed approximately 1m apart except during the frontal experiments that investigated horizontal frontal convergence.

Frontal Convergence

An experiment in horizontal convergence at the front was conducted from 10.30am to 10.50am on the 14th March, parallel to the Navy Pier at Point Murat. This involved deploying two surface drogues and the deep drogue at the shore-side of the front and the other two surface drogues on the other side of the front. The purpose of this was to examine the direction of the drifters' motion in relation to the front and to each other and to compare the track of the deep drogue to its surface counterparts. The drogues were released at the time when the current direction changed from flood to ebb and there was minimal tidal current influence allowing the horizontal convergence at the front to predominate.

Convergence was again explored on the 15th of March at 9.30am at the time of current direction change from flood to ebb when the four surface drogues and deep drogue were placed in a line transect perpendicular to the shore at Point Murat (the Navy Pier). The deep drogue was positioned furthest out from shore and the first surface drogue was placed approximately parallel to the end of the Pier. The drogues were deployed about 5m apart and left in the water until 10.50am when they were retrieved from the front. At 11.05am, as the ebb current was increasing to its maximum, three of the surface drogues and the deep drogue were placed in a line transect perpendicular to the shore with the deep drogue furthest out to sea. The drifters were left and the front was mapped with a Garmin eTrex by running along it in the zodiac until the drifters were retrieved at 11.55am.

3.1.3 Water Structure Profiling

The study of density stratification in the water column is made possible through the use of instrumentation that describes the properties of the water with depth. Conductivity-temperature-depth (CTD) profilers have been used from the earliest oceanographic studies of frontal systems (Simpson 1971; Simpson & Hunter 1974; Simpson, Allen & Morris 1978). These instruments have developed into versatile, compact devices, not only measuring the conductivity (salinity), temperature and depth (pressure), but also the chlorophyll *a* (Fogg et al, 1985; Munk & Nielsen 1994) and the irradiance (photosynthetically active radiation). The CTD is used in oceanographic studies in two particular ways. The most common use is in a line transect where the depth versus distance is plotted, showing contours of the particular water property being considered (see Lough & Manning 2001 for similar CTD contour methods to this study). The CTD is also used as a mooring where the instrument is at fixed depth and the water property is plotted versus time. This method has been used on the Clyde Sea front (Simpson & Rippeth 1993; Kasai, Rippeth & Simpson 1999) where the structure of the front is examined through its oscillation back and forth past the CTD.

Thirteen CTD measurements were taken on a 22.64km transect perpendicular to the tip of the North West Cape and Muiron Islands through the entrance of the Gulf, starting approximately 16km outside the Gulf. Eleven stations were sampled in depths that ranged from 60m outside the Gulf to 20m inside the entrance. The instrument was a Sea-Bird SBE CTD and the data was processed using the manufacturer's software SEASOFT VERSION 4.218. The CTD was lowered over the starboard side of the RV Cape Ferguson and released to the desired depth whilst taking eight samples per second and relaying this data to a laptop computer where it was stored for later analysis. The sensors in the CTD recorded pressure (depth in meters), temperature (°C), salinity (psu or ‰), chlorophyll *a* concentration (µg/L) and irradiance (photosynthetically active radiation). The information that is gained from a CTD transect is used to describe the water column and is essential for defining the structure of a frontal system.

Moored CTD readings were taken on the 14th, 15th and 16th of March for 11.4 hours, 9.3 hours and 6.9 hours respectively. The CTD was fixed at a depth of approximately 7m on the starboard side of the RV Cape Ferguson, which was anchored midway between the northern tip of the Cape and Point Murat (southern tip). The depth recorded was the variation in the tidal level and this ranged from 6.5m to 8.5m. The CTD recorded the change in temperature, salinity, chlorophyll *a* and irradiance with time. The purpose of this moored CTD sampling is to observe the movement of the front past a fixed point with respect to time.

3.1.4 Eulerian Measurements

Circulation is studied through the use of Eulerian instrumentation that creates a profile of the structure of currents in the water column with depth and time, such as ship-borne or moored acoustic Doppler current profilers (ADCP) and moored current meters. ADCP have been used in frontal studies since the early 1990's in research including that of Simpson & Rippeth (1993) in the Clyde Sea where the profiles obtained before and after the breakdown of stratification through mixing indicated a modification in the circulation. Hill et al. (1993) made estimates of along-front and cross-front residual velocity fields through the front on Dogger Bank in the North Sea using an ADCP. A ship-mounted 300kHz ADCP with 3.1m bins was used to measure current speed and direction on Georges Bank (Yoshida & Oakey 1996) while Kasai, Rippeth & Simpson (1999) used both a 150kHz and 300kHz ship-board ADCP with 4m depth bins in the Clyde Sea. The latter measured horizontal velocities and along and cross-frontal components of residual flow and found some evidence of an along-front shear where the strongest temperature and salinity gradients had been observed. Lough & Manning also used both a 150kHz and 300kHz ADCP to profile the velocity field and they resolved the along-bank component as a consistent tidal front jet. Limitations in the use of ADCP arise from the errors due to instrument noise and from the near-bottom and near-surface flow that is lost due to a shadow zone in the surface 10m and in the bottom layer that has a thickness of approximately 15% of the total water depth. Lough & Manning (2001) describe the errors they found with the vertical components of the residual velocity as exceeding the errors involved with de-tiding, a tidal analysis technique described in Simpson, Mitchelson-Jacob & Hill (1990) that was used by Hill et al. (1993), Simpson & Rippeth (1993) and Kasai, Rippeth & Simpson (1999).

Two kinds of Eulerian measurements were made in the entrance to Exmouth Gulf using four instruments, but only two of the instruments are analysed in this study so only these will be discussed. The first instrument was an InterOcean S4 vector averaging current meter (VACM) that was moored in 5m of water midway between the northern and southern tip of the North West Cape, at the anchorage of the RV Cape Ferguson (21°47.9'S, 114°10.9'E). The InterOcean S4 was in place from 16.30 on the 11th of March until 13.30 on the 11th of May 2002. This instrument recorded the vector averaged current speed in cm/s, the direction of the current in degrees, surface temperature (°C) and depth (m), sampling 1 minute on every 5 minutes. The data was processed by InterOcean Systems S4 Current Meter Application Software Version 2.72, which converted the data to physical units. The second instrument was a 300kHz RDI Workhorse acoustic Doppler current profiler that was moored under the Navy Pier at Point Murat in 15m of water. The ADCP was in position (21°49.1'S, 114°11.4'E) from 07.50 on the 12th of March until 09.40 on the 30th of April 2002. Data was stored in 3m depth bins, starting 2.53m above the head of the 0.4m instrument. The magnitude of the current speed in mm/s at these different depths throughout the water column and its direction in degrees was recorded by the ADCP in 1 minute ensembles at 30 pings per ensemble. The data was then processed using WinADCP Version 1.08, which can view and export the ADCP data to ASCII files.

3.1.5 Biological Observations

Visual observations of the biota on and around the front were made throughout the expedition. Digital photographs were made of the algal slick, the fish, diving seabirds and the pod of dolphins. Detailed field notes were taken and these were later used to identify the species around the front. The surface expression of the front was approximately 3km to 5km long and ranged from a thin line to a width of approximately 5m displaying small-scale eddies and swirls (less than 1m diameter).

The front was recognised by its surface manifestation of light brown algae that was thought to be the cyanobacteria *Trichodesmium*, bits of seaweed and bubbles. The small schooling bannerfish *Heniochus diphreutes*, that are common around the higher latitudes of Australia, were seen beneath the surface slick and are known to swim midwater and feed on zooplankton (Kuiter 1996). Associate Professor Ron Wooller of Biological Sciences in Murdoch University identified the species of seabird on the front from photographs taken and from the field notes as the bridled tern, *Sterna anaethetus* which breeds on Ashburton, Anchor, Flat and Round Islands, not too far from Exmouth Gulf. Their breeding season is around August to October and they leave the islands around April. The terns had dark feathers on their back, were white underneath and had a split tail and they were observed to circle above the front and dive down suddenly preying on the fish. Bridled terns' diet includes a variety of fish including the shoaling clupid fish, which is brought to the surface by larger predatory fish, larval beaked salmon, goatfish and lanternfish. The presence of the birds circling over the water revealed to us the position of the front. Bottlenose dolphins often appeared to be on or near the front but this observation may be biased, as dolphins may be attracted towards humans in boats whilst looking for a free meal (personal experience in Shark Bay), so it is possible they were following the zodiac.

3.2 DATA ANALYSIS

3.2.1 Quasi-Lagrangian Drifters

Drifter trajectories are analysed for several oceanographic properties that are of interest in the circulation of a water mass. An investigation by List, Gartrell & Winant (1990) in the coastal waters of southern California used oceanographic drogues and current meters to examine the diffusion and dispersion of the water. They employed techniques described by Okubo (1974) for the dispersion calculations and compared their results to current meter measurements. Diffusion was calculated using estimations suggested by Okubo & Ebbesmeyer (1976) and Yanagi, Murashita & Higuchi (1982), as well as an original approach involving the separation of each particle into a mean movement. A study by Molinari & Kirwan (1975) determined relative cluster motion, horizontal divergence, vorticity, shear deformation rate and normal deformation rate. Okubo & Ebbesmeyer (1976) developed similar techniques and found not only the mean flow, dispersion and eddy diffusivities but also the field of mean vorticity, divergence and deformation rates. In the present study, the quasi-Lagrangian drifter trajectories around the North West Cape were analysed to calculate their speeds, dispersion, secondary circulation and convergence to the frontal system.

Speed matrices were constructed using the recorded GPS positions with time following the approach outlined in Okubo & Ebbesmeyer (1976), with the coordinates (*x, y*) of the drifters at time (*t*). Latitude and longitude was converted to coordinates (*x*, *y*) using a conversion function in MATLAB® obtained from David Johnson, which requires the input of latitude, longitude, zone, hemisphere and ellipsoid.

$$u(t) = \begin{pmatrix} u_1(t) \\ u_2(t) \\ . \\ . \\ . \\ u_n(t) \end{pmatrix} \qquad v(t) = \begin{pmatrix} v_1(t) \\ v_2(t) \\ . \\ . \\ . \\ v_n(t) \end{pmatrix}$$

where $u(t)$ is the speed component in the *x* direction and $v(t)$ is the speed component in the *y* direction. The number of drogues for the particular trajectory is represented by *n*. The speed of the drifters was then calculated as the resultant of the *x* and *y* components. An index map for each drogue speed plot is included for reference of the position to the North West Cape.

Dispersion was calculated observing the approach described by List, Gartrell & Winant (1990) who found the dispersion coefficient to be a function of the variance with time. The variance was calculated relative to the position of the centroid of the drogues with respect to time. For the *x* and *y* components respectively, the centroid of the set of drogues is

$$\bar{x}_i = \frac{\sum_j x_{ij}}{N} \qquad \bar{y}_i = \frac{\sum_j y_{ij}}{N}$$

where N is the number of drogues and (x, y) is the position of drogue j at time i. The variance is found from sum of the differences between the position of each drogue to its centroid position for both the x and y directions.

$$\sigma_{x_i}^2 = \frac{\sum_j \left(x_{ij} - \bar{x}_i\right)^2}{(N-1)} \qquad \sigma_{y_i}^2 = \frac{\sum_j \left(y_{ij} - \bar{y}_i\right)^2}{(N-1)}$$

The variance is then calculated from the sum of the x and y variance components, defined by Okubo (1974) and cited in List, Gartrell & Winant (1990) as the dispersion of the drogue distribution.

$$\sigma_i^2 = \frac{\left(\sigma_{x_i}^2 + \sigma_{y_i}^2\right)}{2}$$

For large numbers of drogues it is possible to calculate the relative dispersion coefficient and the spatially dependent relative dispersion coefficients (using the x and y components of the variance). Although there are a limited number of drogues, the variance was used to calculate the relative dispersion coefficient following Okubo (1974) cited in List, Gartrell & Winant (1990).

$$K(t_i) = \frac{1}{2}\frac{\partial \sigma_i^2}{\partial t} \approx \frac{1}{2}\frac{\Delta \sigma_i^2}{\Delta t}$$

Data, concerning the convergence of the drogues to the frontal system, were analysed through plotting the drifter trajectories using MATLAB® and examining their behaviour in relation to the frontal system. The position of the front with time was recorded using a Garmin eTrex whilst in the zodiac during one of the two frontal experiments conducted and this data was plotted together with the drogue trajectory allowing a visual assessment of the convergence of the drogues to the front.

Secondary circulation exists for curved flow patterns such as river bends, flow around islands and flow around headlands and acts normal to the plane of mean flow. The direction of the secondary circulation is towards the land on the bottom of the water column and is in the opposite direction on the surface, away from the land. There is evidence that secondary circulation is the cause of upwelling at the tip of a headland or island and this effect extends downstream (Alaee, Ivey & Pattiaratchi 2002). Although the principle of secondary circulation is the same for river bends as for oceanic systems, there are differences in the physical factors affecting each. Oceanic flow is generally tidally forced and therefore oscillatory. This may contribute to the discrepancies found when using the river bend model proposed by Kalkwijk & Booij (1986), cited in Alaee, Ivey & Pattiaratchi (2002), to estimate secondary circulation for oceanic situations. The technique described by Alaee, Ivey & Pattiaratchi (2002) used the expression for secondary flow found by Kalkwijk & Booij (1986), derived from the momentum equation in the normal plane.

$$\frac{\partial u_n}{\partial t} + u_s \frac{\partial u_n}{\partial s} - \overline{u_s \frac{\partial u_n}{\partial s}} - \frac{\partial}{\partial z}\left(k_z \frac{\partial u_n}{\partial z}\right) - \frac{\tau_n}{\rho h} = -\frac{u_s^2 - \overline{u_s^2}}{R_s} - f\left(u_s - \overline{u_s^2}\right)$$

where u_n is the transverse velocity, u_s is the streamwise velocity, s is the streamwise coordinate, z is the vertical coordinate, k_z is the vertical eddy viscosity coefficient, τ_n is the bottom shear stress in the n-direction, ρ is the mass density, h is the depth, R_s is the radius of curvature in the s-direction and f is the Coriolis parameter. This simplifies further when the viscous term and non-linear term are neglected and the equation is assumed to be in steady state. From this the relative importance of advection due to friction is expressed as an equivalent Reynolds number R_{ef} and the relative importance of the driving forces expressed as a modified Rossby number R_{om}.

$$R_{ef} \sim \frac{h}{LC_D} \qquad\qquad R_{om} = R_o = \frac{2u_s}{fR_s}$$

where h is the depth, L is the streamwise length scale, C_D is the bottom drag coefficient and R_o is the Rossby number.

The secondary circulation is calculated according to the importance of the generation of momentum source (R_{om}) and the dissipation of momentum source (R_{ef}). This is determined through use of a classification table specified in Alaee, Ivey & Pattiaratchi (2002) where the conditions are described in Table 2. The maximum transverse velocity near the surface (U_n) is dependent on a constant factor (K) for each regime and the parameters relating to the dominant forces. Regimes B and D involve inertia and this requires inclusion the parameter *b*, which is the length of the semi-minor axis of the headland or island. The regime is determined and hence the maximum transverse velocity is calculated using this approach for the streamwise velocities measured around the North West Cape. A comparison is made between the predicted transverse velocities and those measured using the acoustic Doppler current profiler.

Table 2. Secondary flow regime parameters and conditions.

Regime	R_{om}	R_{ef}	U_n	**Constant Factor (K)**	**Dominant Forces**
A	< 1	< 1	$K_A \frac{fh}{C_D}$	$K_A = 0.026$	balance between bottom friction and Coriolis forces
B	< 1	> 1	$K_B\, fb$	$K_B = 0.02$	balance between inertia and Coriolis forces
C	> 1	< 1	$K_C \frac{hU_s}{C_D R_s}$	$K_C = 0.11$	balance between bottom friction and centrifugal forces
D	> 1	> 1	$K_D \frac{bU_s}{R_s}$	$K_D = 0.27$	balance between inertia and centrifugal forces

3.2.2 Conductivity-Temperature-Depth

The temperature and salinity data obtained from the CTD transect through the entrance of the Gulf was used with 'SEAWATER© Version 1.2e', a MATLAB® program written by Phil Morgan of CSIRO that calculates different sea water properties such as potential temperature, density, freezing point and thermal expansion coefficient. The SEAWATER© sw_dens subroutine was used to find the density of the water column and determine its stability. The input values for the density function were salinity (psu), temperature (°C), pressure (db) and the output was density (kg/m^3) where all inputs were to have the same dimensions and the depth was converted to pressure using the SEAWATER© sw_pres function. The raw data was interpolated to a grid of specified values, producing a contour plot of the properties of the seawater; density, temperature, salinity, chlorophyll a and irradiance with distance (km) from the deeper waters outside to the shallower waters inside the Gulf.

The moored CTD readings of temperature (°C), salinity (psu) and chlorophyll *a* (μg/L) for the 14th, 15th and 16th of March were also plotted in MATLAB® and the density was calculated using the SEAWATER© function sw_dens. Each water property was plotted with time and these were vertically aligned for comparison.

3.2.3 Vector Averaging Current Meter

The InterOcean S4 vector averaging current meter recorded the current direction, current magnitude, temperature and depth. A vector plot was created using MATLAB® incorporating the direction and magnitude for each data point and displaying this with time on the horizontal axis. This presentation of the data reveals the nature of the ebb and flood tide strength, direction and duration. The depth readings are also plotted showing the time of the change in current direction in relation to the tidal level. Although the vector averaging current meter is at a fixed depth it is an adequate approximation of the currents at that particular site. The drogue trajectories are validated through comparison of their measurements of current speed with the current speed obtained by the vector averaging current meter. List, Gartrell & Winant (1990) also used this validation technique, comparing the Lagrangian drogue measurements with Eulerian current meter measurements.

3.2.4 Acoustic Doppler Current Profiler

The acoustic Doppler current profiler data was plotted in two ways, the first as a colour contour plot of the northerly and easterly directions and the second as a vector plot at 2m intervals through the water column. The first was plotted using MATLAB® with depth on the vertical axis and time on the horizontal axis and a colour axis indicating the strength and direction of the current. Variables including the velocity direction (degrees), the north and east velocity magnitudes (mm/s) and the resolved velocity magnitude (mm/s) were used to achieve this. Current profiles with depth are used to examine the duration, direction and strength of the current in a particular area with depth. This information is particularly useful in describing the dynamics of the circulation around Point Murat at the site of the observed frontal system. The second plot of the velocities around the Navy Pier was created using a MATLAB® vector plotting function where the current speed was the vertical axis and the horizontal axis was the time. From this graph the direction and speed of the current at different levels throughout the water column are seen.

3.3 ADDITIONAL DATA

3.3.1 Bathymetry

Data points were entered using a digitiser[7] to create a map of the bathymetry of Exmouth Gulf showing the locations of the conductivity-temperature-depth transect. A nautical chart of Exmouth Gulf (Commonwealth of Australia 1984) was used to input the data into ArcInfo as tic points. Arcedit was used to build the topology by removing the pseudo nodes, fixing the dangles and cleaning the coverage. A point coverage was created using the latitudes and longitudes of the conductivity-temperature-depth locations. The coverage was viewed in ArcView using the attributes entered with depth and a legend was created appropriate to the bathymetry.

The bathymetry in Figure 4 shows that the majority of the Gulf is shallow, less than 30m. The continental shelf is quite close to the coastline of the North West Cape resulting in a steep decline immediately adjacent to the coast from 5m to 100m in 16km. Between the North West Cape and the Muiron Islands is a shallower ridge of 15-20m separating the deeper, stratified waters from the shallow, well-mixed Gulf waters. There is also a narrower ridge that extends from the Muiron Islands out into the deeper waters. The conductivity-temperature-depth transect is shown on the map as starting in the deeper waters outside the Gulf, over the narrow ridge and major ridge between the land masses and into the shallow Gulf waters.

[7] The bathymetry was digitised with the generous help of Bernadette Streppel (Department of Geography, University of Western Australia).

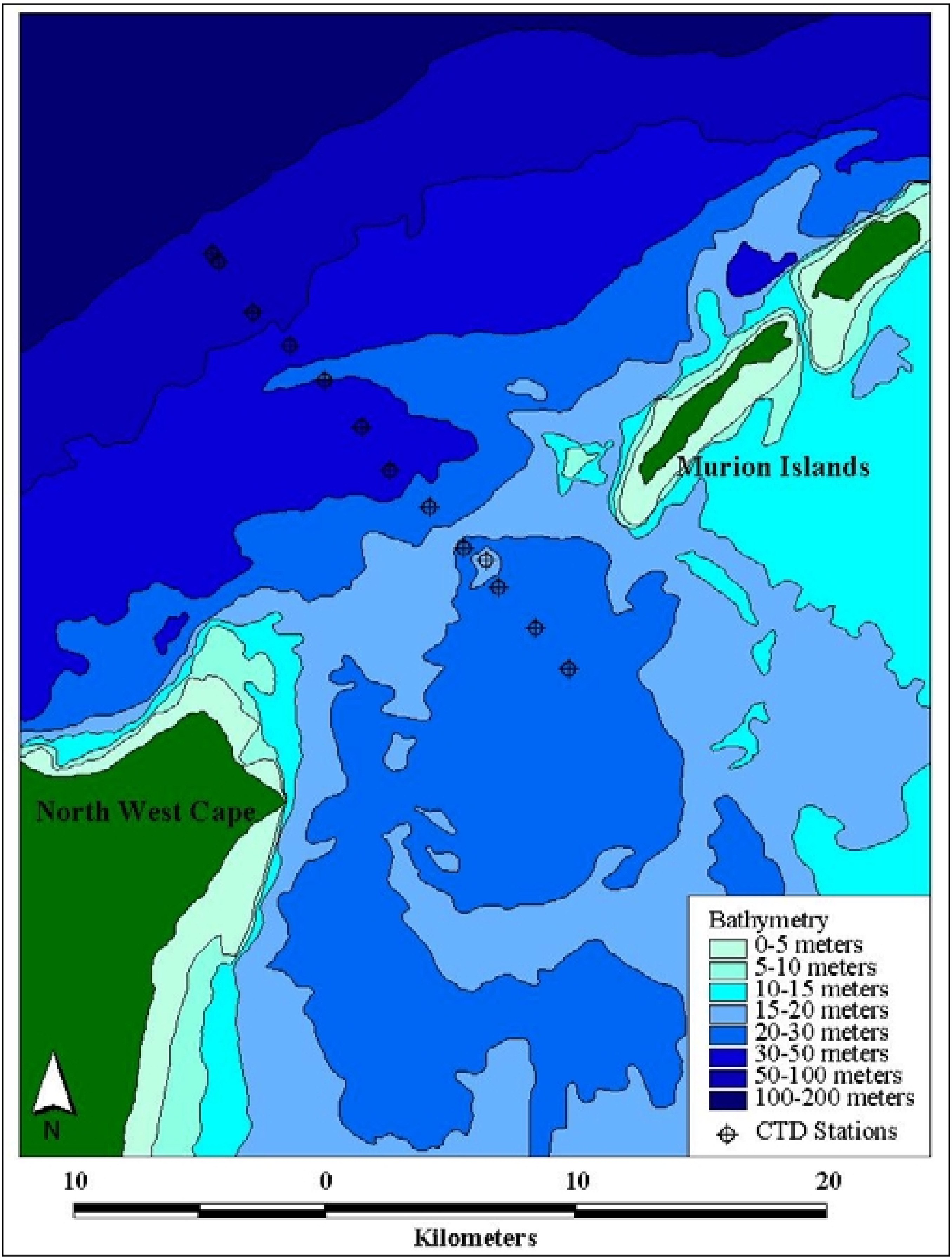


Figure 4. Bathymetry of Exmouth Gulf

3.3.2 Sea Surface Temperatures

Infrared satellite imagery of sea surface temperatures (SST) became a useful tool in the location of frontal systems a few years after the start of the intensive frontal work around the British Isles (Simpson, Hughes & Morris 1977). The sea surface temperature images have primarily been used as a comparative tool with the position of the fronts found using estimates of h/u^3 (Pingree & Griffiths 1978; Simpson & Bowers 1981; Hill et al, 1993).

Simpson, Allen & Morris (1978) used satellite imagery to describe eddies and instabilities of the frontal system and also compared the results of the Simpson-Hunter parameter to the images. Small displacements of fronts as a result of tidal advection or changes in stirring and heating rates have been studied through analysis of SST images where numerous archives of the SST were combined and compared to the ranges of h/u^3 (Simpson & Bowers 1979; Simpson 1981; Mavor & Bisagni 2001). Biological studies also often utilise the satellite imagery as an alternative to calculating the positions of the fronts they are concerned with, such as Kinder et al. (1983) who studied seabirds around the Pribilof Islands fronts and Fogg et al. (1985) whose biological studies were focused in the Irish Sea. Sims et al. (2000) correlated the locations of basking shark courtship events to the positions of fronts off south-west England and demonstrates this through the use of SST imagery.

Satellite imagery of the sea surface temperatures is used in the present study to clarify the observations of fronts and surface slicks made with conductivity-temperature-depth instrumentation. Taylor & Pearce (1999) and Wilson, Taylor & Pearce (2001) have used SST images to identify the Ningaloo Current with regard to their studies of the whale sharks around the Ningaloo Reef region and these show the influx of colder Ningaloo Reef water re-circulating up past the North West Cape. This was particularly apparent in the image of temperatures from the 18th of March 1991 shown in Taylor & Pearch (1999), which is the same time of year exactly as the sampling period of the current investigation (8th – 17th March 2002).

Sea surface temperatures were obtained[8] for the 14th of March 2002 at 13:54 for the study area (21° - 23°S and 114° - 115°E) and the image is shown in Figure 5. The range of temperatures that are displayed are quite high (30 - 36°C) but this is because the data shown is uncalibrated. One of the limitations of SST images are the problems associated with cloud cover, this being the reason why only one day of temperatures was able to be obtained and analysed. Although SST are useful for identifying the boundaries between water masses of different temperatures, they describe nothing of the rest of the water column, only the surface.

The sea surface temperatures presented here show the warmer waters in the Gulf and north-east of the Gulf. Cold water is seen in the channel entrance near the tip of the North West Cape and near the Muiron Islands. A sharp boundary is apparent between this colder water and warm Gulf water, near Point Murat. The shallowest parts of the Gulf near the western coastline and the mudflats on the eastern coast are the warmest while the deeper regions in the south of the Gulf and in the channel entrance are cooler.

[8] Data acquired by the Western Australian Satellite Technology and Applications Consortium (WASTAC). Data processed by the Department of Land Administration (DOLA).

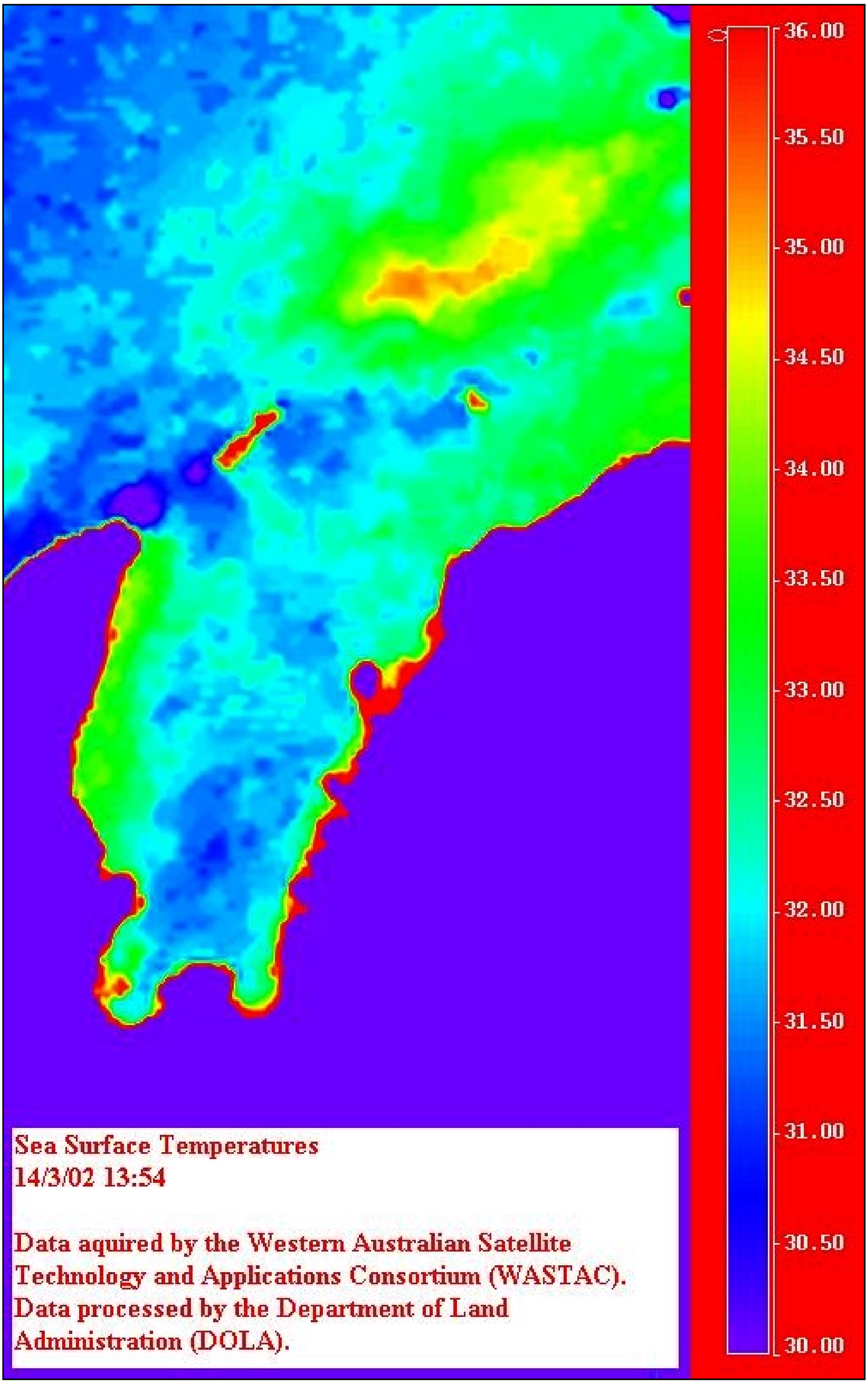


Figure 5. Sea Surface Temperatures for Exmouth Gulf 14th March 2001.

3.3.3 Tides

The nearest standard port that had a data set of tidal height readings[9] was at Exmouth, which is 15km south of the region of interest. The readings for this port are given in Figure 6 showing both the data for the entire month and the specific days during which the field work was conducted. These readings were not used for the moored conductivity-temperature-depth data analysis (section 3.2.2) as Exmouth was too far from the study area and there was a phase lag in the tidal height; instead the water level change recorded by the instrument itself was used. The tide level data for Exmouth was however used to obtain a complete picture of the tides that month and the overall change between spring and neap tides.

The tidal cycle for March 2002 shows the semi-diurnal regime of two high tides and two low tides per day for an entire lunar cycle of springs and neaps. In the period of spring tides during which field work was conducted (12th – 17th of March), the tidal range was between 60 – 245cm. This was during the shift from the neap tides to spring tides where the range increased and the difference between high and low tides became less marked.

3.3.4 Climate

Annual climate averages and monthly data have been obtained[10] for Thevenard Island (21°27.5'S, 115°01'E) at an elevation of 5m, as this was the most realistic observation station near the study area. Wind roses, air temperatures, wind speed and rainfall are used to examine the meteorological processes that affect the Gulf A summary of the climate data for Thevenard Island is given in Figure 7, including (a) air temperatures indicated with a red line, wind direction indicated with a green line and (b) wind speed. Rainfall is not included as there was only 0.8mm at 6am on the 15th of March.

Temperature (Figure 7a) shows an increase during the day and lower temperatures at night and the highest temperatures were experienced on the 15th of March during the field work. Wind speed (Figure 7a) correlates with the temperature, with higher wind speeds on the days of low temperature and little wind on the hotter days. The wind direction (Figure 7b) was predominantly south, south-easterly with some variability prior to the period of field work.

---

[9] Data obtained from the Department of Transport and Infrastructure (Tide and Wave Information), Perth.

[10] Data obtained from Climate and Consultancy Services, Regional Office of the Bureau of Meteorology, Perth.

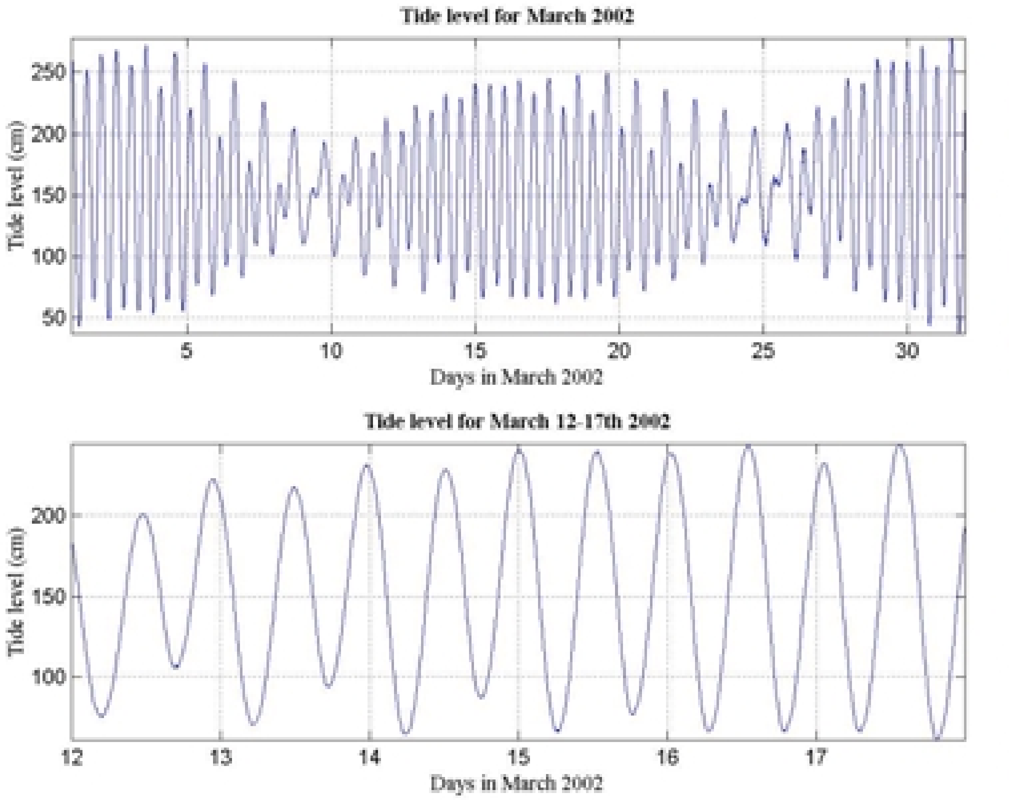


Figure 6. Tide Level at Exmouth for March 2002.

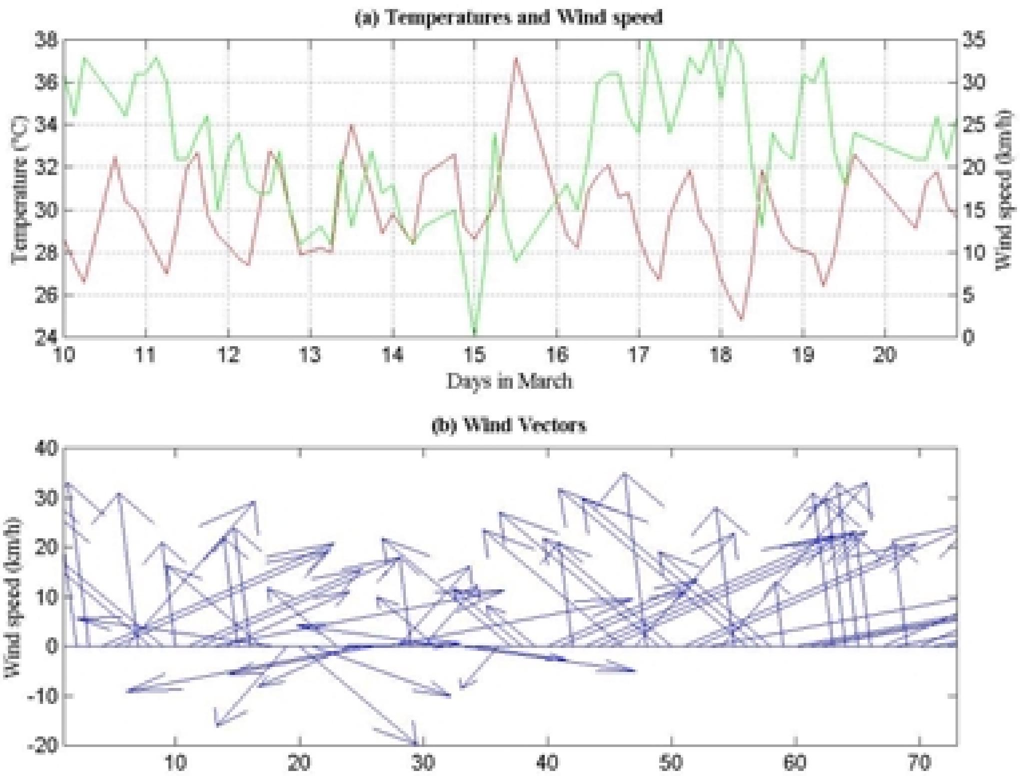


Figure 7. Climate data for Thevenard Island.

3.3.5 Biological Abundance

Meekan et al. (2001) conducted five 10-day expeditions in Exmouth Gulf between October 1997 and March 1998 comparing the fish catches of two light trap designs, small and large. A transect from inside to outside the Gulf through the entrance was made with sampling stations on a line perpendicular to the tip of the North West Cape. No analysis was made in this report on the differences in catches between stations, only on the differences between light trap designs. AIMS is currently undertaking this research (Dr M. Meekan, Research Scientist, pers. comm.). The total fish abundance and numbers of pomacentridae, the predominant reef fish, were plotted for each station into the Gulf, as was the total zooplankton and euphausiids, the predominant zooplankton (Figure 8). The purpose of this is to compare the physical oceanographic features measured through conductivity-temperature-depth instrumentation to the biological data collected on the same transect. There are errors in this approach as the transects were not completed during the same sampling period but the results will still be an indication of the sites of higher fish and zooplankton abundance.

Figure 8a shows the higher fish abundance at site three, the position immediately between the Muiron Islands and the tip of the North West Cape and site four, on the 50m depth contour where the oceanic waters converge with the Gulf waters. Highest zooplankton abundance is observed at sites two, three and four (site two being further into the Gulf). At these higher abundance sites for both the fish and zooplankton, approximately a five-fold increase is observed in numbers when compared to the remainder of the transect.

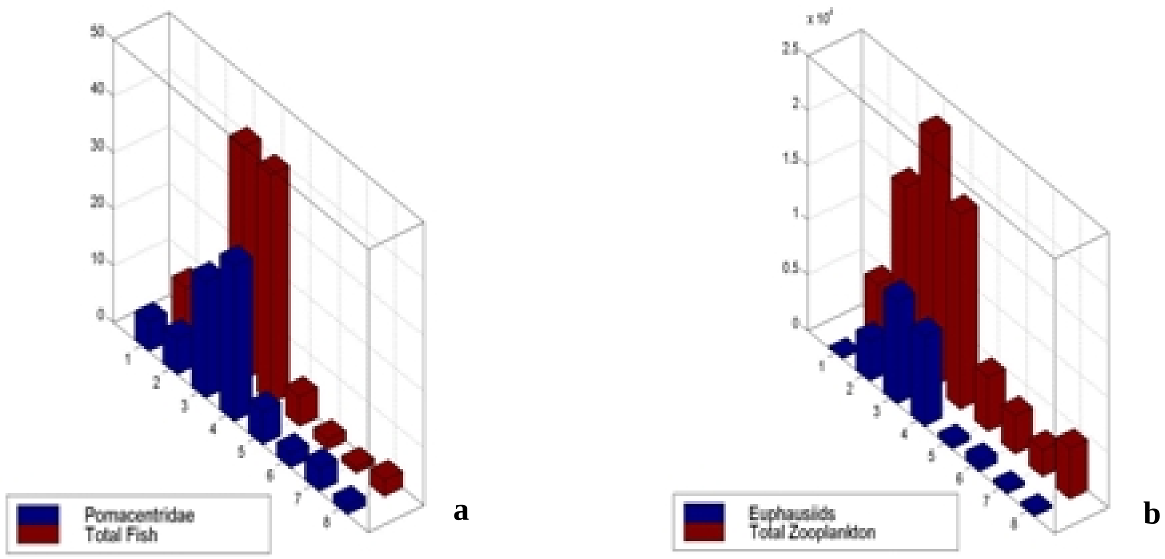


Figure 8. Biological abundance in transect through entrance of Exmouth Gulf.

4.0 Results

4.1 QUASI-LAGRANGIAN DRIFTERS

4.1.1 Current Speed

The drogue speeds that were calculated are presented in Appendix I for each discrete set of measurements made. Figure 9 is a representative compilation that includes an index map of the drogue trajectories in relation to the North West Cape coastline and a plot of the tidal currents at that particular time in the tidal cycle, along with the individual drogue speeds. The deep drogue is labeled for comparison with the surface drogues. The current measurements made by the current meter do not match exactly with the drogue speeds due to the Eulerian nature of the instrument. It was fixed at 5m depth midway between the northern and southern tip of the North West Cape while the quasi-Lagrangian drogues were in the surface 1m of water and moved north to south along the Cape. Therefore only the measurements taken by the drifters while in the vicinity of the current meter will correspond to a degree. The purpose of plotting the Eulerian measurements with the drogue speeds is to obtain a general notion of the state of the currents at that particular time.

The current speed plots in Appendix I are arranged in ‘sets’, where a set includes the drifters that were deployed and retrieved simultaneously. The first nine sets were sampled during Thursday 14th March, sets 10 – 14 were taken on Friday 15th and the last four were from Saturday 16th March. The change in current speed in these plots is attributed to a number of factors including the position with respect to the coastline, the state of the tide and therefore the strength of the tidal currents and the wind driven surface current. The position of the drifters with regard to the land is affected both by their distance out from the land and their location in relation to the northern or southern tips of the Cape. These current speeds obtained by the drifters are validated in section 4.3.2 and section 4.4.3 through comparison with the Eulerian measurements taken by a vector averaging current meter and an acoustic Doppler current profiler respectively.

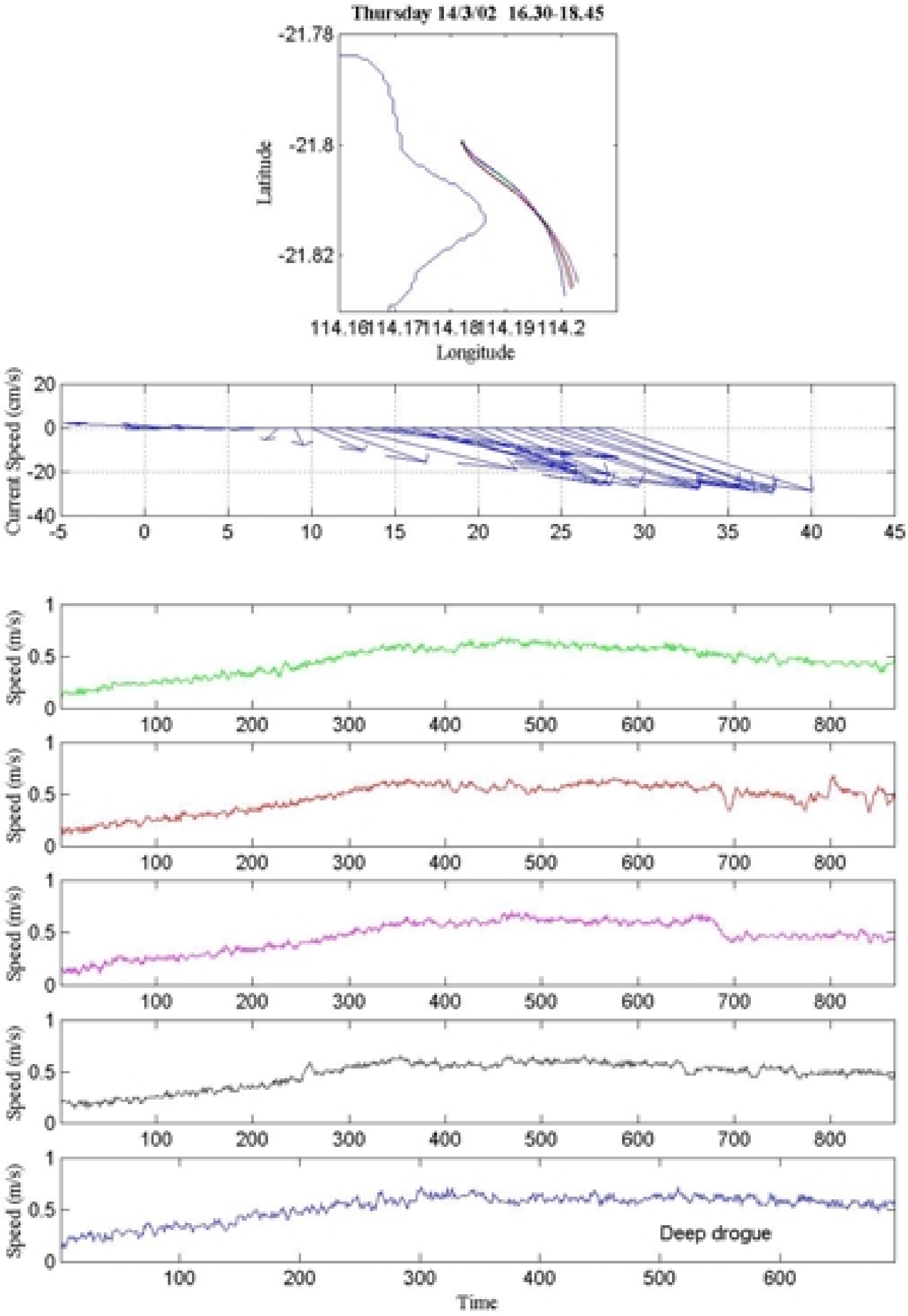


Figure 9. Drogue tracks adjacent to North West Cape, current meter speeds and drifter speeds on Thursday 14/3/02, 16.30-18.45 (SET 9).

Point Murat

From Figure 9, which was sampled from 16.30 – 18.45 on the 14th March with a set of four surface drogues and one deep drogue, there are several observations. The increase in speed of the current (from the moored current meter data) is matched with an increase in the speed of the drifters. Section 4.3.2 discusses the difference in the actual magnitudes of the drogue speeds and the current meter. The drifter set was deployed at the anchorage of the vessel that was midway between the northern tip of the Cape and Point Murat and travels from this point parallel to the coastline in a south-easterly direction. Upon reaching Point Murat the drifters travel in a more southerly direction, showing slight curvature towards the coastline yet still following the direction of the currents. This pattern around Point Murat is obvious in the drifter sets 1, 2, 3, 5, 6, 8, 9, 10 and 12.

Northern tip of North West Cape

Another similarity observed between drifter sets are the trajectories around the northern tip of the North West Cape, as in sets 4 and 14. Figure 11 shows the drifters released from the anchorage of the vessel and being taken parallel to the coastline in a north-easterly direction. The second plot in Figure 11 shows the ebbing current measured by the current meter, in a north-easterly direction. The drogues follow a curved path around the cape and their speeds increase corresponding to the increase in speeds measured by the current meter. The magnitudes are again different between the drogues and the moored current meter and this difference is discussed in section 4.3.2.

4.1.2 Dispersion

Dispersion was plotted with time for each set of drogues released (Appendix II). All plots have the same scale with the exception of sets 3 and 11 that showed dispersion an order of magnitude larger and were accordingly plotted to this scale. These two sets were the only ones showing the presence of eddies. Sets 12g, 14g and 15g are the dispersion between a surface drogue and the deep drogue while the rest of the plots show only the dispersion between the surface drifters. Comparing the 12g and 14g plots to their respective ‘surface only’ plots reveals that the dispersion between the surface and deep drogue is greater than the dispersion between only surface drifters for the same set of drogues.

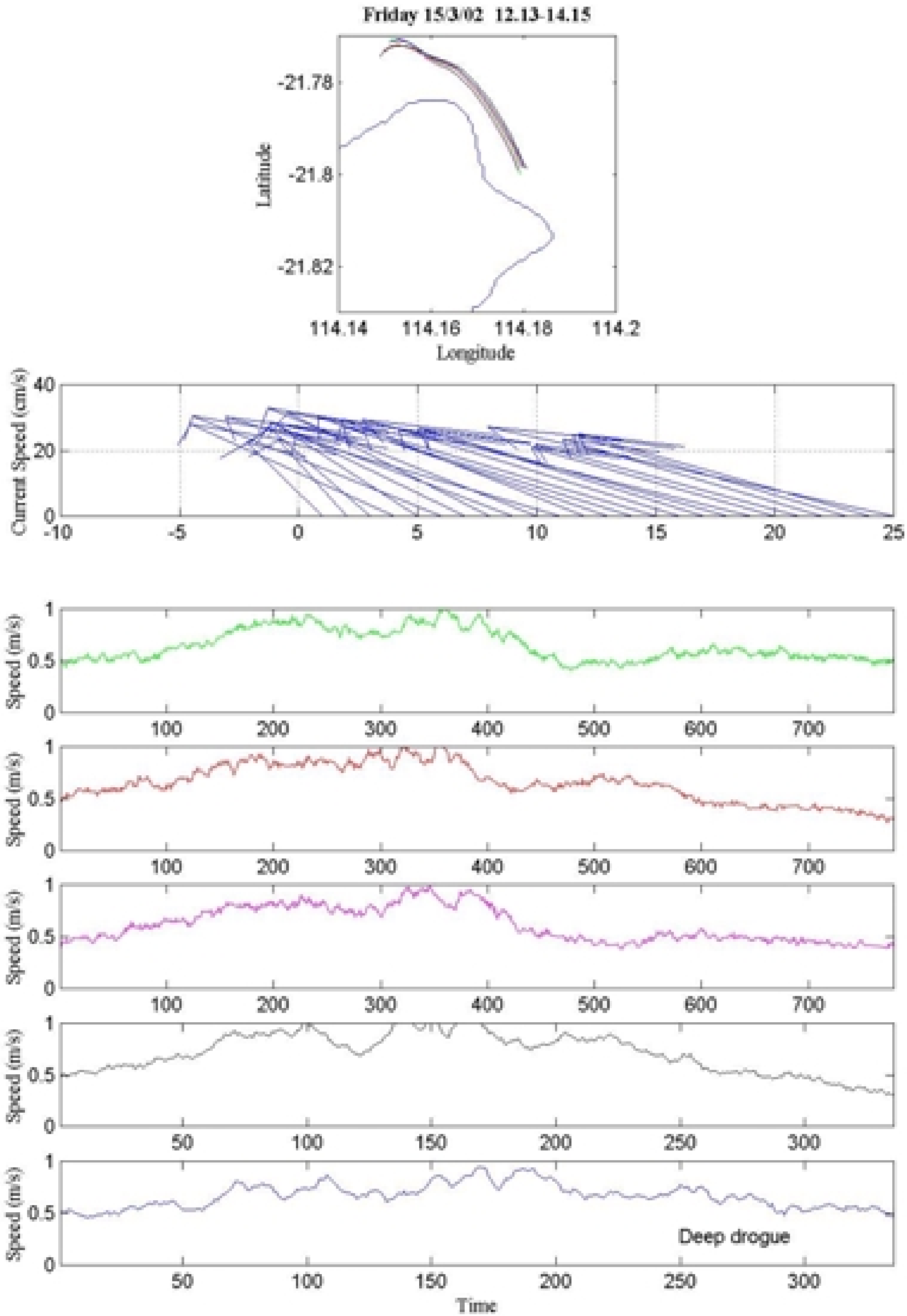


Figure 10. Drifter results around northern tip of North West Cape on Friday 15/3/02, 12.13-14.15 (SET 14).

Dispersion was then plotted with the length scale (Figure 11) as in List, Gartrell & Winant (1990) and compared Okubo's Data (1974). Okubo (1974) proposed a 4/3 rds law where the slope of the line of least squares through the logarithmic plot of the data is 4/3. The slope of the plot of the dispersion versus the length scale for this data set agrees with the 4/3 rds law. The dispersion coefficients are low, varying from 1 – 100 m^2/s, but this is acceptable as this range is what is used in numerical models.

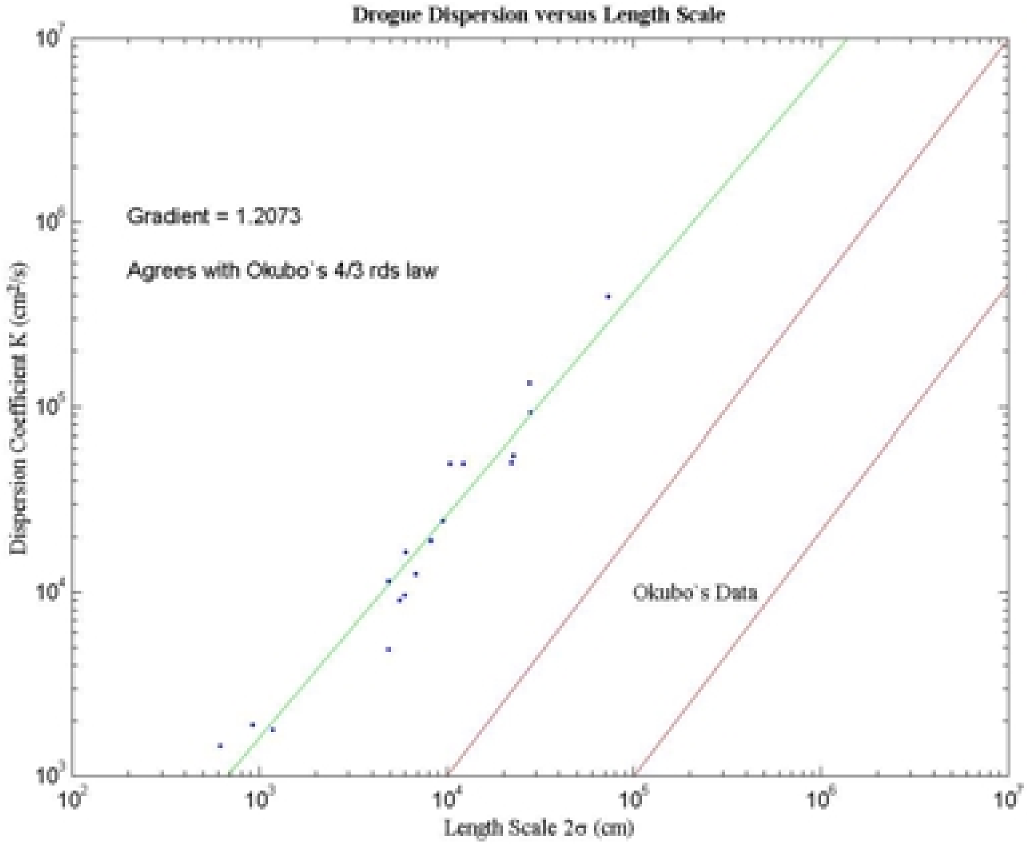


Figure 11. Dispersion coefficient plotted with length scale and compared to Okubo (1974) data.

4.1.3 Frontal Experiments

Three separate investigations into horizontal convergence were made using the sets of drogues around the frontal zone during different tidal states. An enlargement of the first experiment at 10.30am on Thursday 14th March is given in Figure 12. The experiment was conducted adjacent to Point Murat, near the Navy Pier. The deep drogue (blue) and two surface drogues (green and pink) were released on the shoreward side of the front while the other two surface drogues (red and black) were deployed on the seaward side of the front, which ran parallel to the coastline. The three drogues deployed on the shoreward side initially moved horizontally towards the front while the two released on the seaward side initially moved along the front. The position of the drogues with time corresponds exactly to the location of the front measured with a Garmin eTrex in the zodiac. When collected, the drogues had dispersed in relation to each other but were all on the surface slick of the frontal system.

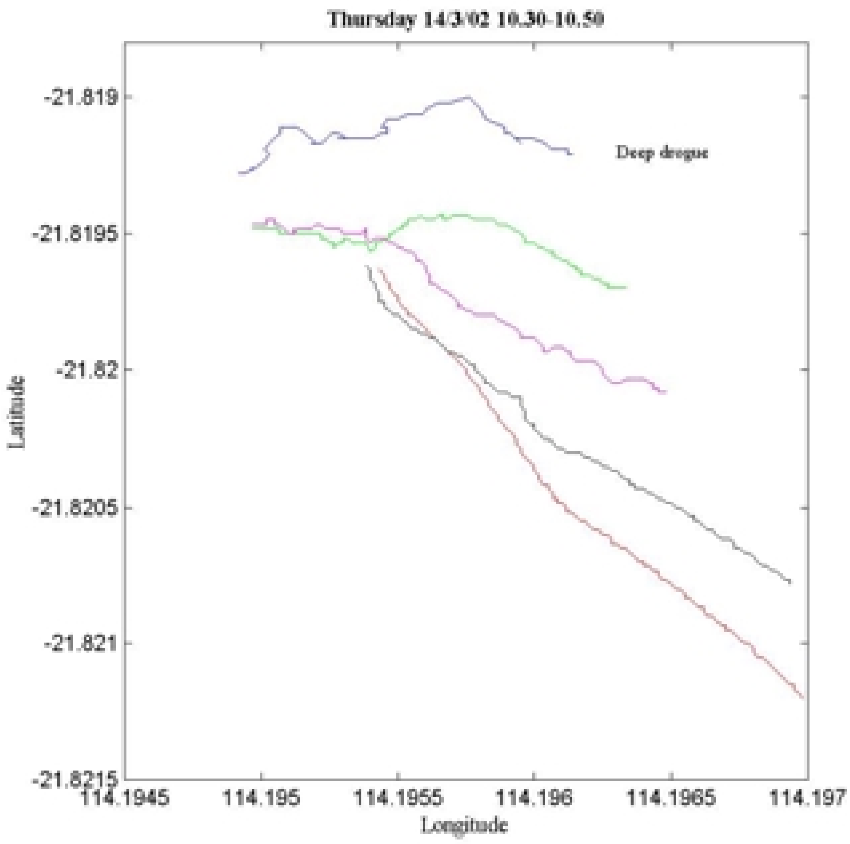


Figure 12. Frontal convergence experiment near Point Murat on Thursday 14/3/02, 10.30-10.50.

The second experiment testing horizontal convergence was conducted at 9.30am on Friday 15th March, again with five drogues around Point Murat at the surface slicks (Figure 13). The drogues were deployed in a line perpendicular to the coast with the deep drogue furthest out from the land. All three drogues moved towards one point and continued along this trajectory until they were removed from the water.

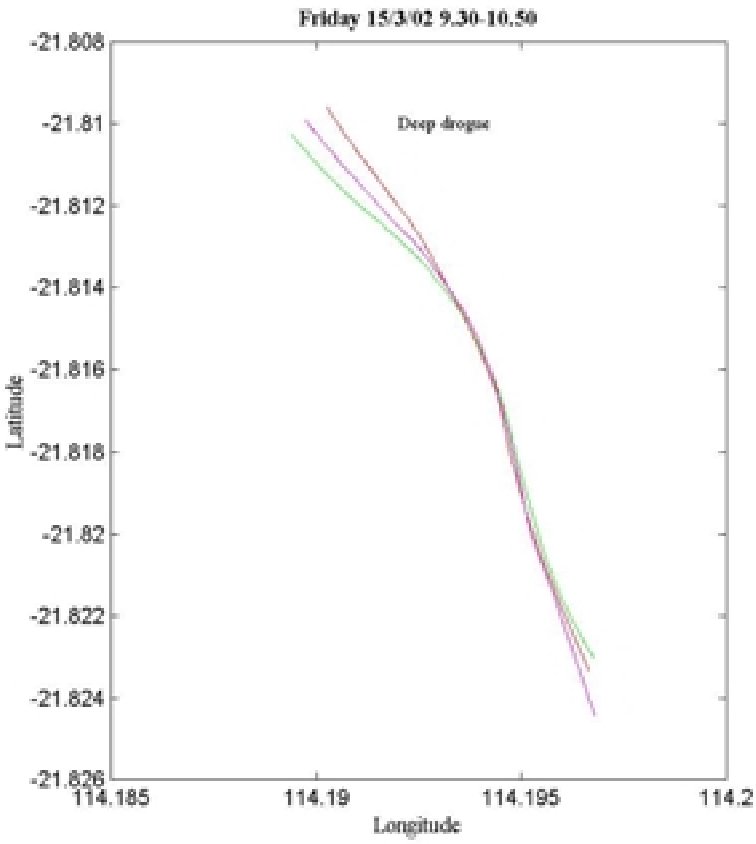


Figure 13. Convergence at Point Murat on Friday 15/3/02, 9.30-10.50.

The final investigation into the horizontal convergence at the frontal system was conducted immediately after the second experiment. Four of the drogues were released in a line transect perpendicular to the Navy Pier and near the surface expression. Figure 14 shows both the drogue trajectories and the position measurements made in the zodiac of the frontal location. From this it is apparent that the drifters stayed on the surface slick until they were collected, moving initially in a south-easterly direction then turning with the currents to move in a north-easterly direction out of the Gulf. The deep drogue (black) was deployed furthest from the coast and its path is not significantly different to any of the surface drogues, with respect to the frontal system. The speed of the movement of the surface slick was then assumed to be equivalent to the drifter speed, approximately 0.3m/s moving out away from the coastline.

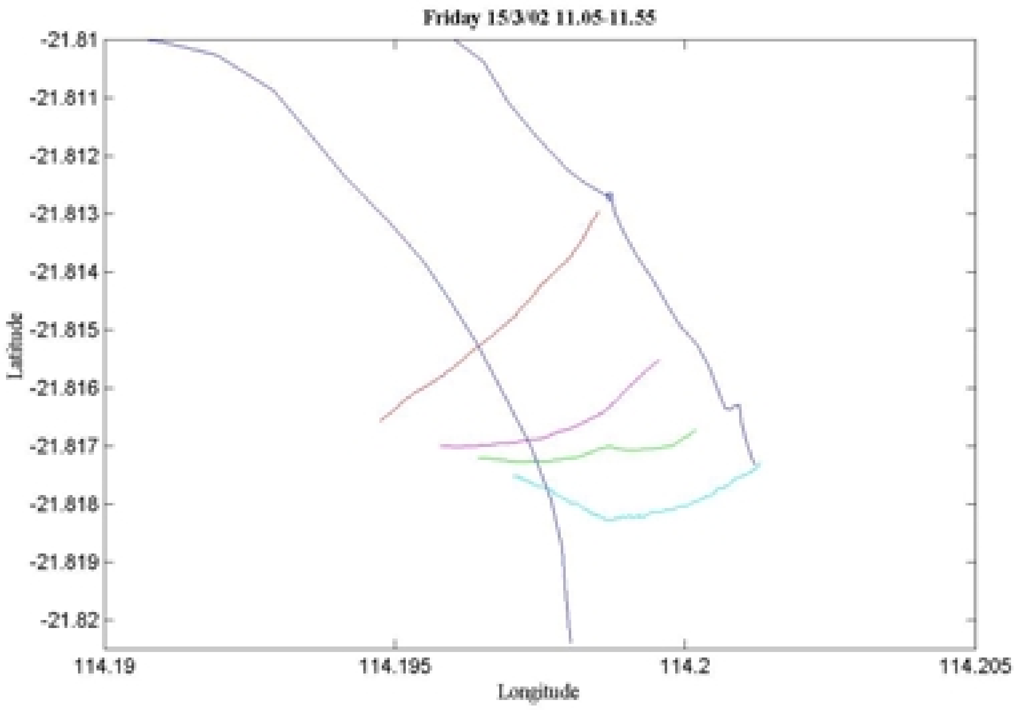


Figure 14. Experiment on surface slicks with drifters on Friday 15/3/02, 11.05-11.55.

4.1.4 Island Wake Parameter

The drogues were observed to with an eddy-like motion in the instabilities of the wake when close to the coast south of Point Murat (Figure 15a & 15b). To plot the circular motion of the drogues in this eddy the centroid of the drogues was taken away from the drogue position (Figure 16). This shows only the rotational movement of the set of drifters in the eddy, removing the translational movement of the set with the current away from the headland.

The island wake parameter was also calculated for Point Murat to determine the likelihood of eddies present in the wake of the headland (Wolanski, Imberger & Heron 1984).

$$P = \frac{U_s h^2}{K_z L}$$

where U_s is the streamwise velocity near the surface, h is the water depth, L is the streamwise length scale and the constant $K_z \sim 0.1$. Using the same parameters as listed in Table 4 and the streamwise velocity of $U_s = 0.5$-1m/s, the island wake parameter P = 0.6-1.2. From Table 3 the parameter P = O(1) to >1 with increasing current speeds. The wake description is a stable wake for low current speeds with increasing instabilities for higher speeds. This is indicating that eddy-like instabilities and motion are possible for the high current speeds.

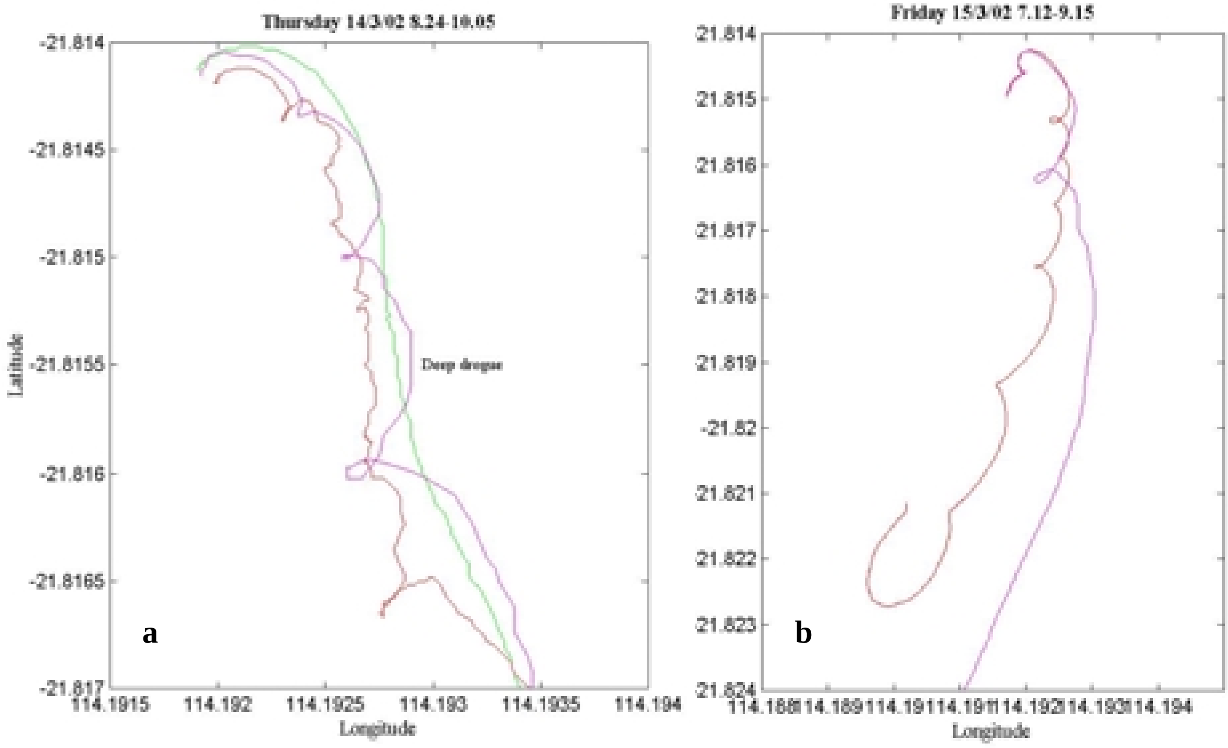


Figure 15. Drifter tracks whilst caught in wake south of Point Murat on (a)Thursday 14/3/02, 8.24-10.05 and (b)Friday 15/3/02, 7.12-9.15.

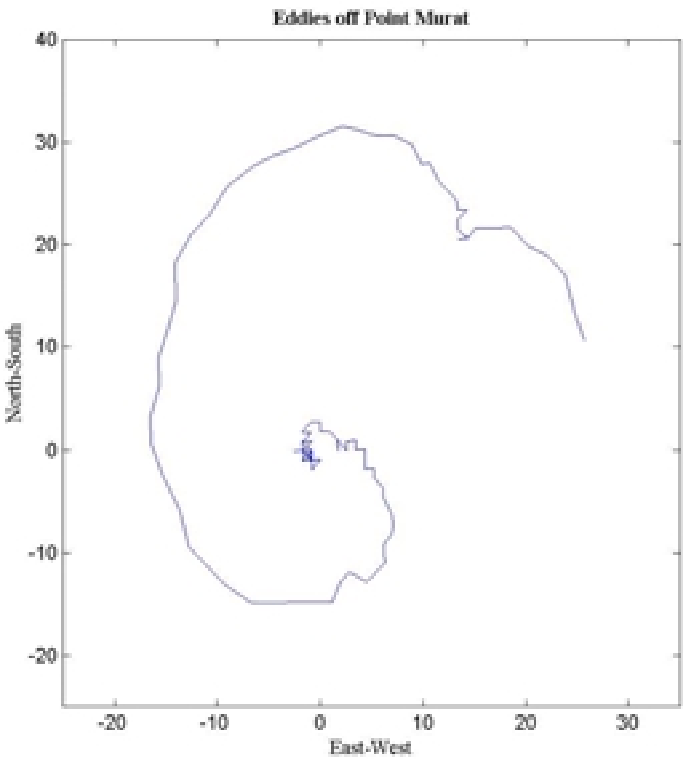


Figure 16. Drifter set on Friday 15/3/02, 7.12-9.15 with centroid removed.

Table 3. Characteristics of a wake formed behind an island for various values of the Island Wake Parameter, P (Wolanski, Imberger & Heron 1984).

Island Wake Parameter P	Wake Description
<< 1	Friction dominates; hence quasi-potential flow exists within the wake
= O(1)	Stable wake
> 1	Instabilities occur in the wake
>> 1	Friction is negligible; similar to that formed at high Reynolds numbers (*i.e.* eddy shedding)

4.1.5 Secondary Circulation

The secondary circulation was calculated using the known parameters for Point Murat (Table 4). These parameters were used to find R_{ef} and R_{om} (methodology described in section3.2.1) and the predicted flow regime. The coriolis parameter was found using the formula $f = 2\ \Omega\ \sin\phi$, where $\Omega = 7.29 \times 10^{-5}$ and the latitude $\phi = -21.8°$. The streamwise velocity was found using the drogue results (section 4.1.1) taking the average values around the Point Murat headland.

Table 4. Parameters used in secondary circulation calculation.

Parameter	Value
h: water depth	17m
L: streamwise length scale	2527m
C_D: bottom drag coefficient	0.0025
U_s: streamwise velocity near surface	0.5m/s
f: Coriolis parameter	5.41×10^{-5}
R_s: radius of curvature in s-direction	3438m
b: semi-minor axes	4825m
K_D: constant factor for Regime D	0.27

From this R_{ef} = 2.64 and R_{om} = 5.37, both greater than 1, meaning the headland is classified as Regime D. The transverse velocity U_n is found using the equation for Regime D

$$U_n = K_D \frac{bU_s}{R_s}$$

For the average streamwise velocity of the drogues near the surface, U_n = 0.1895m/s. Using the maximum drogue velocity observed, U_s = 1m/s, the maximum transverse velocity is found to be U_n = 0.3789m/s. The transverse velocity is then 37.9% of the streamwise velocity.

Secondary circulation is demonstrated in Figure 17 where the surface and deep drogues were deployed together on the outgoing tidal current and their paths separated. The surface drogue moved away from the coastline and the deep drogue moved into the coast. This verifies the claim that secondary circulation is occurring at the tips of the North West Cape.

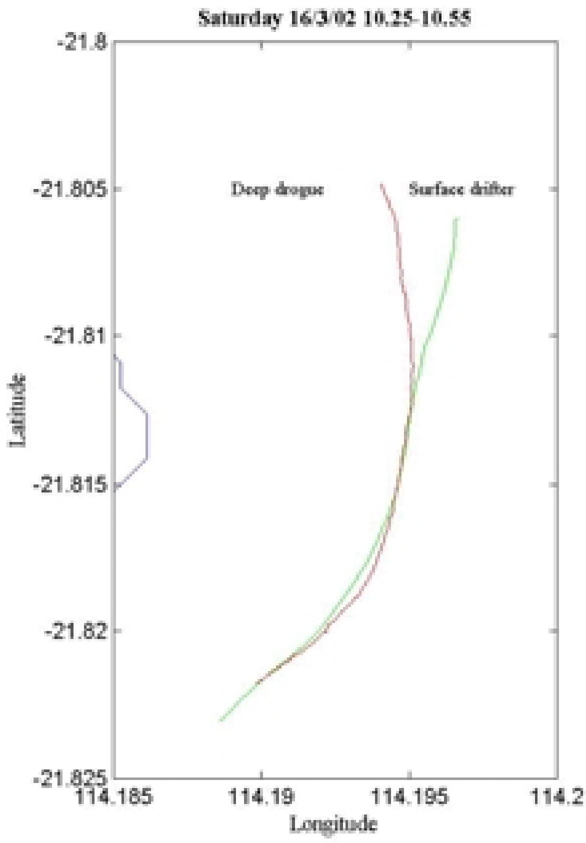


Figure 17. Secondary circulation around Point Murat demonstrated by surface and deep drogue separation on Saturday 16/3/02, 10.25-10.55.

4.2 CONDUCTIVITY-TEMPERATURE-DEPTH

4.2.1 Transect

The results of the conductivity-temperature-depth measurements are presented in Figure 18. The 22.64km transect started at 21°38.34'S, 114°10.02'E and was conducted in a south-easterly direction to 21°46.37'S, 114°16.89'E. The transect shows four distinct areas each showing significantly different features in density, temperature and salinity. The first section ('deep waters') is from the start of the transect at the 100m isobath 5km across the continental slope to the edge the continental shelf at the 50m isobath, an inclination of approximately 0°76'. There is a shallower ridge of approximately 23m adjacent to the 50m isobath that is considered part of the second distinct section of the transect (the 'ridge'), the region from the start of the continental shelf over the bank to the 30m isobath. The third section is referred to as the 'basin' as it is once again deeper and is from the 30m isobath 5.25km to the 20m isobath, with an average depth of 35m. The final region is from the 20m isobath to the end of the transect (the 'Gulf waters'), showing a constant shallow depth of approximately 20m.

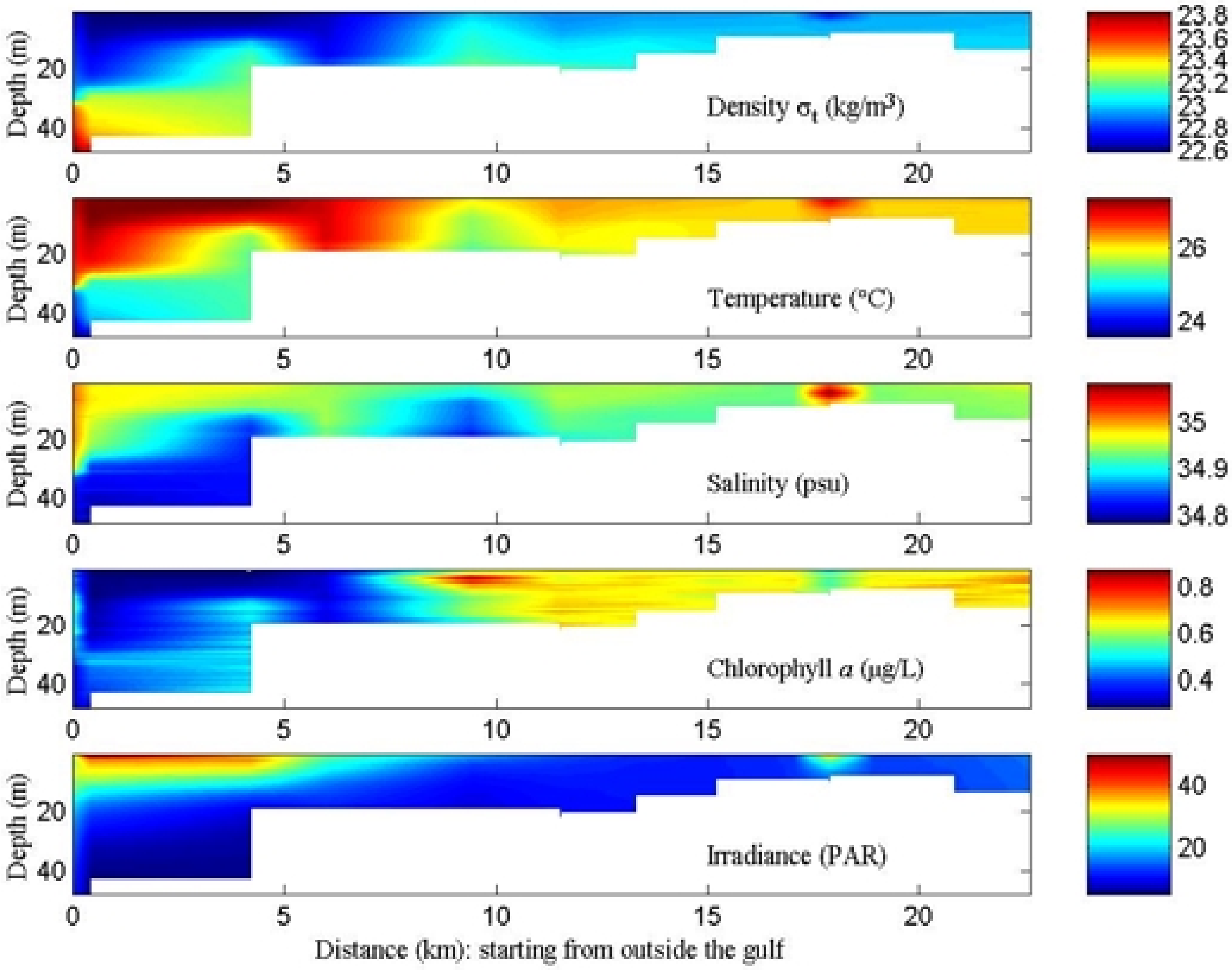


Figure 18. Conductivity-temperature-depth profiles through the entrance to Exmouth Gulf.

Deep waters

The density structure in the deep waters outside the Gulf shows a gradient of less dense water overlying the denser water, revealing its stability. The density ranges from 1022.6kg/m^3 at the surface to 1023.9kg/m^3 at the bottom of the water column. Density is presented as σ_t=density-1000 in Figure 18. Following this pattern, the temperature also shows a stratification of the deeper waters with warm water overlying the colder water. The range of temperature from 23.3°C to 27.1°C from the bottom of the water column to the surface is significant. The salinity shows an inverse structure to the temperature with higher salinity water above the lower salinity water, a seemingly unstable situation. The explanation for this is the narrow range of the salinity, 34.8‰ to 35‰, only a slight change that is considerably less significant than the temperature gradient and is most likely caused by evaporation at the surface. The stratification is therefore definitely a thermocline, a temperature-driven gradient and not a halocline driven by salinity.

Ridge

The density is well mixed vertically over this shallower bank, approximately 1022.7kg/m^3 throughout. Warm water also reaches from the surface to the bottom of the water column above the ridge with temperatures between 26.8°C and 27.1°C and the salinity is constant at approximately 34.9‰.

Basin

In the deeper basin adjacent to this ridge there is a minor stratification, not as marked as the deep waters outside the Gulf, yet visible in the transect plot. The density ranges from 1023.2kg/m^3 to 1022.8kg/m^3 from the bottom to the surface with the densest water mixing to the surface in the middle of the basin. The same occurs in the temperature section with a gradient from 25.4°C to 26.2°C and colder waters reaching the surface midway through the basin. Salinity is again the inverse of temperature with the higher salinity overlying the lower salinity.

Gulf waters

The shallow waters of the Gulf exhibit a vertically mixed water column with a patch approximately 1.5km wide at a station sampled 12km from the start of the transect. The patch shows warmer water of 27°C with a higher salinity of 35‰ and lower density of 1022.6kg/m^3. The rest of the Gulf waters are lower in temperature (26°C), lower in salinity (34.93‰) and higher in density (1023kg/m^3) throughout the water column.

Horizontal gradients

Chlorophyll *a* and irradiance (photosynthetically absorbed light) vary with distance along the transect each displaying a distinct horizontal gradient. Chlorophyll *a* ranges from 0.325µg/L in the deep waters to a peak of 0.882µg/L at 4m below the surface in the basin 10km along the transect. This feature is an elongated sub-surface patch approximately 2.33km wide. Chlorophyll *a* is high and uniform throughout the rest of the basin and the shallower waters of the Gulf with the exception of a small patch corresponding with the higher temperatures and higher salinity observed 12km along the transect. This patch is slightly lower in concentration, approximately 0.541μg/L on average.

The irradiance plot shows higher light penetration in the deeper stratified waters outside the Gulf and less irradiance in the mixed waters past the entrance to the Gulf. Light penetrates further with decreasing turbidity and this is true for the less turbid oceanic waters outside the Gulf and more turbid Gulf waters. The plot shows higher irradiance values of 27.8 that decrease to 11.9 with depth outside the Gulf and values between 11.8 and 12 inside the Gulf. There is a small patch of higher irradiance that corresponds with the higher temperature, higher salinity and lower chlorophyll *a* patch described earlier.

4.2.2 Mooring

The conductivity-temperature-depth profiler was moored in 7.5m of water at 21° 47.937'S, 114°10.911'E at the site of the observed surface expression. The data recorded by the different water property instruments attached to the CTD that measured temperature (°C), salinity (psu) and chlorophyll *a* (μg/L) is presented in Figure 19 for each of the three days moored sampling. The last plot of Figure 19 is part of the data from the InterOcean S4 vector averaging current meter that will be considered in section 4.4.

Density

The density in Figure 19 is presented as σ_t=density-1000 (kg/m^3) for the three sampling periods. Density was calculated from the measured temperature and salinity using SEAWATER©. During the first data set on Thursday 14th March the density is seen to increase sharply from 1022.5kg/m^3 to 1022.8kg/m^3 with the highest velocities of the incoming current (referring to the current vector plot). The density decreases with a distinct gradient from a value of approximately 1022.8kg/m^3 to 1022.2kg/m^3 with the excursion of the tidal current, resulting in a sharp gradient at the highest outgoing velocities. The density once again increases slowly to 1022.4kg/m^3 during the change in direction of the tidal current, back into the Gulf. The same is apparent for the sampling during Friday 15th where the density is also decreased on the outgoing current. There is no significant signal of decreasing density for Saturday 16th as the water was sampled for too short a period of time to capture the entirety of the outgoing current. The plot of density correlates strongly with the temperature change, as the salinity change is less significant.

Temperature

The temperature plot in Figure 19 shows the inverse pattern to the density plot. The temperature on Thursday 14th is initially at 28°C and decreases to 27°C in a sharp gradient corresponding to the highest velocities of the incoming tidal current. The temperature gradually increases during the change in direction of the current and peaks sharply at 29.6°C, at the highest velocities of the outgoing current. After the excursion of the tidal current the temperature gradually decreases to 28.3°C. The plot for Friday 15th shows a constant temperature during the current direction change and a similar increase from 27.4°C to 28.9°C during the maximum outgoing velocities. The data for Saturday 16th shows no significant change in temperature, only a slight rise from 27.6°C to 28.1°C over the entire data set.

Salinity

The plot of salinity follows the temperature pattern exactly for every sampling day showing only a small anomaly compared to the change in temperature. During the first day the salinity was initially 35.2‰ decreasing sharply to 34.8‰ with the incoming current and increasing slowly with the increasing velocities out of the Gulf. The same sharp peak is noted for salinity at the maximum velocities, with values reaching 35.5‰ then decreasing gradually with the change in current direction. The salinity is 35‰ throughout the data for Friday 15th and shows an increase to 35.3‰ only at the maximum current velocities. The salinity is constant at 35‰ for the entirety of the Saturday 16th sampling set.

Chlorophyll a

Chlorophyll *a* at 7.5m depth was initially at 0.38µg/L during the incoming current on the first sampling day. This value decreased slightly to 0.3µg/L just before the maximum current velocities and increased gradually to 0.5µg/L from the time of the maximum velocities to the minimum velocities of the changing current direction. Chlorophyll *a* values were higher during Friday 15th with initial values around 0.43µg/L increasing to 0.5µg/L during the maximum outgoing current and decreasing back to 0.43µg/L with the decreasing velocity.

The pattern observed for Saturday 16th is similar to the plot obtained for Thursday 14th. The chlorophyll *a* is initially at 0.42μg/L and stays constant through the changing of the current direction. Chlorophyll *a* increases gradually with the increase in the outgoing current velocities.

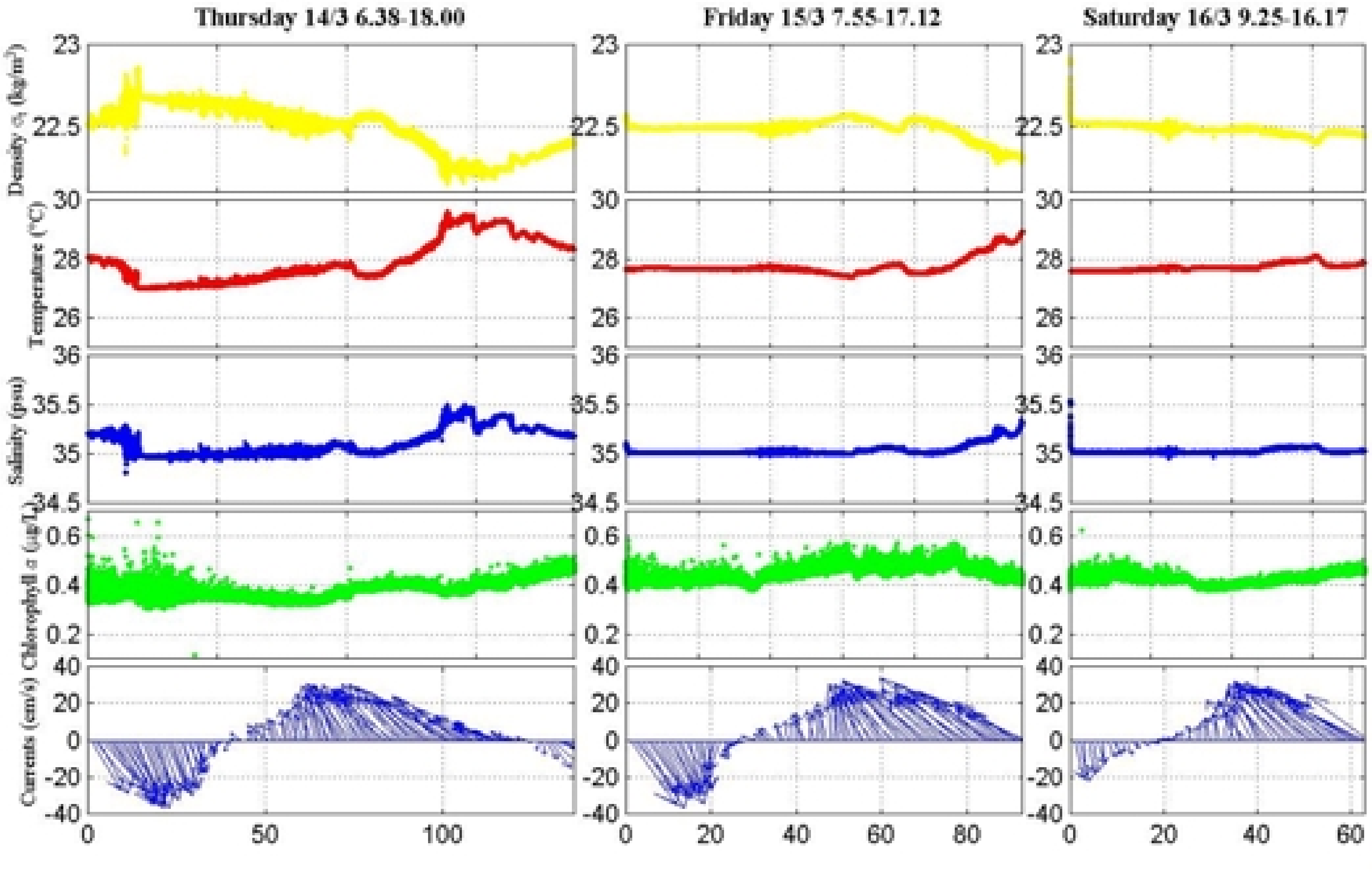


Figure 19. Time-series of moored conductivity-temperature-depth measurements.

4.3 VECTOR AVERAGING CURRENT METER

4.3.1 Current Profile

The InterOcean S4 vector averaging current meter was positioned at 21°47.937'S, 114°10.911'E in 5m of water. The relevant results for the CTD sampling period of the 14th, 15th and 16th of March are presented as vectors of the current speeds and direction in the bottom plot of Figure 19. This part of the data is plotted in the same figure as the moored CTD for comparison of the changes in density, temperature, salinity and chlorophyll *a* with the current speed and direction. A plot of the currents for the entire three days is shown (Figure 20a) with the water level also measured by the instrument (Figure 20b). The tidal currents enter the Gulf on a bearing of approximately 173° and leave the Gulf on a bearing of approximately 330°. The flood currents range from 0.6cm/s to 40.4cm/s with a mean speed of 21.79c … ave a smalle … erage consid … using MATI … th the highes

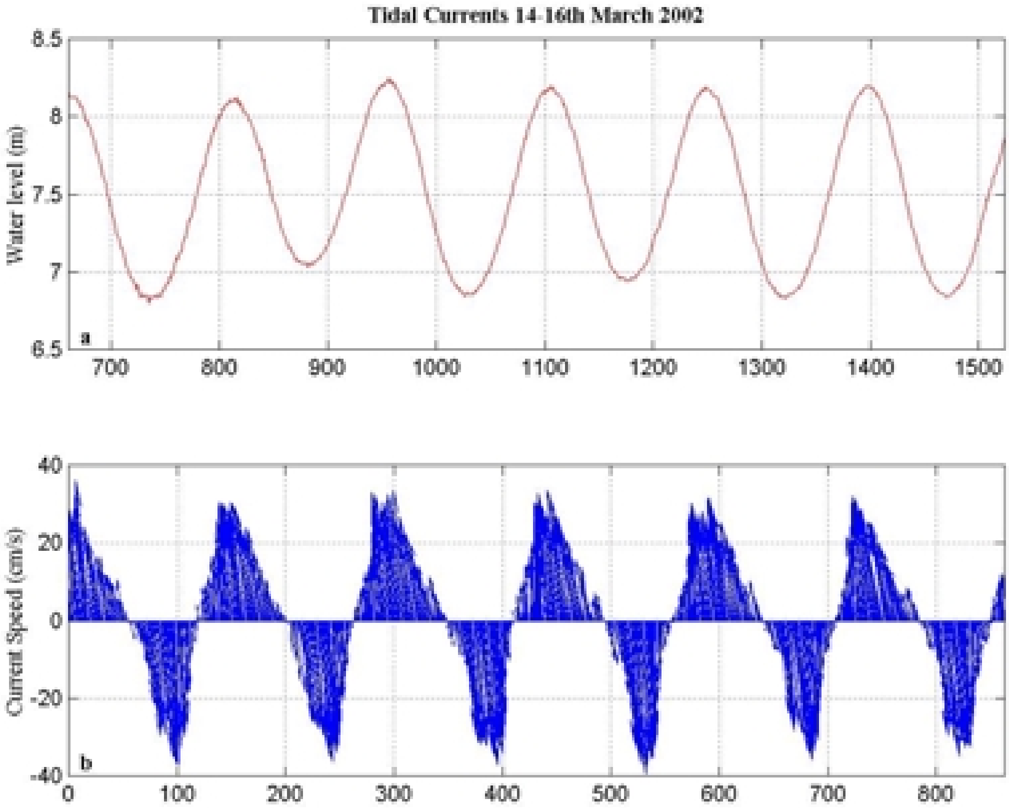


Figure 20. InterOcean S4 vector averaging current meter results for 14th-16th March.

4.3.2 Validation of Drifter Speeds

The results obtained from the InterOcean S4 vector averaging current meter were compared with current speeds obtained by the drogues. To eliminate the variability of the speeds measured by the drogues during the first half minute when they were just released, an average was taken of the speeds for two minutes after this. Only the drogue sets that were released from the RV Cape Ferguson at anchorage midway between the northern and southern tips of the North West Cape were used in this validation. This is the position the current meter was also moored. Taking an average of the current speeds over the two minutes eliminated the variability of using only one data point. The average found was then compared to the current measured for that time by the InterOcean S4. The results of the validation testing are presented in Table 5. The calculated drogue speeds were plotted with the measured current meter speeds to determine the correlation between them (Figure 21). The correlation coefficient (R^2) was found to be 0.988, an indication of a very strong relationship. The current meter was moored at 5m while the surface drogues were at 1m and the deeper drogue was at 3m. … and Eulerian measuremen… peeds was not an error but a…

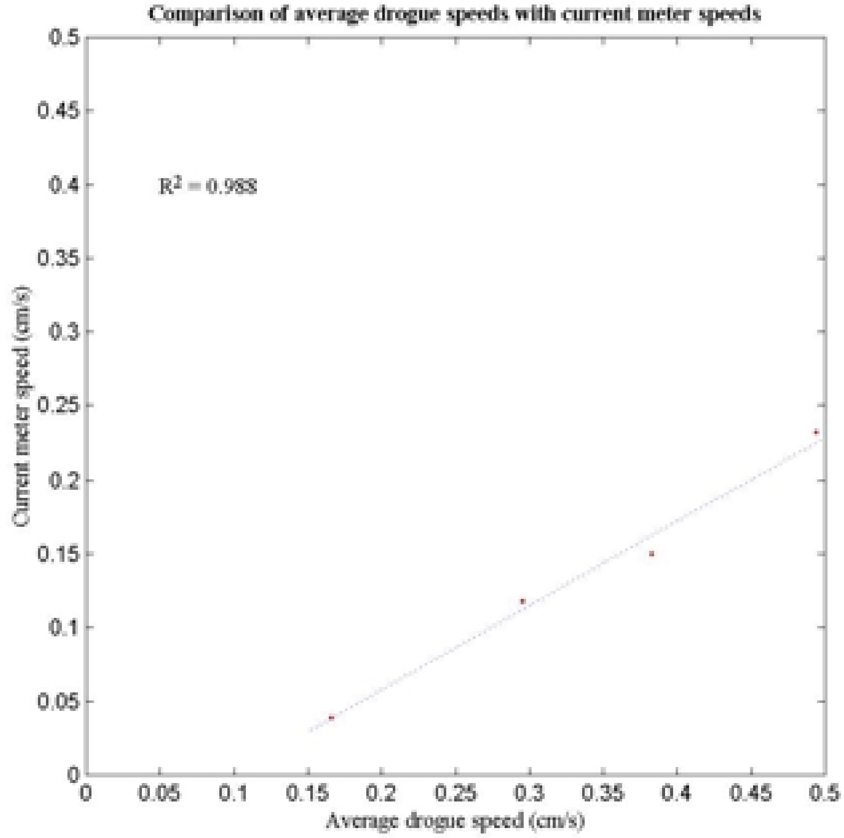


Figure 21. Correlation between drifter results and vector averaging current meter results.

Table 5. Validation of drogue speeds through comparison with measured current meter speeds.

Appendix I Reference	Drogue depth (m)	Drogue speed (cm/s)	Current meter speed (cm/s)
Set 8 14/3/02 11.10-12.02	1	0.3418	0.150
	1	0.4333	
	1	0.3636	
	1	0.4288	
	3	0.3478	
	AVERAGE	0.3830	
Set 9 14/3/02 16.30-18.45	1	0.1368	0.039
	1	0.1482	
	1	0.1399	
	1	0.1991	
	3	0.2060	
	AVERAGE	0.1660	
Set 10 15/3/02 5.28-7.00	1	0.2749	0.118
	1	0.3025	
	1	0.3131	
	3	0.2909	
	AVERAGE	0.2953	
Set 14 15/3/02 12.13-14.15	1	0.4871	0.232
	1	0.5199	
	1	0.4483	
	1	0.5161	
	3	0.4925	
	AVERAGE	0.4928	

4.4 ACOUSTIC DOPPLER CURRENT PROFILER

4.4.1 Current Profile

A vector plot of the current directions and magnitudes from the acoustic Doppler current profiler results are plotted from the top of the water column to the top of the instrument for 12/3/02 – 30/4/02 and are presented in Figure 22. The current profile for the 14th, 15th and 16th of March are shown in Figure 23 separated into easterly and northerly directions. Only these three days during the sampling period are presented in Figure 23 for clarity as the entirety of the profile is 45 days long and is a repetition of the same pattern as these three days.

From Figure 22 it is clear that the tidal currents are ebbing the majority of the time. The direction of the currents from the surface to 10m is north-easterly, out of the Gulf. The surface profile is stronger than at depth and also shows a more constant direction. The deeper profiles have a weak flood current component into the Gulf.

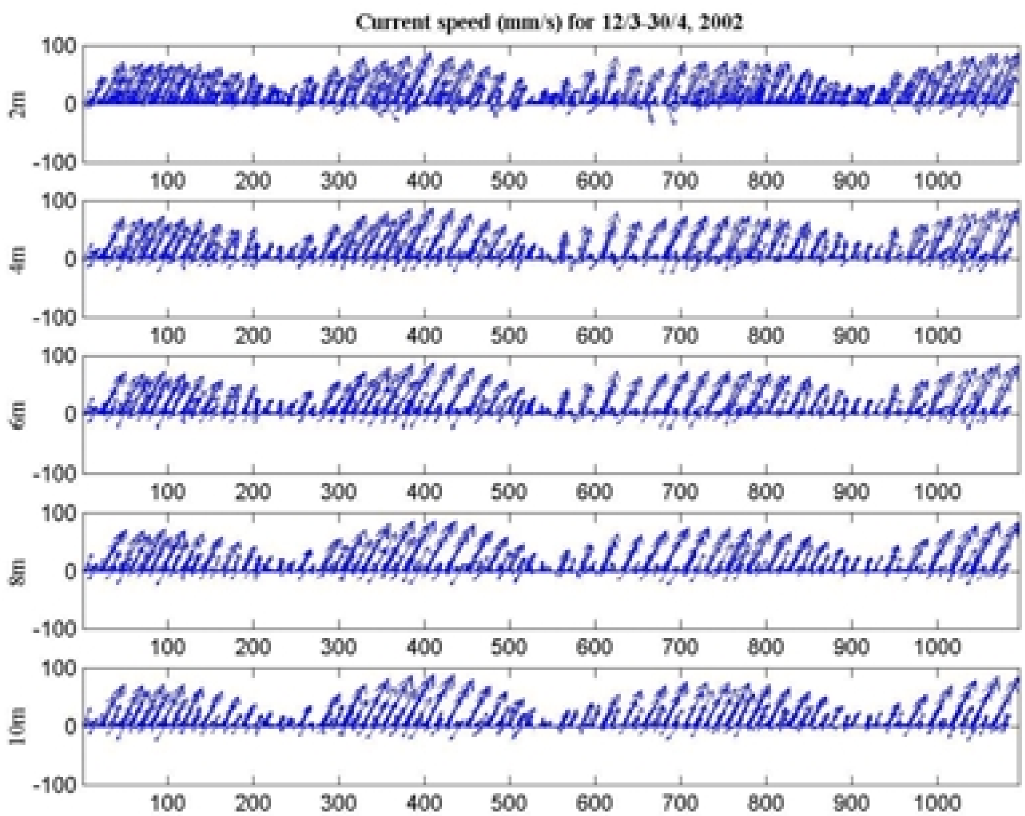


Figure 22. Acoustic Doppler current profiler results for 12/3/02 - 30/4/02.

The colour profile in Figure 23 shows higher current speeds on the ebb tide for both the northerly and easterly directions. The surface layer shows stronger current speeds than at depth. Approximately 29% of the total tide cycle is still water, and very low flood current speeds with a maximum of only a third of the ebb speed strength. The entire range of speeds recorded at the Navy Pier by the instrument reaches 0.1m/s, only 20% of the current meter speeds recorded by the vector averaging current meter (section 4.3.1). These minimal speeds are acceptable because the ADCP was sheltered at the Navy Pier and the tidal currents are ebbing in this region the majority of the time.

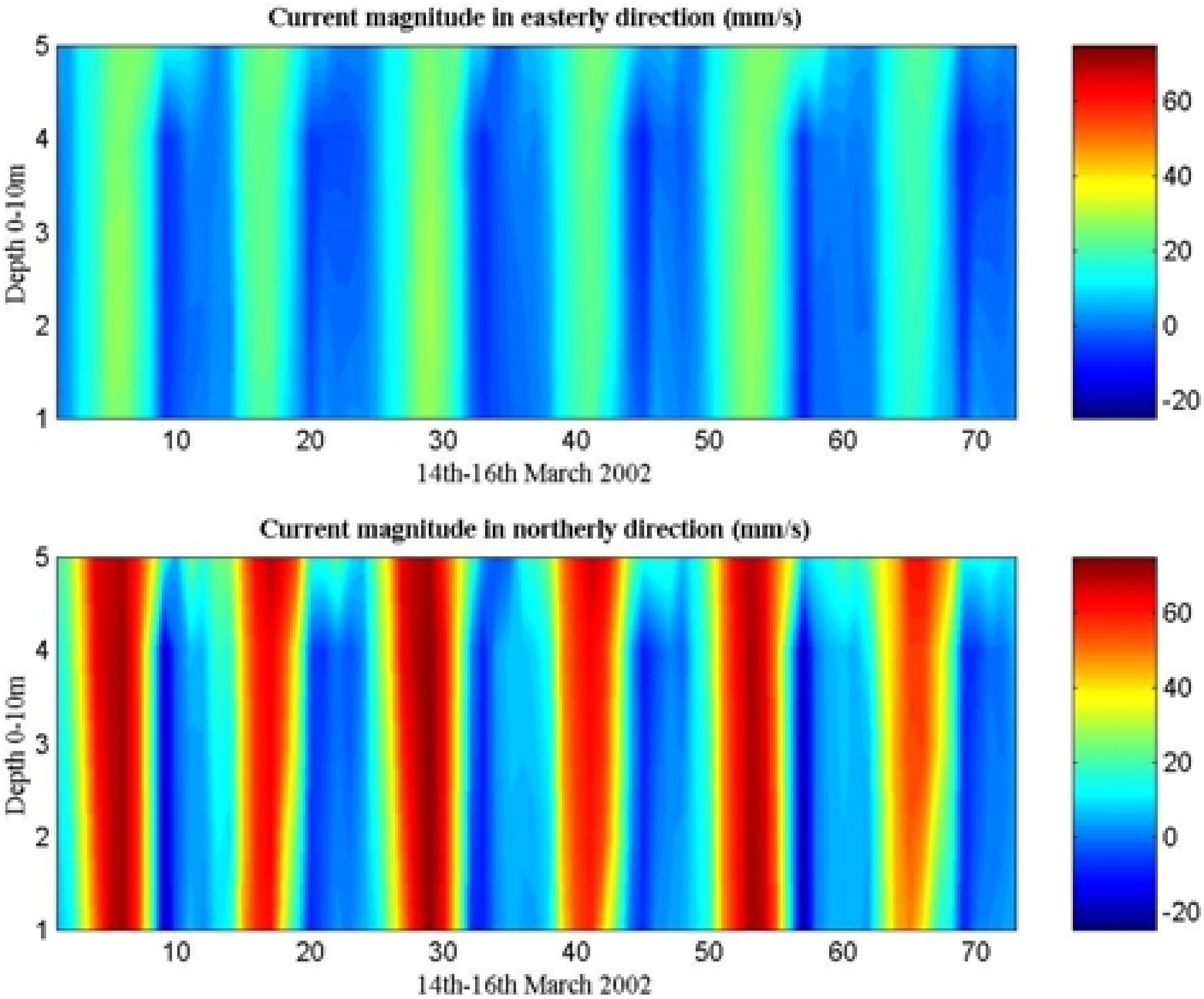


Figure 23. Acoustic Doppler current profile for 14th-16th March 2002.

5.0 Discussion

A detailed study of the oceanography of the North West Cape was made aboard the research vessel Cape Ferguson where various measurements were made describing the water properties, circulation and mixing around the Cape. This field data were then analysed and conclusions are drawn from the results obtained. Each instrument's results are examined separately and the observations are compiled into a comprehensive description of the oceanography around the North West Cape.

The picture that emerges has a strong resemblance to the topographically controlled fronts discussed by Wolanski & Hamner (1988) who describe the effects of headlands, islands and reefs in shallow coastal waters and their biological influence. The observations of surface expressions made around the Cape were small scale features only approximately 5m wide and 3 – 5km long, not a typical example of a frontal system such as those studied around the Irish Sea (Simpson & Hunter 1974) and Georges Bank (Lough & Manning 2001). These larger systems are of the order of 20km long and 20m wide and exhibit the surface expression approximately 0.5m deep, much more obvious than the surface expressions observed around the North West Cape. Wolanski & Hamner (1988) describe the processes associated with the small-scale frontal systems that they classify as zoocurrents generated by nerocurrents. Nerocurrents are the local coastal (littoral) currents that interact with the topography and accumulate biological matter including zooplankton. These long lines of plankton buoyant on the surface are termed 'zoocurrents'. Around the North West Cape the tidal currents sweep past the headland through the deeper part of the entrance channel, mix the different water masses and accumulate plankton in streams or surface expressions that are observed around Point Murat.

Although the system is small, the oceanographic processes responsible for the observations around the North West Cape are similar to the large-scale systems studied by Simpson & Hunter (1974) and Pingree (1975). A boundary is formed between the shallow vertically mixed waters inside the Gulf and the deeper stratified waters outside the Gulf due to a sharp decline in the bathymetry adjacent to the coastline. This is seen in the CTD transect (section 4.2.1) where the density structure shows stability with the less dense water overlying the denser water. The stratification is temperature driven and this is seen in the significant difference between the surface and bottom temperatures in the temperature profile. The deep waters are stratified in temperature with a difference between the surface and bottom of 3.8°C. It is apparent in the salinity profile results that the structure is not salinity driven, since there is fresher water underneath the more saline water. This is possible since the difference in the salinity is insignificant, only 0.2‰. The high evaporation in the Gulf accounts for the higher salinity in the surface water mass. The more saline water does not significantly sink to the bottom waters due to the strong stratification in temperature and the mild difference in salinity.

The boundary between these water masses of different properties is eroded during the strongest spring tides causing a movement of the boundary into the stratified region, extending the area of mixed water. When the tidal currents slow to neap tides the boundary moves back as more water is once again stratified with the level of nutrients from the mixed waters. This is the cause of the higher productivity in the entrance to the Gulf, at the boundary of the two water masses. The chlorophyll *a* profile in the conductivity-temperature-depth results shows the highest productivity in the entrance to the Gulf. The chlorophyll *a* peak is not at the surface due to the harmful effects of the ultraviolet radiation, therefore the bloom is observed at approximately 3m depth. Meekan et al. (2001) found the highest zooplankton numbers at the boundary between the well-mixed and stratified water in the entrance to the Gulf, where the predominant zooplankton were euphausiids. The fish catches were also highest at this boundary and the reef fish pomacentridae predominated.

From the time-series (moored) CTD measurements midway between the northern and southern tip of the Cape an interaction of the two water masses is seen. The colder upwelling Ningaloo Current water on the northern tip of the Cape is pushed into the Gulf with the incoming tidal current. The water mass south of this upwelling is higher in temperature and forms a boundary with the upwelled water. The action of the strong localised tidal currents cause mixing of these water masses and a frontal system that manifests as the surface expressions is observed around Point Murat. These surface expressions are the ‘zoocurrents’, described in Wolanski & Hamner (1988), that are created through the interaction of the topography of a region, in this case the headland, and the littoral (coastal) currents. Convergence was confirmed at these fronts through the experiments conducted involving the drifters, indicating the complexity of the system around the North West Cape. Biological matter is accumulated with the plankton slick at the fronts, attracting higher order organisms that feed off the abundant prey. This accumulation of plankton occurs through the divergence at the front, where the water is drawn into the boundary and pulled down. The particles that are seen at the surface have enough buoyancy to overcome the divergent force and therefore stay at the surface but cannot move away. Another possible cause of the plankton at the boundary of the two water masses is *in situ* growth where the plankton biomass increases due to the enhanced nutrients at the boundary. Although these are the biological processes described at larger scale frontal systems, they are applicable to the North West Cape considering the physical oceanographic processes are similar.

The eulerian measurements that were taken around the North West Cape depict the current systems that drive the oceanographic processes investigated. The InterOcean S4 vector averaging current meter that was placed midway between the two tips of the Cape at 5m depth measured current speeds up to 0.4m/s both in a south-easterly direction for the incoming tidal currents and in a north-westerly direction on the outgoing currents. The flood currents were slightly stronger at this point than the ebb currents, but the period of time that the currents were ebbing was longer than the flooding period. The current meter speeds were approximately 40% of the speeds recorded by the drifters that floated at the surface of the water column. This is acceptable as the current speed decreases in strength with depth, due to the action of bottom friction. The winds at the time of the field sampling were south-easterly (moving the water in a north-westerly direction) with wind speeds ranging between 10-35km/hr. This is a significant wind speed and adds to the movement of the surface layer of the water column with the movement caused by the tidal currents. The drogues were constructed to minimise the effect of the wind above the surface therefore the lagrangian movement recorded is attributed only to the motion of the surface layer of water driven by the tidal currents and the wind shear.

The current meter results were different from those of the acoustic Doppler current profiler that was moored on the Navy Pier at Point Murat. The current profile obtained from this instrument showed the current only ebbing and between ebbing currents the water was still. This is attributed to the position of the current profiler in the sheltered region on the southern side of the headland. The maximum current speeds were only 0.1m/s, 10% of the surface speeds. At this point the flooding current is not perceived as the water moves around the headland and is caught in the eddy-like motions of the headland’s wake. Instabilities in the wake of the headland at the Pier were confirmed through the plotting of the drifters caught in the wake of the headland. The plots clearly show the rotational movement of the drifters as they are carried away from the headland by the current. The calculation of the 'Island Wake Parameter' that indicated the presence of instabilities for the high current speeds in the stable wake.

The strong localised tidal currents through the entrance channel of the area interact with the topography causing secondary circulation, instabilities and the surface expressions observed around Point Murat. Alaee, Ivey & Pattiaratchi (2002) explain that upwelling is possible at the tips of headlands through the action of secondary circulation, even without the presence of eddies. As the tidal currents enter the Gulf, the inertia and centrifugal forces act to drive a transverse velocity, 37.9% of the streamwise velocity normal to the Cape, moving the surface waters away from the coastline. This process induces the bottom waters to replace the surface waters that are moving away, causing upwelling of the colder deeper waters. The difference between the surface drogue and the deep drogue exemplifies this phenomenon where the surface drogue is moved away from the coast and the deep drogue moves towards the shore. From the sea surface temperatures this phenomenon is seen to be upwelling around the northern tip of the North West Cape, where the cold Ningaloo Current water that pushes up through the entrance of the Gulf between September and mid-April. Eddies were not found around this northern tip of the Cape where the drifters recorded a smooth track all the way around. Upwelling of colder, nutrient rich deep water is also seen in the sea surface temperature results around the Muiron Islands. The centrifugal force caused by the flow curvature is strongest off the tips of the North West Cape due to the high flow speed and small radius of curvature (Alaee, Ivey & Pattiaratchi 2002). The results of the drogues deployed around the North West Cape at various times during the tidal cycle are described in section 4.1.1 where it is apparent that the drogues converge adjacent to the northern and southern tips of the Cape. The dispersion decreased around the tips of the Cape as the drifters were drawn together. This is attributed to the centrifugal force around Point Murat and the northern tip of the Cape that pulls the drogues close together adjacent to the coastline.

Wolanski & Hamner (1988) describe eddy formation as being an important effect of island (and headland) wakes in the accumulation of organisms through upwelling and downwelling. Ekman pumping causes upwelling in eddies through the action of bottom friction causing the surface to slope upward at the eddy centre. This creates a gradient for the water to move away from the centre and hence causing upwelling of nutrient rich water from bellow. At the outside of the eddy there is downwelling. Eddies form around obstacles such as islands, in shallow coastal regions influencing the movement of pollutants, wastes, plankton, fish larvae and other particulates (Dietrich et al, 1994; Wolanski et al, 1996). Pollutants can become trapped in the eddy and cause biological damage or affect survival rates of spawn and juvenile biota, therefore eddies have a significant effect on biological systems such as coral reefs due to the upwelling and downwelling zones they cause. With the presence of eddies in the wake of the headland at Point Murat it is likely that the cause of the high abundance of organisms on the Pier is due to the spawn being carried into the Gulf and caught in the eddies off Point Murat. The Navy Pier is covered in coral and has a large, diverse fish community that has been investigated by McIlwain & Halford (2001) who suggested further studies be carried out adjacent to and on the Navy Pier for heavy metal contamination.

Dispersion was examined to investigate the capacity of the currents around the North West Cape to dissipate contaminants and other particulates. There is notable dispersion in the surface drogue tracks in the areas that are not near Point Murat and the northern tip of the Cape. Dispersion decreases at these headland features and the surface drogues are drawn together. There was also significant convergence when the drogues were released close to the frontal systems around Point Murat.

As an overview, strong tidal currents dominate the Cape circulation mixing the stratified deeper water with the shallow Gulf waters. Secondary circulation is observed at Point Murat and at the northern tip of the Cape causing upwelling of nutrient rich cold water. Surface expressions develop due to the interaction of these strong tidal currents with the headland topography and the difference in water properties between the two water masses. These fronts are responsible for the accumulation of biological matter and plankton, attracting higher order species. The Point Murat headland shelters the Navy Pier resulting in an area with only ebbing currents and eddy-like rotations are recorded in this area south of the Navy Pier.

6.0 Conclusions

The North West Cape is an exciting region to study as much of the research is pioneering work. The circulation patterns around the Cape are now better understood through the use of eulerian and lagrangian current profiling tools. The tidal currents that drive the flow through the entrance of Exmouth Gulf are strong and localised near the Cape and influence the mixing at the boundary between stratified and vertically well-mixed water. Cold nutrient rich water is observed to be upwelling on the northern and southern tips of the Cape as well as adjacent to the Muiron Islands and this is attributed to secondary circulation created by these strong tidal currents. Due to the upwelling there is higher productivity in the entrance to the Gulf.

The tidal mixing of two water masses manifests as surface expressions that are observed particularly around Point Murat. These aggregations of planktonic and organic matter are the cause of the biological activity found in the region. The frontal expressions attract higher order and larger predators to the food source and are of interest to researchers investigating the physical-biological oceanographic links around the North West Cape.

The presence of instabilities (or small eddies) that are prominent around the Navy Pier at Point Murat suggest that the accumulation associated with these systems is responsible for the diversity in species composition at the Pier. Biological spawn is possibly carried into the Gulf and along the coast and is then trapped in the wake south of Point Murat, consequently settling on and near the Pier. The potential accumulation of contaminants is also possible near the Pier and this must be considered when making development plans for the area.

7.0 Recommendations

Future research work is recommended around the North West Cape, particularly adjacent to the Navy Pier at Point Murat. The conclusions of this study have found the area to be highly vulnerable due to the frontal and eddy systems observed here. These phenomenon are capable of accumulating biological and potentially harmful matter, therefore it is recommended that no major construction proceeds within the entrance to Exmouth Gulf and near the Navy Pier. The following points are suggestions for further investigations at the North West Cape.

- Three-dimensional hydrodynamic modeling around the North West Cape investigating the fate and transport of potentially hazardous contaminants, waste and biological matter, particularly around Point Murat, is recommended. The Hamburg Shelf-Ocean model (HAMSOM) or Model for Estuaries and Coastal Oceans (MECO) are suggested as possible modeling tools for this region.

- Ongoing research into the physical-biological links is necessary, focusing on the effect of the upwelling Ningaloo Current waters, tidal mixing, primary production and the phenomenon of the high biological abundance around the Cape. An interesting study would be to examine the correlation between this upwelling and the spatial distribution of the fauna.

- Further research is also required on the western side of the North West Cape investigating the effects of increased tourism and construction on the entire Ningaloo Marine Park area, including the entrance to the Gulf and the surrounds. It is essential that developers understand that the construction of tourism facilities will result in increased pressure on a much larger area surrounding the site than anticipated and this requires a thorough examination of all physical and biological oceanographic processes associated with the region.

8.0 References

Alaee, M.J., Ivey G., & Pattiaratchi, C. 2002, 'Secondary circulation induced by flow curvature and Coriolis effects in island wakes', Environmental Dynamic Reference: ED1269MA. (Submitted to: *Ocean Dynamics*).

Ayukai, T. & Miller, D. 1998, 'Phytoplankton biomass, production and grazing mortality in Exmouth Gulf, a shallow embayment on the arid, tropical coast of Western Australia', *Journal of Experimental Marine Biology and Ecology*, vol. 225, pp. 239-251.

Barnes, R.S.K. & Hughes, R.N. 1988, *An Introduction to Marine Ecology*, 2nd edn, Blackwell Scientific Publications, London.

Bo Pedersen, F. 1994, 'The oceanographic and biological tidal cycle succession in shallow sea fronts in the North Sea and the English Channel', *Estuarine, Coastal and Shelf Science*, vol. 38, pp. 249-269.

Bowman, M.J. 1977, 'Introduction and historical perspective', in *Oceanic Fronts in Coastal Processes*, eds M.J. Bowman & W.E. Esaias, Springer-Verlag, New York.

CALM 1998, 'New Horizons – the way ahead in Marine Conservation and Management', Government of Western Australia, Department of Conservation and Land Management.

Clayton, M.N. & King, R.J. 1990, *Biology of Marine Plants*, Longman Cheshire Publisher, Melbourne.

Colman, J.G. 1997, 'A review of the biology and ecology of the whale shark', *Journal of Fish Biology*, vol. 51, pp. 1219-1234.

Commonwealth of Australia 1984, 'Exmouth Gulf and Approaches', Nautical Chart, Aus 744.

Creswell, G.R. & Golding, T.J. 1980, 'Observations of a south-flowing current in the southeastern Indian Ocean', *Deep-Sea Research*, vol. 27A, pp. 449-466.

D'Adamo, N. & Simpson, C.J. 2001, 'Review of the oceanography of Ningaloo Reef and adjacent waters', Technical Report: MMS/NIN/NIN-38/2001. March 2001. Marine Conservation Branch, Department of Conservation and Land Management. (Unpublished report).

Davis, R.E. 1991, 'Lagrangian Ocean Studies', *Annu. Rev. Fluid Mech.*, vol. 23, pp. 43-64.

Demers, S., Legendre, L. & Therriault, J.C. 1986, 'Phytoplankton responses to vertical tidal mixing', in *Tidal mixing and plankton dynamics*, eds M.J. Bowman, C.M. Yentsch & W.T. Peterson, Springer-Verlag, New York.

Dietrich, D.E., Bowman, M.J., Liu, L.A. & Mestas-Nunez, A. 1994, *Numerical studies of small island wakes*, Mississippi State University, Center for Air Sea technology, Technical Report 94-1.

Drake, C.L., Imbrie, J., Knauss, J.A. & Turekian, K.K 1978, *Oceanography*, Holt, Rinehart and Winston, United States of America.

Durazo, R., Harrison, N.M. & Hill, A.E. 1998, 'Seabird observations at a tidal mixing front in the Irish Sea', *Estuarine, Coastal and Shelf Science*, vol. 47, pp. 153-164.

EPA 1991a, 'Proposed offshore petroleum exploration drilling in EP 325, NW Shelf', Environmental Protection Authority, Western Australia, Bulletin 546.

EPA 1991b, 'Proposed exploration drilling, Exmouth Gulf', Environmental Protection Authority, Western Australia, Bulletin 504.

Fearnhead, P.G. 1975, 'On the formation of fronts by tidal mixing around the British Isles', *Deep-Sea Research*, vol. 22, pp. 311-321.

Fogg, G.E., Egan, B., Hoy, S., Lochte, K., Scrope-Howe, S. & Turley, C.M. 1985, 'Biological studies in the vicinity of a shallow sea tidal mixing front I. Physical and chemical background', *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, vol. 310, pp. 407-433.

Franks, P.J.S. 1997, 'New models for the exploration of biological processes at fronts', *ICES Journal of Marine Science*, vol. 54, pp. 161-167.

Gordon, D. 1999, 'Summary of International Conventions, Commonwealth and State Legislation and other Instruments Affecting Marine Resource Allocation, Use, Conservation and Environmental Protection on the North West Shelf of Australia', International Risk Consultants. IRC Environment. Perth. (Unpublished report).

Hendrix, J. 1997, *Experience Hendrix: The Best of Jimi Hendrix*, Universal MCAD 11671.

Heyward, A.J., Revill, A.T. & Sherwood, C.R. 2000, 'Review of Research and Data Relevant to Marine Environmental Management of Australia's North West Shelf', Produced for the Western Australian Department of Envionmental Protection. (Unpublished report).

Hill, A.E., James, I.D., Linden, P.F., Matthews, J.P., Prandle, D., Simpson, J.H., Gmitrowicz, E.M., Smeed, D.A., Lwiza, K.M.M., Durazo, R., Fox, A.D. & Bowers, D.G. 1993, 'Dynamics of tidal mixing fronts in the North Sea', *Philosophical Transactions: Physical Sciences and Engineering*, vol. 343, pp. 431-446.

Houghton, R.W. & Ho, C. 2001, 'Diapycnal flow through the Georges Bank tidal front: A dye tracer study', *Geophysical Research Letters*, vol. 28, pp. 33-36.

Hunt, G.L., Russell, R.W., Coyle, K.O. & Weingartner, T. 1998, ‘Comparative foraging ecology of planktivorous auklets in relation to ocean physics and prey availability’, *Marine Ecology Progress Series,* vol. 167, pp. 241-259.

Ingmanson, D.E. & Wallace, W.J. 1985, *Oceanography: An Introduction*, 3rd edn, Wadsworth Publishing Company, California.

James, I.D. 1978, ‘A note on the circulation induced by a shallow-sea front’, *Estuarine and Coastal Marine Science*, vol. 7, pp. 197-202.

Johnson, D., Stocker, R., Byrne, D., Head, R., Imberger, J. & Pattiaratchi C. 2001, ‘A compact, low-cost GPS drifter for use in the oceanic nearshore zone, lakes and estuaries’, (Submitted to: *Journal of Atmospheric Ocean Technology*).

Kasai, A., Rippeth, T.P. & Simpson, J.H. 1999, ‘Density and flow structure in the Clyde Sea front’, *Continental Shelf Research*, vol. 19, pp. 1833-1848.

Kinder, T.H., Hunt, G.L., Schneider, D. & Schumacher, J.D. 1983, ‘Correlations between seabirds and oceanic fronts around the Pribilof Islands, Alaska’, *Estuarine, Coastal and Shelf Science*, vol. 16, pp. 309-319.

Kuiter, R.H. 1996, *Guide to Sea Fishes of Australia*, New Holland Publishers, Australia.

Le Fevre, J. 1986, ‘Aspects of the biology of frontal systems’, in *Advances in Marine Biology,* vol. 23, eds J.H.S Blaxter & A.J. Southward, Academic Press, England, pp. 163-299.

Le Fevre, J., Viollier, M., Le Corre, P., Dupouy, C. & Grall, J. 1983, ‘Remote sensing observations of biological material by LANDSAT along a tidal thermal front and their relevancy to the available field data’, *Estuarine, Coastal and Shelf Science*, vol. 16, pp. 37-50.

Legendre, L., Demers, S. & Lefaivre, D. 1986, ‘Biological production at marine ergoclines’, in *Marine Interfaces Ecohydrodynamics*, ed. J.C.J. Nihoul, Elsevier Oceanography Series, New York.

List, E.J., Gartrell, G. & Winant, C.D. 1990, ‘Diffusion and dispersion in coastal waters’, *Journal of Hydraulic Engineering*, vol. 116, pp. 1158-1179.

Loder, J.W., & Wright, D.G. 1985, ‘Tidal rectification and frontal circulation on the sides of Georges Bank’, *Journal of Marine Research*, vol. 43, pp. 581-604.

Loder, J.W., Drinkwater, K.F., Oakey, N.S. & Horne, E.P.W. 1993, ‘Circulation, hydrographic structure and mixing at tidal fronts: the view from Georges Bank’, *Philosophical Transactions: Physical Sciences and Engineering*, vol. 343, pp. 447-458.

Lough, G.R. & Manning, J.P. 2001, 'Tidal-front entrainment and retention of fish larvae on the southern flank of Georges Bank', *Deep-Sea Research II*, vol. 48, pp. 631-644.

Mann, K.H. & Lazier, J.R.N. 1996, *Dynamics of marine ecosystems: biological-physical interactions in the oceans*, Blackwell Science, Boston, pp. 179-210.

Mavor, T.P. & Bisagni, J.J. 2001, 'Seasonal variability of sea-surface temperature fronts on Georges Bank', *Deep-Sea Research II*, vol. 48, pp. 215-243.

McCormick, J.M. & Thiruvathukal, J.V. 1981, *Elements of Oceanography*, 2nd edn, CBS College Publishing, United States of America.

McIlwain, J.L. & Halford, A.R. 2001, 'A quantitative assessment of the fish and benthic assemblages associated with the Point Murat Pier, Exmouth Gulf', Produced for the Royal Australian Navy. Australian Institute of Marine Science, Townsville. (Unpublished report).

McKinnon, A.D. & Ayukai, T. 1996, 'Copepod egg production and food resources in Exmouth Gulf, Western Australia', *Marine and Freshwater Research*, vol. 47, pp. 595-603.

Meekan, M.G., Wilson, S.G., Halford, A. & Retzel, A. 2001, 'A comparison of catches of fishes and invertebrates by two light trap designs, in tropical NW Australia', *Marine Biology*, vol. 139, pp. 373-381.

Molinari, R. & Kirwan, A.D. 1975, 'Calculations of differential kinematic properties from lagrangian observations in the Western Caribbean Sea', *Journal of Physical Oceanography*, vol. 5, pp. 483-491.

Morin, P., Wafar, M.V.M. & Le Corre, P. 1993, 'Estimation of nitrate flux in a tidal front from satellite-derived temperature data', *Journal of Geophysical Research*, vol. 98, pp. 4689-4695.

Munk, P. & Neilsen, T.G. 1994, 'Trophodynamics of the plankton community at Dogger Bank: predatory impact by larval fish', *Journal of Plankton Research*, vol. 19, pp. 1225-1245.

Okubo, A. & Ebbesmeyer, C.C. 1976, 'Determination of vorticity, divergence, and deformation rates from analysis of drogue observations', *Deep-Sea Research*, vol. 23, pp. 349-352.

Pearce, A.F. & Griffiths, R.W. 1991, 'The mesoscale structure of the Leeuwin Current: a comparison of laboratory models and satellite imagery', *Journal of Geophysical Research*, vol. 96, pp. 16,739-16,757.

Peterson, W.T. 1986, 'The effects of seasonal variations in stratification on plankton dynamics in Long Island Sound', in *Tidal mixing and plankton dynamics*, eds M.J. Bowman, C.M. Yentsch & W.T. Peterson, Springer-Verlag, New York.

Pickard, G.L. 1979, *Descriptive Physical Oceanography: An Introduction*, 3rd edn, Pergamon Press, Great Britain.

Pingree, R.D. & Griffiths, D.K. 1978, 'Tidal fronts on the shelf seas around the British Isles', *Journal of Geophysical Research*, vol. 83, pp. 4615-4622.

Pingree, R.D. 1975, 'The advance and retreat of the thermocline on the continental shelf', *Journal of the Marine Biological Association U.K.*, vol. 55, pp. 965-974.

Pingree, R.D., Forster, G.R. & Morrison, G.K. 1974, 'Turbulent convergent tidal fronts', *Journal of the Marine Biological Association U.K.*, vol. 54, pp. 469-479.

Pingree, R.D., Pugh, P.R., Holligan, P.M. & Forster, G.R. 1975, 'Summer phytoplankton blooms and red tides along tidal fronts in the approaches to the English Channel', *Nature*, vol. 258, pp. 672-677.

Preen, A.R., Marsh, H., Lawler, I.R., Prince, R.I.T. & Shepherd, R. 1997, 'Distribution and abundance of dugongs, turtles, dolphins and other megafauna in Shark Bay, Ningaloo Reef and Exmouth Gulf, Western Australia', *Wildlife Research*, vol. 24, pp. 185-208.

Richardson, K. & Bo Pedersen, F. 1998, 'Estimation of new production in the North Sea: consequences for temporal and spatial variability of phytoplankton', *ICES Journal of Marine Science*, vol. 55, pp. 574-580.

Savidge, G. 1976, 'A preliminary study of the distribution of chlorophyll *a* in the vicinity of fronts in the Celtic and Western Irish Seas', *Estuarine and Coastal Marine Science*, vol. 4, pp. 617-625.

Simpson, C.J. & Masini, R.J. 1986, 'Tide and seawater temperature data from the Ningaloo Reef Tract, Western Australia, and the implications for coral mass spawning', Department of Conservation and Environment, Perth. Bulletin 253.

Simpson, J.H. & Bowers, D. 1979, 'Shelf sea fronts' adjustments revealed by satellite IR imagery', *Nature*, vol. 280, pp. 648-651.

Simpson, J.H. & Bowers, D. 1981, 'Models of stratification and frontal movement in shelf seas', *Deep-Sea Research*, vol. 28A, pp. 727-738.

Simpson, J.H. & Hunter, J.R. 1974, 'Fronts in the Irish Sea', *Nature*, vol. 250, pp. 404-406.

Simpson, J.H. & Rippeth, T.P. 1993, 'The Clyde Sea: a model of the seasonal cycle of stratification and mixing', *Estuarine, Coastal and Shelf Science*, vol. 37, pp. 129-144.

Simpson, J.H. 1971, 'Density stratification and microstructure in the Western Irish Sea', *Deep-Sea Research*, vol. 18, pp. 309-319.

Simpson, J.H. 1981, 'The shelf-sea fronts: implications for their existence and behaviour', *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, vol. 302, pp. 531-543.

Simpson, J.H., Allen, C.M. & Morris, N.C.G. 1978, 'Fronts on the continental shelf', *Journal of Geophysical Research*, vol. 83, pp. 4607-4614.

Simpson, J.H., Hughes, D.G. & Morris, N.C.G. 1977, 'The relation of seasonal stratification to tidal mixing on the continental shelf', in *A voyage of discovery*, ed. M. Angel, supplement to *Deep-Sea Research*, pp. 327-340.

Sims, D.W. & Quayle, V.A. 1998, 'Selective foraging behaviour of basking sharks on zooplankton in a small-scale front', *Nature*, vol. 393, pp. 460-464.

Sims, D.W., Fox, A.M. & Merrett, D.A. 1997, 'Basking shark occurrence off south-west England in relation to zooplankton abundance', *Journal of Fish Biology*, vol. 51, pp. 436-440.

Sims, D.W., Southall, E.J., Quayle, V.A. & Fox, A.M. 2000, 'Annual social behaviour of basking sharks associated with coastal front areas', *Proceedings of the Royal Society of London B*, vol. 267, pp. 1897-1904.

State of the Fisheries WA, 2001, 'State of the Fisheries Report', Fisheries Western Australia.

Steinberg, C., Brinkman, R., McAllister, F. & McLean, C. 1999, 'AIMS Data Report: North West Cape. October 1998 – March 1999', Australian Institute of Marine Science. (Unpublished report).

Taylor, J.G. & Pearce, A.F. 1999, 'Ningaloo Reef currents: implications for coral spawn dispersal, zooplankton and whale shark abundance', *Journal of the Royal Society of Western Australia*, vol. 82, pp. 57-65.

Taylor, J.G. 1996, 'Seasonal occurrence, distribution and movements of the whale shark, *Rinocodon typus*, at Ningaloo Reef, Western Australia', *Marine and Freshwater Research*, vol. 47, pp. 637-642.

Tchernia, P. 1980, *Descriptive Regional Oceanography*, Pergamon Press, Great Britain.

Tomczak, M. & Godfrey, J.S. 1994, *Regional Oceanography: an introduction*, Pergamon, London.

Townsend, D.W., Graham, J.J. & Stevenson, D.K. 1986, 'Dynamics of larval herring (*Clupea harengus L.*) production in tidally mixed waters of the eastern coastal Gulf of Maine', in *Tidal mixing and plankton dynamics*, eds M.J. Bowman, C.M. Yentsch & W.T. Peterson, Springer-Verlag, New York.

Valiela, I. 1995, *Marine Ecological Processes*, 2nd edn, Springer, New York.

Willis, R.J. 2002, 'Australian National Tide Tables 2002', Australian Hydrographic Publication No. 11.

Wilson, S.G., Pauly, T. & Meekan, M.G. 2001, 'Daytime surface swarming by *Pseudeuphausia latifrons* (Crustacea Euphausiacea) off Ningaloo Reef, Western Australia', *Bulletin of Marine Science*, vol. 68, pp. 157-162.

Wilson, S.G., Taylor, J.G. & Pearce, A.F. 2001, 'The seasonal aggregation of whale sharks at Ningaloo Reef, Western Australia: currents, migrations and the El Nino/ Southern Oscillation', (Unpublished).

Wishner, K., Durbin, E., Durbin, A., Macaulay, M., Winn, H. & Kenney, R. 1988, 'Copepod patches and right whales in the Great South Channel off New England', *Bulletin of Marine Science*, vol. 43, pp. 825-844.

Wolanski, E. & Hamner, W.M. 1988, 'Topographically controlled fronts in the ocean and their biological influence', *Science*, vol. 241, pp. 177-181.

Wolanski, E., Asaeda, T., Tanaka, A. & Deleersnijder, E. 1996, 'Three-dimensional island wakes in the field, laboratory experiments and numerical models', *Continental Shelf Research*, vol. 16, pp. 1437-1452.

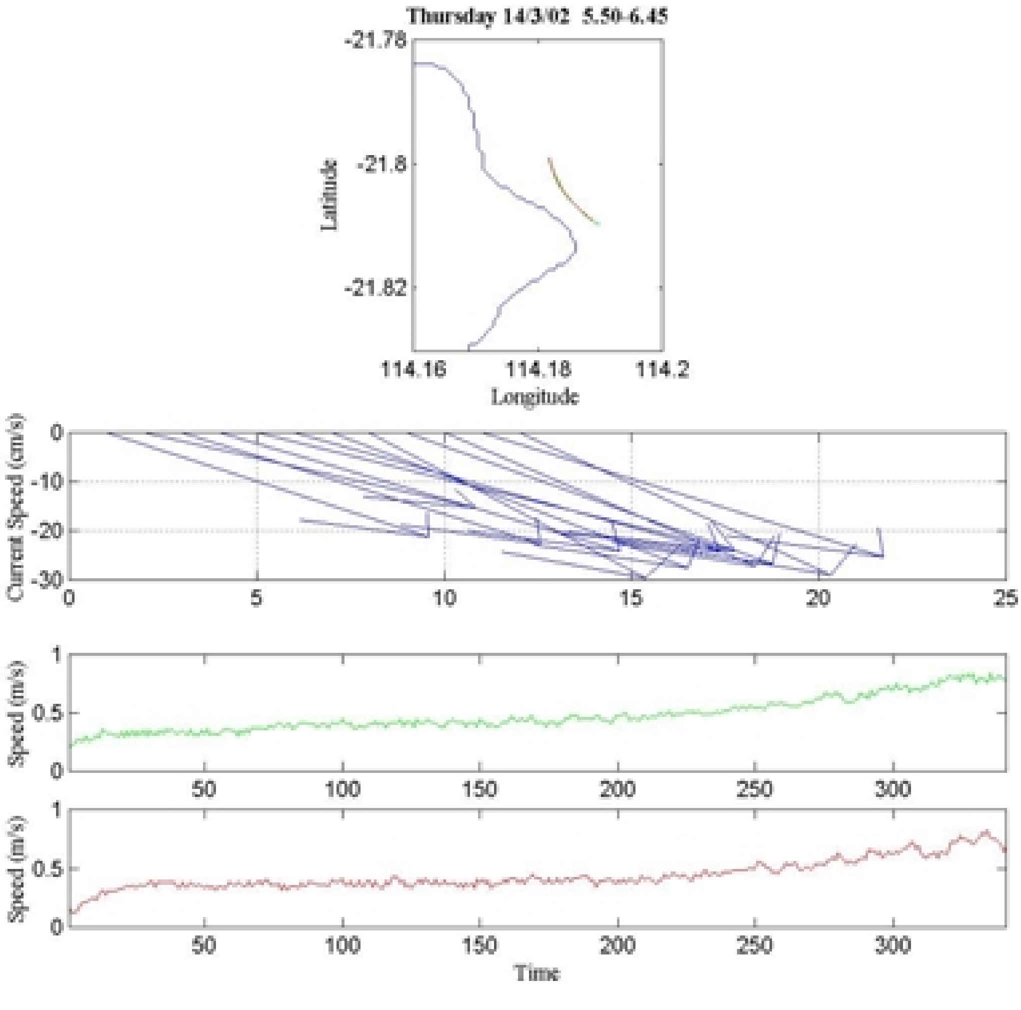
Wolanski, E., Imberger, J. & Heron, M.L. 1984, 'Island wakes in shallow coastal waters', *Journal of Geophysical Research*, vol. 89, pp. 10,553-10,569.

Yoshida, J. & Oakey, N.S. 1996, 'Characterization of vertical mixing at a tidal-front on Georges Bank', *Deep-Sea Research II*, vol. 43, pp. 1713-1744.

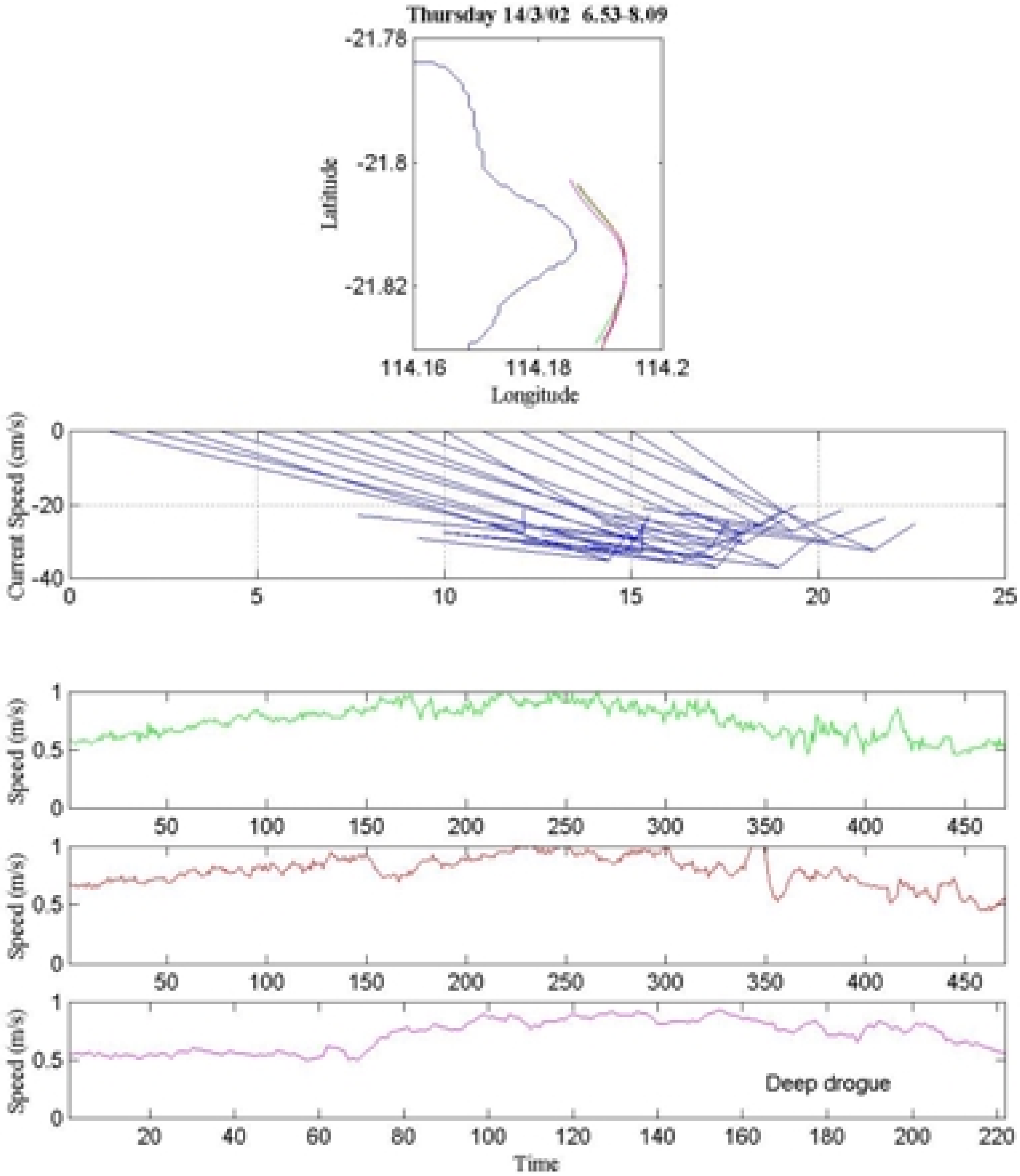
9.0 Appendices

9.1 APPENDIX I

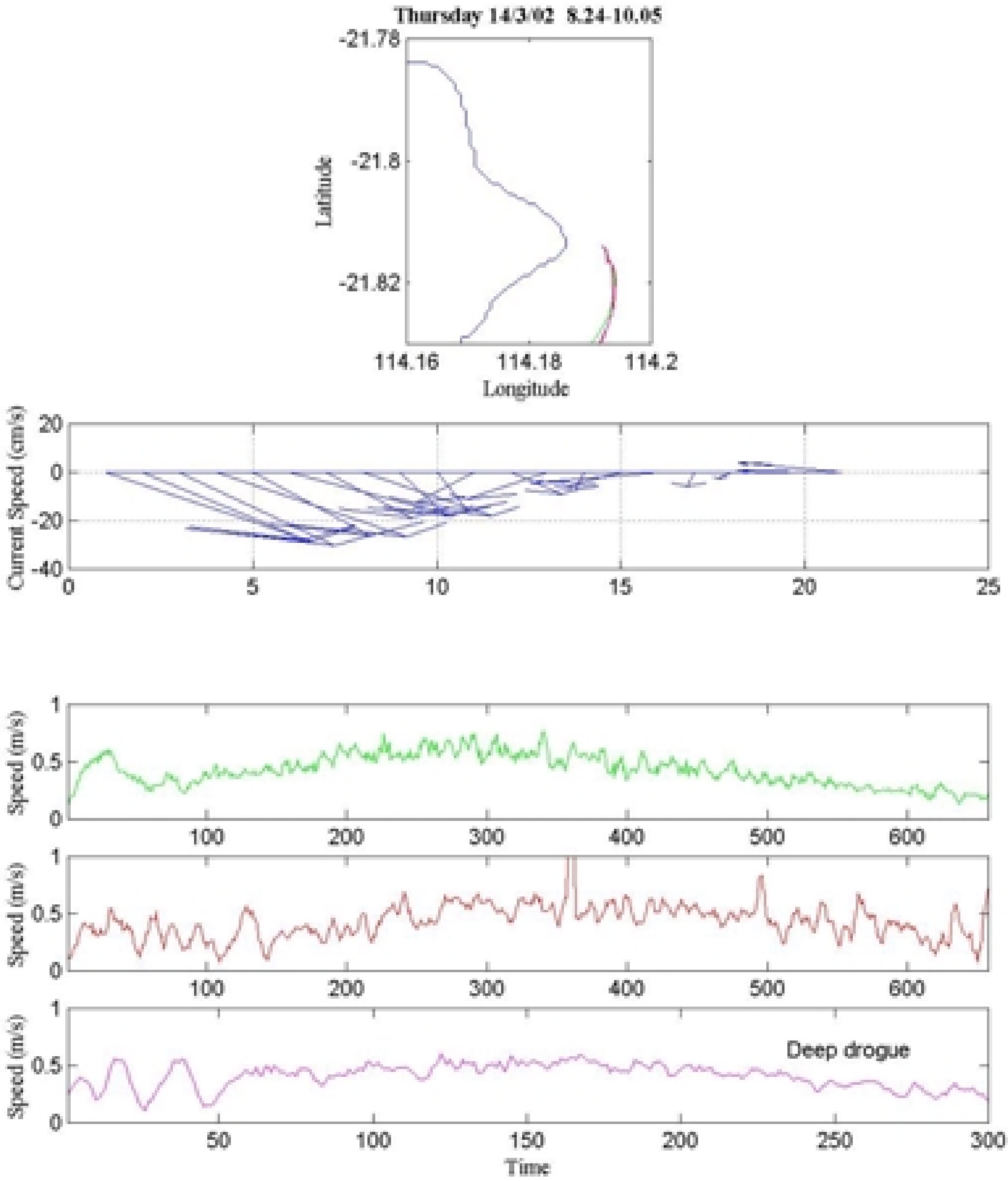
SET 1



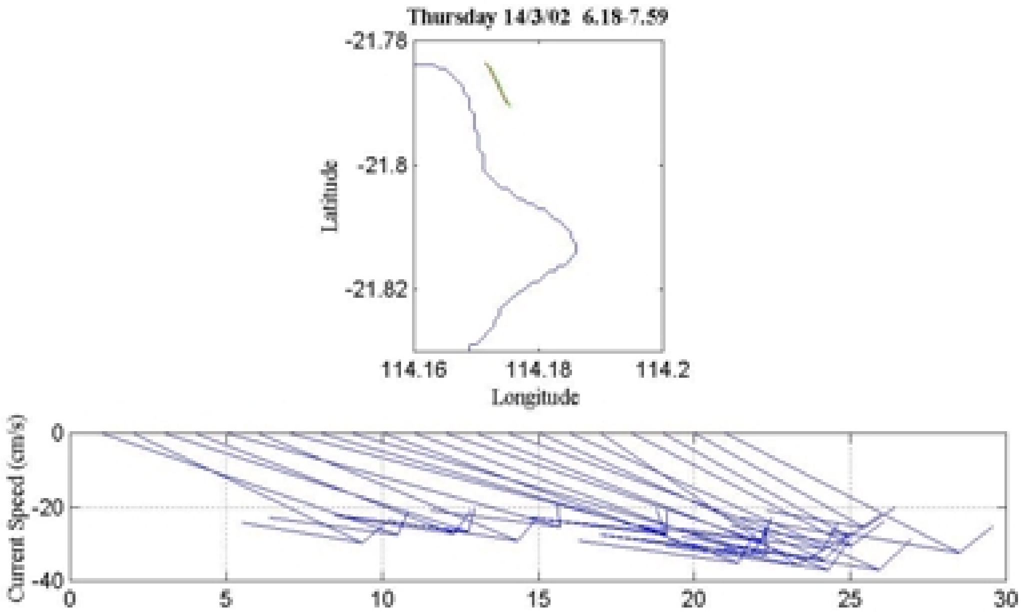
SET 2

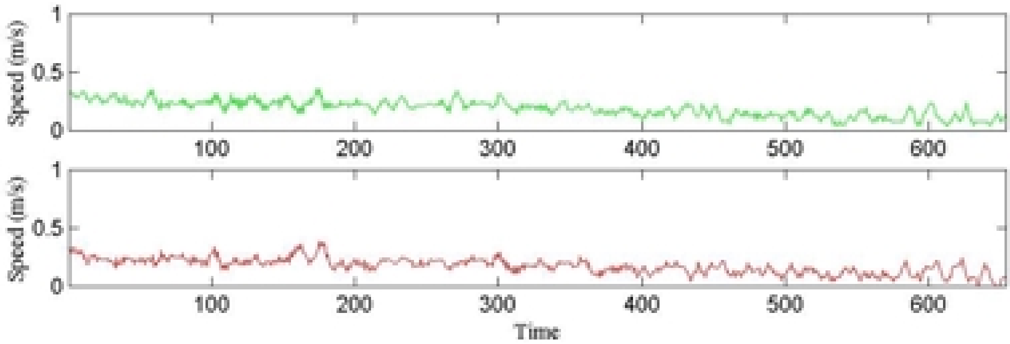

Thursday 14/3/02 6.53-8.09
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

SET 3

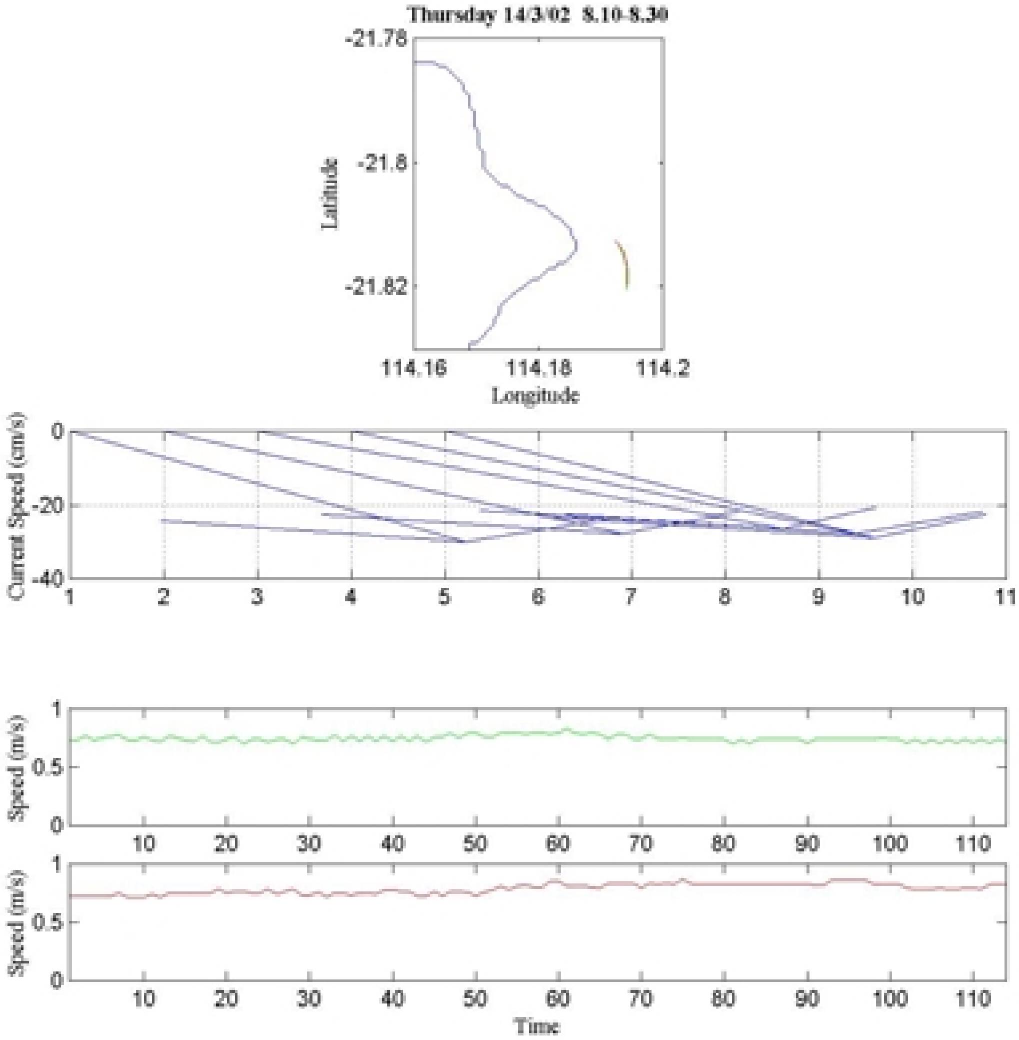

Thursday 14/3/02 8.24-10.05
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

SET 4

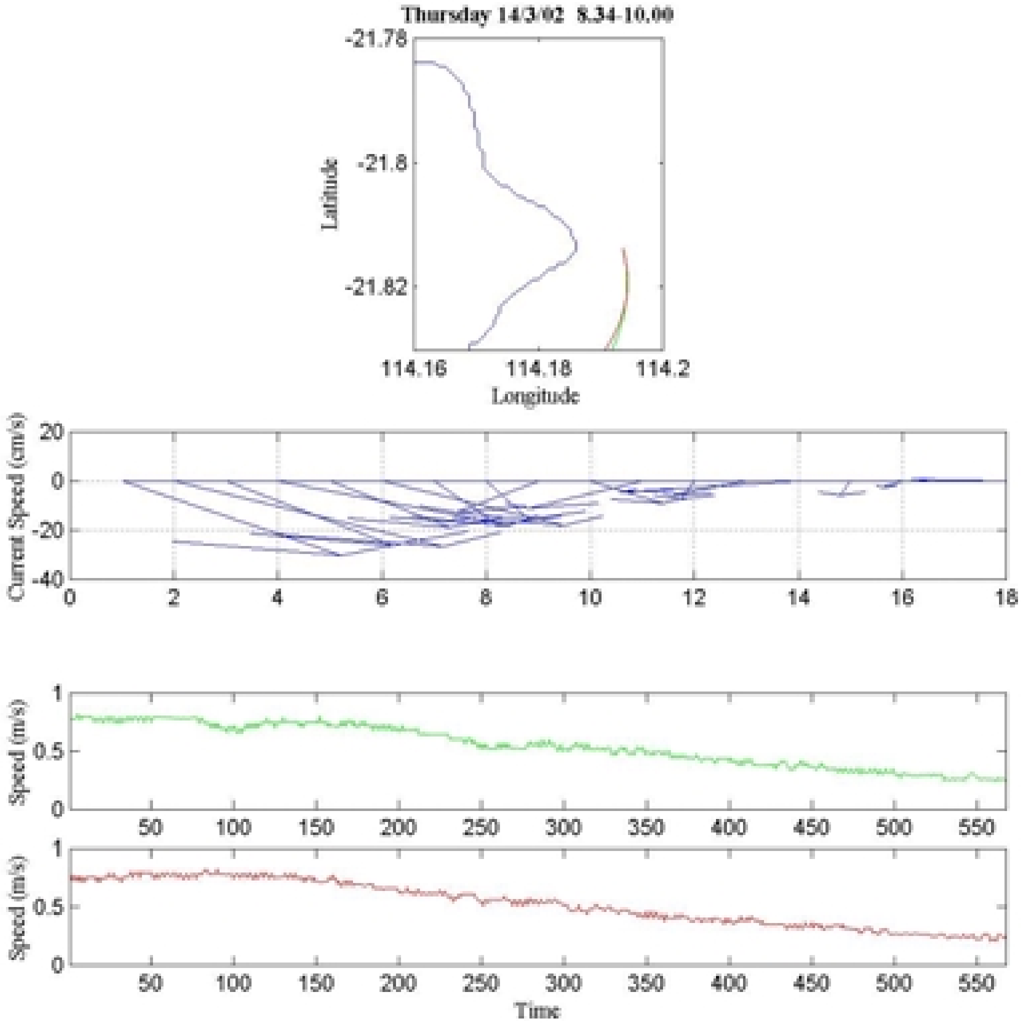

Thursday 14/3/02 6.18-7.59
-21.78
-21.8
-21.82
Latitude
114.16
114.18
114.2
Longitude
Current Speed (cm/s)
0
-20
-40
0
5
10
15
20
25
30


Speed (m/s)
1
0.5
0
100
200
300
400
500
600
Speed (m/s)
1
0.5
0
100
200
300
400
500
600
Time

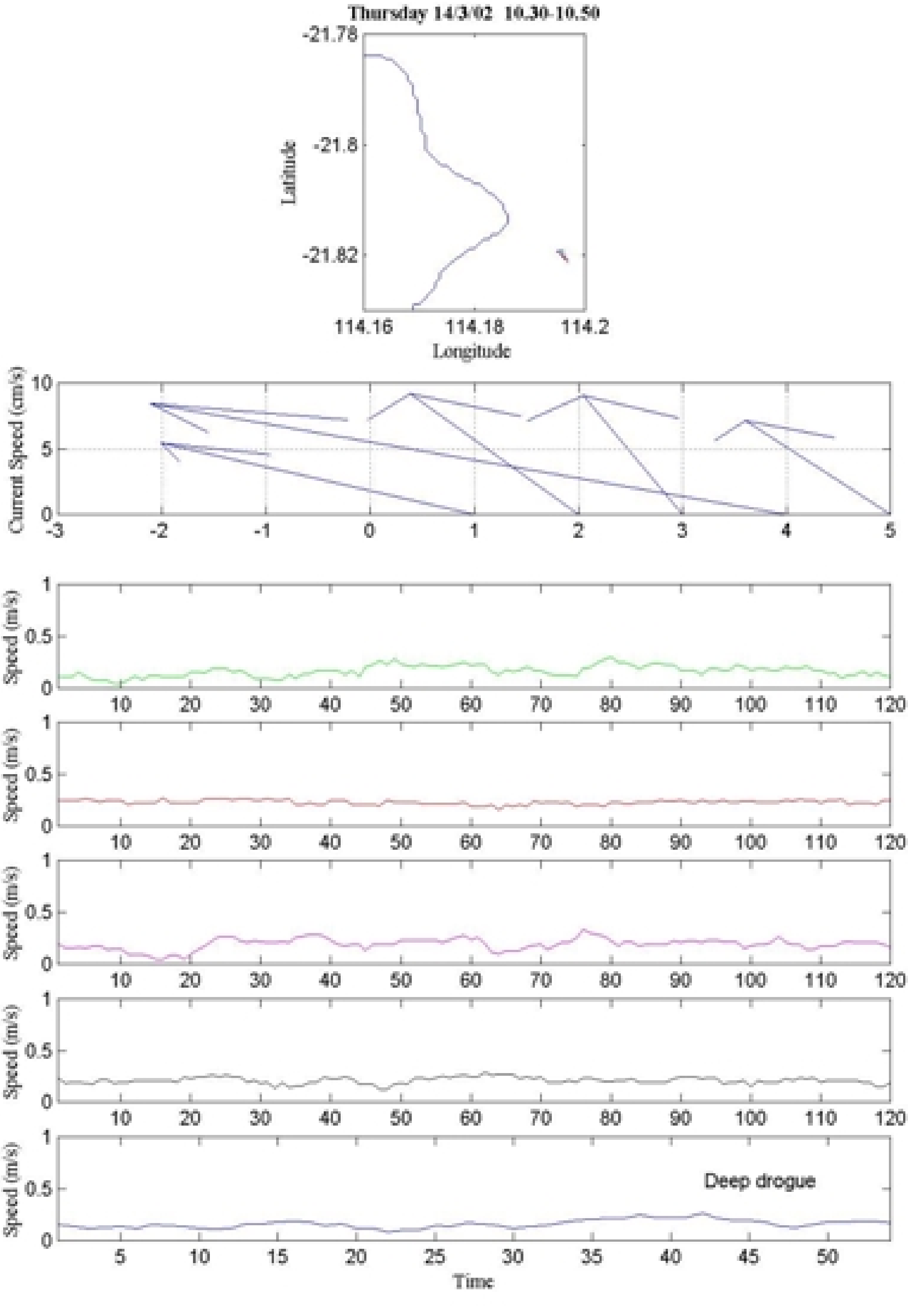
SET 5


Thursday 14/3/02 8.10-8.30
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Speed (m/s)
Time

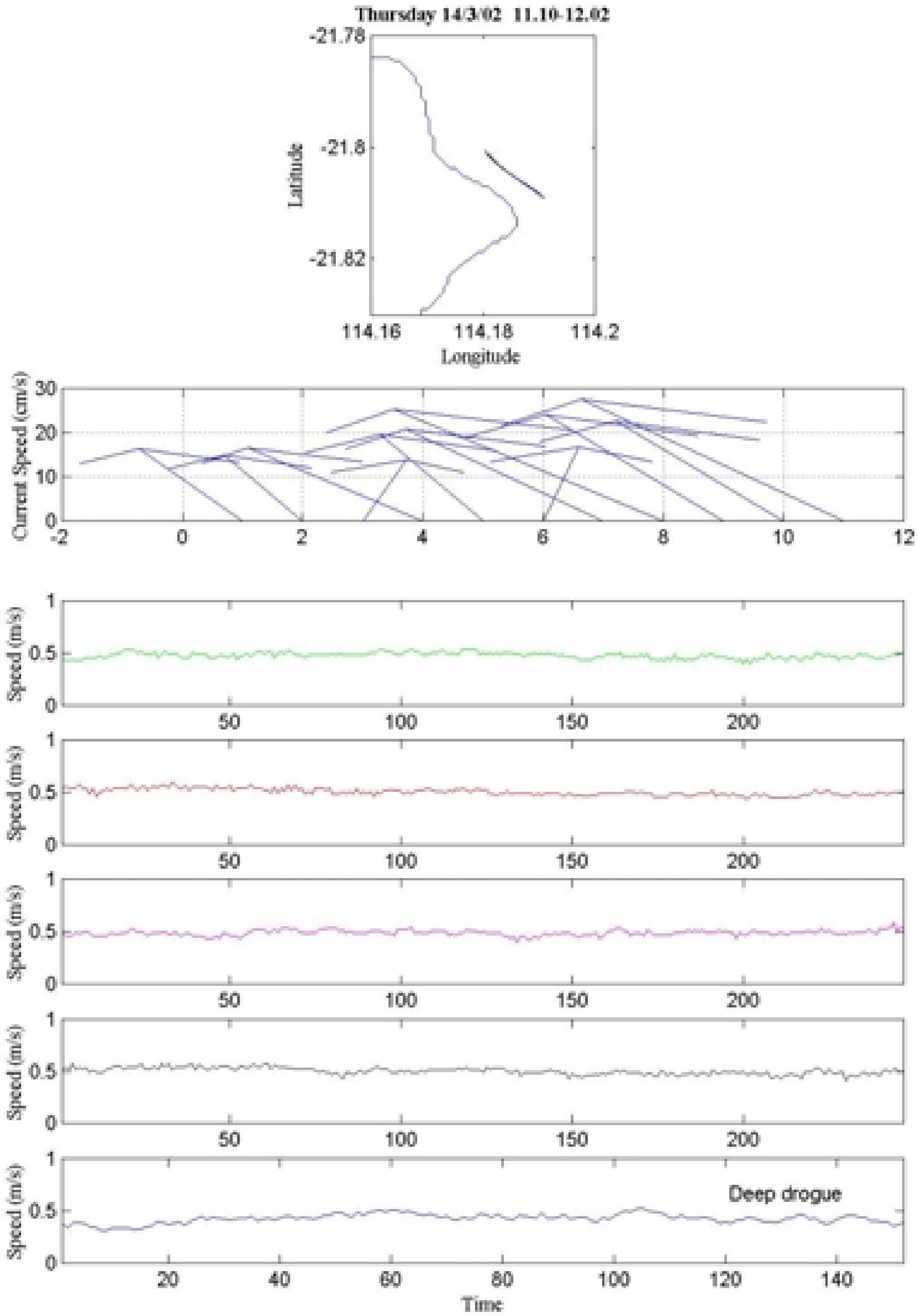
SET 6


Thursday 14/3/02 8.34-10.00
-21.78
-21.8
-21.82
Latitude
114.16
114.18
114.2
Longitude
Current Speed (cm/s)
20
0
-20
-40
0
2
4
6
8
10
12
14
16
18
Speed (m/s)
1
0.5
0
50
100
150
200
250
300
350
400
450
500
550
Time

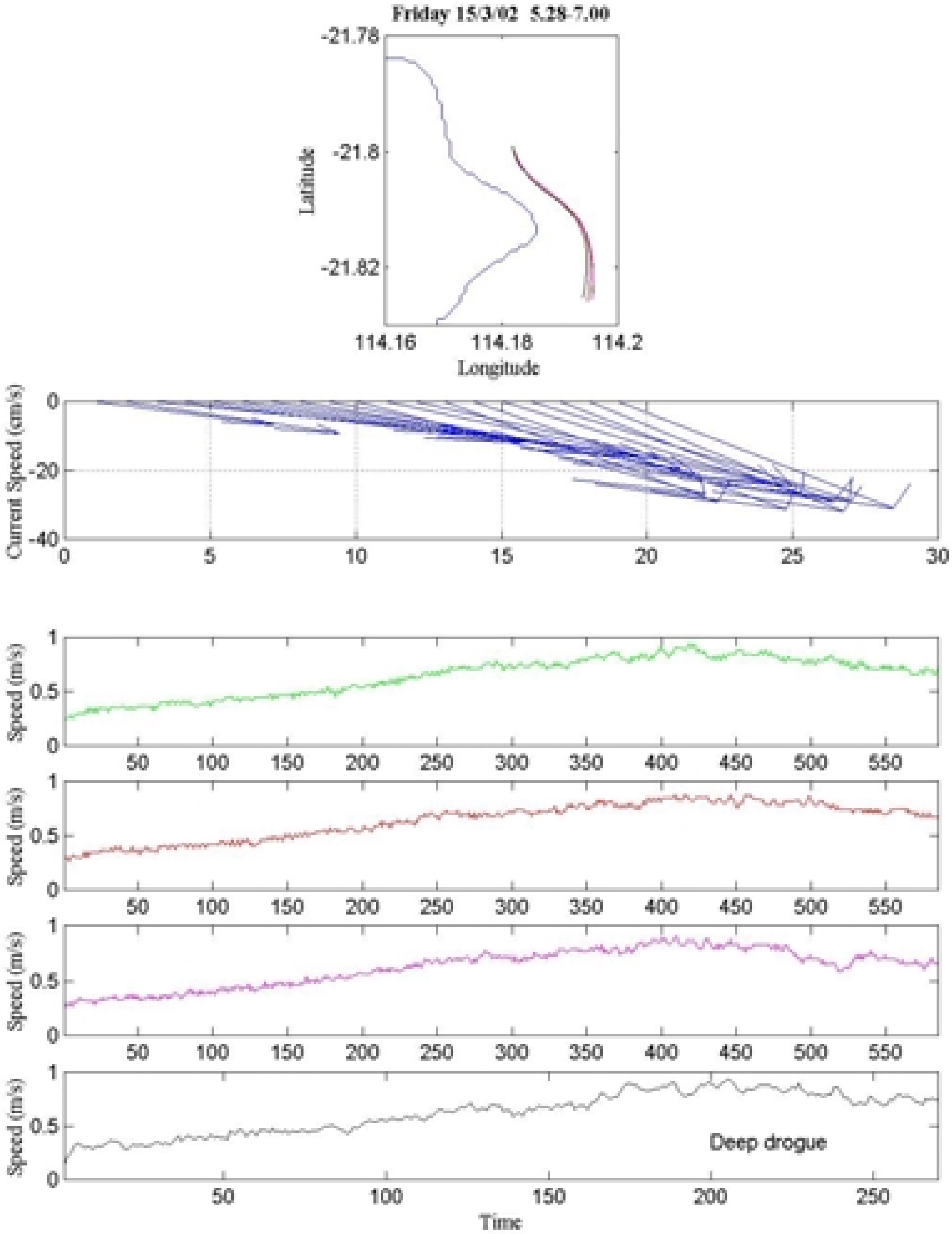
SET 7


Thursday 14/3/02 10.30-10.50
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

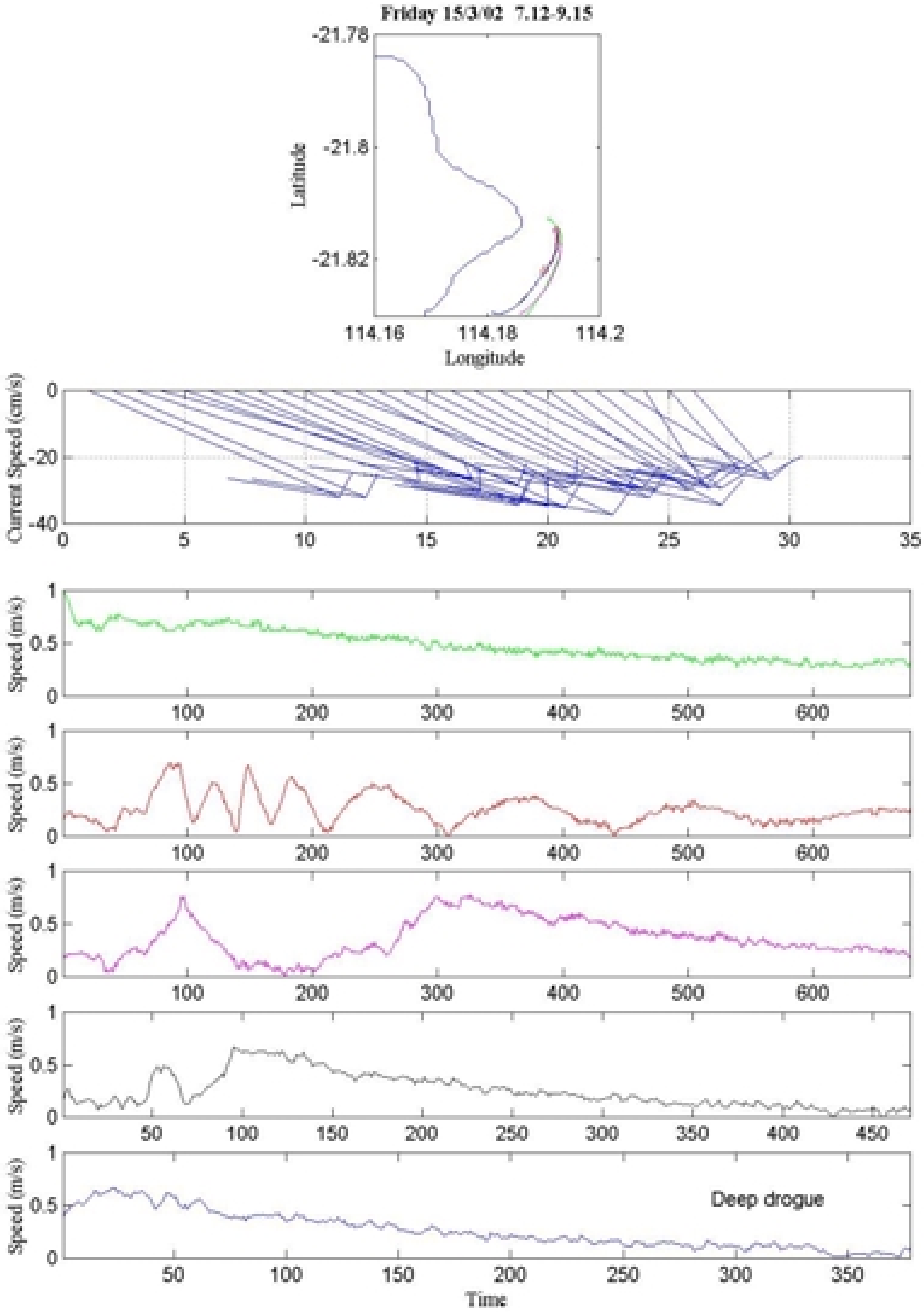
SET 8


Thursday 14/3/02 11.10-12.02
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

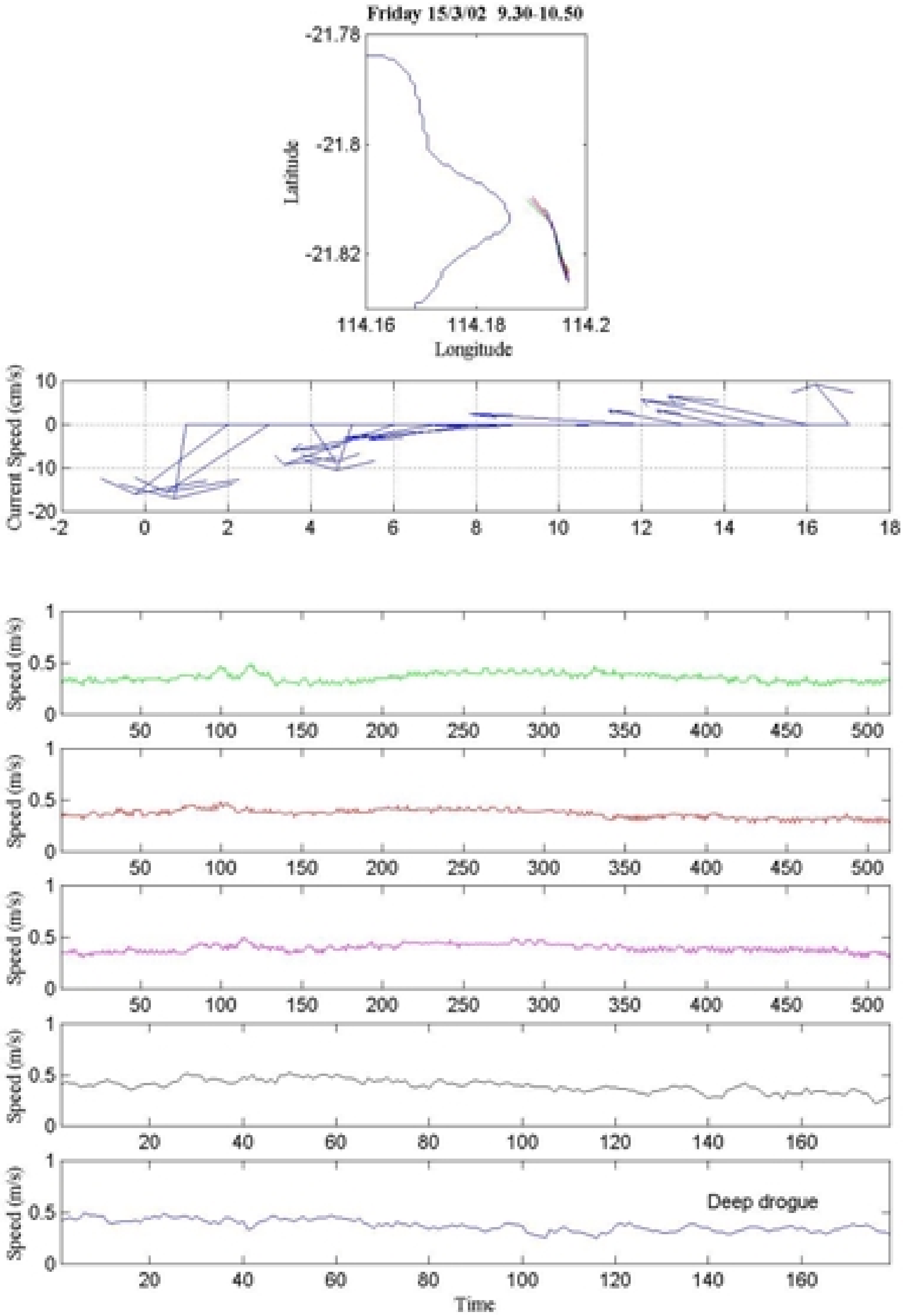
SET 10


Friday 15/3/02 5.28-7.00
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

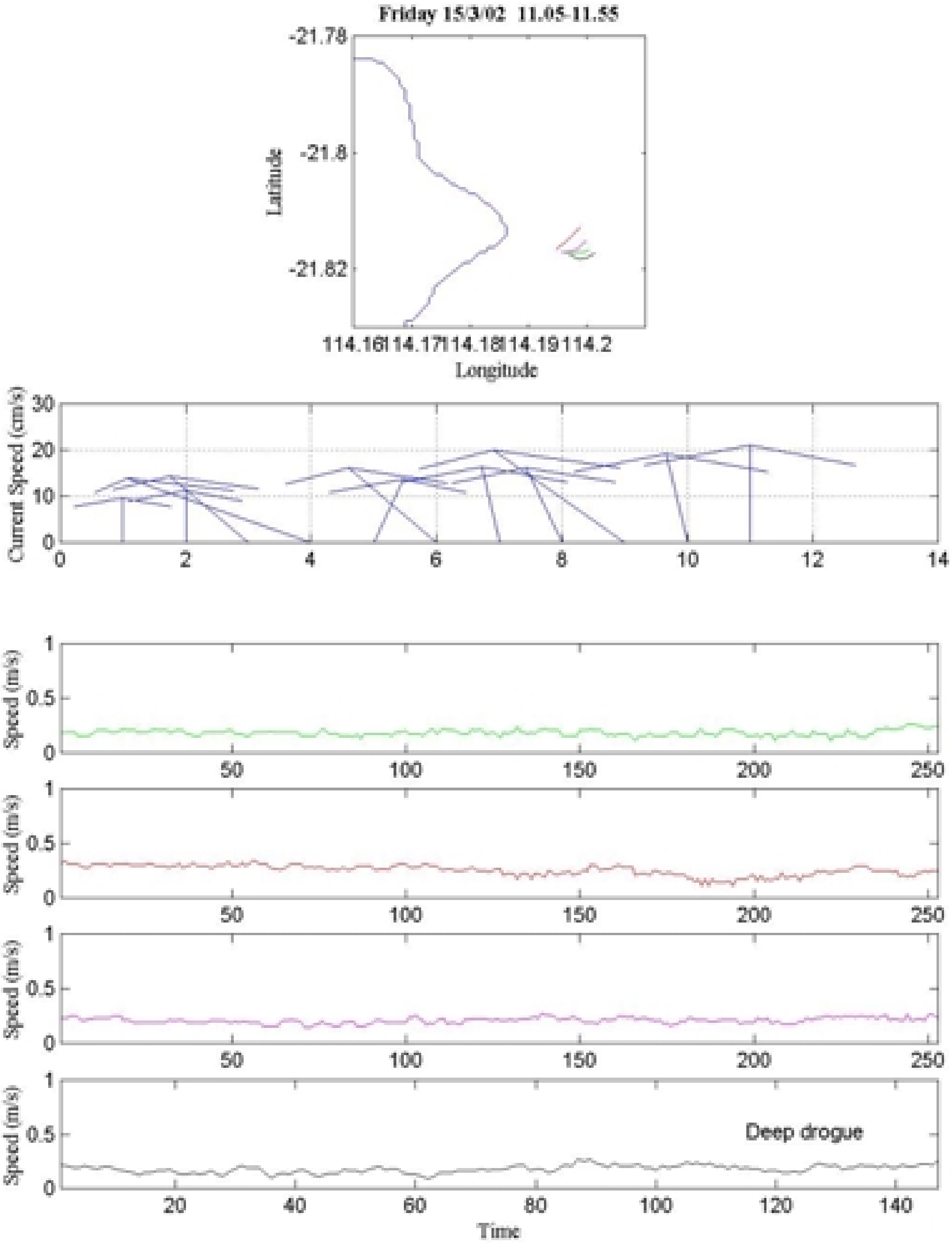
SET 11


Friday 15/3/02 7.12-9.15
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

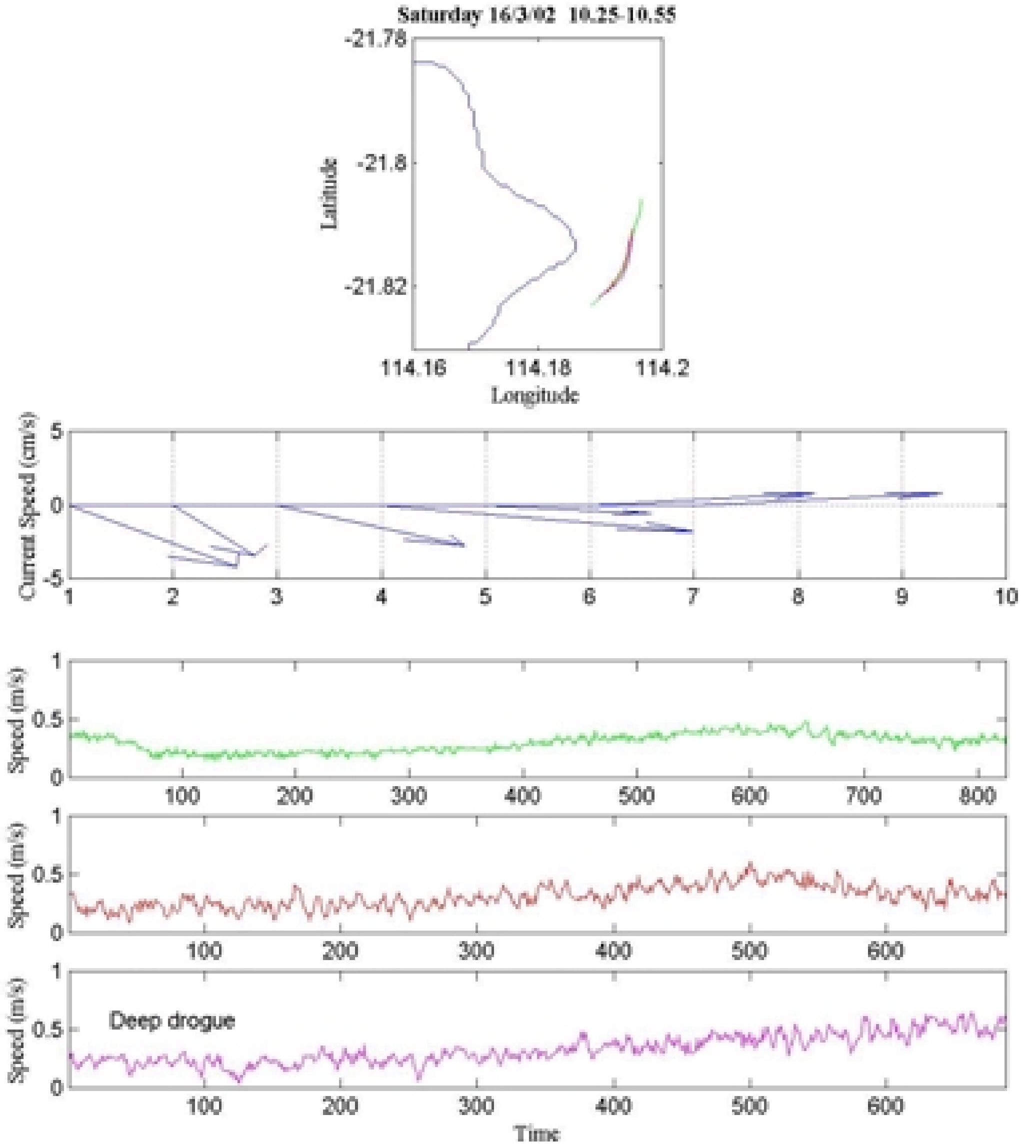
SET 12


Friday 15/3/02 9.30-10.50
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

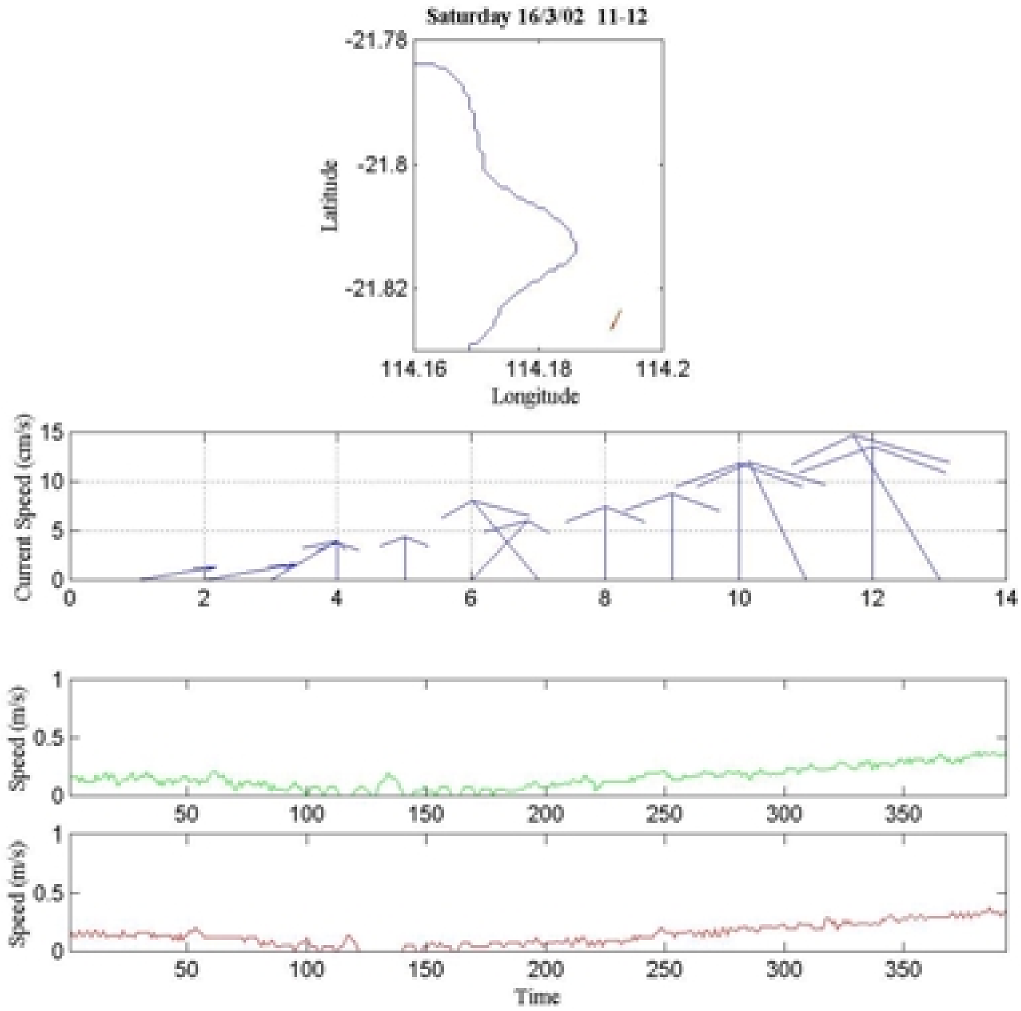
SET 13


Friday 15/3/02 11.05-11.55
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

SET 15

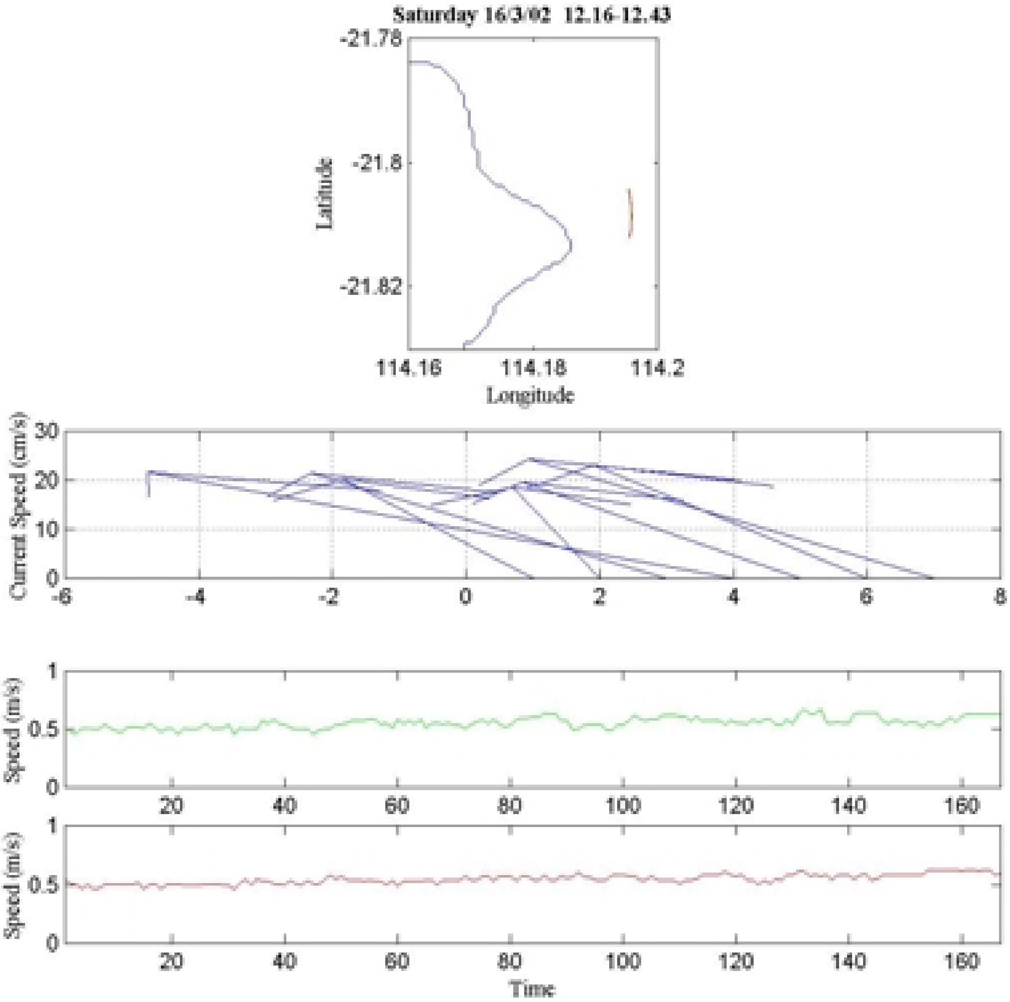

Saturday 16/3/02 10.25-10.55
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Deep drogue
Time

SET 16

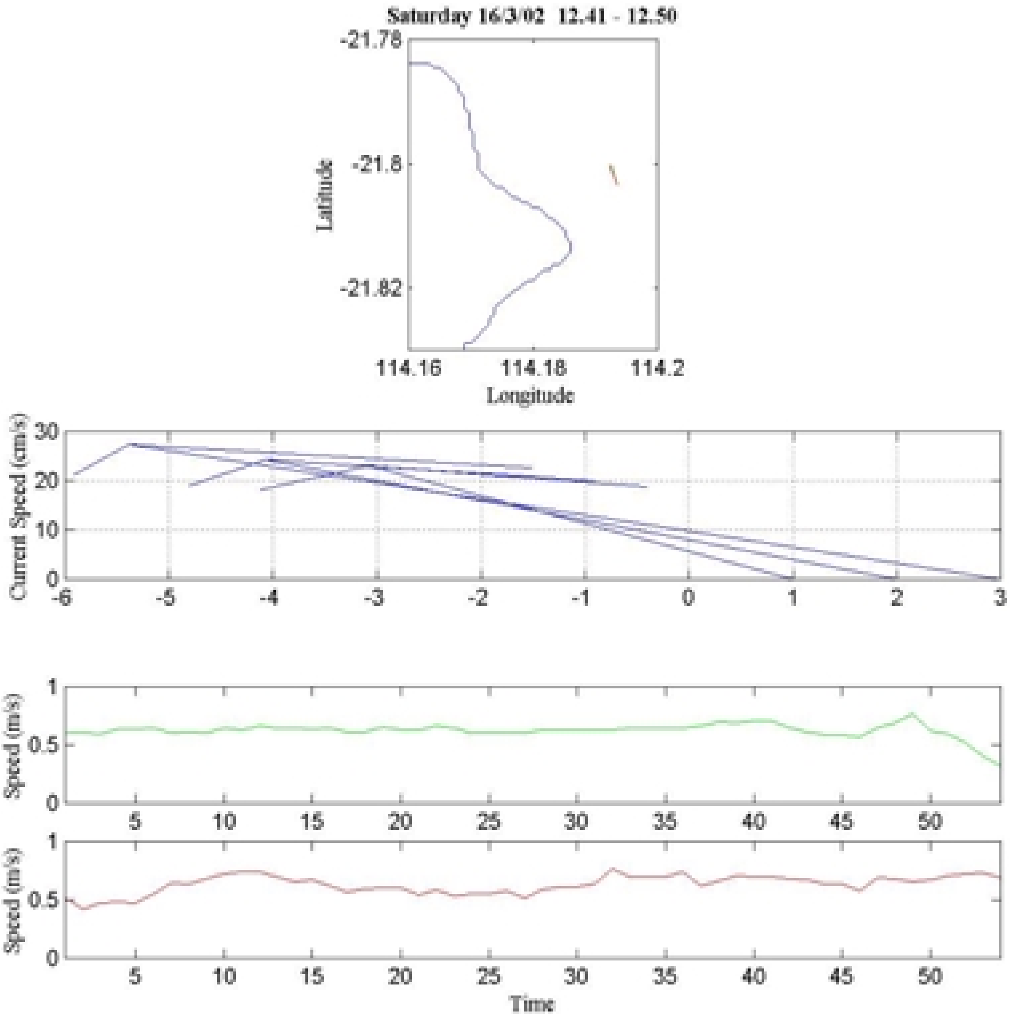


Saturday 16/3/02 11-12
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Time

SET 17

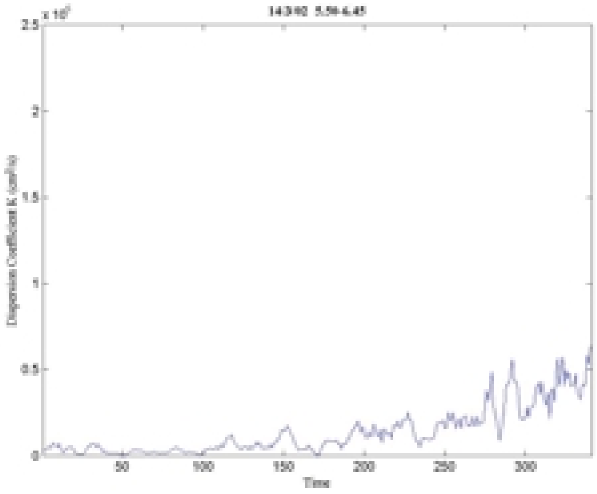

Saturday 16/3/02 12.16-12.43
Latitude
Longitude
Current Speed (cm/s)
Speed (m/s)
Speed (m/s)
Time

SET 18

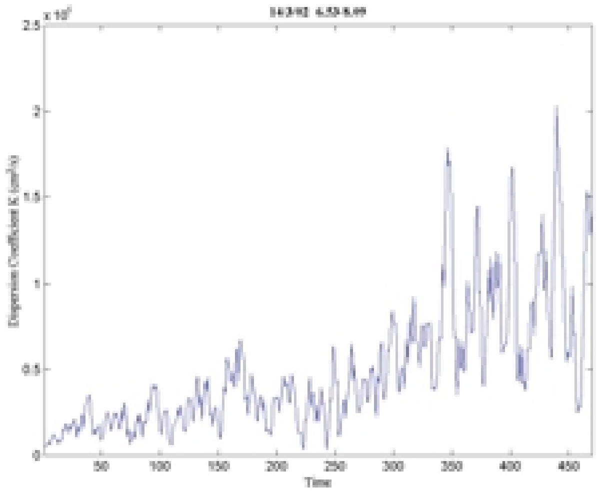

Saturday 16/3/02 12.41 - 12.50
Latitude
-21.78
-21.8
-21.82
114.16
114.18
114.2
Longitude
Current Speed (cm/s)
30
20
10
0
-6
-5
-4
-3
-2
-1
0
1
2
3
Speed (m/s)
1
0.5
0
5
10
15
20
25
30
35
40
45
50
Speed (m/s)
1
0.5
0
5
10
15
20
25
30
35
40
45
50
Time

9.2 APPENDIX II

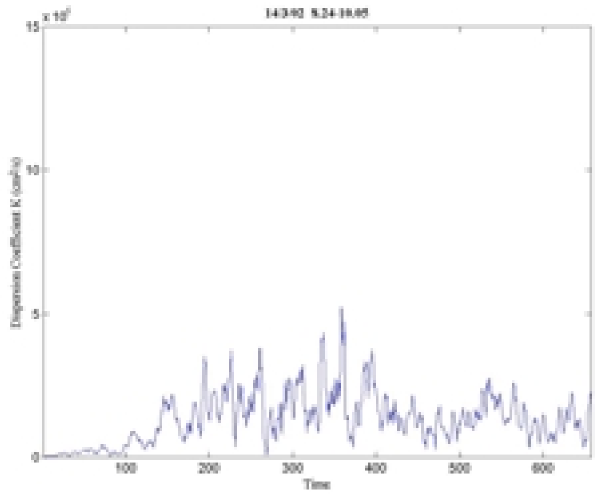
SET 1



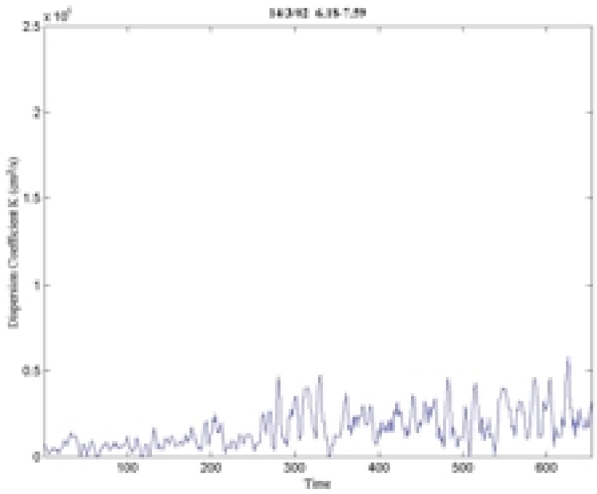
SET 2



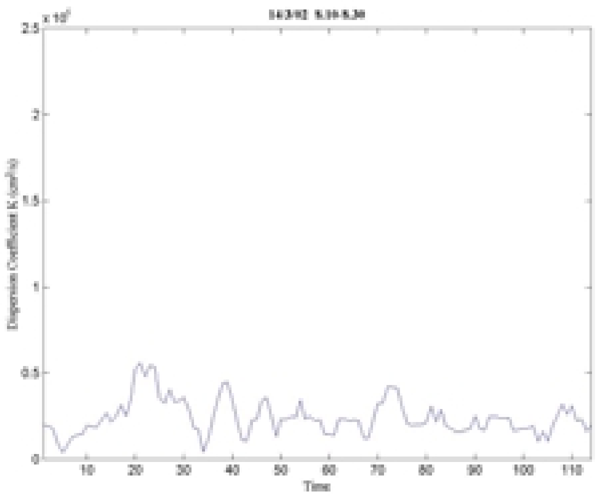
SET 3



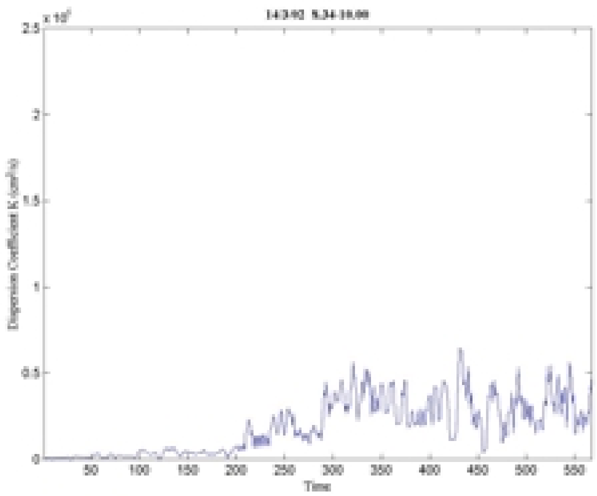
SET 4



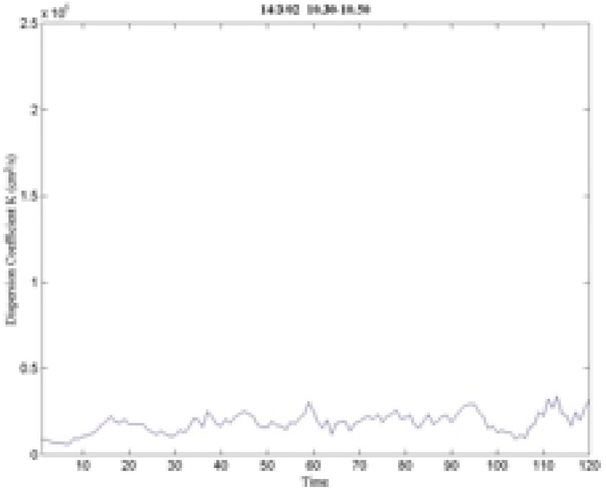
SET 5



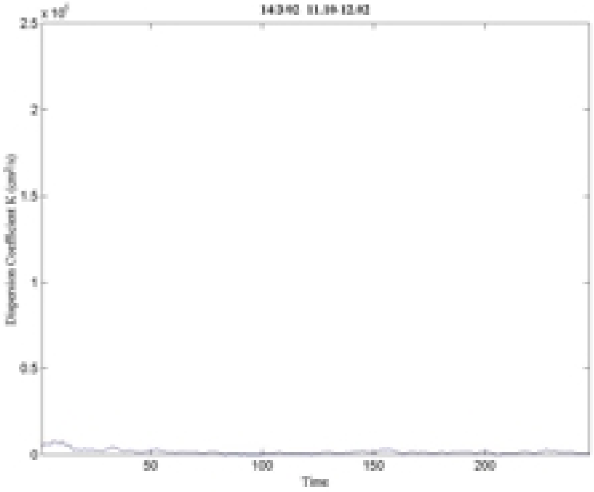
SET 6



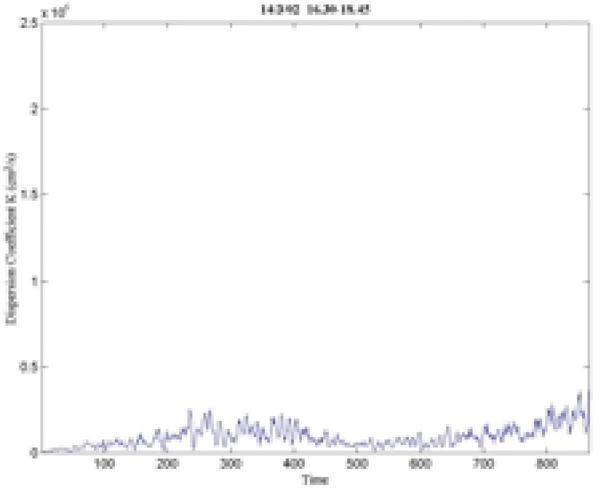
SET 7



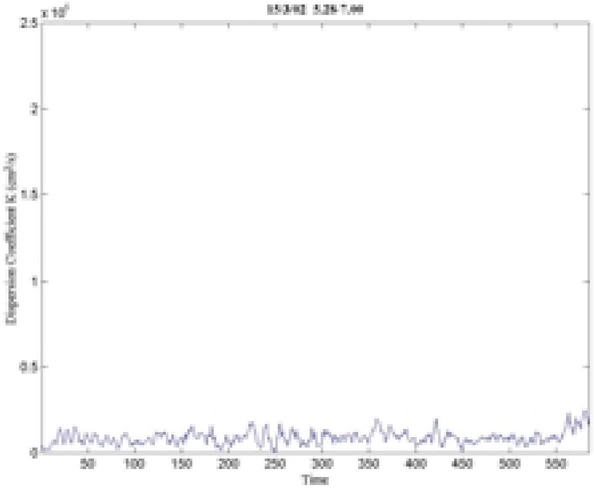
SET 8



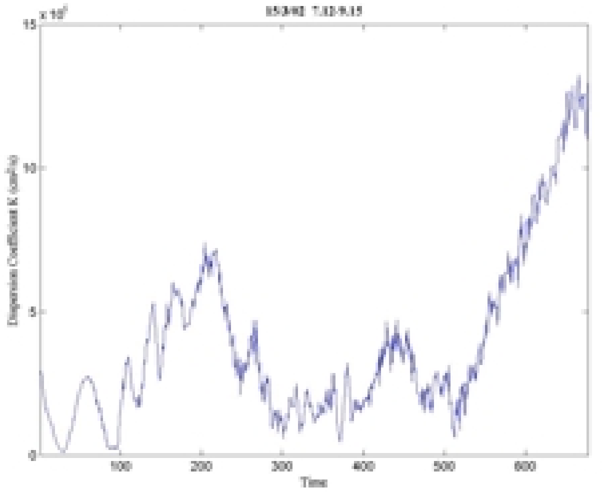
SET 9



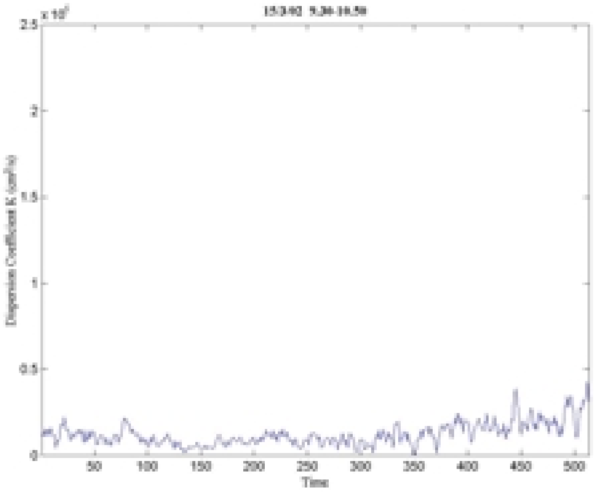
SET 10



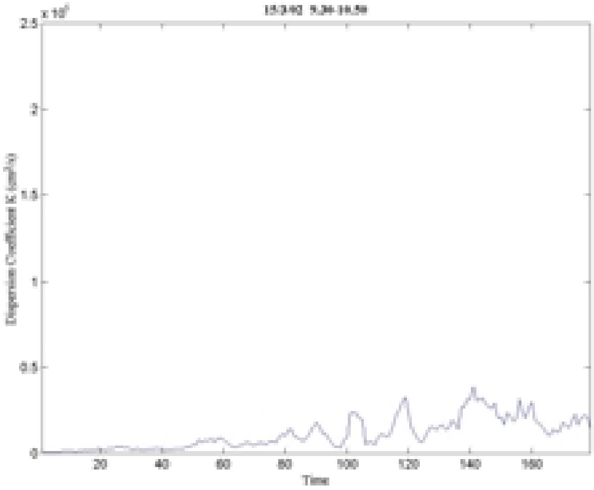
SET 11



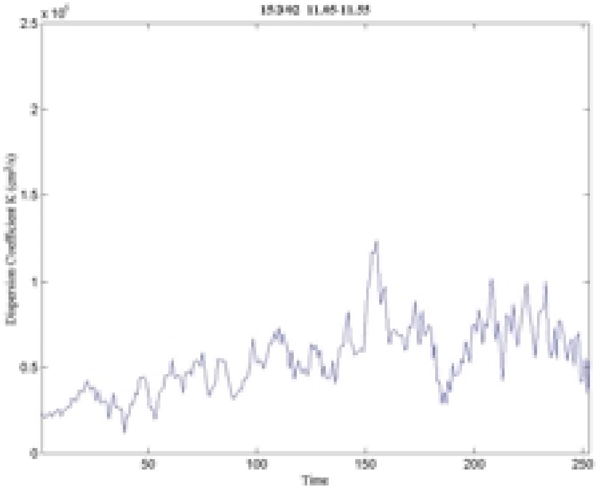
SET 12



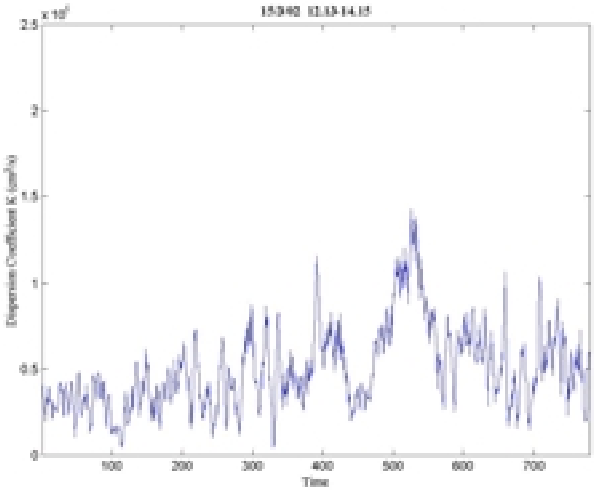
SET 12g



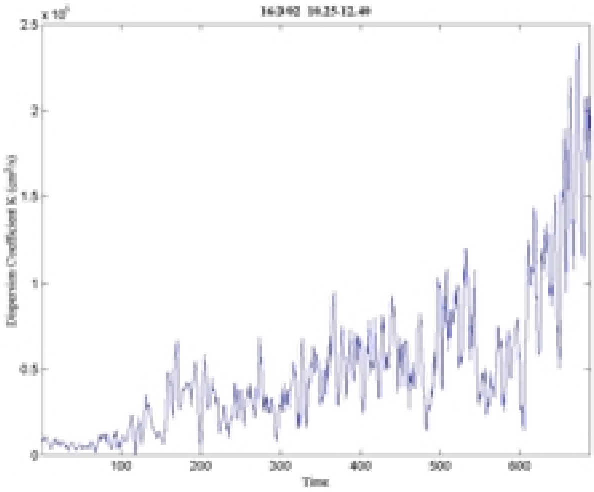
SET 13



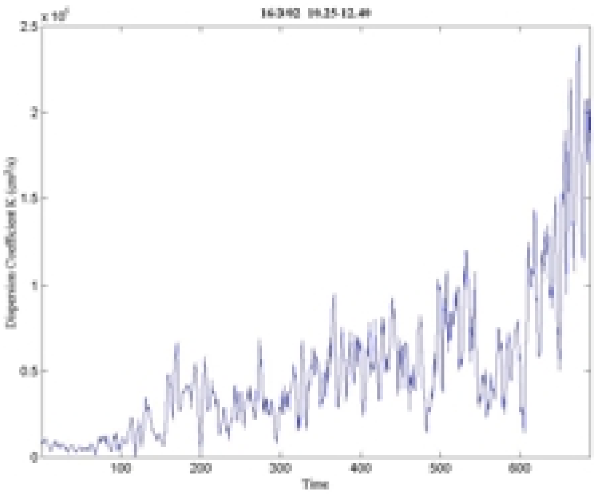
SET 14



SET 14g



SET 15g



SET 16