MARINE MANAGEMENT SUPPORT:
NINGALOO

REVIEW OF THE OCEANOGRAPHY OF NINGALOO REEF AND
ADJACENT WATERS


Prepared by
N. D’Adamo and C.J. Simpson

March 2001

Marine Conservation Branch
Department of Conservation and Land Management
St. Henry’s
Fremantle, Western Australia, 6160
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SUMMARY

This review of the oceanography of the Ningaloo Marine Park and adjacent waters has been prepared as a contribution to a review of the park’s management plan: Ningaloo Reef Marine Park (State Waters) Management Plan 1989-1999 (CALM, 1989). The results indicate that the circulation and transport of the park’s lagoonal waters are driven principally by waves, tides and winds. It appears that the overall circulation is dominated by wave-pumping of water over the reef tract, with the tides having a modulating role and with prevailing winds and seabreezes tending to drive nearshore lagoonal water predominantly northwards. Wave-pumping is generated by the regular breaking and shoaling of waves along the barrier reef, causing an associated set-up of water which creates a sea level gradient directed into the lagoon from the ocean. Once crossing the individual reef segments, the oceanic water fans and spreads symmetrically, running along the shore-parallel channels of the lagoonal regions before exiting as jets through the gaps. Under this process, most of the water flux into the lagoons occurs across the reef, with outflows concentrated through the many gaps that punctuate the reef.

In terms of flushing, the net effect of waves, tides and winds has been estimated to result in residence times for the lagoonal waters of less than about one day. However, field evidence exists to suggest that pockets of water enclosed by strong shoreline curvatures are likely to have longer local residence times as a result of trapping by the topography. This was inferred from the presence of localised maxima or minima in nearshore salinity-temperature fields.

Tides modulate the strength of the wave-induced circulation but are not effective in changing the overall flow patterns to any great deal. A major effect of wind appears to be the regular stirring of the water column via surface mixing, thereby precluding the formation of any regular or sustained stratification in the lagoons, a feature that is otherwise often a characteristic of less-energetic semi-enclosed coastal embayments. The relatively vigorous mean currents in the lagoons also contribute to sustained vertical mixing via bottom-generated turbulence. Generally, wind-driven advection within the lagoonal areas does not dominate wave-induced circulation. However, close to the shore and at the water surface the wind may have its most pronounced effect in superposing a downwind flow pattern on the mean circulation of the lagoon.

Upon jetting through the gaps, some of the lagoonal outflow peels off from the lateral reef edges, forming re-circulating vortices, which curl back in towards the main reef tract to again become part of the wave-induced inflow over the reef. However, a significant amount of the outflow jets out to sea, thereby becoming entrained in the strong southward (autumn/winter) or northward (spring/summer) coastal currents, known respectively as the Leeuwin and Ningaloo Currents.

The Leeuwin Current is driven by a broad north-to-south sea-level slope between northwest and southwest Australia. It is the major agent responsible for the transport of northern tropical waters to the Ningaloo Reef edge, with its waters sourced mainly from the Pacific-Indian Throughflow to the north and Eastern Gyral Current to the west. The Ningaloo Current (a ‘counter-current’, driven by strong south-southwesterly prevailing winds and seabreezes) tends to flow along the extent of the Ningaloo Reef, but with a major perturbation to the flow at Point Cloates, where it appears to form a characteristic counterclockwise circulation. The dynamical interaction between the Leeuwin and Ningaloo currents off Point Cloates may re-direct some of the water from the Ningaloo Current back towards the south. During spring/summer, the Ningaloo Current drives the northward transport of relatively cool water close to the coast, thereby forcing the Leeuwin Current to flow further offshore than it normally does. Temperature and chlorophyll signals in satellite images indicate that the Ningaloo Current is likely to be associated with the introduction of nutrient-rich water off Ningaloo Reef through coastal upwelling and/or advection.

There are indications from past and recent field studies that upwelling may also occur over the continental shelf due to the sub-surface shoaling and breaking of shoreward-propagating internal waves.
In terms of regional biological connectivity, recent oceanographic modelling over the North West Shelf suggests that shelf currents connect the reef environs of Ningaloo Marine Park with those of the proposed Dampier Archipelago/Cape Preston and Montebello/Barrow Islands marine conservation reserves. The simulated release of neutrally buoyant particles (representing larvae) suggests that Ningaloo Reef acts as a source for recruitment to these other reefs during summer and as a sink for recruitment from those reefs during autumn. Typical travel times between Ningaloo and these other reef areas are predicted to be in the order of tens of days.

The overall oceanographic picture that has now emerged (Taylor and Pearce, 1999) for the Ningaloo Reef region is one consisting of a persistent inner-lagoonal circulation regime throughout the year, driven principally by wave-pumping over the reef modulated by tide and wind effects (Hearn et al., 1986; Hearn and Parker, 1988), adjacent to an annually reversing nearshore current system along the shelf break, comprising the southward Leeuwin Current in autumn/winter (Godfrey and Ridgway, 1985; Cresswell, 1991; Pearce, 1991) and northward Ningaloo Current in spring/summer (Taylor and Pearce, 1999).

The counterclockwise eddy emanating from the Ningaloo Current at Point Cloates may bear an important relation with the relatively different diversities and abundances that exist between the plant and animal communities to the north and south of Point Cloates.

The recent advances in the understanding of primary productivity off Ningaloo Reef, most likely driven by upwelling, is now being considered as a factor that is possibly related to the annual aggregation of Whale Sharks off Ningaloo Reef. Ongoing biological and oceanographic studies continue to address these issues. The improved understanding that is now evolving on the local and regional hydrodynamics of the region confirms and strengthens the notion that the temporal and spatial patterns of key ecological processes in the region are strongly influenced by both local and shelf-scale hydrodynamic processes. A refinement in the understanding of fundamental hydrodynamic processes, along with the associated development of predictive models for such, should therefore form high priority areas for the research and monitoring that is required to underpin effective management of the Ningaloo Marine Park and any proposed extensions.
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**  **  **
1 INTRODUCTION

This report reviews the oceanography of the Ningaloo Marine Park and its adjacent waters, including the proposed southern extension to the park, as shown in Figure 1. It forms a contribution to a review of the park’s management plan: Ningaloo Reef Marine Park (State Waters) Management Plan 1989-1999 (CALM, 1989). The review of the plan is being undertaken by the Marine Conservation Branch of the Department of Conservation and Land Management (CALM). The review is required under the Conservation and Land Management Act 1984. An understanding of the physical water properties and the nature of circulation and exchange is required for management because of the need to correctly understand key ecological processes which are intrinsically linked to the hydrodynamics (e.g. recruitment) and the movement and dispersion of undesirable substances (e.g. contaminants, water borne marine pests).

A number of excellent reviews and issue-specific papers have been written concerning the oceanography of the Ningaloo Marine Park and surrounding waters, including Hearn et al. (1986), Hearn and Parker (1988), Simpson and Masini (1986), Simpson (1991), Simpson et al. (1993), Buchan and Stroud (1993), Sanderson (1997, 2000), Scott (1997), Taylor and Pearce (1999). However, a full understanding of the park’s hydrodynamic characteristics is yet to be developed. Accordingly, there are a number of studies currently underway involving investigations of the hydrodynamics (through field, analytical, and modelling strategies) of both the inner lagoons and adjacent oceanic waters of the Ningaloo Reef area. Some of these are being conducted by the Australian Institute of Marine Science (AIMS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Departments of Environmental Engineering and Zoology of the University of Western Australia (UWA). In addition, commercially-motivated studies have been and are being undertaken in the region and these also provide valuable sources of information and understanding, such as the wave measurements currently being undertaken off North West Cape by WNI Science and Engineering. Work on identifying oceanographic processes off Ningaloo Reef is also being undertaken through the use of remote sensing techniques at the Curtin University of Technology. The spatial domain of the multi-disciplinary North West Shelf Joint Environmental Management Study (Department of Environmental Protection and CSIRO) includes Ningaloo Reef.

A long-term program to monitor water temperature in the Ningaloo Marine Park has recently been initiated through a collaboration between the Marine Conservation Branch and Exmouth District office of CALM and the Department of Geography of the Australian National University. The first deployment commenced in July 2000, involving two temperature loggers recording lagoonal water temperatures at Tantabiddi. These data are currently being acquired in the field and as such are not available to this review.

This review will draw on both the existing literature and also on the preliminary results of current studies and unpublished data available from other sources (e.g. D’Adamo, 1997 and 1999).

2 PHYSICAL CHARACTERISTICS

The Ningaloo reef tract is comprised of a barrier reef, punctuated by gaps, which runs approximately parallel to the coastline from about Gnarraloo Bay in the south to Point Murat in the north (Figure 2). The total length of reef is approximately 280 km, making this the largest fringing coral reef system in Australia. As Taylor and Pearce (1999) point out, it is the only extensive coral reef in the world fringing the west coast of a continent. The distance offshore to the main reef flat varies from as little as a few hundred metres to as much as about 7 km, with an average of about 2.5 km. Gaps regularly intercept the main reef line, providing for a series of individual elongated reef segments. The gaps have relatively deep channels through which the majority of lagoonal flushing occurs. Hearn and Parker (1988) used aerial photographs of the northern part of the reef to estimate that these gaps occupy about 15% of the length of
the main reef under light swell conditions. The reef is backed by a shallow, sedimentary lagoon, which has a mean depth at AHD of approximately 2 m, interspersed with occasional patch and nearshore platform reefs.

As Hearn and Parker (1988) have described, “…over the northern part of the reef the 200 m contour is some 10 km from shore. At the southern end of the reef this distance increases to about 50 km. The reef follows the coastline and the lagoon has maximum width near Coral Bay: over this central region it also appears to have a more open and broken topography.” The continental slope, broadly identified by the 100 m contour, comes to within 6 km of the northern part of Ningaloo Reef, making it Australia’s narrowest stretch of continental shelf.

Hearn et al. (1986) used the bathymetrical characteristics along the reef to suggest that it could be divided into three discrete sectors, the ‘northern’, ‘central’ and ‘southern’ sectors, respectively, as follows.

**Northern Sector – North West Cape to Point Cloates (approx. 120 km)** The lagoon is less than 3 km wide and parallel to a straight coast. The shelf break is also parallel to the shore and the shelf is about 10 km wide.

**Central Sector – Point Cloates to Point Maud (approx. 50 km)** The lagoon is some 6 km wide and 50 km long and has the structure of a long embayment with a major break in the reef at its southern end near Point Maud.

**Southern Sector – Point Maud to Gnarraloo Bay (approx. 90 km)** The reef at Amherst Point is very scattered and a definite structure is only evident some 35 km south of Point Maud, at Pelican Point. In this sector the lagoon is about 1 km wide.

Hearn et al. (1986) point out that the northern sector is rather unique in that such long lengths of straight barrier reef so close to shore are comparatively rare on the continental shelf.

Taking a closer look at the bathymetry, a typical topographical layout for the northern part of the reef is presented in Figure 3a (from Hearn and Parker, 1988), showing the region including and to the south of Osprey Bay. Although not shown, the main reef line continues unbroken for four kms north of Sandy Bay. The figure was used by Hearn and Parker (1988) to point out the role of wave diffraction, stating that this mechanism through the pass opposite Osprey Bay appears to have been responsible for the sediment accumulation which forms Sandy and Osprey bays. The accompanying Figure 3b (from Hearn et al., 1986) schematises the wave diffraction for two gaps associated with this stretch of Ningaloo Reef, in relation to the accumulation of sand along the shoreline.

To characterise the cross-section of Ningaloo Reef and its lagoonal regions, Hearn et al. (1986) constructed a cross-sectional profile, with habitat and geomorphological classifications, for a transect running off the northern part of Mangrove Bay. This has been reproduced in Figure 4 and highlights the cross-sectional undulations associated with the exposed reef flat and submerged lagoon, the typical variability in habitat cover and the results of calculations on relative water flux through the cross-section due to wave-pumping. As would be expected, the greatest flux occurs through the deepest portion of the cross-section.

### 3 METEOROLOGY

The climate of the area (Hearn et al., 1986) is arid, with an annual evaporation of about 2700 mm. This greatly exceeds that of annual rainfall, which averages at approximately 250-300 mm, and for which a
major proportion falls in short intense bursts during occasional storms and cyclones. Typical mean monthly rainfall from February to July is about 30-50 mm. Evaporation peaks during December/January (approximately 350 mm per month) and is weakest in June (120 mm per month). As Hearn et al. (1986) also point out, the infrequent and variable rainfall pattern results in there being no normal terrestrial runoff into the marine park, with storm water flowing mainly through seasonal creeks which are mostly situated near passes in the reefs.

Hearn et al. (1986) provide global radiation data for Ningaloo Reef which indicate mean monthly values ranging from a minimum of 168 W m$^{-2}$ (entering the water) in July to a maximum of 336 W m$^{-2}$ (entering the water) in January.

At the broadest scale, the wind patterns over Ningaloo Reef are controlled by the annual north-south movement of the belt of anti-cyclonic high pressure systems that circumnavigates the globe. In winter, the higher latitudinal position of the ‘anti-cyclonic belt’, as it is called, results in strong prevailing offshore ‘trade’ winds over the Pilbara. In summer, as the belt moves to its southernmost latitudes, monsoonal wind systems move into the area and influence the weather along with regular prevailing south-southwesterly winds and sea-breezes. On an annual basis, winds directed toward the northern quadrants dominate the wind fields. Cyclones form off northwest Australia during summer/autumn, with an average of about 2 per year crossing the Pilbara coast. Intense winds (up to about 300 km hr$^{-1}$) can accompany cyclones.

To provide a more detailed description of the winds, Taylor and Pearce (1999) used wind records from Cape Cuvier (45 km south of Gnaraloo) to demonstrate the seasonal wind patterns for Ningaloo reef. They describe the wind patterns as follows (see Figure 5, from Taylor and Pearce, 1999): “During much of the year, prevailing south-easterly trade winds during the night and morning are replaced by stronger south-southwesterly sea-breezes in the afternoon. The mean wind speed in summer is 7-9 m s$^{-1}$, but this falls to only about 3 m s$^{-1}$ in winter due to the more variable wind directions in that season. Peak wind speeds exceed 14 m s$^{-1}$ in all months”. Taylor and Pearce (1999) point out that this pattern is essentially similar to those described by Hearn et al. (1986) for Carnarvon (110 km south of Gnaraloo) and Learmonth (Figure 2).

Taylor and Pearce (1999) describe the winds for the remainder of the year, as follows: “A strong and persistent southerly wind blows between about September and March, and by April the prevailing winds swing more to the east (particularly during the mornings), delaying the onset of the south-southwesterly sea-breeze and often giving a period of calm conditions in the middle of the day. In some years, large continental high pressure systems produce strong daytime north-easterly winds in May and June.”

4 TIDES AND WATER LEVEL

In terms of predictable astronomic changes to water level (i.e. tides), the reef is located just north of the west coast's major tidal transition zone (Charitha Pattiaratchi, UWA, pers. comm.). The transition zone is centred around Carnarvon and separates the South Western Australian tidal zone (diurnal and micro-tidal) and the North Western Australian tidal zone (semi-diurnal and macro-tidal) (Simpson and Masini, 1986). The tides in the area are mixed, predominantly semi-diurnal and with a maximum range at springs of about 2 m. The form factor (i.e. the ratio of the sum of amplitudes of the diurnal to semi-diurnal harmonic tidal components) was calculated by Hearn et al. (1986) to be about 0.8. Simpson and Masini (1986) analysed the tides of the area and suggest that tides in the lagoon, along most of Ningaloo Reef, are better correlated in phase and amplitude with the predicted tides at Carnarvon than at Point Murat.

Apart from tides, meteorological effects can change water level on a frequent basis. For example, typical strength onshore and offshore winds can produce coastal water level changes in the order of ±0.1 m, respectively (Tony Lamberto, WA Department of Transport, pers. comm.).
Changes in barometric pressure will alter sea-level in the ocean by about 1 cm per hectopascal (hPa) change in pressure due to what is known as the isostatic response of sea level to barometric pressure (increasing pressure causes a fall in water level and vice-versa).

Cyclones can cross the region (average of about 2 per year) and can induce water surges and decreases of order 2-3 m or more during severe cyclones. For example onshore wind forcing during Cyclone Vance (22 March 1999) was found to elevate water levels at Exmouth by nearly 3 m (Tony Lamberto, WA Department of Transport, pers. comm.).

To the north of the area, the forcing of coastal water towards or away from the coast during cyclones and wind events associated with the passage of high and low pressure systems will transmit southwards as what are known as ‘continental shelf waves’ (CSW) (Webster, 1983; Harrison, 1983). These are low frequency oscillations which have characteristic amplitudes of 0.1-0.2 m, wave lengths of order 500-1000 km and periods of order 5-10 days, consistent with the spatial and temporal scales of the meteorological systems that create them. They are known to propagate as coastal water mounds, with the Earth’s rotational force maintaining their position against the coast as they travel southwards. Little investigation on their dynamical influence within the many lagoonal and embayment systems along the WA coast has been mounted to date, with the exception of recent work carried out for the Swan River Estuary by Associate Professor Charitha Pattiaratchi and colleagues at the University of Western Australia. That work demonstrates a noticeable and significant effect on the position of the salt wedge in the Swan River Estuary during the passage of CSW’s that were generated by cyclones off northwest Australia (Associate Professor Charitha Pattiaratchi, University of Western Australia, pers. comm.).

Tsunami waves can form in the Indian Ocean and run onto the northwest coast of Australia (including North West Cape), resulting in significant surges of water and associated damage to coastal environs and structures (Pattiaratchi and Woo, 2000). Tsunamis are formed primarily as a result of earthquakes in oceanic and coastal regions, where large impulsive displacements of seawater follow rapid deformations of the Earth's crust. Other factors that may generate tsunamis include landslides and volcanic eruptions. These displacements then travel through the ocean as wave trains which are fast (> 900 km hr⁻¹), very long in wave-length (>100 km) and small in height (<1 m from crest to trough). As tsunamis cross the continental shelf they become slower due to shoaling effects, but gain in height from their characteristically imperceptible magnitudes in the ocean to large magnitudes at the coast (up to 5-10 m). They can run up onto the coast, yielding potentially catastrophic impacts with water running inland for distances of 10s to 100s of metres. When a tsunami reaches the shore, it may appear as a rapidly rising or falling tide, a series of breaking waves, or even a bore (a propagating step-like wave with a steep breaking front (Pattiaratchi and Woo, 2000)).

Statistically, tsunami's are infrequent phenomena, with occurrences expected less than once per 100 hundred years, on average. Pattiaratchi and Woo (2000) reviewed the occurrence of tsunamis in the Indian Ocean, based on data from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Centre website (http://www.ngdc.noaa.gov/seg/hazard/tsu.html). They found that of the 45 tsunami events believed to have occurred since the year 49 BC in the Indian Ocean to the north of Australia, only 3 have been recorded to have arrived along the northern Australian coastline (1883, 1977 and 1994). These three tsunamis generated water level surges of up to 6 m at various coastal sites between Exmouth and Broome. For example, the 1994 tsunami (due to the 'East Java Earthquake') was inferred to have reached heights at the coast of up to 4 m along North West Cape, with lower heights of 2-3 m between Exmouth and Karratha (WNI, 1998). The inferred heights were based on visual observations of the effects of inland water damage and penetration (Pattiaratchi and Woo, 2000). For example, clear evidence of the 1994 event included marine debris strewn across coastal car parks of the northern half of Ningaloo Marine Park (Foley, 1994; Barry Hamstrum, Perth Office of the Bureau of Meteorology, pers. comm.). The primary reason for differences in the heights believed to have occurred along the northwest coast
coast during the 1994 event is related to the width of the continental shelf: the broader the shelf then the
greater the 'shoaling' effect in reducing the energy in an approaching tsunami. Off the North West Cape
the relatively narrow shelf results in tsunami's arriving at the coast with relatively high energy and height
compared to the coast adjacent to the wider continental shelf to the north of the Cape.

5 WAVES

Hearn et al. (1986) describe the swell that arrives at Ningaloo Reef to be dominated by a consistent swell
from the southwest in winter and more southerly in summer. Scott (1997) provides an overview of the
wave climate off the North West Shelf, including the region off the northern sector of Ningaloo Reef,
drawing on the comprehensive measurements presented in Buchan and Stroud (1993).

As relevant for the Ningaloo region, the quantitative overview of wave climate presented by Figures 6a
and b (reproduced from Buchan and Stroud, 1993) shows the monthly percentage frequency of occurrence
of significant swell height and swell direction for Exmouth Plateau. Exmouth Plateau is centered
approximately 200 km northwest of North West Cape. Note that 'significant wave height' is the average
of the highest one-third of actual wave heights. As Scott (1997) describes, the wave climate off Ningaloo
Reef shows a strong dependence with weather conditions. Highest waves generally occur in conjunction
with summer cyclones, with extreme values over 10 m and periods 8-13 s. For example, Cyclone Olivia
(10 April 1995) generated a wave nearly 19 m in true height (peak to trough) at the North Rankin A
platform, which is situated approximately 135 km north-northeast of Dampier (information from WNI
Science and Engineering). Cyclone waves, which propagate radially out from the cyclone regions,
generally arrive at the coast from the north-northeast. Swell generated by monsoon winds arrives from the
north. Long-period swell (12-20 sec) arrives from the south-southwest after generation in the Southern
Ocean by weather lows and fronts south of 50°S all year round. Swell refracts as it passes over the shelf,
thereby making a normal approach to the coast.

Local winds create shorter period waves (known as sea) as a result of the direct action of the wind on the
water surface. The magnitude of sea depends on the wind strength and fetch length. Sea has a period of 2-
8 s and it is not uncommon for waves of up to 1-2 m to be produced in superposition to prevailing swell
during say 20 knot sea-breezes off the open coast. Offshore winds also produce sea, but their effect is felt
further offshore than onshore breezes due to the sheltering effect of the land. Depending on the nature of
the coastal terrain, the effects of sheltering by land can be significant for up to 10 km offshore (Scott,
1997).

WNI Science and Engineering undertook directional wave measurements about 25 km north-northwest of
the tip of North West Cape during late February to mid-March 1999 and late June 1999 to early
September 2000. Water depth at the monitoring site was approximately 200 m. The following precis of the
results from these two deployment periods has been provided by Scott Noreika (WNI Science and
Engineering, pers. comm.). Note that all references to wave heights are with respect to 'significant wave
height':

"The deepwater wave climate off the North West Cape is dominated by perennial long period (14 - 22 s)
southwest swell. The swell waves (periods > 9 s) have a mean annual height of about 1.5m and
seasonally are a little larger in winter than in summer. The sea waves (periods ≤ 9 s) have a mean
annual height of about 1.2m and seasonally are significantly larger in summer than in winter. Sea waves
are also predominantly from the southwest, but have a significant northeast component in winter. The
total waves off the North West Cape are significantly more severe than those seen/experienced anywhere
else along the North West Shelf (when continuing northeastwards into the Timor Sea). The total waves
(combined sea and swell) have a mean annual height of about 2.0m (with little seasonal variation) and
will regularly reach 3.5 - 4.0m in the winter months and 3.0m in the summer months (due to non-cyclonic conditions). The predominant total wave direction is from the southwest, throughout the year."

Ningaloo Reef significantly attenuates incident swell (Hearn et al., 1986), rendering wind-generated sea waves as the dominant wave type in the lagoonal waters of Ningaloo Reef. The characteristics of swell wave attenuation by Ningaloo Reef are yet to be fully understood. AIMS conducted intensive oceanographic investigations in the lagoons and adjacent ocean area near Vlamingh Head during 1997, including inner and outer lagoon wave measurements, but these data were still under analysis at the time of writing this report (AIMS, 2000).

6 REGIONAL CURRENTS

Hearn et al. (1986) discuss the effect of the Leeuwin Current on the hydrodynamics of Ningaloo Reef and its lagoons and suggest that because of the close proximity of the shelf break to the reef, the Leeuwin Current is likely to have a significant influence. The Leeuwin Current is a poleward boundary current driven by a broad north-to-south sea-level slope, and is the major agent responsible for the transport of northern tropical waters to the Ningaloo Reef edge, with its waters sourced mainly from the Pacific-Indian Throughflow (PIT) to the north and Eastern Gyral Current (EGC) to the west. The PIT carries Pacific Ocean water into the region via the straits and channels of the Indonesian Archipelago. The EGC carries Indian Ocean water into the region in an approximately eastward direction along the approximate latitude of North West Cape (Wijffels et al., 1996).

Hearn et al. (1986) reason that because of the relatively shallow nature of the Ningaloo Reef lagoonal systems, the influence of the regional pressure head that drives the Leeuwin Current must be all but overcome by bottom friction in the lagoons. This would therefore inhibit any direct flow of Leeuwin Current water into the lagoons under the action of the regional sea-level slope alone.

Hearn et al. (1986) suggest that the main effect of the Leeuwin Current is likely to be the advection of warm tropical water onto the shelf break, close to the reef, where it could then enter the lagoons via ocean/lagoon exchange processes, discussed below. Hearn et al. (1986) refer to Simpson and Masini’s (1986) temperature data for the lagoon to suggest that there is a strong coupling (through hydrodynamic exchange) between the lagoonal waters and adjacent shelf zone. This was supported by the strong correlations that Simpson and Masini (1986) found between long-term lagoonal water temperature measurements and those detected through GOSSTCOMP (Global Operational Sea Surface Temperature Computation: National Environmental Satellite Service, National Oceanic and Atmospheric Administration, Washington, D.C.) over the adjacent ocean (at weekly intervals) by the satellite sea-surface temperature sensor (Figure 7).

In contrast to the Leeuwin Current, the Ningaloo Current (a summer ‘counter-current’, driven by strong south-southwesterly prevailing winds and sea-breezes) tends to flow equatorward along the extent of the Ningaloo Reef (Taylor and Pearce, 1999; Steinberg et al., in prep)). The Ningaloo Current is believed to have a major perturbation to its flow at Point Claroes, where it appears to form a characteristic counterclockwise circulation. The dynamical interaction between the Leeuwin and Ningaloo currents off Point Claroes may re-direct some of the flow back towards the south. Figure 8 (from Taylor and Pearce, 1999) presents a schematic of the Ningaloo Current and its re-circulating eddy in relation to the Leeuwin Current. During spring/summer and possibly into autumn, the Ningaloo Current drives the northward transport of relatively cool water close to the coast, thereby forcing the Leeuwin Current to flow further offshore than it normally does. Taylor and Pearce (1999) believe that the combined influence of the southward propagating Leeuwin Current and blocking effect of Point Claroes jointly contribute to the re-circulation in the region. Sea-surface temperature (see Taylor and Pearce, 1999) and chlorophyll (Associate Professor Mervyn Lynch, Curtin University, pers. comm.) images derived from data collected
by satellite-based sensors indicate that the Ningaloo Current is likely to be associated with the introduction of nutrient-rich water off Ningaloo Reef through coastal upwelling and/or advection.

Taylor and Pearce (1999) suggest that the Ningaloo Current may be an important determinant in the dispersal of coral larvae following autumnal mass reef spawning. Furthermore, they suggest that the circulatory movement generated by the interaction of the northward flow with the southward propagating Leeuwin Current at Point Cloates may be important in retaining planktonic biomass within the Ningaloo ecosystem. They postulate that this process may be responsible for the extremely active food chain at this time of the year and the presence of whale sharks (Colman, 1977). Taylor and Pearce (1999) also postulate that the re-circulation may, through natural selection, influence the timing of spawning of corals and other invertebrates throughout the year. These are areas that require further study, some of which are currently being addressed through field and modelling studies. These studies include the ecological programs of AIMS on the North West Shelf (see Steinberg et al., 1999; AIMS, 2000) and studies of the behavioural and environmental factors influencing whale shark aggregations being conducted by the University of Western Australia (PhD study, Steve Wilson, pers. comm.).

There are indications that upwelling may also occur over the continental shelf due to the sub-surface shoaling and breaking of shoreward-propagating internal waves. AIMS’s North West Shelf studies (AIMS, 2000) have produced a significant amount of oceanographic data aimed at investigating the factors driving productivity on the shelf. These data are currently under analysis, but preliminary results (Craig Steinberg, AIMS, pers. comm.) indicate that upwelling is an important mechanism and vector for the vertical transport of nutrients onto the shelf from deeper colder waters. Upwelling is discussed in greater detail in Section 8, below.

Numerical modelling of broad-scale circulation and mixing patterns over the North West Shelf has recently been conducted by CSIRO Marine Research, as part of the North West Shelf Joint Environmental Management Study (Dr Scott Condie, CSIRO, pers. comm.). Preliminary model results suggest that, on a regional scale, shelf currents connect the reef environs of Ningaloo Reef with those of the Dampier Archipelago/Cape Preston and Montebello/Barrow Islands regions. The simulated release of neutrally buoyant particles (representing larvae) suggests that Ningaloo Reef may act as a source for recruitment to the northern reefs during summer and as a sink for recruitment from the northern reefs during autumn. Typical travel times between Ningaloo Reef and these other reef areas are predicted to be in the order of tens of days.

Another current oceanographic study relevant to the region is that of Ms Mun Woo, who is undertaking a doctoral study of broad-scale re-circulation off Point Cloates through the Department of Civil Engineering, University of Western Australia under the supervision of Associate Professor Charitha Pattiaratchi.

7 LAGOONAL CIRCULATION AND MIXING

To date, the most comprehensive investigations that have been completed on the hydrodynamics of the lagoonal waters of Ningaloo Reef are those of Hearn et al. (1986) and Sanderson (1997; 2000), and the following descriptions are based on these studies.

Hearn et al. (1986) concluded that the circulation and transport of the park’s lagoonal waters are dominated by wave-pumping of water over the reef tract, with the tides providing a modulating effect on the mean wave-induced circulation. This is driven by the regular breaking and shoaling of waves along the barrier reef and associated set-up of water, which creates a sea level gradient directed into the lagoons from the ocean. The regular action of incident swell sets up an almost constant elevation of the water surface against the oceanic reef front. This drives what Hearn et al. (1986) reasoned to be a persistent flow
of water over the reef crest into the lagoon, the dynamics of which being described principally by a force balance due to the effects of the pressure gradient (due to the surface slope) and bottom friction. Under this process, most of the water flux into the lagoonal areas occurs across the reef, with outflows concentrated through the many gaps that punctuate the reef.

Figure 9 presents a schematic, adapted from Hearn et al. (1986), which presents the main flow patterns inferred for lagoon and adjacent reef areas.

The water level slope that is set up against the reef is not present through the gaps due to their relatively deep profile. Hence, by contrast, the mean water level in the gaps is lower than that in the lagoons and as such these sites carry the lagoonal outflow, in balance with the flow that is entering via the reef crests.

Once having crossed the individual reef segments, oceanic water fans and spreads symmetrically, running along the shore-parallel channels of the lagoonal regions before exiting as jets through the gaps. There appears to be a preference for flow nearer the shoreline to flow northwards, consistent with the slightly oblique nature of the incident swell (i.e. originating from the south-southwest) and with the generally south-southwesterly nature of relatively strong sea-breezes over the area.

Hearn et al. (1986) calculated that wave-pumping induces currents of between about 0.1 and 2 m s⁻¹ throughout the Ningaloo lagoonal systems. Hearn et al. (1986) concluded that flows over the reef crests may attain speeds of up to about 0.5 m s⁻¹, and that typical flow speeds in the lagoons and lagoonal channels are between about 0.1 and 0.5 m s⁻¹. Outflows through the gaps between reef segments were estimated to have characteristic speeds of up to 1-2 m s⁻¹ during high spring tide.

The estimates given for typical current speeds in the marine park lagoons by Hearn et al. (1986) are consistent with current measurements made by Sanderson (1997; 2000) within and in the vicinity of Turquoise Bay and Winderabandi Point. For these sites, Sanderson (1997; 2000) found that waves and tides were both significant in driving currents, with prevailing south-southwesterly winds and seabreezes responsible for imposing a net northward drift on the nearshore circulation for much of the time.

The ‘fanning’ or approximately symmetrical nature of the water that flows over the crests and through the lagoons is also exemplified by grooves (visible in aerial photographs) that are shaped by the flow at the bed of the lagoons, as highlighted by Hearn et al. (1986). Hearn et al. (1986) refer to these grooves, or ‘lines’, as representing long-term averages of bottom current trajectories.

Tides modulate the strength of the wave-induced circulation but are not effective in changing the overall flow patterns to any great deal. A major effect of wind appears to be the regular stirring of the water column via surface mixing, thereby precluding the formation of any regular or sustained stratification in temperature, salinity (and therefore density) within the lagoons, a feature that is otherwise often a characteristic of less energetic semi-enclosed coastal embayments. Generally, wind-driven advection within the lagoonal areas does not dominate wave-induced circulation. However, close to the shore and at the water surface the wind may have its most pronounced effect in superposing a downwind flow pattern on the mean circulation of the lagoon.

Furthermore, in terms of vertical mixing, Hearn et al. (1986) suggest that the relatively strong mean currents in the lagoons would be sufficient in their own right to lead to bottom-induced mixing of a sufficient intensity to completely mix the water column on a regular basis.

Hearn et al’s (1986) and Sanderson’s (1997; 2000) general conclusions on the mean circulation patterns for the Ningaloo Reef lagoonal waters have been confirmed by recent intensive field and modelling studies undertaken during December 1997 by AIMS, with field support from CALM, in the Vlamingh Head area (see AIMS 2000; Massel and Brinkman, 2000a, b). A comprehensive suite of oceanographic instruments
were deployed over 14 days, including fixed point current meters, acoustic doppler current meters, wave-rider buoys, water level gauges, drifter-drogues and meteorological stations. The aim was to investigate all significant short-term oceanographic processes that occurred in and influenced the study region. The study region was selected as typical of much of Ningaloo Reef: a series of barrier reefs running parallel to the coast punctuated by deep, narrow channels, separated from the coast by wide lagoons open at both north and south ends. Massel and Brinkman (2000a, b) found that wave-pumping over the reef crest was the dominant forcing which drove mean circulation in the system, as previously suggested by Hearn et al. (1986). Furthermore, the current meter data showed little evidence of inflow into the lagoon other than flow over the reef crest due to wave-pumping. Mean flow through the lagoon was similar to that described by Hearn et al. (1986). Throughout the 14-day survey the wind blew mainly from the south-southwest, at speeds generally greater than 10 knots, as is typical for the region in December. The wind was found to have only a minor influence on the mean wave-induced circulation.

The drogues deployed in the gaps indicated that upon exiting through the gaps, some of the lagoonal outflow peeled off from the lateral reef edges, forming re-circulating vortices, which curled back in towards the main reef tract to again become part of the wave-induced inflow over the reef. However, a significant amount of the outflow moved out to sea. Hence, depending on the time of year, the outflow would presumably become entrained in the strong southward (autumn/winter) or northward (spring/summer) coastal currents, known respectively as the Leeuwin and Ningaloo Currents.

In terms of flushing, Hearn et al. (1986) calculated that the net effect of waves, tides and winds results in typical residence times for the lagoonal waters of about one day or less. Hearn et al. (1986) calculated that wave-pumping would induce flushing times for typical lagoonal regions of order 6-12 hours, with tidal forcing capable of flushing the lagoons in 2-5 days and wind-induced currents capable of flushing the lagoons in 1-1.5 days. All of these estimates are based on mean forcing conditions and hence the estimates will change according to the relative strengths of the forces involved.

The hydrodynamic effects of salinity, temperature (and hence, density) gradients throughout the lagoons of Ningaloo Reef and between the lagoons and adjacent ocean are yet to be investigated in detail. It is however evident from the results of opportunistic salinity-temperature surveys conducted in Ningaloo Marine Park (see Figures 12 and 13, referred to in Section 8) that significant lagoonal and cross-shelf stratification in these parameters may be characteristic of the area. This introduces the possibility that density gradients may have an influence on vertical mixing and on exchange between the lagoons and adjacent ocean. For example, density differential between the lagoons and adjacent ocean could lead to layered exchange through the reef gaps; if the lagoon water were more dense than the adjacent ocean then outflowing lagoon water would tend to flow out as a relatively dense submerged current, with ocean water flowing into the lagoon as a relatively buoyant surface current. Further investigation into the effects of density gradients on lagoonal and cross-shelf circulation, mixing and exchange would be required in order to more fully understand this aspect of the oceanography of the area.

The above estimates for flushing times were derived on the basis of the time it would take for the mean volume of a lagoonal section to be replaced with water from the ocean. These estimates may not be entirely valid for more enclosed pockets near the coast. For example, the salinity-temperature stratification data that is presented in Section 8, below, suggests that pockets of water enclosed by strong shoreline curvatures may have relatively long local residence times as a result of trapping by the topography. This was inferred from the presence of localised maxima or minima in the salinity-temperature fields of these nearshore regions.
8 WATER TEMPERATURES, SALINITIES AND UPWELLING

The most comprehensive temporal and spatial monitoring program of water temperature in the lagoonal areas of the Ningaloo Reef was undertaken by Simpson and Masini (1986). Lagoonal temperatures were recorded at the five localities shown in Figure 10 (Sites 1, 2, 3a, 4 and 5). The lagoonal measurements were complemented by one outer reef channel location (Site 3b). Table 1 presents a summary of the Simpson and Masini (1986) data set. As shown, lagoonal water temperatures ranged from a minimum of 17.8 °C (Site 3a, August) to a maximum of 29.8 °C (Site 5, December).

Simpson and Masini’s (1986) data introduced the possibility of major intrusions of oceanic water into the lagoonal regions of Ningaloo Reef. Hearn et al. (1986) investigated the temperature time series collected in the lagoon during May and December 1985 at Sites 2 and 5, respectively (Figure 10). These data are reproduced here in Figure 11. As shown, major unseasonal falls in lagoonal temperatures occurred during 6–7 December, 19 and 23 May 1985. Simpson and Masini (1986) and Hearn et al. (1986) considered the possible causes for these falls and discounted the effects of in-situ heating and cooling because of the relatively rapid and large changes observed in the temperature. Rather, they reasoned that the most likely cause of the temperature changes was rapid advection of relatively cold oceanic water into the lagoon by wave-pumping on neap tides under strong wave conditions. Neap tides were suggested as optimal times for major incursions because the reef crest is covered with water during the whole of the tidal cycle, in contrast to springs when the sea-water level is near or below crest height during ebbs. In terms of the process which is most likely to have been responsible for bringing the cooler water to the outer reef, Hearn et al. (1986) favored the possible explanation of upwelling generated by the sub-sea shoaling and breaking of internal waves (IW's) on the shelf slope. As Hearn et al. (1986) point out, associated vertical water displacements of up to 30 m have been recorded in breaking internal wave regions over the 100 m contour on the North West Shelf. The existence of IW's over the North West Shelf has been established by past studies (see Holloway et al., 1985; Holloway, 1987). Upwelling off North West Cape is also under current investigation by Burrage et al. (2001).

Opportunistic cross-shelf salinity-temperature profiles were undertaken by D’Adamo (1997) along a transect from Tantabiddi outwards and these data (Figure 12) provide an example of the significant vertical and horizontal salinity and temperature stratification that may exist between the lagoon and adjacent shelf zone.

Such structure would provide the background climate for IWs to form, propagate and break over the shelf. Investigation of the occurrence of upwelling and of its influence on the hydrodynamics and biology of the region is currently under investigation by AIMS (AIMS, 2000; Steinberg et al., 1999; Burrage et al., 2001); Steinberg et al., in prep.) and Steve Wilson (PhD study, University of Western Australia, pers. comm.). Steinberg et al. (in prep.) have analysed current meter records and satellite data (of near-surface chlorophyll concentrations) off Ningaloo Reef and have extended Taylor and Pearce’s (1999) work by providing direct current measurements in the Ningaloo Current off Ningaloo Reef, measured at the same time as the satellite imagery. They identified the formation of a counterclockwise eddy at Point Cloates, and suggest that it is in this region that upwelling occurs, providing the source of cold nutrient rich water which then propagates further north adjacent to the reef as the continuation of the Ningaloo Current.
Table 1: Summary of lagoon water temperatures recorded on the Ningaloo Reef tract during 1985 (reproduced from Simpson and Masini, 1986)

<table>
<thead>
<tr>
<th>Site (ref: Fig 10)</th>
<th>Month (1985)</th>
<th>N (No. of samples)</th>
<th>Mean (°C)</th>
<th>Min-Max (°C)</th>
<th>Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>May</td>
<td>1029</td>
<td>24.4</td>
<td>22.7-26.0</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>May</td>
<td>661</td>
<td>26.1</td>
<td>24.9-27.5</td>
<td>2.6</td>
</tr>
<tr>
<td>3a</td>
<td>Aug</td>
<td>179</td>
<td>20.5</td>
<td>17.8-22.1</td>
<td>4.3</td>
</tr>
<tr>
<td>3b</td>
<td>Aug</td>
<td>29</td>
<td>24.1</td>
<td>23.1-25.1</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>Oct</td>
<td>1339</td>
<td>22.1</td>
<td>20.0-24.1</td>
<td>4.1</td>
</tr>
<tr>
<td>5</td>
<td>Dec</td>
<td>752</td>
<td>25.6</td>
<td>21.3-29.8</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Wilson et al. (2000) have prepared a data report on temperature logger data collected by AIMS and CALM between October 1998 and May 1999 at various sites along a cross-shelf transect from Tantabiddi outwards. This transect comprised the Ningaloo Reef lagoon at Tantabiddi, the adjacent reef slope (oceanic side) and water columns over the 50 m and 100 m contours, respectively. Multiple loggers were deployed in array mode at the 50 m and 100 m sites. At Tantabiddi, the logger (positioned near the bottom) recorded from October 1998 to February 1999, returning a minimum water temperature of 20.2 °C on 19 October 1998 and a maximum of 29.5 °C on 21 January 1999. The near-surface logger over the 50 m contour was positioned 9-15 m below the surface and returned a minimum water temperature of 22.2 °C on 19 October 1998 and a maximum of 30.1 °C on 13 March 1999. The temperature logger arrays were deployed to complement the AIMS oceanographic program (see AIMS, 2000) with the specific purpose of investigating the role of wind stress as an agent that may drive upwelling over the near-shelf zone and, with the aid of the inner lagoon logger, shelf-lagoon exchange during upwelling. These data are currently under analysis by AIMS (Craig Steinberg, AIMS, pers. comm.)

In terms of horizontal salinity-temperature (ST) stratification within the lagoonal regions of Ningaloo Reef, unpublished data are available from opportunistic ST surveys conducted in the Bills Bay area during 31 March 1986 (Hearn et al., 1986) and 8 April 1994 and 29 May 1996 (D’Adamo, 1999). These are reproduced in Figure 13 and show that on all three occasions significant horizontal temperature structure existed. As Hearn et al. (1986) point out, the persistent flooding of oceanic water into a lagoonal system that has time to adjust to the effects of atmospheric heating and cooling can be expected to result in the formation of horizontal temperature gradients. The fact that flushing is not instantaneous will generally result in some degree of temperature differential between the oceanic inflow and resident lagoonal water. Of particular interest however are the localised regions of relatively high salinity/low temperature water evident in the southeast and northeast pockets of Bills Bay from D’Adamo’s (1999) data. The fact that there is salinity structure is of significance because evaporative salinity change can be a slower process than heat transfer, in terms of the equivalent altering of the density of water. This suggests that within areas of strong shoreline curvature, there may be relatively poor localised flushing. Mean lagoonal circulation fields may tend to bypass these areas under certain forcing conditions and, as such, these areas should be given special consideration in assessments or predictions of potential impacts from contaminant inputs.

It is noteworthy in the present context to refer to the major coral mortality event which occurred in Bills Bay during the coral spawning period of late March 1989 (Simpson et al., 1993). This resulted from unusually poor flushing caused by a combination of low swell, weak winds and onshore flood tide during and immediately following mass spawning. This restricted the normal patterns of coral spawn dispersal, leading to a major de-oxygenation event, killing large numbers of fish and other animals. Consequently, widespread loss of live coral cover also occurred throughout Bills Bay, with the greatest mortality in the nearshore regions, where the poorest flushing potential may be inferred on the basis of D’Adamo’s (1999) ST data.
9 CONCLUSIONS

The overall oceanographic picture that has now emerged for the Ningaloo Reef region (Taylor and Pearce, 1999) is one consisting of a persistent inner-lagoonal circulation regime throughout the year, which is driven principally by wave-pumping over the reef modulated by tide and wind effects (Hearn et al., 1986; Hearn and Parker, 1988; Sanderson, 1997, 2000), adjacent to an annually reversing nearshore current system along the shelf break, comprising the southward Leeuwin Current in autumn/winter (Godfrey and Ridgway, 1985; Cresswell, 1991; Pearce, 1991) and northward Ningaloo Current in spring/summer (Taylor and Pearce, 1999).

The counterclockwise eddy emanating from the Ningaloo Current at Point Cloates may bear an important relation with the relatively different diversities and abundances that exist between the plant and animal communities to the north and south of Point Cloates.

The recent advances in the understanding of primary productivity off Ningaloo reef, most likely driven by upwelling, is now being considered as a factor that is possibly related to the annual aggregation of Whale Sharks off Ningaloo Reef. Ongoing biological and oceanographic studies continue to address these issues. The improved understanding that is now evolving on the local and regional hydrodynamics of the region indicates that the temporal and spatial patterns of key ecological processes in the region are likely to be strongly influenced by both local and shelf-scale hydrodynamic processes. A refinement in the understanding of fundamental hydrodynamic processes, along with the associated development of predictive models for such, should therefore form high priority areas for the research and monitoring that is required to underpin effective management of the Ningaloo Marine Park and any proposed extensions.
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FIGURES
Figure 1: Location map of Ningaloo Marine Park and proposed southern extension.
Figure 2

Figure 3  
Schematic of a typical cross-sectional profile through the Ningaloo Reef and adjacent lagoon showing habitats, geomorphology and indicative long-shore water flux magnitudes near Mangrove Bay, as calculated by Hearn et al. (1980). Reproduced from Hearn et al. (1980).
Figure 5

Monthly mean wind vectors at Cape Cuvier at 0900 (solid arrows) and 1500 (dashed), and wind "constancy" (a measure of the persistence of the wind direction) at 0900 and 1500 for 1972-75. Data from the Bureau of Meteorology, Perth, Western Australia. Reproduced from Taylor and Pearce (1999).
Figure 6  (a) Mean monthly percentage of occurrence of swell height for Exmouth Plateau. (b) Mean monthly percentage of occurrence of swell direction for Exmouth Plateau. Based on shipping reports over 1952-77 (Buchan and Stroud, 1993). Reproduced from Scott (1997).
Correlation between measured mean seawater temperatures in the Ningaloo Reef lagoon (from sites shown in Figure 10) and mean weekly sea surface temperatures of the adjacent ocean from satellite imagery (GOSSTCOMP). Reproduced from Simpson and Masini (1986).
Taylor and Pearce's (1999) proposed current mechanisms at Ningaloo Reef operating principally from September until mid-April, showing the Leeuwin and Ningaloo Currents and the re-circulating eddy off Point Cloates. Reproduced from Taylor and Pearce (1999).
Figure 9  Schematic of the main flow patterns believed to operate most consistently at Ningaloo Reef, under the dominant forcing of wave-pumping, as inferred from Hearn et al (1986).
Figure 10  Ningaloo Reef 1985 temperature logger sites of Simpson and Masini (1986). Note, Site 3 represents the general locality of two individual sampling points (Sites 3a and 3b, respectively). Reproduced from Simpson and Masini (1986).
Figure 11  Water temperature time series data from Ningaloo Reef, from logger deployments during May and December 1985 by Simpson and Masini (1986). (a) Point Billie (Site 2, Figure 10). (b) Tantabiddi Creek (Site 5, Figure 10). Reproduced from Simpson and Masini (1986).
Figure 12: Vertical (a) salinity and (b) temperature structure data collected along a cross-shelf transect off Tantabiddi on 7 April 1994. Some sites were projected onto the straight line of the plot, as shown in the inset. Adapted from D’Adamo (1997).
Figure 13: Selection of horizontal temperature and salinity fields collected in the Bills Bay area. (a) Temperature (at unspecified depths) on 31 March 1986 (reproduced from Hearn et al. 1986). (b) Bottom temperatures and (c) bottom salinities on 8 April 1994 (reproduced from D’Adamo, 1999). (d) Bottom temperatures and (e) bottom salinities on 29 May 1996 (reproduced from D’Adamo, 1999).
Site location
(to within ~ 100m)
25-9-96
Isohalines (ppt)