PHYSICAL OCEANOGRAPHY OF THE CAIRNS SECTION OF THE GREAT BARRIER REEF MARINE PARK, IN THE CONTEXT OF COTS OUTBREAKS

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Executive Summary

This report surveys the physical oceanography of the Cairns Section of the Great Barrier Reef Marine Park, against a background of the potential influences of the current regime on the Crown-of-Thorns Starfish phenomenon. The various field studies which have been carried out on the shelf, as well as relevant work in the adjacent Coral Sea, are discussed and evaluated. Also treated are a number of theoretical and numerical modelling studies of the current regime.

The ongoing COTS surveys point to a recent but continuing upsurge in the numbers of starfish in the northern portion of the Cairns section. The raises the question of whether such populations are a likely precursor of further COTS outbreak episodes. The last outbreak stimulated considerable research on the COTS phenomenon, a novel aspect of which was the combined role played by physical oceanographic field studies and numerical modelling.

The models of Dight and co-workers at that time linked larval transport processes with the currents on the continental shelf, and demonstrated the general southward trend of successive COTS outbreaks. In addition, they suggested that the prevailing dynamics in the present area of starfish activity may act to sustain low-level, non-outbreaking populations in this region. Further modelling work by Black and Burrage has revealed the variability in the extent of larval transport, due largely to the influences of the East Australian Current on continental shelf circulation.

Improvements in computational facilities now allow these early models to be upgraded in a number of ways, through increased spatial resolution, improved model physics and particle release strategies, and the assimilation of real data into the process of model forcing. Such advances need to be accompanied by the acquisition of improved data sets, so that the models can be more comprehensively verified against physical reality. However, the disappearance of large COTS numbers throughout the Great Barrier Reef has been mirrored by a reduction in research support, which now needs to be redressed. The only available long-term current observations come from the TEACS current mooring array. This has provided invaluable information about oceanic influences on the continental shelf edge and slope, near the northern and southern extremities of the Cairns section. Apart from several current measuring programs discussed in this report, which were set up independently of TEACS, no correspondingly long-term data on currents have been collected on the inner and middle shelf. Such data are crucial for a proper quantitative evaluation, calibration, and further refinement of the various numerical models. This would enhance their use in COTS larval transport modelling and in related studies, and thereby develop their potential use for management decision-making in the Great Barrier Reef Marine Park.

A key feature influencing low frequency ('mean') currents in the GBR Region is the position at the shelf edge of the bifurcation point for the inflowing South Equatorial Current, where it separates into the East Australian Current and the northward flowing Hiri Current. This generally tends to be located in the northern part of the Cairns section, but its position also exhibits considerable variability. The relationship between the bifurcation and other physical factors (e.g., winds, oceanic current regime, and other influences such as ENSO), quite apart from the possible effects on shelf currents and larval transport processes, is essentially unknown. The situation in the Cairns section contrasts with that in both the neighbouring sections, Central and Far Northern, where much more relevant research has been effected. An improved understanding of the region's circulation will require a more concerted effort than has been made to date, not only in data collection and analysis, but also in various types of numerical modelling.

1. Introduction

The Cairns Section of the Great Barrier Reef Marine Park (GBRMP) is characterised by a continental shelf of relatively uniform width, as seen in Figure 1. Reefs are found along the full extent of the central to outer lagoon. In the northern half of this section, the shelf edge is delineated by an almost unbroken line of ribbon reefs, stretching north from around Opal Reef, offshore from Cape Tribulation. In this respect, it is logical to compare the Cairns section with its neighbour, the Far Northern section, which has many outwardly similar features, at least in its southern portion. In some senses this comparison is necessary, since it will be seen below that considerably more effort has been expended on spatially-extensive physical oceanographic investigations of the Far Northern section than in the Cairns section.

Increasing attention can be expected to focus on the Cairns section, as further information on the numbers of *Acanthaster planci,* the crown-of-thorns starfish (COTS), becomes available from the continuing program of field surveys. In recent years, however, there has been a lull in research activity on the COTS phenomenon, after a considerable effort centred around 1990, under the impetus of funding from COTSREC. This support had arisen out of concerns expressed about the consequences of the second of the two major documented outbreaks, which lasted basically through the 1980s. For a recent review of this and the earlier outbreak, see Johnson (1992) and accompanying papers in the volume edited by him, particularly the discussion of the major COTS surveys, given by Moran *et al.* (1992). Recent such surveys, which have successfully identified the progression in year classes of juveniles, indicate that increasing numbers of COTS are appearing in the reefs of the northern half of the Cairns section (U. Engelhardt, *pers. comm.*).

A major facet of some of the COTSREC-funded research was the identification of the physics of larval transport as a key component in the overall process of propagation of COTS outbreaks in the GBRMP, in a predominantly southerly direction. This work led credence to the much earlier hypothesis of southward-directed COTS movement via larval transport advection, as advanced by Kenchington (Kenchington and Morton, 1976; Kenchington, 1977). Another relevant early work which dealt with larval advection in the GBRMP is that of Williams, Wolanski and Andrews (1984). They used current meter measurements in the Central and Cairns sections (Euston Reef), to identify the potential for low frequency, or 'mean' currents to move larvae over significant distances, in a predominantly longshore direction.

A particular feature of the work funded to date by COTSREC has been the role of numerical hydrodynamic models of regional-scale water movement and their application to larval transport modelling, beginning with the work of Dight, James and Bode (1988). This was followed by further modelling, reported in Dight *et al.* (1990 a,b) and James *et al.* (1990), in which the concept of reef connectivities was developed. This work demonstrated quantitatively the mechanisms by which COTS larvae are advected by (modelled) currents on the shelf, as well as the relevant spatial and temporal scales of the phenomenon. These models were successful, not only in predicting the net southward advection of COTS larvae, but also in identifying the northern half of the Cairns Section as a potential location for sustained low-level starfish populations. Additional refinements to the models have been reported by Dight *et al.* (1993), yet the computational constraints which applied at the time meant that all were limited to using relatively coarse model grids. Further correlations between the results of this modelling and the surveys of Moran *et al.* (1992) are given by James and Scandol (1992). COTS population models have also been incorporated into this modelling framework, as reported in the study of Scandol and James (1992).

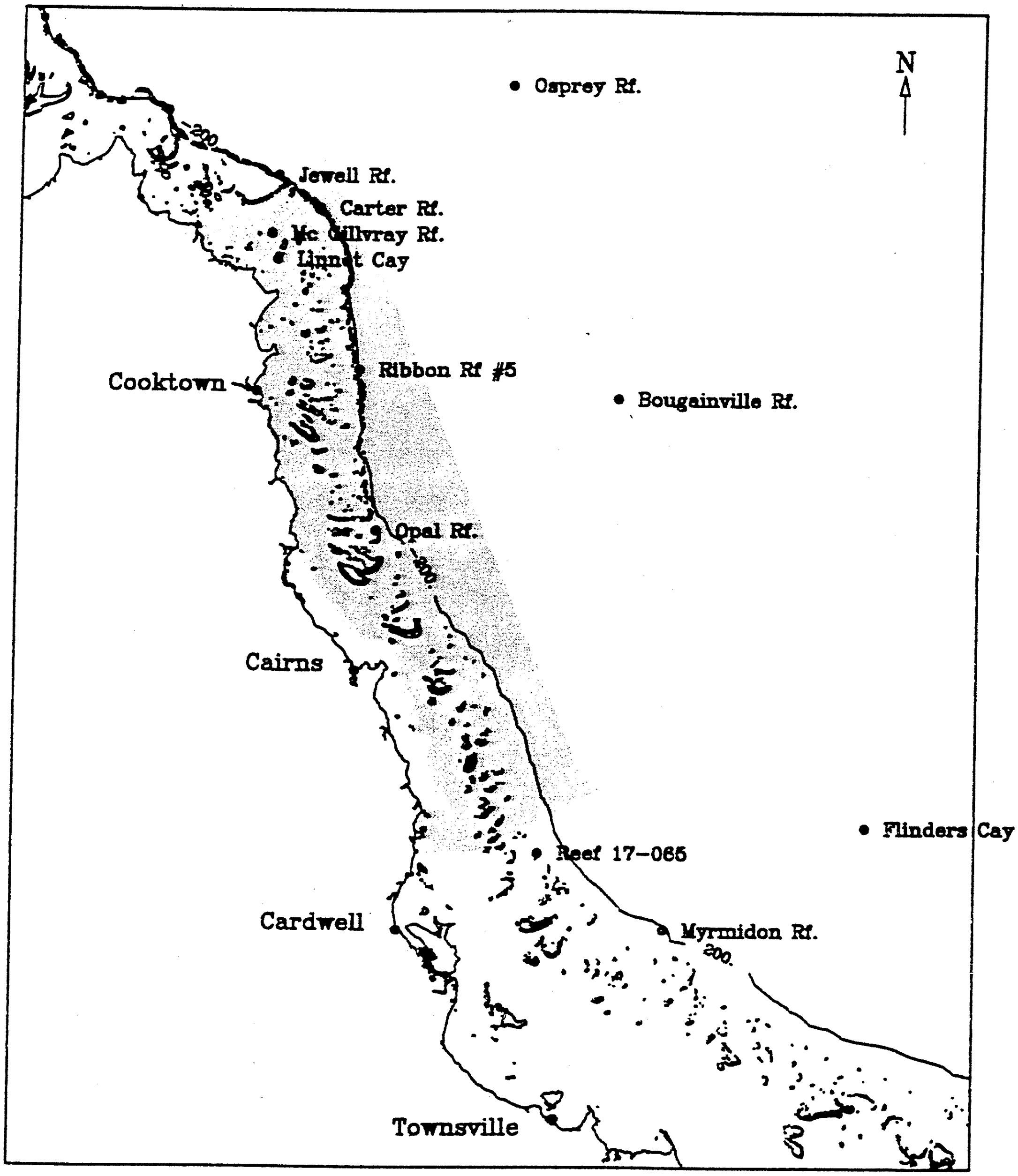

Figure 1. Map of the Great Barrier Reef Marine Park, encompassing the (hatched) Cairns section. Stations at which oceanographic data have been collected (see Table 1) are indicated. The continental shelf edge is denoted by the 200 m isobath.

Most recently, Burrage, Black and co-workers (Burrage, Church and Steinberg, 1991; Burrage, Black and Ness, 1993; Burrage, Steinberg and Black, 1993) have proposed a novel method of hindcasting the low frequency currents, which are responsible for much of the mean transport of water-borne substances within the GBRMP. These so-called 'Linear Systems Models' (LSMs) use optimally-lagged, linear regression procedures, calibrated with current meter measurements on the shelf, and forced by sea level records at Townsville and Noumea, to predict large-scale along-shelf currents in the GBR, historically, over decadal time scales.

Further refinement and testing of all such models will depend crucially on the availability of current meter data within the GBR lagoon. This caution certainly applies to the long-term prediction models of Burrage and Black, mentioned above. These have used data from the Central Section, and need additional information from the Cairns Section, if the same techniques are to be successfully applied further north.

In 1985, J.C. Andrews (AIMS) and J.A. Church (CSIRO, Division of Oceanography) deployed a current meter transect through Magnetic Passage and across the Queensland trough to Flinders Reef. The data from the continental shelf and upper slope (Morrow and Andrews 1986) was analysed by Burrage, Church and Steinberg (1991) to determine the underlying dynamics of the alongshelf flows. The results confirmed that the along-shelf currents are essentially in geostrophic balance, so that the across-shelf sea level slope can be used as an estimator of along-shelf current flow. The data were later used by Black, Burrage and co-workers to develop along-shelf current prediction models for COTS larval dispersal studies (e.g., Black *et al.*, 1993, 1995).

Since 1987, AIMS (Burrage *et al.*, 1995) has maintained TEACS, an array of current meters and tide gauges, focussed on the upper slope and outer shelf of the Cairns Section. On the Cairns shelf itself, a limited number of measurements of currents have been made in specific locations, as discussed below in Sections 2.1.1 and 2.1.2. Apart from the far-sighted TEACS experiment, however, there have been no systematic, long-term current measurements on the Cairns shelf or slope, which could be expected to provide detailed information about the spatial and temporal structure of the circulation. In particular, an understanding of how the East Australian Current (EAC) affects the strength and spatial structure of currents on the shelf is completely lacking. A key factor in understanding the effects of ocean forcing on the shelf is the location of the surface bifurcation of the inflowing South Equatorial Current (SEC) and the resulting influences on shelf circulation. Evidence from numerical models and available data (Hughes 1993) suggests that the bifurcation point varies seasonally and inter-annually (as well as vertically!), and is strongly dependent on the ENSO cycle.

2. Review of Existing Research

Relatively few field experiments have been conducted in the Cairns Section to measure currents. Of these, it appears that only three have produced current records of significant duration (i.e., of the order of months or longer). These are the measurements of Frith, Leis and Goldman (1986), several investigations in the vicinity of Green Island, and the long-term measurements from the TEACS array. All three are discussed below. Apart from this, any further conclusions about the physical oceanography have to be inferred at present from the more extensive studies in the Far Northern section or from oceanic measurements within the Coral Sea.

2.1 Work in the Cairns section

2.1.1 Frith, Leis and Goldman (1986)

Frith *et al.* (1986) reported on the deployment of two Aanderaa current meters at three stations between Lizard Island and Carter Reef, during 1981 and 1982. One meter was deployed for a total of two years, although there were several gaps in the records due to instrument servicing. A second meter was deployed for one year, close up against the leeward edge of Carter Reef, and in the second year another lagoonal station was occupied (similar data gaps also). The major findings were as follows. In the trade wind season (March–September) the non-tidal motion was strongly coherent and in phase with the measured winds. Advection of particles by this current field would largely be alongshore (along the isobaths), with little cross-shelf motion. This is the same as the findings presented by a number of analyses of data collected in the Far Northern section of the GBRMP (Wolanski and Thomson, 1984; Middleton and Thomson, 1985; Cahill and Middleton, 1993). That is, the wind-driven circulation is mostly directly forced, with little evidence of the presence of continental shelf wave motions, as described by Wolanski and Bennett (1983) for the Central section. In the monsoon period (October to February), by contrast, currents are noticeably more variable, and cross-shelf excursions can be considerable. Finally, they noted that their general observations indicated that, during the measurement period, the direction of ocean currents outside the ribbon reefs was to the north.

2.1.2 Green Island current measurements

As part of a study commissioned by the Great Barrier Reef Marine Park Authority (GBRMPA), Stevens, Hatton and Black (1992) analysed sea level and current data recorded near Green Island (27 km NE of Cairns), during deployments in June, 1991 and from late November to early January, 1992. The early deployments involved two S4 current meter sites adjacent to the western edge of Green Island Reef (one close to the sewage outfall) and one in 33 m of water west of the Reef (see Table 1 for deployment details). The later deployments repeated the deeper site and included a new site in 33 m of water between Green Island and Arlington Reefs. All current meters were deployed within 1.5 m of the sea bed. The working paper cited above describes the processing and shows plots of the tidal and low-frequency current data. Burrage *et al.* (in preparation) have developed linear systems models using the records from the two deep sites. These models can be used to produce estimates of long-term currents at the sites based on the Townsville minus Noumea sea level difference used by Burrage, Black and Ness (1993). The resulting model parameters were comparable to near-shore and reef matrix sites located in the central GBR. The accuracy and precision is somewhat compromised by the relatively short duration of the records (a maximum of 44 days), but could be improved with additional deployments, or possibly by using Cairns sea level records, as a predictor. A more detailed analysis of the actual current response to meteorological and oceanographic conditions at the time of deployment is desirable to maximise model skill.

Further current data have been collected off Cairns (north west of Green Island) as part of the dredging study conducted for the Cairns Port Authority (Connell Wagner 1993). Several of the records are of many months duration, with one lasting for almost 11 months. To date, there has been no reporting of these data in the public domain.

Elsewhere, Wolanski and Bennett (1983) and Williams *et al.* (1984) report on currents measured near Euston Reef. However, the location of this current meter, which was hard up against Euston Reef, makes it difficult to infer the strengths of currents in the Lagoon

Table 1. TEACS Current Meter Moorings and Tide Gauges
Depths are instrument depths (or water depth where under a line)

Location	Lat S Lon E	Start/ Finish Date	Time Intvl	Depth (m)	Parameters Recorded			
	ddd mm	mm/yy	min		Curr Sp	Curr Dirn	Water Press	Water Temp
			Current Meter Moorings					
Myrmidon Rf.	18 13 147 21	10/86	60	25 50 75 150 200	*	*	*	*
Jewel Rf.	14 21 145 21	8/87	60	30 80 352	*	*	*	*
			Tide Gauges					
Myrmidon Rf.	18 16 147 23	10/88	60	12	-	-	*	*
Flinders Cay	17 44 148 26	10/88	60	9	-	-	*	*
Osprey Rf.	13 53 146 33	10/88	60	9	-	-	*	*
*Bougainville Rf.	15 30 147 07	10/88 -07/89	60	4	-	-	*	*
*McGillvray Rf.	14 39 145 19	10/88 -07/89	60	6	-	-	*	*
Carter Rf.	14 31 145 34	10/88	60	9	-	-	*	*
Linnet Cay	14 47 145 21	10/88 -10/91	60	6	-	-	*	*
Ribbon Rf. # 5	15 21 145 47	10/90	60	8	-	-	*	*
Opal Rf.	16 11 145 53	10/90	60	8	-	-	*	*
Reef 17-065	17 52 146 44	10/90 -3/93	60	20	-	-	*	*

* Record terminated at Finish Date shown.

proper. As pointed out by Frith *et al.* (1986), their instruments at mid-lagoonal moorings gave far more valuable data than their deployment located right against Carter Reef.

2.1.3 TEACS

This array (Table 1, Figure 1), designed to monitor Transport of the East Australian Current System (TEACS), commenced with the deployment by AIMS of a slope water mooring at Myrmidon reef (19°S) in October, 1986. This re-occupied one of the sites used during the Cross Shelf current mooring transect in 1985 (Morrow and Andrews, 1986). TEACS was expanded to include a second slope water mooring off Jewell Reef (15°S) in the northern GBR in April 1987. The two TEACS current meters located at Jewell and Myrmidon Reefs lie just outside the northern and southern bounds of the Cairns Section, respectively (see Figure 1). Tide gauges (mostly Aanderaa, model WLR4) were deployed at new locations near the coast, at the shelf break and on off-shelf reefs in October 1988 and again in October 1990. Since most locations are paired with permanent State Government installations at the coastline, along-shelf geostrophic current fluctuations can be estimated. The array, which spans the bifurcation region of the SEC in the central GBR, thus comprises two current moorings measuring current and temperature at 2 or 3 levels and six sub-surface pressure gauges distributed along the inner and outer shelf, and further offshore. Data from these instruments have been used to develop linear systems models of along-shelf currents for correlation with Crown of Thorns Starfish outbreaks (Burrage *et al.*, 1991, 1992; Black *et al.*, 1992; Black *et al.*, in preparation) and presently provide ground-truth data for AIMS radar altimeter studies of sea surface heights and currents using the ERS-1 and Topex/Poseidon satellites. Continuation beyond 1995/96 is contingent upon availability of funds from AIMS appropriation and external sources such as the CRC Reef Research Centre. The array is presently being expanded to include two shelf moorings. Longer-term plans involve the addition of real-time telemetry of data, should funding become available.

The TEACS array is designed to monitor seasonal and inter-annual changes in the EAC: see Figure 2, showing (a) along-slope current at Jewell Reef, (b) along-slope current at Myrmidon Reef, both for the years 1987–1991 inclusive, and (c) the along-shelf current predictions for the corresponding period. The array also provides sea-truth data for radar altimetry data from the ERS-1, ERS-2 and TOPEX/Poseidon satellite missions. The altimetry-derived sea levels are being used to determine long-term currents in the Coral Sea.

The Jewell Reef mooring reveals the seasonal and inter-annual fluctuations in the location of the bifurcation, which for near-surface waters (order 50 m depth) occurs, on average, close to the position of the mooring at Latitude 14°S. Influences on shelf circulation in the Cairns section remain speculative at the moment, although the situation is clearer further to the south where the equally long Myrmidon Reef record shows a correlation with the linear systems model predictions of along-shelf current (see Figures 2b and 2c, which give Myrmidon Reef currents and the LSM prediction for same period). Both the observations of slope currents and the along-shelf current predictions show that strong northward flows occurring prior to ENSO events are followed by a relatively rapid transition to strong southward flows in the late stages of the events. This pattern is not, however, uniquely related to ENSO, since it has also occurred on a few occasions during non-ENSO years.

In 1991 AIMS provided a permanent site at Cape Ferguson for a National Tidal Network, Precise Sea-level monitoring station. The National Tidal Facility at Flinders University maintains the gauge, and data is captured via a dedicated phone line. An older

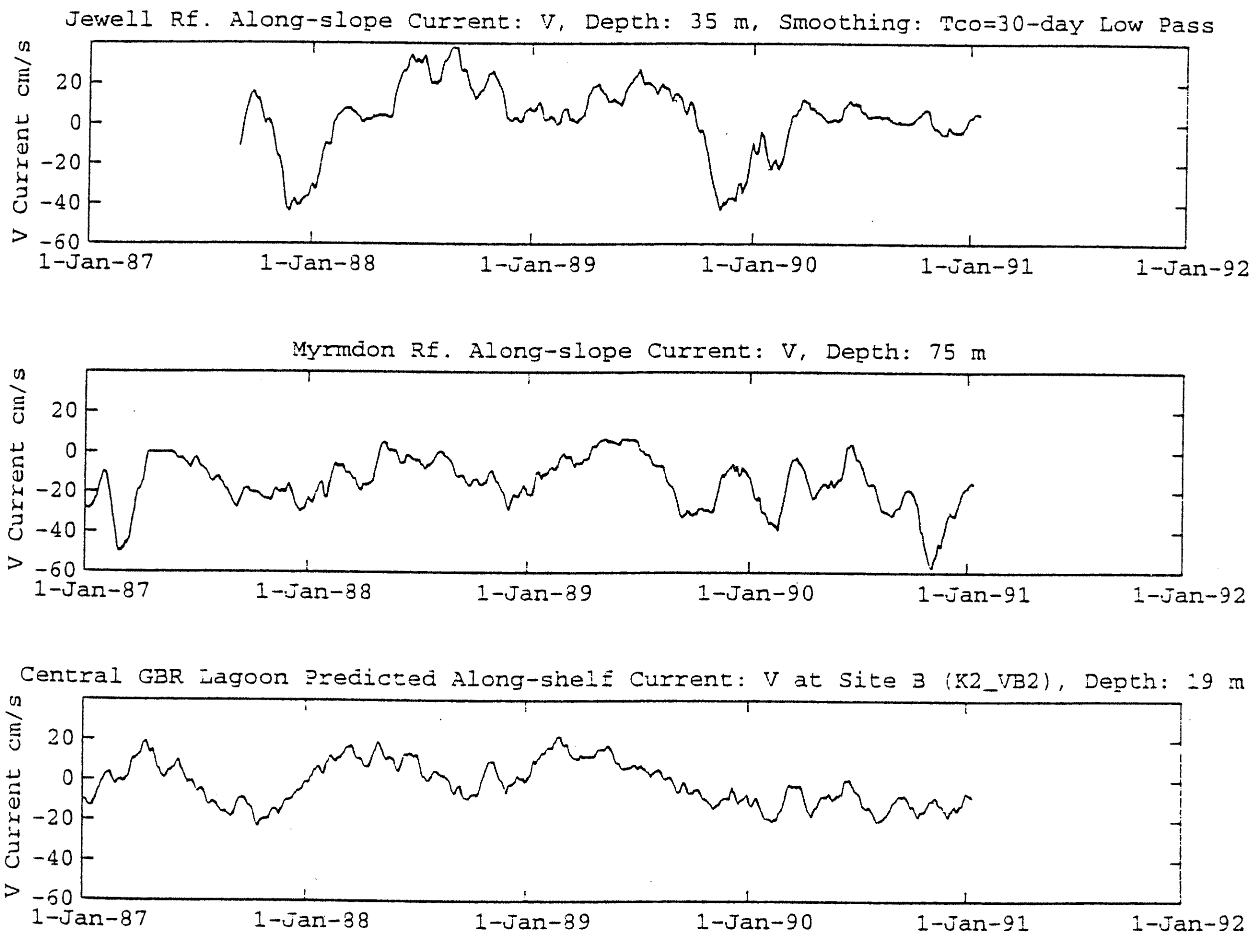

Figure 2. Time series of alongshore currents at (a) Jewell Reef and (b) Myrmidon Reef. In panel (c) are shown the corresponding predictions at Myrmidon using the Linear Systems Modelling methodology discussed in the text.

gauge maintained by the Queensland Department of Transport has operated continuously at Cape Ferguson since April 1984. Using differential Global Positioning System techniques, a high-precision tide gauge could be installed and levelled at Myrmidon Reef. The resulting data could be input to existing linear systems models to produce real-time along-shelf current estimates at selected locations across the continental shelf.

2.2 Work in the Far Northern section

Cahill and Middleton (1993) describe the results of an extensive field study spanning the Far Northern Section of the Great Barrier Reef from Linnett Reef (15°S) to Wyborne Reef (11°S). Although this excludes the major portion of the Cairns section, the results of the data analyses and the inferred dynamics are of interest for comparison and contrast; indeed the region might provide a useful dynamical analogue of the Cairns section. The instrument array, which was deployed from April to October, 1982 consisted of 14 current meters, 9 pressure gauges, and 2 weather stations. Incidentally, this gives an indication of the level of commitment to field observations which might be necessary in order to develop an adequate understanding of the dynamics of the Cairns section. The data was subjected to time series and frequency domain analysis and were compared with the results of an analytical model of the shelf response to local and deep ocean forcing conditions. The analyses and model showed that the currents on the relatively shallow, flat shelf are dominated by the local alongshelf wind forcing and by enhanced bottom friction. By contrast, sea level fluctuations, which were coherent over the entire shelf, were most strongly influenced by inviscid geostrophic flow in the Coral Sea, outside the reef. The study thus bears directly on the issue of the comparative extent to which deep ocean forcing and local forcing determine the physical processes on the shelf which may influence the development of COTS outbreaks.

2.3 Studies in the Coral Sea (East Australian Current)

Church and Boland (1983) and Church (1987) reported on currents measured outside the shelf on cruises of the *R.V. Sprightly* during 1980 and 1981. Note that these currents were computed indirectly by the geostrophic (hydrographic) method, using profiles of the measured water density. This work was mostly concerned with the large-scale structure of the EAC and the location of the surface bifurcation. Church (1987) reported that the bifurcation appeared to be located at around 18°S during the measurement period, but moved north to around 14°S during summer. Whether this phenomenon is characteristic of periodic large-scale changes in the oceanic circulation requires analysis of satellite altimetric data for a more definitive conclusion. The numerical ocean modelling of Hughes (1993) also showed some fluctuations in the surface location of the bifurcation when seasonal forcing was applied, but the magnitude of this modelled change was smaller than that suggested by Church.

2.3.1 *R.V. Franklin* cruises

Three cruises relevant to the physical oceanography of the GBR Region were undertaken in the Coral Sea by AIMS, using the *R.V. Franklin,* in 1988, 1990, 1991. These were a follow-on from an earlier 1986 cruise, reported by Andrews and Clegg (1989). The primary aims were to investigate the oceanic circulation adjacent to the GBR and in the Gulf of Papua. Currents were mainly measured by the geostrophic method using CTD sections. These were supplemented by direct measurements in the upper water column, using a ship-mounted Acoustic Doppler Current Profiler (ADCP). Links with modelling by Hughes (1993) will be taken up below in the discussion of numerical modelling.

2.4 Other related studies

Wijffels (1986) analysed low-frequency sea level data from 6 sea level stations ranging from Mourilyan and Cooktown in the Cairns section through to Port Moresby, Alotau and Lae in Papua New Guinea, for the period October 1984 to December 1985. The purpose of the study was to determine the factors influencing the forcing and propagation of coastally trapped (Kelvin and continental shelf type) waves, and the degree to which the waves were blocked by the relatively dense patches of reef east of Torres Strait. Time series correlation and spectral analyses showed that low-frequency sea level oscillations between Mourilyan and Cooktown were highly coherent with the along-shore wind stress for periods longer than about 8 days, with modest coherence at shorter periods. These waves were found to propagate freely across the entrance to Torres Strait and around the Gulf of Papua where local wind forcing no longer influences the waves. The results of the study appear to be at variance with the hypothesis by Wolanski and Ruddick (1981), that the dense patch of reefs mentioned above should block current flow and hence any incident coastally trapped waves. The author mentioned a possible explanation that the sea level variations observed are associated with deep-water waves propagating unrestricted by reef-induced friction along the continental slope. The results of the measurements and modelling of Cahill and Middleton (1993) may suggest a resolution of this seeming paradox, in that the sea-level signal penetrates the reef matrix, while the current field does not. The implications for the Cairns section appear to be that the local wind forcing might be expected to dominate the current field, while the East Australian Current will more strongly influence low-frequency sea levels.

2.5 Upwelling

Thompson and Golding (1981) describe measurements of tidally-induced upwelling of nutrient-rich waters, in narrow inter-reefal gaps in the Cairns section. They also provide a theoretical description of the phenomenon, and determine the current speeds needed for upwelling of colder, more saline waters from below the thermocline on spring flood tides. The upwelling results from Bernoulli suction, generated by the strong cross-shelf tidal flow through passages between the reefs, adjacent to the shelf edge. While of interest to the overall oceanography of the region (and clearly of biological significance), this type of motion is limited to the immediate vicinity of reefs, and does not impinge significantly upon the issue of regional-scale advection.

The analytical model of Nof and Middleton (1989) provides a new perspective on the question of deep ocean forcing by showing that a geostrophic boundary current, such as the EAC, fluctuating at low (i.e., subtidal) frequencies may influence flows inside the barrier formed by the Ribbon Reefs in the Cairns section of the GBR. Their model, which is strongly nonlinear, is dependent on sea level differences between the boundary current and the outer shelf. This drives a strong flow through the passages, at sub-tidal frequencies. This diversion of the main stream, which comprises cooler nutrient-rich water upwelled from the main thermocline, would subsequently hug the inner wall of the barrier due to Coriolis effects. It would thus flow along the inside of the outer barrier with the barrier on its left (in the southern hemisphere). Hence, the EAC, which has been shown by Burrage *et al.* (1995) to originate near the latitude (14°S) of Jewell Reef, could periodically drive a boundary current southward inside the ribbon reefs. Circumstantial evidence for such a phenomenon was provided by the authors in the form of a satellite-derived chlorophyll image which suggests the presence of nutrient-enriched waters, inshore and south of the major reef passages.

This phenomenon, which the authors refer to as 'geostrophic pumping' is distinct from, and contrasts with, the tidally-induced upwelling mechanism of Thompson and Golding (1981). Because geostrophic pumping acts at low frequencies governed by the longer time scales of the EAC, its effects will predominate during neap tides and may be felt at much larger spatial scales, and certainly on longer time scales than that generated by Bernoulli suction. In other areas of the GBR, notably the Central section, marked cross-shelf excursions of nutrient-rich oceanic waters have been observed and discussed by Andrews and Gentien (1982) and Andrews (1983). In this case, these cross-shelf movements were strongly correlated with measured fluctuations in the EAC. Elsewhere, Wolanski (1986) has proposed that in the Central GBR, where no dense line of ribbon reefs exists at the shelf edge, fluctuating longshore winds could also induce upwelling.

3. Numerical Modelling

3.1 Models of Dight and co-workers

In this work (Dight *et al.,* 1988; Dight *et al.,* 1990 a,b; James *et al.,* 1990), currents were generated by three modes of forcing: winds, tides and the on-shelf signal associated with the EAC, which flows along the shelf edge of the GBR. In the absence of specific current meter data on the Cairns section of the shelf, these models make certain simplifying assumptions about the strength and structure of the EAC and its effects on shelf currents. In spite of these simplifications, the associated larval transport models revealed evidence of a different pattern of currents behind the ribbon reefs in the northern portion of the Cairns section (James *et al.,* 1990). This varied significantly from that exhibited further south, where there was a more straightforward advective transport of particles towards the south.

The philosophy behind the Dight models was based on the desire to determine the most likely trajectories of larvae, in a long-term statistical sense. Multiple particle simulations from a number of release sites were conducted using a Monte Carlo approach. For each 'event', the tides and winds operating at the time were selected randomly, and an overall pattern of particle destinations was built up for each release location – the "connectivity" between source and sink reefs. No attempt was made in this work to determine particle trajectories for any particular set of environmental forcing scenarios. However, Black and co-workers have used this 'hindcasting' approach to good effect – see below.

A key restriction on this early modelling was the lack of powerful computer resources. As a result, several simplifying assumptions had to be invoked. The grid resolution was relatively coarse, and certainly so on the scale of variations in individual reef geometry, at 5 nautical miles (5 nm = 9.2 km). In addition, the dynamics were linearised. Under this assumption, computed current vectors from tidal modelling were added to those from the separate wind-driven flow (using quasi-steady dynamics) and an invariant 'EAC'. While all these points can be criticised, the objective of that exercise was the modelling of COTS, not of predicting currents with extreme precision (which the absence of any suitable field data precluded anyway). Accordingly, the results must be judged on the merits of what was revealed from this modelling, namely the strength and structure of the dominant southward advection, the computation of reef inter-connectedness, and the identification of the northern Cairns section as a possible area of sustained low-level COTS populations.

3.2 Linear Systems Modelling (Black, Burrage and co-workers)

Burrage, Black and Ness (1993) developed a suite of linear systems models which allow low frequency along shelf currents to be specified using readily available meteorological and oceanographic forcing data. These models, which are essentially statistical, nevertheless reflect our understanding of regional hydrodynamics. Using optimally lagged, multi-linear regression, they allow predictions to be made quickly and economically from input time series and a few specified parameters. The models were calibrated using current meter mooring data obtained from a transect across the Central Great Barrier Reef in 1985 (Morrow and Andrews, 1986) and validated using data from similar deployments in 1987 and 1990. The most useful and most accurate models of this type are based on the geostrophic across-shelf momentum balance. Using as input coastal-offshore sea-level differences between Townsville and Noumea, New Caledonia (from 1976), they can be used to predict currents over time spans of up to 15 years with an estimated accuracy (bias) of < 5.0 cm s^{-1}, a precision (standard error) < 10.0 cm s^{-1}, and a forecasting skill (percentage of variance predicted) > 0.7. They accurately respond to fluctuations at weather time scales, and at seasonal and inter-annual scales. Using only Townsville sea level data (from 1966) the models can be used to predict currents for an additional 10 year period (to 1975) with a reduced accuracy of less than 15 cm s^{-1} and a precision < 10 cm s^{-1}.

The predicted currents were used directly by Black, Moran, Burrage and De'ath (1993, 1995) to drive an elementary along-shelf larval dispersal model to show that periods of relatively slow alongshelf currents were associated with the primary outbreaks of COTS which began in 1968 and 1979. They were also used by Black, Gorman and Burrage (1995) to provide boundary conditions for a 4.5 km resolution numerical hydrodynamic simulation model of the central Great Barrier Reef. The assimilation of the 25-year historical current prediction into the model has enabled it to accurately track fluctuations in the intensity of shelf currents, due to changes in the strength of the EAC. The results of the data assimilation model were input into a 2D water quality/larval dispersal model to simulate dispersal of COTS larvae for two particular outbreak years. The runs for the 1978 and 1982 COTS spawning periods showed a contrast between the effects of relatively weak flows and self-trapping by reefs of the 1978 primary outbreak year, and the relatively fast currents and secondary outbreak dispersal occurring in 1982. Further runs of this hydrodynamic model at a resolution of 2.25 km are planned, but are subject to availability of funds.

3.3 Shelf-scale hydrodynamic modelling

This has been reported to some extent by both of the groups discussed above (VIMS and JCU). However, the lack of quality field data at sufficient locations has hindered the direct testing of numerical models. The models of Black have largely been applied to the Central section and southern parts of the Cairns section, where more field data have been available (see references cited above). Recently, the JCU group (L. Mason, *pers. comm.*) has developed a 1 nm grid, covering the area shown in Figure 1. Good agreement between observed and computed tidal elevations has been obtained. Tidal current data are less readily available, and no direct comparisons have yet been possible.

3.4 Basin-scale circulation modelling

The only work of significance in this area is that carried out in the thesis of Hughes (1993). Summaries of various aspects of this work have also been reported in Burrage (1993), Hughes *et al.* (1995) and Burrage *et al.* (1995). This modelling work concentrated on the circulation of the Coral Sea, although the model itself was global, in order to overcome problems experienced with open boundary conditions. The value of this work lies not only in the new information which the modelling provides, but also because it was supported by data from the *Franklin* cruises described in Section 2.3.1. The model results show the bifurcation of the SEC near the shelf edge, thus forming the poleward EAC and the equatorward Hiri Current, which flows around the Gulf of Papua. The model and the *Franklin* data (both hydrographically derived and directly measured ADCP currents) show the strong interaction between the inflowing SEC and the topography of the Queensland Plateau. This results in a complex three-dimensional current pattern, particularly in the region of the Townsville Trough. In the near-surface waters, flow is directed to the south – the EAC; deeper into the water column, the water flows northward, thus constituting the undercurrent reported by Church and Boland (1983). There is effectively no low frequency flow through the shallow, reef-studded Torres Strait, although tidal currents are particularly strong in this area.

The $1^{o} \times 1^{o}$ resolution of the global model of Hughes (1993) was insufficient to resolve the continental shelf of the Cairns Section. In fact, the numerical properties of the model used (Bryan-Cox) mean that it was essentially confined to deep-water areas of the ocean. Thus, even in those parts of the GBR where the grid size should be sufficient to resolve the shelf (e.g., off Mackay), no shelf currents were computed. Any effects of the ocean circulation on the shelf remain largely speculative, as they can only be inferred from Hughes' model. Further information on this important problem awaits the development of much higher resolution ocean-shelf models, as well as the acquisition of additional long-term data sets.

4. Oceanographic Characteristics of the Cairns Section.

Based on the above research, a number of features of the oceanography of this region can be enunciated.

4.1 Uniqueness of the Cairns Section

1) Proximity to bifurcation of the South Equatorial Current

This implies that the upper slope and possibly the outer shelf is subject to seasonally-reversing poleward or equatorward along-shelf currents. In the Cairns and Far Northern Sections these may be imposed upon the outer shelf by the East Australian Current (EAC) or by the Hiri Current which recirculates around in the Gulf of Papua, in a manner depending on the season. Works such as Middleton (1987) and Nof and Middleton (1989) demonstrate mechanisms whereby the offshore influences of these ocean currents can be imposed as a pressure gradient forcing on the shelf. The lack of quantitative data on observed fluctuations in the EAC, along with the uncertain role of the GBR reef structure on this transmission mechanism, presently limit our available knowledge of how currents vary across the shelf. This is particularly so in the northern portion of the Cairns section, where increasing numbers of COTS are now being found.

2) Location on a latitudinal N-S temperature gradient

It has been postulated that the Cairns region might attain near-optimum temperature conditions for development and maintenance of COTS populations – see "Water temperature along the Great Barrier Reef during the spawning period of Crown-of-Thorns Starfish", in Black (1992).

3) Relatively dense outer reef barrier and narrower shelf compared with Central GBR

These structural characteristics imply relatively higher friction and lower exchange between Barrier reef lagoon and the Coral Sea, and generally more restricted circulation by comparison with the Central section of the GBR. The studies in the Far Northern section of Cahill and Middleton (1993) in particular, as well as Wolanski and Thomson (1984), show that low frequency currents on the shelf are predominantly forced by direct wind stress, with little evidence of conventional shelf-trapped wave motions which have been reported south of the Cairns section (Wolanski and Bennett, 1983). Cahill and Middleton (1993) have observed that low frequency sea levels in the Far Northern Section are correlated with oceanic signals, in contrast with the currents which are predominantly wind driven.

4.2 Relevant Issues

A number of issues which need to be addressed in the future arise from the above considerations:

1) Degree of penetration of deep ocean influence into the Cairns section.

The degree of penetration of the East Australian Current and Hiri Current, coupled with the prevailing wind direction and strength, will together determine the strength and direction of the seasonal mean flows on the continental shelf. The relative significance of these two influences needs to be determined by use of *in situ* current meter moorings on the shelf and slope, and by use of 3D density-stratified numerical hydrodynamic models. Some exploratory work in this area has recently commenced at JCU, using the DieCAST model of Dietrich and Lin (1994). The plan in this work is to nest a relatively high resolution, stratified domain of the GBR shelf and adjacent Coral Sea, within a global, seasonally-forced model.

2) What physical factors are likely to influence COTS outbreaks?

In the report cited above, Black (1992) lists the physical factors likely to influence COTS outbreaks. These include, for example, low-frequency and tidal currents, sea water temperature and salinity, and turbidity. Of these, the tidal currents can be determined to a satisfactory degree of accuracy, using a combination of existing observations and numerical hydrodynamic models. The same is true in general of the low-frequency currents. However, there is a dearth of current records of sufficient duration on the shelf for reliably estimating model parameters. Surface temperatures can be obtained in principle from the NOAA polar orbiting satellites, although there are difficulties in obtaining enough cloud free images with sufficiently low atmospheric water vapour content, during the monsoon season in the southern and central GBR. In the Cairns section, sufficiently long sequences of such data are generally not available. Surface and subsurface *in situ* temperature observations have been acquired by AIMS at specific locations on the outer shelf, as reported in the companion review by Furnas (1996).

There is an opportunity to correlate the sub-surface temperature variabilities with sub-surface slope water currents, but this has not yet been done. Future effort could usefully be expended in modelling the relationship between sub-surface temperatures, currents and meteorological forcings, but to date such work has also not been undertaken. Turbidity can be observed in an approximate way using the visible channels from the NOAA AVHRR instrumentation, with the proviso again that high levels of cloudiness in the northern region limit the available data volume. Finally, river inflow and *in situ* salinity observations are made routinely by the Biological Oceanography group and by the reef monitoring program at AIMS, as described by Furnas (1996). There is a very real prospect for airborne mapping of salinity at O(10 km) spatial scales using passive microwave radiometer technology which has been developed in the US and elsewhere (Lagerloef *et al.*, 1995). This could allow extreme events such as floods induced by localised cyclone activity to be adequately monitored, even in the presence of cloud (which does not inhibit the microwave signal significantly). However, this capability is yet to be demonstrated in the GBR, and the technology is not presently available in Australia.

3) What time scales of variability are important: turbulence, tidal, weather, seasonal, inter-annual, ENSO, decadal?

The crucial time scales for population dispersal is determined by the pelagic phase or time between spawning and successful settlement. However, conditions experienced over turbulent and tidal time scales, and the daily weather time scales immediately after spawning can strongly determine the spawning success. For example, buoyant materials such as fresh coral eggs congregates into slicks which are moved by the wind and tide (e.g., Wolanski, Burrage and King, 1989), while neutral or slightly negatively buoyant materials (COTS spawn) may be trapped by turbulence in unfavourable substrates. Once mixed throughout the water column COTS and mass-spawning coral larvae are subject to the prevailing wind and pressure-gradient driven currents, the details of which determine the ultimate location at time of settlement. Because seasonal and interannual time scales dominate the current variability spectrum, these time-scales will significantly influence the likelihood of a 'good' or 'bad' spawning season. ENSO and longer decadal time scales also significantly affect variability and introduce the possibility that climatic trends related to such physical variables as sea temperature and freshwater runoff will produce long-term ecosystem change.

4) What are the relevant spatial scales? Do those which are important to the COTS phenomenon operate on the scale of individual reefs, reef complexes (or 'patches'), the outer barrier, continental shelf and upper slope, or the Coral Sea basin?

Again, in the first few days to a week after spawning, the interactions of tidal and wind-driven currents with the local reef or reef patch topography strongly influence the degree of trapping by, or dispersal away from, the natal reef. Given the prevailing along-shelf flow and the barriers to across-shelf transport present in the Cairns section of the GBR, there may be considerable anisotropy in the subsequent dispersal length scales which are much shorter across-shelf O(10 km) than along-shelf O(100 km). Hybrid models utilising linear systems model predictions of along-shelf current coupled with simulated larval dispersal models (Black *et al.*, 1995) show that net larval transport in the along-shelf direction may vary over a range of several hundred km north or south, depending on the particular year. Given the perceived importance of longshore transport of COTS larvae, a key issue is the way in which the northern portion of the Cairns section is connected dynamically to the southern part and thence to the Central and Southern sections of the GBRMP. Immediately to the north of the Cairns section, between Lizard

Island and Cape Melville, the existence of a narrow shelf and the presence of substantial cross-shelf reef structures, suggest a significant hydrodynamic constriction on along-shelf advective processes. In what way, therefore is the Cairns section connected in this direction to the rest of the GBRMP? Questions such as these can probably be resolved only by combining a fairly comprehensive field monitoring program with 3D numerical hydrodynamic current modelling and Lagrangian dispersal modelling effort in an expanded version of the existing regional hydrodynamics project CRC Reef Research Centre, Task 1.2.1.

5) How do physical factors (e.g., currents, sediments, freshwater inflows affecting viability of COTS larvae during spawning events) link with biological processes, likely to be significant in determining the success and evolution of incipient COTS outbreaks?

The timing of periodic (e.g., seasonal) fluctuations and extremes of physical processes relative to that of biological events such as spawning and settling, is crucial to the success of many marine organisms, such as COTS, mass-spawning corals, reef fish, etc. These links can best be explored by a combination of laboratory and field studies designed to isolate singular events or processes, and by the development of coupled physical and biological numerical models which can keep track of and emulate the various interacting factors. This kind of work is very much in its infancy in the GBR region and indeed in the rest of the world. There have been a number of proposals put forward to undertake this kind of work which is relatively expensive and logistically involved, but to date their level of importance has not been matched by the available funds.

6) What physical factors might affect the viability of corals and their susceptibility to COTS attack, e.g., cyclones and associated storm wave attack, elevated temperatures causing bleaching, floods resulting in increased turbidity and decreased salinity, etc.

The discussion of points 4) and 5) is relevant to this question. In addition, it is important to realise that due to their severity and infrequency, such extreme conditions can make dramatic changes to ecosystems and yet present few opportunities to accumulate statistically reliable descriptions of their characteristics and effects. This is true of ENSO events and also applies to the historical COTS outbreaks. We simply have too few realisations to enable an adequate appreciation of various determining factors and their impacts. This highlights the importance of long-term monitoring. It also puts into perspective the importance of developing risk management strategies in the face of such uncertainty. Patience and persistence are essential if a more comprehensive understanding of the relevant scientific processes is to be reached.

4.3 Contrast and Comparison with other Sections

1) The Central section of the GBRMP has a more open reefal structure and a wider shelf. Flows are essentially geostrophic, and strongly influenced at low frequencies by the EAC. In the Far Northern Section of the GBR, currents are frictionally dominated, strongly wind-driven, and more isolated from the influences of oceanic currents by the relatively solid ribbon reef barrier. The characteristics of the Cairns section probably fall between these two extremes.

2) The tidal patterns are essentially straightforward, but with some modifications due to the presence of the reef barriers. The dynamics are closer to those of the Far Northern than the Central section, where the reefs are so sparse that their influence on tidal propagation can largely be ignored (Andrews and Bode, 1988). There are strong

contrasts with the tides of the Mackay/Capricorn section. Here, semidiurnal tidal amplitudes are very large, and the reef matrix plays an active role in the associated amplification process.

5. Conclusions and Recommendations

The main questions of importance have largely been addressed in Sections 4.1 and 4.2. There is presently little understanding, and certainly not of any quantitative nature, of the effects of ocean forcing on shelf circulation in the Cairns section of the GBRMP. The modelling of Dight and others (and now apparent evidence from field surveys) introduces the possibility that the northern portions of the Cairns section may in some ways be hydrodynamically self-contained. The behaviour of any such sub-system, assuming it exists, is likely to be influenced by its proximity to the EAC bifurcation point, and therefore by the seasonal and inter-annual variability of its location. However, such an hypothesis remains speculative at this stage, in the absence of adequate field data. Further to the south of the Cairns section, advection of larvae by low frequency currents is expected to be directed predominantly towards the south. However, the data from TEACS (Figure 2b) demonstrate the inherent variability in the current signal, and show that current reversals do occur.

By analogy with the Far Northern section, wind-driven currents are most likely to be directly forced, especially in the northern half of the section, which is characterised by the almost unbroken line of ribbon reefs at the shelf edge. As a result, modelling of wind-driven currents on a regional scale should be relatively straightforward. Nevertheless, it remains to be seen whether field data, which will need to be obtained simultaneously on the shelf at appropriate spatial and temporal scales, support this contention.

It is the absence of good data sets on currents which constitutes the major shortcoming to an improved understanding of the circulation physics of this region. Numerical models can provide (and have already provided) a much improved understanding of the prevailing dynamics. Indeed, unlike field data, which are usually only available at a few selected locations, models can provide an integrated view in both time and space of all the significant physical influences. The numerical modelling by Dight and co-workers of the spread of COTS larvae, has shown that it is possible to make credible predictions about reef connectivities. It has also suggested that the northern part of the Cairns section may be able to sustain low-level, non-outbreaking COTS populations. Similar statements can be made about the value and successes of the modelling performed by Black and Burrage.

In spite of these successes, however, modelling results will continue to be viewed largely as plausible speculation, unless they can be supported more directly by actual field measurements. In reality, it is asking much of GBR Marine Park managers to base their policies and strategies on the results of modelling, unless such validation can be obtained. This impasse can only be broken by the expenditure of money on a well-planned program of field measurements at strategic locations. An adequately verified model could then be used to explore a far wider range of parameters than is ever likely to be covered by time- and space-limited field experiments. In fact, any sensible planning for risk assessment can only be undertaken by the wise use of accepted models, to explore the wider range of conditions likely to be encountered during extreme and unusual events. At present, the authors plan to conduct limited deployments on the continental shelf of profiling current meters in the Cairns section this year, under Project 1.2.1 of the CRC Reef Research Centre. These data will provide time series which are simultaneous with those collected at the shelf edge under the TEACS program. While clearly an improvement on the present situation, the need for a much wider spatial spread of data collection, and for longer-term time series like those in TEACS, is obvious. The results of the recent surveys in the Cairns section suggest that it is now timely to mount additional investigations into the physical factors that could influence COTS populations and their spread. We recommend that the strategy of amalgamating field-based data collection and numerical modelling be considered more widely as the appropriate methodology for developing a more comprehensive understanding of the dynamical processes influencing larval transport and other important physically-based phenomena in the GBRMP, and their biological and ecological consequences, with a view to ultimately developing predictive skill.

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Appendix 1. Terms of Reference

1. The review should present detailed information on the characteristics of the physical oceanography of the Cairns Section of the Great Barrier Reef Marine Park.

2. The review should compare and contrast these characteristics with other areas or Sections of the Marine Park with a view to identifying any unique features.

3. The review should discuss how these features may influence the development of primary outbreaks of crown-of-thorns starfish.

4. The review should identify any deficiencies in available information relevant to the question of the uniqueness of the physical oceanography of the Cairns Section and make recommendations for any additional work required to address these deficiencies.

References:

Andrews, J.C. (1983) Thermal waves on the Queensland shelf. *Australian Journal of Marine and Freshwater Research,* **34**, 81–96.

Andrews, J.C. and Bode, L. (1988) The tides of the central Great Barrier Reef. *Continental Shelf Research,* **8**, 1057–1085.

Andrews, J. C. and Clegg, S. (1989) Coral Sea circulation and transport deduced from constrained minimisation of modal information models. *Deep-Sea Research,* **36A**, 957–974.

Andrews, J. C. and Gentien, P. (1982) Upwelling as a source of nutrients for the Great Barrier Reef ecosystems: a solution to Darwin's question? *Marine Ecology Progress Series,* **8**, 257–269.

Black, K. P. (Ed.) (1992) The temperatures and water currents of the Great Barrier Reef during Crown-of-Thorns Starfish outbreaks since 1966. Victorian Institute of Marine Sciences, Report to the Great Barrier Reef Marine Park Authority, 55 pp.

Black, K. P., Gorman, R. and Burrage, D.M. (1995) Assimilation of a 25-year historical current prediction in a Central Great Barrier Reef numerical model. *Continental Shelf Research* (in review)

Black, K.P., Moran, P.J., Burrage, D.M. and De'ath, G. (1992) Self-seeding of reefs is implicated as a cause of Crown-of-Thorns Starfish outbreaks. In 'The Temperature and Water Currents of the Great Barrier Reef During Crown-of-Thorns Starfish Outbreaks since 1966', Black, K. P. (Ed.), pp. 19–48. Victorian Institute of Marine Sciences, Report to the Great Barrier Reef Marine Park Authority, 55 pp.

Black, K.P., Moran, P.J., Burrage, D.M. and De'ath, G. (1993) Are the hydrodynamics guilty of causing or stimulating outbreaks of crown-of-thorns starfish on the Great Barrier Reef? In 'The Possible Causes and Consequences of Outbreaks of the Crown-of-Thorns Starfish', Proceedings of a workshop held in Townsville, 10 June, 1992. Engelhardt, U. and B. Lassig (Eds.) Great Barrier Reef Marine Park Authority Crown-of-Thorns Starfish Research Committee. GBRMPA Workshop Series No. 18, pp. 95–102.

Black, K.P., Moran, P.J., Burrage, D.M. and De'ath, G. (1995) Slow currents are associated with crown-of-thorns starfish outbreaks. *Marine Ecology Progress Series,* **125**, 185–194.

Bode, L., Dight, I.J., Burrage, D.M., Hughes, R.D. and Mason, L.B. (1995) Coral Sea Oceanography and Turtle Hatchling Dispersal from Raine Island. Report prepared for the Raine Island Corporation, Brisbane, Australia, 26 pp + appendices.

Burrage D. M. (1993) Coral Sea Currents, The Seas Around Us – Number 3. *Corella,* **17**, 135–145.

Burrage, D. M., Black, K.P. and Ness, K.F. (1993) Long-term current prediction on the continental shelf of the central Great Barrier Reef. *Continental Shelf Research,* **14**, 803–829.

Burrage, D. M., Black, K.P. and Steinberg, C.R. (1994) Long-term sea-level variations in the central Great Barrier Reef. *Continental Shelf Research,* **15**, 981–1014.

Burrage, D. M., Black, K.P. and Steinberg, C.R. (1996) Current variability and prediction at Green Island, in the northern Great Barrier Reef (in preparation).

Burrage, D. M., Church, J.A. and Steinberg, C.R. (1991) Linear systems analysis of momentum on the continental shelf and slope of the central Great Barrier Reef. *Journal of Geophysical Research,* **96**, 22,169–22,190.

Burrage, D.M., Hughes, R.D., Bode, L. and Williams, D.McB. (1995) Dynamic features and transports of the Coral Sea circulation. In Bellwood, O., Choat, H. and Saxena, N. (Eds.), Recent Advances in Marine Science '94. Sixth Pacific Congress on Marine Science and Technology, 4–8 July, Townsville: PACON International and James Cook University of North Queensland, pp. 95–105.

Burrage, D. M., Steinberg, C.R. and Black, K.P. (1993) Predicting long-term currents in the Great Barrier Reef. *Proceedings, 11th Australasian Conference on Coastal and Ocean Engineering,* 23–27 August, 1993, The Institute of Engineers, Australia, National Conference Publication No: 93/4, pp. 573–578.

Cahill, M. L. and Middleton, J.H. (1993) Wind-forced motion on the northern Great Barrier Reef. *Journal of Physical Oceanography,* **23**, 1176–1191.

Church, J.A (1987) East Australian current adjacent to the Great Barrier Reef. *Australian Journal of Marine and Freshwater Research,* **38**, 671–683.

Church, J.A. and Boland, F.M. (1983) A permanent undercurrent adjacent to the Great Barrier Reef. *Journal of Physical Oceanography,* **13**, 1747–1749.

Connell Wagner (1993) Long term spoil dump monitoring associated with Cairns harbour dredging. Report for Cairns Port Authority, prepared by Connell Wagner (Qld) Pty Ltd, 29 pp + Appendices.

Dietrich, D.M. and Lin, C.A. (1994) Numerical studies of eddy shedding in the Gulf of Mexico. *Journal of Geophysical Research,* **99**, 7599–7615.

Dight, I.J., James, M.K. and Bode, L. (1988) Models of larval dispersal within the central Great Barrier Reef: Patterns of connectivity and their implications for species distributions. *Proceedings, 6th International Coral Reef Symposium,* Townsville, Vol. 3, 217–224.

Dight, I.J., Bode, L. and James, M.K. (1990a) Modelling the larval dispersal of Acanthaster planci: I. Large scale hydrodynamics, Cairns Section, Great Barrier Reef Marine Park. *Coral Reefs,* **9**, 115–123.

Dight, I.J., James, M.K. and Bode, L. (1990b) Modelling the larval dispersal of Acanthaster planci: II. Patterns of reef connectivity. *Coral Reefs,* **9**, 125–134.

Dight, I.J., James, M.K., Bode, L. and Stewart, L. (1993) "Modelling approach to hydrodynamics and the large-scale larval dispersal of *Acanthaster planci:* sensitivity analyses". Marine Modelling Unit, James Cook University, Department of Civil & Systems Engineering, Report prepared for the Great Barrier Reef Marine Park Authority, 85 pp.

Frith, C.A., Leis, J.M. and Goldman, B. (1986) Currents in the Lizard Island region of the Great Barrier Reef Lagoon and their relevance to potential movements of larvae. *Coral Reefs,* **5**, 81–92.

Furnas, M. (1996) Biological and chemical oceanographic features of the Cairns-Cooktown region relevant to Crown-of-Thorns starfish outbreaks. Australian Institute of Marine Science, Townsville, Report to Crown of Thorns Starfish Research Committee, 82 pp.

Hughes, R. D., D. M. Burrage and L. Bode (1995) A Western Boundary Current along the Coast of Papua New Guinea. *Deep-Sea Research* (in review).

James, M.K., Dight, I.J. and Bode, L. (1990) Great Barrier Reef hydrodynamics, reef connectivity and Acanthaster population dynamics. In 'Acanthaster and the Coral Reef: A Theoretical Perspective'. R. Bradbury, Ed., Lecture Notes in Biomathematics No. 88, Springer-Verlag, 17–44.

James, M.K. and Scandol, J.P. (1992) Larval dispersal simulations: correlation with the crown-of-thorns starfish outbreaks database. *Australian Journal of Marine and Freshwater Research,* **43**, 569–582.

Johnson, C. (1992) Settlement and recruitment of *Acanthaster planci* on the Great Barrier Reef: questions of process and scale. *Australian Journal of Marine and Freshwater Research,* **43**, 611–627.

Kenchington, R. and Morton, B. (1976) Two surveys of the Crown of Thorns Starfish over a Section of the Great Barrier Reef: Report of the Steering Committee for the Crown of Thorns Survey. Australian Government Publishing Service, Canberra, 186 pp.

Kenchington, R.A. (1977) Growth and recruitment of Acanthaster planci (L.) on the Great Barrier Reef. *Biological Conservation,* **11**, 103–118.

Lagerloef, G.S.E., Swift, C.T. and Le Vine, D.M. (1995) Sea surface salinity: the next remote sensing challenge. *Oceanography,* **8**, 44–50.

Middleton, J.H. (1987) Steady coastal circulation due to oceanic alongshore pressure gradients, *Journal of Physical Oceanography,* **17**, 604–612.

Moran, P.J., De'ath, G., Baker, V.J., Bass, D.K., Christie, C.A., Miller, I.R., Miller-Smith, B.A. and Thompson, A.A. (1992) Patterns of outbreaks of Crown-of-thorns starfish (*Acanthaster planci* L.) along the Great Barrier Reef since 1966. *Australian Journal of Marine and Freshwater Research,* **43**, 555–568.

Morrow, R.A. and Andrews, J.C. (1986) Field survey physical oceanography, cross shelf, May 1985 to December 1985. Report No. DRP004, Australian Institute of Marine Science, Townsville, 24 pp. + appendices.

Nof, D. and Middleton, J.H. (1989) Geostrophic pumping, inflows and upwelling in Barrier Reefs. *Journal of Physical Oceanography,* **19**, 874–889.

Pickard, G. L., Donguy, J.R., Henin, C. and Rougerie, F. (1977) *A Review of the Physical Oceanography of the Great Barrier Reef and Western Coral Sea.* Monograph Series No. 2, Australian Institute of Marine Science, 135 pp.

Scandol, J.P. and James, M.K. (1992) Hydrodynamics and larval dispersal: a population model of *Acanthaster planci* on the Great Barrier Reef. *Australian Journal of Marine and Freshwater Research,* **43**, 569–582.

Stevens, A., Hatton, D. and Black, K.P. (1992) Green Island current meter measurements, June and November, 1991. Victorian Institute of Marine Sciences Working Paper No. 26, 22 pp.

Thompson, R. and T. J. Golding (1981) Tidally induced upwelling by the Great Barrier Reef. *Journal of Geophysical Research,* **86**, 6517–6521.

Thomson, R. E. and Wolanski, E.J. (1984) Tidal period upwelling within Raine Island entrance Great Barrier Reef. *Journal of Marine Research,* **42**, 787–808.

Wijffels, S.E.A. (1986) An analysis of low-frequency sea level variations around the border of the north-western Coral Sea, to investigation of role of coastally-trapped waves. Research Report 44, Flinders Institute for Atmospheric and Marine Science, The Flinders University of South Australia, 90 pp.

Williams, D.McB., Wolanski, E. and Andrews, J.C. (1984) Transport mechanisms and the potential movement of planktonic larvae in the central region of the Great Barrier Reef. *Coral Reefs,* **3**, 229–236.

Wolanski, E., and Ruddick, B. (1983) Water circulation and shelf waves in the northern Great Barrier Reef lagoon. *Australian Journal of Marine and Freshwater Research,* **32**, 721–740.

Wolanski, E., and Bennett, A.F. (1983) Continental shelf waves and their influence on the circulation around the Great Barrier Reef. *Australian Journal of Marine and Freshwater Research,* **34**, 23–47.

Wolanski, E., Burrage, D. and King, B. (1989) Trapping and dispersion of coral eggs around Bowden Reef, Great Barrier Reef, following mass coral spawning. *Continental Shelf Research,* **9**, 479–496.

Wolanski, E., Drew, E., Abel, K.M. and O'Brien, J. (1988) Tidal jets, nutrient upwelling and their influence on the productivity of the alga Halimeda in the Ribbon Reefs, Great Barrier Reef. *Estuarine, Coastal and Shelf Science,* **26**, 169–201.

Wolanski, E. (1994) *Physical oceanographic processes of the Great Barrier Reef.* CRC Press, Boca Raton, Florida, 194 pp.

Young, I.R., Black, K.P. and Heron, M.L. (1994) Circulation in the ribbon reef region of the Great Barrier Reef. *Continental Shelf Research,* **14**, 117–142.