

Are the hydrodynamics guilty of causing or stimulating outbreaks of crown-of-thorns starfish on the Great Barrier Reef ?

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Abstract

Are there causal links between the outbreaks of starfish and the GBR hydrodynamics? The evidence suggests that hydrodynamics are certainly implicated and may play a significant role in determining the evolution of outbreaks. Secondary outbreaks appear to be a consequence of larval recruitment from other sources. An initial outbreak seeds nearby reefs causing subsequent outbreaks some 2 - 4 years later. The excursion of the dispersing larvae is determined by (i) the current strength during the pelagic phase, (ii) the interaction of the continental shelf coastal currents with the reef-scale circulation, and (iii) the location along and across the shelf of the source of larvae. A 25-year time series of predicted currents in the central GBR confirms that the observed distribution and migration of outbreaks may be simply a response to inter-reef larval exchange, carried by a reversing low frequency current from a reef saturated with spawning adults. However, cyclical behaviour in the outbreaks may yet prove to be related to other ocean-scale factors, eg. longshore oscillations in the point of attachment of the East Australian current. Even, El Nino events may play a role. The cause of initial outbreaks appears far more complex. Do the adult numbers simply build up until a threshold in fertilised larval numbers is exceeded and an outbreak results? Do hydrodynamics interact with reef morphology to create zones of relatively high recruitment on and around reefs, as suggested by Black and Moran (1991)? Such zones may also maintain low level populations of adults until a drop in the coastal current strength during the spawning season causes many larvae to be retained, and local recruitment increases dramatically. Several successive years of low currents may be needed to create an "outbreak". Small-scale tests over distances of metres have clearly shown that the larvae are passive, ie. their swimming speeds and buoyancies are negated by the action of random vertical turbulence in natural currents. Measured negative buoyancies are

unlikely to bring larvae to the sea bed. They may, however, help them to attach once they get close.

This paper takes a broad view of cause and effect at a number of physical scales. Much of what we have learned implicates the hydrodynamics. This is hardly surprising as passive larvae undoubtedly find themselves at the whim of the currents.

Introduction

Through the use of numerical techniques which are typically applied to engineering and environmental assessments (Healy *et al.* 1987, Colman and Black 1988, Keough and Black 1992) in conjunction with field data analyses (Gay *et al.* 1991, Burrage *et al.* 1991), some of the problems relating to Great Barrier Reef (GBR) hydrodynamics have been unravelled, at least in the vertically-homogeneous case (Black and Gay 1987, Deleersnijder *et al.* 1992, Dight *et al.* 1990, a). Consequently, some of the mysteries surrounding dispersal of passive larvae have been dispelled. This has enabled several studies of crown-of-thorns starfish (COTS) to seek links between the physical oceanographic characteristics of the GBR and the outbreaks of COTS (Dight *et al.* 1990b, Black and Moran 1991, James and Scandol 1992).

The development of better models and a better knowledge of the processes has resulted in a constant improvement in the techniques being applied. For example, boundary conditions applied by Dight *et al.* (1990, a) were partially schematic in that variations in the East Australian Current were not considered. Moreover, their models did not fully represent or account for the circulation around the individual reefs (Dight and Black 1991). Similarly, the small-scale models of Black (1992b) did not initially attempt to simulate particular years during the outbreaks, although actual currents were modelled (Gay *et al.* 1991, Black *et al.* 1990). Both groups, however, established a basis for a broader understanding of GBR dispersal.

More recently, grid size refinements and new methods to predict the currents during the outbreak years have greatly enhanced our ability to examine particular events at a regional scale (see below). More field data from micro to regional scales have been collected (Benzie *et al.*, *in prep.*, Moran *et al.* 1992) so that the dispersal at small scales and the results at large scales can be jointly assessed. These efforts make it possible to examine the "*Acanthaster* phenomenon" (Moran 1986) in a hydrodynamic context.

Secondary Outbreaks

We choose to distinguish between "primary" and "secondary" outbreaks. Secondary outbreaks result from an infestation originally derived from a primary source. The primary source represents the initial location or region where the outbreak starts. There may be no primary source, as such, as low-level populations of starfish may exist throughout the GBR at all times.

Dight *et al.* (1990a, b) were the first to use numerical techniques on a regional scale to model COTS larval dispersal during the pelagic period of 14 - 28 days. With "coarse" grid models (9 km cells) of the Central and Cairns Sections of the GBR, they demonstrated the potential for large excursions exceeding 10's of kilometres during the pelagic period. Their results appear to qualitatively match progressive excursions constructed from current meter measurements in the central GBR (Williams *et al.* 1984).

Most importantly, the measurements and the simulations indicate a net southward drift in the regions of the reefs and offshore (Williams *et al.* 1984, Andrews 1983, Burrage *et al.* 1991), although reversals do occur.

The observation of a net southward current coincides with an observed tendency for southward drift in COTS outbreaks (Reichelt *et al.* 1990, Moran *et al.* 1992). Indeed, recent detailed surveys of starfish numbers have identified a clear southerly trend in the movement of outbreaks over successive years (Moran *et al.* 1992) and confirmed the less definitive patterns in the earlier data sets (Reichelt *et al.* 1990). Thus, the trends in outbreak progression and the currents may be linked (James and Scandol 1992).

However, current reversals occur during the spawning period and a much more convincing case would be established if actual currents could be deterministically correlated with observations of starfish movements during particular years. Ultimately, confirmation would be obtained by simulating the actual cases numerically. These matters are being treated presently by Black and co-workers (Black, Burrage, Moran and De'ath).

As current measurements were not available in sufficient detail to establish the above correlations, the group's attention was directed towards oceanographic predictive techniques to provide more accurate empirical and numerical models.

Burrage, Black and Ness (*submitted*) utilised earlier results of Burrage *et al.* (1991) to predict currents in the central GBR over the 25 year period during the known modern history of the starfish outbreaks. Using the sea level differences between Townsville (in the central GBR) and Noumea (in the western Pacific) to estimate currents, the procedure utilised the observed geostrophic balance between cross-shelf sea gradient and currents on the shelf. The results were confirmed using data from circulation experiments (Burrage *et al.* 1991, Gay *et al.* 1991). The method provided a useful technique to formulate boundary conditions for more comprehensive numerical simulations of the hydrodynamics and dispersal during the outbreaks.

To test the correlation between outbreak movement and currents, a simple advection model was developed using the predicted currents to specify the dispersal ranges during spawning (Black, Moran, De'ath and Burrage, *in prep.*). Successive outbreak years since 1966 were examined. The predicted larval excursions were compared with the observed movement of starfish outbreaks. Comparisons of the predictions with the observed dispersal ranges showed a high degree of correlation and, while two of the years were anomalous, the preliminary results almost unambiguously confirmed that secondary starfish outbreaks could indeed be caused by larvae coming from infested reefs "upstream". Small-scale numerical models confirmed that the circulation patterns around individual reefs would allow this to occur. The bulk of the flow goes around the downstream reefs, but the tidal currents cause some of the passing material to be trapped (Black 1992a).

Primary Outbreaks

Studies of small-scale circulation and dispersal around individual reefs and reef groups, and of inter-reef dispersal at small-scales has indicated a complex hydrodynamic environment acting to retain material around individual reefs for times which can be of the same order as the COTS pelagic period (Black *et al.* 1991). By

directing attention towards correlations between COTS outbreaks and hydrodynamic processes, while simultaneously establishing a basis for our present understanding of reef and reef group-scale dispersal of COTS larvae, correlations between outbreaks on individual reefs and passive dispersal patterns were obtained (eg. Black and Moran 1991). Are there possible links between these factors and primary outbreaks of COTS? A number of hydrodynamic processes could be responsible.

Recent work by Moran *et al.* (1992) suggests that the primary outbreaks occurred in the Cairns Section around 16°S during the two documented infestations in the 60's, 70's and 80's. If we assume this region is the initial source, we must identify processes which distinguish the area from other parts of the GBR; all regions evidently contain some low-level background populations of COTS at all times. While asking what hydrodynamic processes may cause the outbreaks, we must equally consider why outbreaks don't occur elsewhere in the GBR. Indeed, the region may be a larval "sink" where larvae from outside are more likely to settle. Alternatively, the region may simply retain larvae better than other locations.

A number of possible hydrodynamic explanations or hypotheses are considered:

(i) *Regional variations in low frequency currents along the length of the GBR cause some areas to retain more larvae than others.*

The modelling of Dight *et al.* (1990b) indicated slower currents and therefore smaller larval excursions in the Cairns Section of the GBR than in the Central Section. As the primary outbreaks are thought to initiate in the Cairns Section (Moran *et al.* 1992), the slower currents may be correlated with the establishment of outbreaks. Indeed, small-scale modelling shows that local retention around reefs or within reef groups is critically dependent on current strength (Black *et al.* 1989). In slower currents, larvae could be retained in greater numbers at an individual reef scale, as well as at a regional scale.

However, very little current meter data is available in the Cairns Section to confirm these findings. Recently, Steven and Black (1992) obtained current measurements in deep water near Green Island, but a full analysis of this data is pending. Prior measurements made close to Green Island (Wolanski and Bennett 1983) offered some information about regional circulation.

Further north, useful measurements away from the reefs have been made by Frith *et al.* (1986) in the region of Lizard Island, but these measurements are north of the "primary" source and have not been used to confirm the findings of Dight *et al.* (1990a).

(ii) *Slow currents over successive years cause a build up in locally retained larvae (from regional to individual reef scales).*

The 25-year time series shows inter-annual variability which was correlated with El Nino Southern Oscillation events (ENSO) (Burrage, Black and Ness, *submitted*; Burrage, Black and Steinberg, *in prep.*). The time series is characterised by periods of several years of net northerly or weak currents during the spawning period. These are interspersed with a succession of years when pronounced southerly flows predominated (Black, Moran, De'ath and Burrage, *in prep.*).

The number of spawning larvae retained around the natal reef is a strong function of the low frequency current strength and variations in retained numbers occur in response to the variability in flow patterns (Black *et al.* 1990). As such, a succession of years during which the currents were slow could cause a build up in local numbers to reach outbreak proportions. This could occur at a reef scale or a regional scale. In particular, in a region which already experiences relatively small currents on the average, slow currents during a succession of years could provide sufficient impetus to initiate an outbreak.

(iii) *Net northerly currents during the pelagic dispersal period cause larval numbers to increase.*

Periods of northerly current may cause greater retention of larvae within the GBR matrix or within the primary outbreak region. No evidence to support this possibility is presented here, although the inter-annual cycles in the 25-year time series are being examined to see if the current reversals play a significant role.

(iv) *The pumping action of the flood-tidal jets between the ribbon reefs brings nutrient rich water onto the shelf.*

The jets between the reef gaps have a very significant influence on the shelf circulation. In particular, they bring nutrients from deep offshore waters onto the shelf (Wolanski *et al.* 1988, Young *et al.* 1992) and the momentum of the jet carries the nutrients several kilometres shorewards. Young, Black and Heron (1992) have supplemented the measurements of Frith *et al.* (1986) with their own data (current meters, surface radar, satellite images) to develop a numerical model of the region at a fine (400 m grid) scale. The model shows wide variability in "nutrient" concentration shorewards of the reefs, as a function of reef gap width, gap orientation and spacing between gaps. In general, bands of high concentration occur several kilometres shoreward of the reefs. Wolanski *et al.* (1988) had previously demonstrated a likely correlation between currents (bringing nutrients from the ocean) and the presence and shoreward location of *Halimeda*-banks in the region.

Starfish larvae from "distant" sources may be carried into the GBR lagoon by the jets. Alternatively, the nutrients may enhance starfish fecundity, recruitment success or growth causing the region to be more suited to starfish recruitment and development.

(v) *Other possible factors.*

Babcock and Mundy (*unpublished*) noted that development and fertilisation of starfish were significantly higher in inshore water than in water from the offshore reefs. The reasons for the higher development and fertilisation rates are not known. This result highlights the need to examine various factors that differentiate the nearshore and offshore zones and the longshore variability.

A number of physical factors, unrelated to dispersal, need to be included in this discussion. These are:

- salinity variations (in response to rainfall variations);
- temperature changes (the starfish are particularly sensitive to excess temperatures, Babcock and Mundy 1992);
- pollutants, nutrient run-off from land sources and turbidity.

Some of these factors are now being examined and the groundwork has been established for more detailed assessments in all of the above categories (eg. Burrage, Black and Steinberg, *in prep.*, Black, *unpublished*).

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References

- Andrews JC (1983)
Water masses, nutrient levels and seasonal drift on the outer central Queensland shelf (Great Barrier Reef).
Aust. J. Mar. Freshwater Res. 34: 821-834
- Babcock RC and Mundy CN (1992)
Reproductive biology, spawning and field fertilization rates of *Acanthaster planci*.
In: Johnson C (ed.), Crown-of-thorns starfish on the Great Barrier Reef: Reproduction, recruitment and hydrodynamics.
Aust. J. Mar. Freshwater Res. 43: 9-18
- Benzie, Black and Moran (*in prep.*)
Field investigations of the spawning of crown-of-thorns starfish over scales of metres.
- Black KP and Gay SL (1987)
Eddy formation in unsteady flows.
J. Geophys. Res. 92 (C9): 9514-9522
- Black KP, Gay SL and Andrews JC (1990)
Residence times of neutrally-buoyant matter such as larvae, sewage or nutrients on coral reefs.
Coral Reefs 9: 105-114
- Black KP and Moran PJ (1991)
The influence of hydrodynamics on the passive dispersal and initial recruitment of larvae of the crown-of-thorns starfish on the Great Barrier Reef.
Mar. Ecol. Prog. Ser. 69: 55-65
- Black KP, Moran PJ and Hammond LS (1991)
Numerical models show coral reefs can be self-seeding.
Mar. Ecol. Prog. Ser. 74: 1-11
- Black KP (1992a)
The relative importance of local retention and inter-reef dispersal of neutrally buoyant material on coral reefs.
Coral Reefs (in press)
- Black KP (1992b)
Developments in our knowledge of dispersal on the Great Barrier Reef.
In: Sammarco P (ed.), Proc. Boden Conference, Springer Verlag (in press).

Black KP, Moran PD, Burrage DM and De'ath G (in prep.)

The relationship of secondary outbreaks of *Acanthaster planci* to currents during the pelagic dispersal period.

Burrage DM, Black KP and Ness KF (1992)

Long-term current prediction in the central Great Barrier Reef.

Cont. Shelf Res. (submitted)

Burrage DM, Black KP and Steinberg CR (1992)

Long-term sea level variations and geostrophic currents in the central Great Barrier Reef. (in prep.).

Burrage DM, Church JA and Steinberg CR (1991)

Linear systems analysis of momentum on the continental shelf and slope of the central Great Barrier Reef.

J. Geophys. Res. 96(c12): 22169-22190

Colman RS and Black KP (1988)

Use of numerical models in port design and management.

2nd Australasian Port, Harbour and Offshore Engineering Conf., Brisbane, Institute of Engineers, ACT, Australia, pp. 32-36

Deleersnijder E, Norro A and Wolanski E (1992)

A three-dimensional model of the water circulation around an island in shallow water.

Cont. Shelf Res. 12: 891-906

Dight IJ, Bode L and James PD (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 IJ, James PD and Bode L (1990b)

Modelling the larval dispersal of *Acanthaster planci*: II. Patterns of reef connectivity.

Coral Reefs 9: 125-134

Dight IJ and Black KP (1991)

Numerical simulation of larval dispersal and recruitment to coral reefs from the mainstream.

Coastal Zone '91. (ASCE) 3: 1995-2009

Frith CA, Leis JM 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

Gay SL, Andrews JC and Black KP (1991)

Dispersal of neutrally-buoyant material near John Brewer Reef.

In: Bradbury R (ed.), *The Acanthaster Phenomenon: a modelling approach*, Lecture notes in biomathematics, Springer Verlag.

Healy TR, Black KP and de Lange WP (1987)

Field investigations required for numerical model studies of port developments in large tidal inlet harbours.

Int. Geomorph., pp. 1099-1112

James MK and Scandol JP (1992)

Larval dispersal simulations: correlation with the crown-of-thorns starfish outbreaks database.

In: Johnson C (ed.), Crown-of-thorns starfish on the Great Barrier Reef: Reproduction, recruitment and hydrodynamics.

Aust. J. Mar. Freshwater Res. 43: 9-18

Keough MJ and Black KP (1992)

Predicting the scale of marine impacts: Understanding planktonic links between populations.

Proc. 2nd Int. Temp. Reef Symp. (*in press*).

Moran PJ (1986)

The *Acanthaster* phenomenon.

Oceanogr. Mar. Biol. Ann. Rev. 24: 379-480

Moran PJ, De'ath G, Baker VJ, Bass DK, Christie CA, Miller IR, Miller-Smith BA and Thompson AA (1992)

Patterns of outbreaks of crown-of-thorns starfish (*Acanthaster planci* L.) along the Great Barrier Reef since 1966.

In: Johnson C (ed.), Crown-of-thorns starfish on the Great Barrier Reef: Reproduction, recruitment and hydrodynamics.

Aust. J. Mar. Freshwater Res. 43: 9-18

Reichelt RE, Bradbury RH and Moran PJ (1990)

Distribution of *Acanthaster planci* outbreaks on the Great Barrier Reef Between 1966 and 1989.

Coral Reefs 9: 97-103

Steven A and Black K (1992)

Green Island current meter measurements. June and November, 1991.

Victorian Institute of Marine Sciences, Working Paper (*in press*).

Williams D McB, Wolanski E and Andrews JC (1984)

Transport mechanisms and the potential movement of planktonic larvae in the central regions of the Great Barrier Reef.

Coral Reefs 3: 229-236

Wolanski E and Bennett AF (1983)

Continental shelf waves and their influence on the circulation around the Great Barrier Reef.

Aust. J. Mar. Freshwater Res. 34: 23-47

Wolanski E, Drew E, Abel KM 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.

Estuar. Coast. Shelf Sci. 26: 169-201

Young IR, Black KP and Heron ML (1992)

Circulation in the ribbon reef region of the Great Barrier Reef.

Cont. Shelf Res. (*in press*).