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Abstract

Patterns of wave energy play a significant role in shaping the long-term structure of coral reef communities worldwide. For example, sections of reefs have been shown to vary greatly in morphology (dominant size class, growth form) as coral colonies adapt in response to local-scale differences in the wave heights typically experienced. These differences result in zonation (crest, lagoon, and slope), producing characteristic growth forms and species assemblages that vary in their vulnerability to damage from waves (Done 1993). Those communities experiencing the greatest typical wave energy align themselves parallel to the water flow, adopt stream-lined forms and are usually smaller in size – all of which reduces their vulnerability to wave damage (Tunnicliffe 1982). Also important to the state of reef community structure at a given time is the recent history of waves generated by high intensity, episodic events such as tropical cyclones (Hughes and Connell 1999). The greatest potential for cyclone damage occurs when waves approach a part of a reef that is typically sheltered from heavy wave action under routine conditions (Harmelin- Vivien 1994). In this case, corals are often more fragile and/or weakly attached to the reef, and much less wave energy is required for damage to occur than in for corals that are routinely exposed to the same forces.

Keywords

automated, GIS, method, for, modeling, relative, wave, exposure, within, complex, reef, island, systems, case, study, Great, Barrier, Reef

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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An Automated GIS Method For Modeling Relative Wave Exposure Within Complex Reef-Island Systems: A Case Study Of The Great Barrier Reef

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Keywords*: wave exposure, GIS, coral reef, Great Barrier Reef*

EXTENDED ABSTRACT

Patterns of wave energy play a significant role in shaping the long-term structure of coral reef communities worldwide. For example, sections of reefs have been shown to vary greatly in morphology (dominant size class, growth form) as coral colonies adapt in response to local-scale differences in the wave heights typically experienced. These differences result in zonation (crest, lagoon, and slope), producing characteristic growth forms and species assemblages that vary in their vulnerability to damage from waves (Done 1993). Those communities experiencing the greatest typical wave energy align themselves parallel to the water flow, adopt stream-lined forms and are usually smaller in size – all of which reduces their vulnerability to wave damage (Tunnicliffe 1982). Also important to the state of reef community structure at a given time is the recent history of waves generated by high intensity, episodic events such as tropical cyclones (Hughes and Connell 1999). The greatest potential for cyclone damage occurs when waves approach a part of a reef that is typically sheltered from heavy wave action under routine conditions (Harmelin-Vivien 1994). In this case, corals are often more fragile and/or weakly attached to the reef, and much less wave energy is required for damage to occur than in for corals that are routinely exposed to the same forces.

Waves lose much of their energy at the leading edge of the first reef (or other shallow water obstacle) they encounter (Massel 1996, Young and Hardy 1993). This creates a *within-reef shelter* effect, where the lee side of the reef receives relatively little wave energy, and a *between-reef shelter* effect, where reefs beyond the first obstacle lie within a long energy 'wave shadow'. Waves passing over reefs lose energy due to changes in water depth, friction from interaction with the sea bottom, and breaking (Lugo-Fernandez et al 1998). Research suggests that waves that re-form after encountering reefs in the Great Barrier Reef (GBR) retain only about 5% of their original energy (Gourlay 1994). In fact, the GBR acts as an almost complete barrier to long period waves (swell) approaching the complex from the open sea (Young and Hardy 1993). This is the case even at high tide and regardless of differences in the density of reefs from north to south along the GBR (Young 1989). Thus, the relative position of a coral community along a reef with respect to nearby reefs, islands and other shallow water obstacles plays a key role in determining its exposure to locally generated (short period) waves approaching from a particular direction. The distance across which wind blows uninterrupted over water between two points limits the magnitude of the waves that form (other important factors are duration and intensity). This distance, between a particular site along a reef and the nearest wave-blocking obstacle, is the fetch. Measuring the fetch at various angles around a site approximates the relative exposure of that site to waves approaching from different directions for any given wind intensity and duration. In this case, the fetch is limited to those areas of water for which the depth is sufficient for developing waves not to ‘feel the bottom’ until they break in the shallow areas that surround each site of interest.

This paper introduces a fully automated GIS model that estimates the relative exposure of sites of interest within complex reef-island systems to incoming wave energy. For each site, the model estimates fetch in all directions, which is recorded in a spatial database that can be queried to estimate a site’s relative exposure to incoming waves, enabling a comparison of site exposure during routine versus high-energy conditions. As a case study, the model was applied to the GBR. Preliminary tests suggest that an index of relative exposure (during tropical cyclone versus routine conditions) may help predict high levels of cyclone wave damage to reefs. Refining the index should lead to more effective models for predicting cyclone wave damage to reefs, enabling long-term modeling of cyclone disturbance dynamics.

1. IDENTIFYING REEF SITES

Relative exposure to incoming waves can vary across very small distances due to local-scale differences in the topography of a reef. For example, for reef sites located only 100s of m apart at Oublier Reef (central GBR) that were surveyed following cyclone Justin (1997), wave damage ranged from devastation to none (Puotinen 2005). To capture this local scale variability, I defined a series of 'sites' around the perimeter of each reef of the GBR at a 1 km interval (**Figure 1**) at which to model relative exposure to incoming waves under routine versus cyclone conditions.

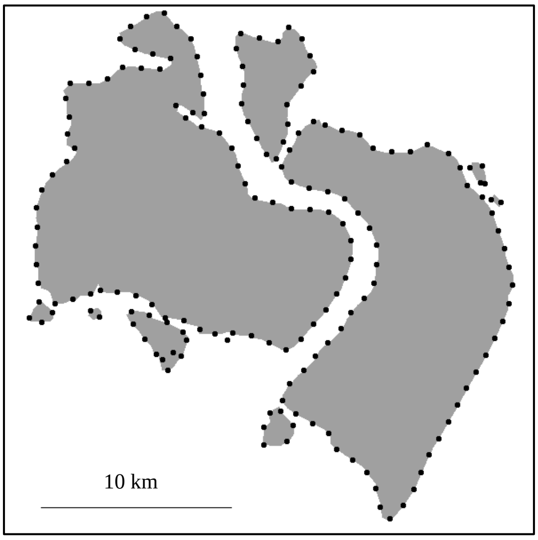


Figure 1. Reef sites (black circles) were created along the perimeter of GBR reefs (gray polygons) every 1 km (using ArcView™ extension 'Poly2pts.avx' by W. Huber).

For the 2,728 reefs of the GBR, this produced a total of 24,224 individual sites, which are unevenly spread across the region (**Figure 2**).

	Longitude												
Latitude	142	143	144	145	146	147	148	149	150	151	152	153	*Total*
10	861	1160	142										2163
11	192	2378	277										2847
12		1706											1706
13		1203	383										1586
14		94	629	671									1394
15				969									969
16				562	266								828
17					781								781
18					536	551	52						1139
19					43	29	840	1114	240				2266
20							363	438	1763	540	35		3139
21								589	454	1463	1411		3917
22								119	159	36	470		784
23									113	377	125		615
24										8	40	42	90
Total	1053	6541	1431	2202	1626	580	1255	2260	2729	2424	2081	42	24224

Figure 2. The Great Barrier Reef divided into one-degree latitude by one-degree longitude blocks. The number within each block indicates the number of reef sites (spaced every 1 km along the perimeter of each reef) located therein: white = < 1,000, light grey = 1,000-2,000, dark grey = 2,000-3,000 and black = >3,000.

2. CONSTRUCTING FETCH LINES

The exposure of a site to locally generated waves approaching from a given direction depends largely on the distance of water over which winds can blow uninterrupted to the site in that direction (fetch). While others have developed semi-manual methods in GIS to estimate fetch in complex island systems (Ekebom et al 2003), using such a method was not feasible given the vast size of the GBR site dataset. Thus, I developed a fully automated procedure implemented in workstation Arc-Info™ software using AML™. In the program (Puotinen 2005, Appendix 2), fetch is estimated by calculating the straight-line distance between each reef site and the nearest potential wave-blocking obstacle (i.e. island, coastline, reef, area of shallow water) in all directions at intervals of 7.5 degrees. For each of the 24,224 sites, a fetch line was created in each of the 48 directions. These were then combined to create a GIS vector line coverage for each site. The fetch distances were recorded in a spatial database linked to the site locations. Constructing each of the 48 fetch lines at each site involved the following key steps:

- The angle of the line to be created was adjusted to reference it to the x axis (90 – [angle – 360]). This enabled correct operation of the trigonometric formulae.
- Trigonometry was used to calculate the x,y coordinates of the to-node of the fetch line given its from-node coordinates, angle and length. Originally a maximum fetch distance of 50 km was used (Puotinen 2003), but this was later expanded to 500 km.
- A vector polygon coverage containing reefs, islands, the mainland and areas of shallow water (less than 50 m depth) was created to represent potential wave-blocking obstacles. The segments of each fetch line that intersected potential wave blocking obstacles were erased.
- This produced a set of line segments for each original fetch line, the number of which varied based on the number of

wave-blocking obstacles that crossed the 500 km line. The length of the segment that begins at the coordinates of the from-node (the reef site) represents the fetch to the nearest obstacle. This segment was identified by selecting each segment in turn and checking the coordinates of its from-node. The length of the correct segment was saved to the spatial database, and the other segments were discarded.

For each site, this generated an array of 48 fetch lines in all directions (**Figure 3**).

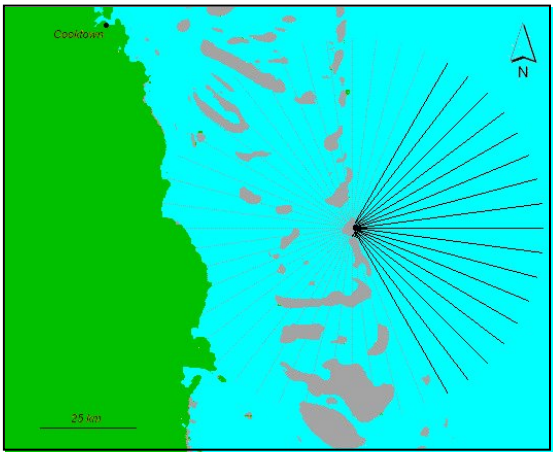


Figure 3. Example of an array of fetch lines around a reef site (shown for a maximum fetch distance of 50 km). Gray lines indicate directions in which the site is completely blocked by barriers (zero fetch). Barriers include land / island (green), and reef (gray).

Every site on a reef perimeter was assigned a fetch of zero for all those fetch lines that lie across the body of the reef (and/or nearby land in the case of fringing reefs). Fetch lengths greater than or equal to 500 km were all set to 500 km, which was assumed to represent unlimited fetch.

The configurations of the resultant arrays of fetch lines varied by the relative position of the site within the surrounding reef matrix (**Figure 4**). For example, the site shown in A is highly sheltered from almost all possible incoming wave directions due to its position within a matrix of nearby reefs. In contrast, the site shown in C is highly exposed to waves approaching from the northeast to the west. Holding all other factors constant, one could expect that corals found at the latter site would thus be more adapted to high wave conditions (and therefore less vulnerable to cyclone damage).

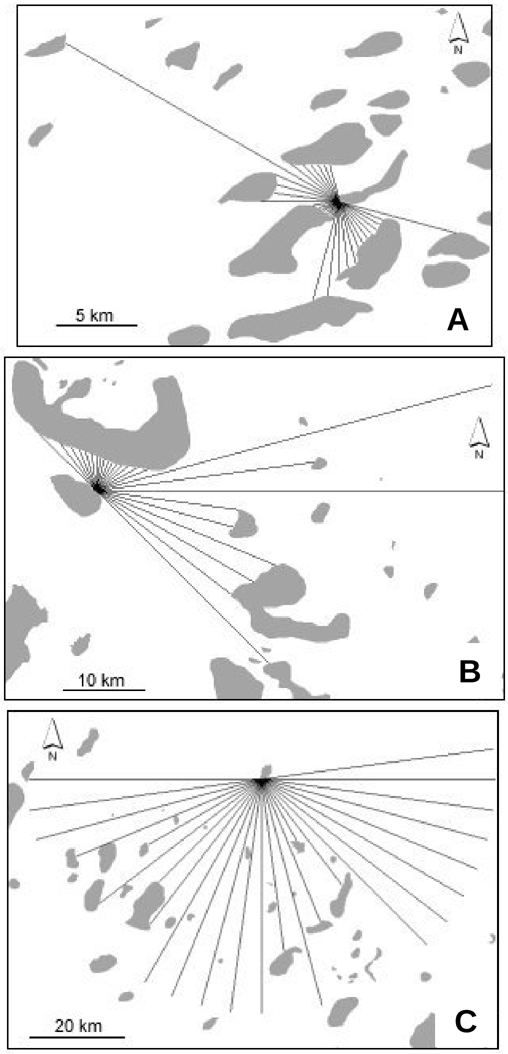


Figure 4. Indicative array of fetch lines (shown for a maximum fetch distance of 50 km) around a reef site that is [A] – very sheltered, [B] – somewhat exposed and [C] – very exposed to locally generated wind waves. Note the differences in the scale bars.

3. ESTIMATING SITE EXPOSURE

From the extensive spatial database of fetch that has been created (fetch measured in 48 compass directions for 24,224 sites across the GBR), it is possible to estimate the exposure of individual sites to incoming waves under normal 'routine' conditions, as well as under high-energy conditions (i.e. during tropical cyclone events). This was done for selected reef sites surveyed for

damage following three cyclones as a test of the extent to which relative exposure can explain levels of cyclone wave damage observed during field surveys (Puotinen 2005).

3.1. Calculating routine exposure

For much of the year, winds in the GBR region (and thus locally-generated waves) predominantly approach from the southeast (Orpin et al 1999, Hopley 1982). Holding other factors constant, sites with a long fetch in these directions can be expected to be more wave-adapted and thus less vulnerable to cyclone wave damage. To estimate the routine exposure for each site, I averaged the set of distances from that site to the nearest obstacle in the 90-degree arc centred on 135 degrees (southeast). For example, for selected sites surveyed by Ayling (1991 unpublished data) following cyclone Joy, the highest routine exposure was predicted for sites located on the south to eastern flank of reefs (**Figure 5**).

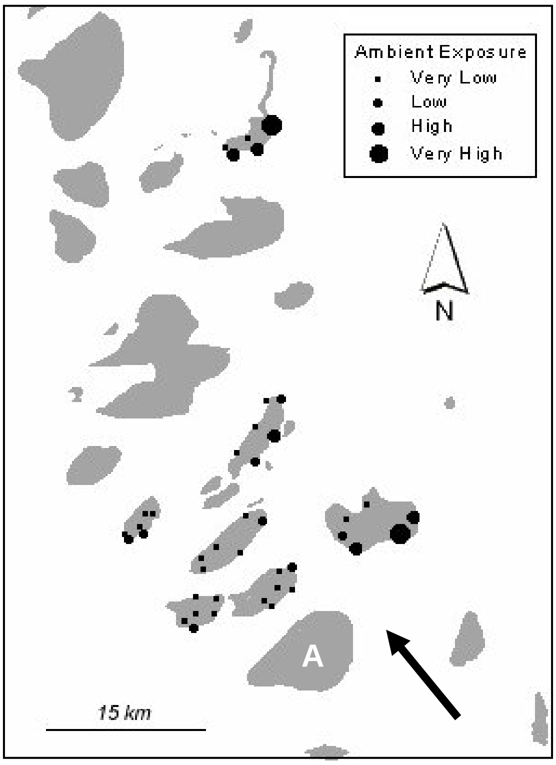


Figure 5. Routine (ambient) exposure of selected reef sites (black circles) surveyed following cyclone Joy (Ayling unpublished data 1991) to wave energy based on their relative position within the matrix of reefs (gray polygons), islands and coastline. Waves typically approach reefs in the direction of the arrow.

Note how reefs located to the northwest of reef A are predicted to receive less wave energy normally than the reef located to the northeast (between reef shelter effect). The same is true for sites located on the side of the reef facing into the incoming waves (southeast) versus those located elsewhere (within reef shelter effect).

Lewis (2001) calculated a similar index, but based his on a raster depth model of the GBR at a relatively coarse resolution (500 m raster pixel). Delineating the exposure differences between reef sites from local scale features, which can be quite significant, would be impossible at such a coarse resolution. Therefore it was necessary to measure the fetch distances using the computationally intensive, but more precise, vector approach described here. Accordingly, using a cost distance approach at a resolution sufficient to resolve local scale features would be computationally prohibitive across the vast GBR region (340,000 km^2).

3.2. Calculating cyclone exposure

If the dominant incoming wave direction at a reef site during a cyclone is known (or can be estimated), it is possible to use the fetch database to calculate the exposure of that site to incoming cyclone wave energy. Although direct measurements of wave energy (i.e. from a deployed buoy) are rarely collected during cyclones on the GBR, it is possible to reconstruct the spread of cyclone-generated winds in the vicinity of the storm using data from the Australian Bureau of Meteorology and meteorological models implemented in GIS (Puotinen 2003, 2005). A study of cyclone Ivor (1990), Joy (1990), and Justin (1997) has shown that maximum wind speed modeled in this way provides a useful proxy for the potential for wave development and subsequent reef damage at sites of interest (Puotinen 2005). From this modeling, the longest uninterrupted period during which winds exceeded gale force (high energy conditions capable of generating heavy seas that can damage reefs) can be determined for each site of interest. The average wind direction during this period gives a reasonable estimate of the direction from which the bulk of locally generated waves approached a given site during a cyclone. Using this, exposure during each of the five cyclones was calculated as the average length of the fetch lines from that site in directions ranging $\pm$45 degrees from the average wind direction during the high-energy period. Fetch lines were averaged in this way to minimise the impact of known uncertainty in the modelled wind directions (Puotinen 2005)

and to account for the imperfect correlation between wind and wave directions (Denny 1988).

For example, for selected sites surveyed by Ayling (1991 unpublished data) following cyclone Joy, predicted cyclone exposure was highest for sites located on the eastern flank of reefs (**Figure 6**).

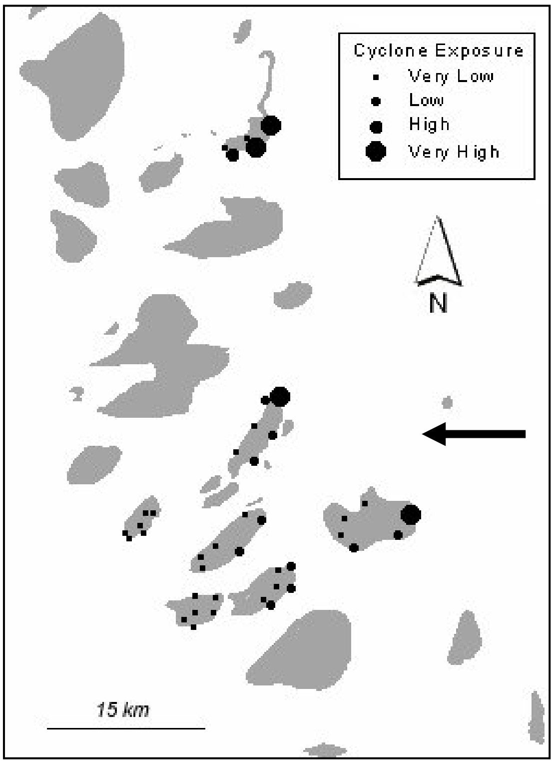


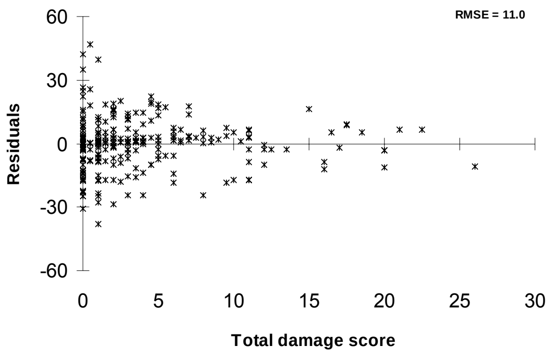
Figure 6. Exposure of selected reef sites (black circles) to wave energy during cyclone Joy (1990) based on their relative position within the matrix of reefs (gray polygons), islands and coastline. Waves approached reefs in the direction of the arrow during high-energy conditions.

Again, as with Figure 5, note the between reef (less exposure on reefs to the west of other reefs) and within reef (less exposure on the western side of individual reefs) shelter effects that were captured by the model.

3.3. Calculating relative exposure

Holding other factors constant, reef sites that are normally highly sheltered from waves could be expected to contain larger and more fragile coral colonies than otherwise. The greatest potential for physical damage from waves occurs when these normally sheltered sites are exposed to sustained high levels of cyclone energy (Harmelin-Vivien 1994). I approximated this by subtracting the exposure of each site during the cyclone from its exposure under normal conditions. A highly negative value of this index indicates that a site was much more exposed during the cyclone than normal, and thus may have been more vulnerable to wave damage.

Limited field data exists documenting wave damage to coral reefs from past cyclones. In these surveys, damage is typically estimated along a qualitative scale from 0 (none) to 5 (widespread) for several types of possible damage (i.e. breakage, dislodgement, smothering by sand). A *total damage score* is calculated as the sum of damage recorded of all types. Examining this for sites surveyed following cyclones Ivor, Joy and Justin (Puotinen 2005) indicates that the relationship of total damage (of 8 types) to relative exposure is



strongest for higher levels of damage (**Figure 7**).

Figure 7: Residuals of predicted relative exposure (normal exposure minus exposure during cyclonic conditions – y axis) versus total recorded damage score (x axis) at reef sites surveyed for cyclone wave damage during cyclone Ivor, Joy and Justin (Puotinen 2005, n= 316). Residuals and RMSE (standard deviation of residuals) are expressed in km. Positive residuals indicate that the relative exposure of sites was less during the cyclone than expected given the level of damage observed. Negative residuals indicate the reverse.

The relative exposure index does not take into account the severity, duration and distribution of wave energy generated by a given cyclone – it merely estimates how exposed a given site would be to that energy (and is not intended to be used for prediction on its own). Thus, some variation in total damage score should be expected (i.e. sites highly exposed to low wave energy, and sites minimally exposed to high wave energy would both be expected to sustain low levels of damage). Total damage scores above 10 at a site indicate widespread wave damage of more than one type.

This can only occur when cyclone wave conditions are severe. It is in these cases (where the index performed best – residuals are lowest) that a shelter effect would be expected to make the most difference.

4. FUTURE DEVELOPMENTS

Some of the noise in the relationship between the relative exposure index and total damage score could be due to poor resolution in the vector mapping of reef boundaries (i.e. inability to recognize that a site is actually sheltered because local scale wave-blocking features are not captured). An on-going effort to re-map the reefs of the entire GBR by the Great Barrier Reef Marine Park Authority (Cullen et al 1999) may help remedy this issue in future. In addition, a future study is planned to rate each of the 24,224 sites by their level of routine exposure and then compare these ratings to ecological (i.e. field survey data from coral ecologists at the Australian Institute of Marine Science) and geomorphologic (location of characteristic high-energy features such as the reef crest as identified from satellite imagery and aerial photography) data indicating levels of exposure to test the skill of the model.

A further issue is that the data set of field observations of cyclone wave damage is quite small (n = 316), covering only three cyclones (Ivor, Joy, Justin) over two seasons (1990, 1997). However, a recent extensive cyclone damage survey, which covers a full range of relative exposure conditions and damage severities, was conducted following severe cyclone Ingrid (category 4, March 2005) in May 2005. This survey (490 sites visited on 32 reefs in the far northern GBR – Fabricious, Done and Puotinen unpublished data) offers the chance to further explore the worth of the relative exposure index in predicting cyclone damage to reefs.

Once the relative exposure model has been extended and tested further, it can be used to help predict which reef sites are likely to sustain damage during future cyclones. This can help design effective damage surveys, as the spatial distribution of damage is highly patchy and logistics / expense prevent covering a large area. This was done to some degree during the field survey of wave damage from cyclone Ingrid (Fabricious, Done and Puotinen unpublished data). However, one problem encountered in doing so was that the location of some mapped reef boundaries did not match the location of sites surveyed (with GPS) along the edge of a reef (**Figure 8**). This mismatch could be due to positional error in the reef polygons and/or error in GPS coordinates taken at surveyed sites. Fixing it requires manually identifying the appropriate fetch site to use for each survey site or moving the survey point the to reef edge and recalculating the 48 fetch lines. The latter defeats the purpose of creating the fetch database, and the former cannot be done automatically (for example, by using the closest fetch site to the survey site) due to the nature of the errors (**Figure 8 B** – survey sites are actually closer to fetch sites on an adjoining reef due to an offset in GPS coordinates).

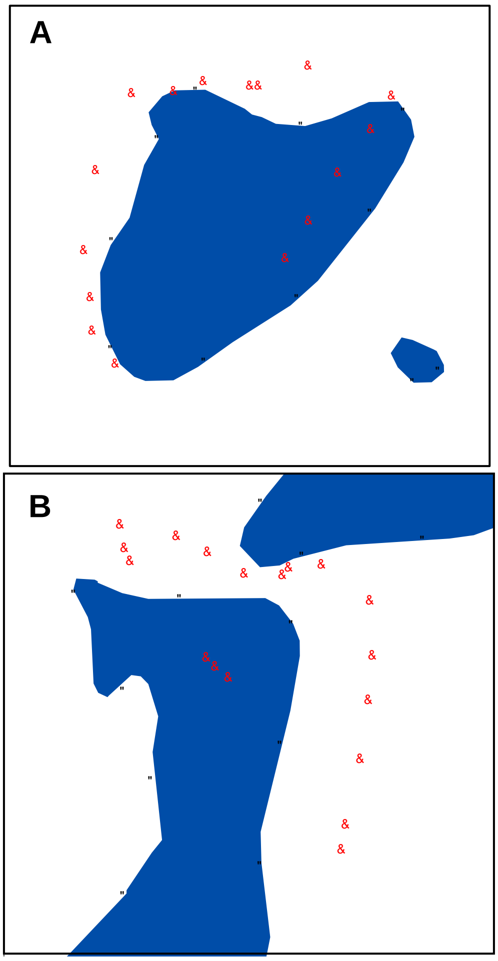


Figure 8. Mismatch between reef sites surveyed using GPS during cyclone Ingrid in May 2005 (red circles) and fetch database sites (black squares) on two selected reefs (blue polygon).

Despite these limitations, the extensive fetch database (24,224 sites across the entire GBR for 48 modelled incoming wave directions) provides a valuable resource for modelling a range of reef processes across this vast region. Once adjustments to the model are complete, relative exposure will be calculated for each of the 24,224

sites for each of 85 cyclones that passed near the GBR from 1969 to 2003 (wind speeds / directions have already been generated for these – Puotinen 2005). Further, in 2006-7, the model will be applied to the equally vast reef complexes found along the Western Australian coast. These reefs are highly variable in their level of exposure to routine wave conditions, and are frequently exposed to high intensity cyclone events. The tracks taken by these cyclones from 1910 to 2003 have already been mapped in GIS (Puotinen, unpublished data).

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