Modelling tropical cyclone disturbance of the Great Barrier Reef using GIS

M. Puotinen

School of Tropical Environment Studies and Geography, James Cook University, Townsville, Australia

Abstract: Tropical cyclones periodically cross the Great Barrier Reef (GBR). Physical damage from the large waves they generate can significantly alter coral reef community structure over time. Yet cyclone disturbance of the GBR has not yet been examined for more than a few events and for only part of the region. Meteorological models can be used to hindcast the likely magnitude and distribution of cyclone energy from the Australian Bureau of Meteorology's tropical cyclone database. This hindcast energy, along with measures of the spatial patterning of reefs, can be linked statistically to field observations of reef impact to predict the distribution of cyclone impacts on areas not surveyed. Implementing the requisite meteorological and spatial models within a GIS has made it feasible to apply these techniques over a longer time period (3 decades) and across a larger area (the entire GBR) than has been done before. The resultant cyclone history can be used to examine the degree to which broad measures of current reef community structure (dominant size classes and growth forms) can be explained by cyclone disturbance alone. This paper will demonstrate these modelling techniques using cyclone Joy (1990) as a case study.

Keywords: *Tropical cyclone; Coral reef; Disturbance; GIS; Modelling*

1. INTRODUCTION

Tropical cyclones periodically cross the GBR. The large waves they generate break along shallow reefs, resulting in physical impacts ranging from broken corals to removal of entire sections of substrate. Over time, repeated widespread impacts can significantly alter coral reef community structure. Thus, effective management of the GBR requires an understanding of the cyclone disturbance regime (which reefs are likely to be affected and how often). However, the spatial distribution of cyclone impacts over time across even single reefs for most of the GBR is poorly known. Though cyclone disturbance patterns operate over century time scales and 100s of km space scales, most studies have examined cyclone impacts for single storm events across several reefs (Done 1992) or for many storm events for a single reef (Connell et al 1997). Further, detailed field observations of cyclone impacts to reefs are rare (Puotinen 2003). To examine cyclone impacts across the GBR over time thus requires reconstructing a likely disturbance history from what information is available.

The amount of energy available to impact reefs during a cyclone depends on its intensity, size and speed. However, the degree to which a particular site is damaged depends just as much on that site's vulnerability to impact as it does on the nature of the cyclone itself. Thus, a combination of hindcast cyclone energy and reef vulnerability measures are used with field observations of cyclone damage to build a predictive model of the spatial distribution of cyclone disturbance across the GBR. This model will be applied to each cyclone passing near the GBR from 1969-1999. This paper demonstrates some of the results for cyclone Joy (Figure 1).

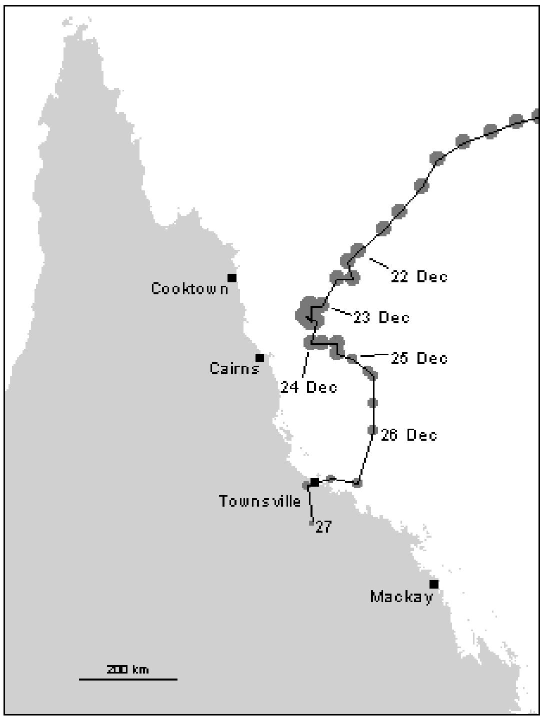

Figure 1. Path of cyclone Joy (December 1990). The size of each circle indicates the intensity of the cyclone at that position (larger = more intense).

2. HINDCASTING CYCLONE ENERGY

2.1 Introduction

Very few direct observations of cyclone wind and wave speeds exist in Australia, as instruments are expensive and tend to fail during the extreme conditions typically experienced. Also, because cyclone paths are virtually impossible to predict, it is difficult to know when and where to deploy instruments in time to measure cyclone energy. However, basic cyclone characteristics (the location of the cyclone along its path, its intensity and its speed and direction of forward motion) are recorded by the Australian Bureau of Meteorology in their tropical cyclone database. Meteorological models can be used to reconstruct (hindcast) the distribution of cyclone energy from these basic characteristics. The first step is to generate a wind field for each relevant eye position (at one-hourly intervals) during the cyclone. From these, numerical models can be used to predict the resultant cyclone wave fields.

2.2 The Cyclone Wind Model

While the most sophisticated cyclone wind models use numerical modelling techniques to solve the equations of motion using a planetary boundary layer model, a simpler and less computationally intensive analytic approach is also often used. The latter approach estimates cyclone wind speeds based on the air pressure gradients that drive the system, most often derived from the pressure field as defined by Holland (1980). Winds are then adjusted for the asymmetry caused by the forward motion of the cyclone (higher wind to the left of the cyclone path in the southern hemisphere). Coral reef researchers have used simple, empirically driven versions of this approach to hindcast cyclone energy from single storms at particular reefs (Kjerfve et al 1993 - Hurricane Greta at Belize Barrier Reef; Kjerfve et al 1986 - Hurricane Allen at Discovery Bay, Jamaica; Done 1992 - Cyclone Ivor in the north-central GBR). Recently McConochie et al (1999) adapted and enhanced Holland's basic model particularly for use in the Coral Sea. Their model provides the ability to simulate both a primary and secondary vortex - the latter accounting for the low pressure trough in which Coral Sea cyclones are often embedded.

For this project, I implemented the equations from the McConochie model to run in the GIS software ArcGIS using the Arc Macro Language (AML). A raster solution (using the GRID module) was primarily used, in order to enhance visualisation and testing of the results. However, a vector implementation was also developed for ease in extracting results for specific points of interest (sites on reefs that have been surveyed following a cyclone). Energy parameters predicted by the model include 10 metre wind speeds (adjusted for the forward motion of the cyclone, the Coriolis effect and boundary layer effects) and wind direction (adjusted for surface friction). These parameters were hindcast every hour for each cyclone in a grid spanning the entire GBR (area ~340,000 sq km) at a resolution of 1 km. I modelled both a primary and primary + secondary vortex. Synoptic scale winds, though potentially important for certain cyclones, were not considered due to a lack of data and time.

Predicted wind speeds and directions for cyclone Joy were compared to observations taken by the Bureau of Meteorology at the Fitzroy Island Lighthouse (Figure 2). When a secondary vortex is

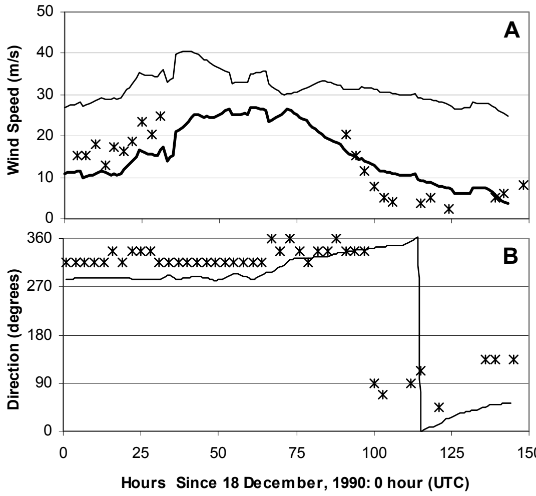

Figure 2. 10 metre surface wind speeds (A) and directions (B) during Cyclone Joy (December 1990) at the Fitzroy Island Lighthouse (latitude: 16.93^0S, longitude: 146^0E). Asterisks show measurements taken by the Bureau of Meteorology weather station (altitude: 124 metres). The lines in (A) show winds predicted from the primary (thick) and primary + secondary (thin) vortices.

included in the simulation, winds are over-predicted, particularly towards the end of the storm. The primary vortex alone performs better, although it still over-predicts at the end of the storm and under-predicts at the start. Unfortunately, observations are missing when the cyclone was most intense and closest to the weather station (when the model was most likely to predict well). The predicted wind direction falls within 45 degrees of the observed direction, except during the last 50 hours of the storm, where the observed directions become erratic. The mismatch between the predicted and observed conditions could be due to changes to the cyclone eye diameter along its path which are unknown, and to which the model is sensitive. Also, in the GBR, the positional uncertainty of the cyclone eye ranges from 30 to 50 km (Holland 1981). Finally, the model simulates conditions at 10 metres above sea level while the observations were recorded at 124 metres.

Hardy et al (2001) recently developed a numerical wave model specifically for the GBR. Its use for this project was not feasible because the differential equations used by the model could not easily be implemented in GIS, and the computer processing time needed to run it for all the cyclones would be prohibitive. Further, the requisite bathymetric data, though recently available, is of coarse resolution and uneven quality. Given that most of the GBR is protected from long period swells, local wind-sea can usually be estimated reasonably well from 10 metre mean surface wind speed.

3. MODELLING REEF VULNERABILITY

The distribution of physical damage to coral reef communities from cyclones is typically very patchy, and cyclone Joy is no exception (Figure 3).

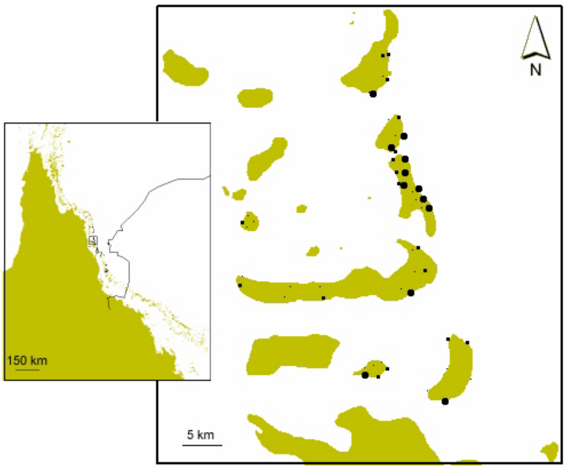

Figure 3. Selected reef sites surveyed for physical damage following cyclone Joy (1990). Small, medium and large circles indicate zero, low and high total damage.

The vulnerability of any given site on a reef to damage depends on many highly variable factors. The most obvious of these is the degree of exposure of a site to cyclone waves. Waves dissipate much of their energy when breaking at the leading edge of the first reef (or other shallow water obstacle) they encounter (Young and Hardy 1993). This creates a within-reef shelter effect, where the back of the reef receives relatively little wave energy, and a between-reef shelter effect, where reefs beyond the first obstacles lie within a 'wave shadow'. The extent of the latter depends on the size, shape and orientation of the obstacle as well as the distance between it and the next reef. Beyond this, the nature of the reef sites themselves influences vulnerability. Key factors include the slope and depth of the site, the ambient wave climate (which helps determine the dominant colony size and growth form, the strength of adhesion to the reef matrix and the stability of the reef matrix itself), and the time since the last physical disturbance (Done 1992).

3.1 Within-Reef Shelter

Predicted wind speeds for each eye position were adjusted based on the proximity of each reef site to the 'leading edge' of that reef with respect to the incoming cyclone wind direction. First, the aspect (direction into which each reef site faces) was calculated at a 500 metre resolution across each reef. Then, following Done (1992), the cosine of the difference between the aspect of the site and the incoming wind direction was found. This was then multiplied by the wind speed at that site (negative values were set to 0). Wind speeds were thus maximised when the difference was 0 (at the leading edge of the reef) and minimised when the difference was 90 or more (Figure 4).

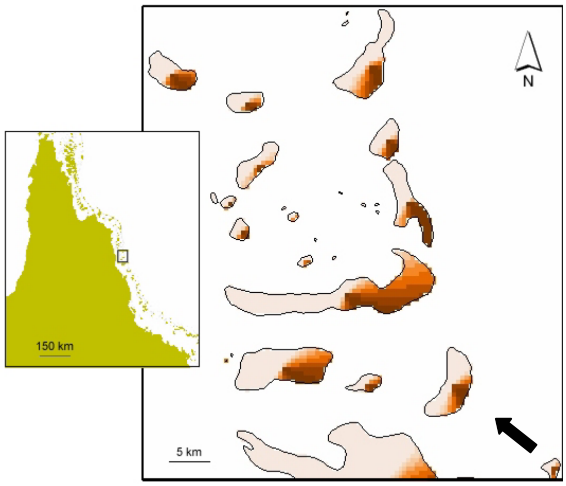

Figure 4. Concentration of predicted surface wind speeds (adjusted for within-reef shelter) at the 'leading edge' of selected reefs with respect to the incoming wind direction (arrow) for one eye

position of cyclone Joy (1990). Darker colours represent higher wind speeds.

3.2 Between-Reef Shelter

The exposure of a site to local wind-sea depends largely on the distance of water over which winds can blow uninterrupted to the site (fetch). To estimate this, I calculated the distance between each reef site and the nearest obstacle in all directions at intervals of 45 degrees. The longest uninterrupted period where winds, adjusted for within-reef shelter, exceeded gale force was found. Exposure during the cyclone was calculated as the average distance across the range of directions of winds approaching the site during this period (Figure 5).

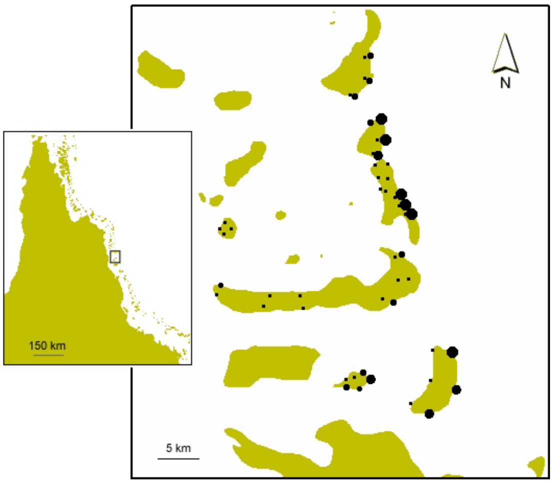

Figure 5. Exposure of selected reef sites surveyed following cyclone Joy to local wind-sea from the longest unbroken period of winds exceeding gale force. Larger circles indicate longer distances to the nearest obstacle in the predominant direction of wave approach during the period (greater exposure). Directions vary by site and thus are not shown here.

The analysis assumes that obstacles block 100% of the incoming energy from a given direction. While this is likely true for the coastline and islands, some wave energy may survive after encountering reefs. The extent of this 'leakage' will depend on the size, shape and orientation of the reef as well as the water depth and the tide. Specifically, reefs block more energy when waves approach at low tide (Hardy 2001). So, some sites are likely more exposed under certain circumstances than predicted by the model. While a tide model of the GBR is under development by researchers at James Cook University, at present predicting the tide for every site of interest over the entire time period is a major undertaking that was beyond the scope of this project.

3.3 Ambient Exposure

By averaging the distance to the nearest obstacle to the east, southeast and south, I approximated the ambient exposure of each site to local wind-sea (Figure 6).

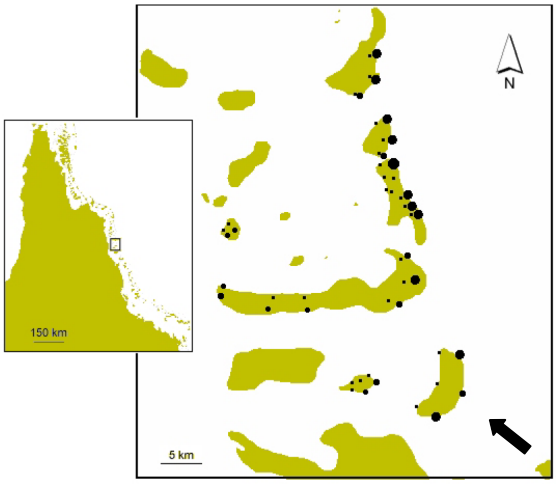

Figure 6. Ambient exposure of selected reef sites surveyed following cyclone Joy to local wind-sea. Larger circles indicate longer distances (greater exposure) to the nearest obstacle in the direction of typical wave approach (arrow).

Sites that are normally sheltered from wave energy may contain larger coral colonies exhibiting more fragile growth forms (Done 1992). The largest potential for physical impact occurs when these normally sheltered sites are exposed to cyclone energy after a long period undisturbed. To approximate this, I subtracted the exposure distance of sites during the cyclone from their ambient exposure. Where values were positive, the site was less exposed during the cyclone than normal (fewer impacts expected). Where values were negative, the site was more exposed during the cyclone than normal (more impacts expected). Zero values indicate no difference. Sites that were predicted to be more exposed than normal during cyclone Joy sustained slightly more damage than those that were exposed less than normal (Table 1). Interestingly, sites predicted to be equally as exposed during the cyclone as normal sustained the least damage.

Table 1. Relative exposure during cyclone Joy and total damage sustained (maximum recorded damage = 22.5).

	Total Damage		
Cyclone Exposure	*Mean*	*Max*	*Min*
< normal	4.31	20	0
same	1.3	9	0
> normal	5.54	22.5	0

4. PREDICTING REEF DAMAGE

Classification and regression tree (CART) analysis is used to determine how well observed patterns of physical impacts from cyclones for which field observations of damage are available (such as Joy) can be explained by hindcast cyclone energy and reef vulnerability measures. CART is ideal for this task because it can handle both numeric and categorical data, deals effectively with missing observations, allows for a multi-level categorical response variable (levels and types of damage), is non-parametric, and is easy to use (De'ath et al 2000).

A range of trees were built to examine whether the type of damage sustained during cyclone Joy made a difference to how well it could be explained by cyclone energy and reef vulnerability factors. Below is the tree that explains the distribution of collapsed slabs of the reef matrix (Figure 7).

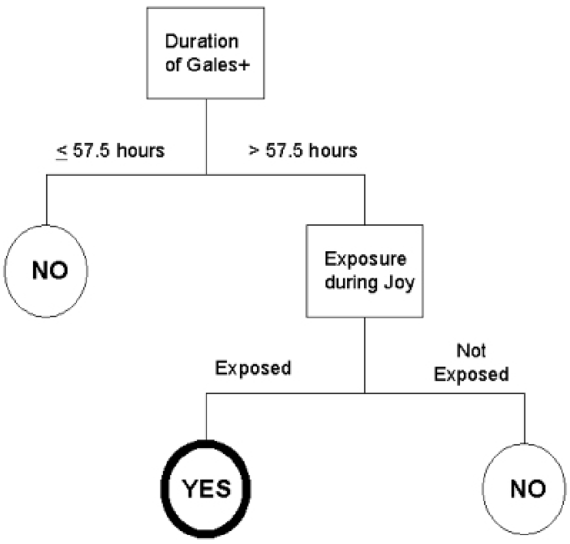

Figure 7. Classification tree to explain the distribution of collapsed slabs of the reef matrix across 199 reef sites surveyed following cyclone Joy (1990).

Sites were classified as containing collapsed slabs or not based on the duration of gale force or higher winds during the storm and the level of exposure to cyclone energy. Sites predicted by the tree to contain collapsed slabs (yes) are those that sustained gale force+ winds for more than 57.5 hours and were located in an exposed position on the reef.

Each tree differed in its ability to correctly classify sites into damage categories (Table 2).

Table 2. Cross-validated (10-fold) classification accuracy (% cases accurately predicted) attained by classification trees comparing damage to hindcast cyclone energy and reef vulnerability measures for cyclone Joy.

	Classification Accuracy		
Type of Damage	**Yes**	**No**	**Mean**
Collapsed Slabs	89.5%	93.9%	91.7%
Debris Scars	78.6%	84.3%	81.5%
Substrate Peeled Back	77.0%	83.2%	80.1%
Sand Movement	85.7%	69.8%	77.8%
Piles of Coral Rubble	67.1%	85.8%	76.5%
Broken Corals	61.3%	91.3%	76.3%
All types	57.3%	86.8%	**72.1%**
Soft Coral Stripping	60.0%	79.3%	69.7%
Massive Corals Dislodged	50.6%	83.1%	66.9%

A different combination of energy and vulnerability factors was important for each tree. For example, the duration of gale force or higher winds was the most important energy factor to explain patterns in collapsed slabs, broken corals, and piles of coral rubble. In contrast, the maximum energy sustained over the entire storm was more important for sand movement, substrate peeling, and damage in general. For vulnerability factors, the degree of exposure of each site under ambient conditions was important for some trees, while the exposure during the cyclone was important for others. Because of these differences, the combined damage tree is one of the least accurate in describing damage patterns, especially for predicting where damage will occur.

Similarly, the set of trees built for each of the other two cyclones (Ivor - 1990, Justin - 1997) for which complete field data is available will differ in the combination of energy and vulnerability factors used, as well as in their classification accuracy. Cyclone Justin, for example, was unusually long-lived, slow moving and large in extent - modelled wind speeds and directions are likely to be less reliable (as found by McConochie et al 1999). For these reasons, classification success may be less for the combined CART model that will be used to predict the distribution of damage across the GBR from each of the remaining cyclones.

5. CONCLUSION

Predicting the spatial distribution of cyclone impacts on coral reef communities is a difficult task. Not only does much of the needed data not exist (particularly for assessing reef community vulnerability), but there is a mismatch of scales between hindcast cyclone energy factors (1-5 km) and reef damage observations and vulnerability measures (1-10 m). Further, there is considerable uncertainty in the data that does exist, or can be generated (Puotinen 2003). Despite this it was possible to predict where damage (and particular types of damage) occurred across the GBR during cyclone Joy based on hindcast cyclone energy and reef vulnerability measures. However, given that the final predictive model will be based on such a small set of field observations (three cyclones with complete data, three cyclones with partial data), it is unknown whether its apparent classification accuracy will be be achieved for the rest of the cyclones for which damage will be estimated.

Cyclone energy hindcasts could be improved by considering the effects of storm surge and tides (although this would require a considerable effort) and, if data is available, incorporating synoptic winds. Examining archives at the Australian Bureau of Meteorology's Research Centre may yield more accurate eye diameters. Though time consuming, this would be quite useful as the wind model is sensitive to the eye width which is known to be highly variable. Conducting field surveys of reef damage after future cyclones would expand the very limited ecological database.

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