Mapping tropical cyclone disturbance of the Great Barrier Reef

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Abstract
Tropical cyclones periodically cross the Great Barrier Reef (GBR). The large waves they generate can damage coral reefs. This paper will describe the challenges of mapping cyclone disturbance across such a vast geographic region, and how cartographic visualisation can help us understand the implications of these challenges on the quality of the results.

Keywords
reef, great, cyclone, tropical, barrier, disturbance, mapping

Disciplines
Medicine and Health Sciences | Social and Behavioral Sciences

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Mapping Tropical Cyclone Disturbance of the Great Barrier Reef

Marji Puotinen

Tropical cyclones periodically cross the Great Barrier Reef (GBR). The large waves they generate can damage coral reefs. This paper will describe the challenges of mapping cyclone disturbance across such a vast geographic region, and how cartographic visualisation can help us understand the implications of these challenges on the quality of the results.

Australia’s Great Barrier Reef (GBR) forms the largest coral reef system in the world, including nearly 3000 individual reefs that stretch for more than 2000 km along the Queensland coast and cover an area of over 348 000 km² (CRC Reef Research Centre, 2002). In recognition of its outstanding natural beauty and bio-diversity, the GBR has been protected within a Marine Park since 1975 and a World Heritage Area since 1981. Further, the GBR region supports a billion-dollar tourism industry as well as several economically important fisheries. However, a range of natural and human-caused disturbances threaten the region, including tropical cyclones, coral bleaching, crown-of-thorns starfish and reduced water quality.

Over time, tropical cyclones track throughout the entire GBR region (Figure 1). The large waves they generate break along shallow reef areas, resulting in impacts ranging from broken corals to removal of entire sections of reef structure. Severe disturbance, where long-lived, large coral colonies are destroyed or major damage is widespread (Figure 2), can require centuries or longer for reefs to fully recover. Over time, repeated widespread impacts have the potential to significantly alter coral reef community structure, which may reduce the value of particular reefs as tourist destinations or fisheries, or as habitat for other resident species. In combination with other disturbances, this can cause permanent changes. For example, in Jamaica, hard corals now struggle to compete with algae after damage from two hurricanes was exacerbated by overfishing (Hughes, 1994). Thus, to provide for “the protection, wise use, understanding and enjoyment of the Great Barrier Reef in perpetuity”, the Great Barrier Reef Marine Park Authority needs to understand which reefs are likely to be affected by cyclones and how often.

Mapping the risk of cyclone disturbance across the GBR over time poses many challenges. While the region is vast and cyclones affect large areas at a time, damage surveys and reef vulnerability to impacts take place over short time periods and across small areas (square metres) – creating a mismatch of scales. Further, the positional and attribute uncertainty inherent in key data sets, such as cyclone paths and reef polygons, is unquantifiable but estimated to be significant.

Given these difficulties, is it really necessary to map cyclone disturbance across the entire GBR? While local-scale studies of cyclone disturbance of particular reefs or groups of reefs are valuable, it is not possible to build a regional picture from these studies alone. Such studies presently cover only a limited extent of the GBR and a short time span of the cyclone history (Table 1).
Figure 1. Number (A) and paths (B) of tropical cyclones that tracked near Queensland, Australia from 1910 to 1999. Tracks were generated from the tropical cyclone database (Australian Bureau of Meteorology 2000).

Figure 2. Dislodgment, breakage, and burial of massive coral heads during Cyclone Ivor, 1990. The white bar equals ~1 metre. Photograph by Dr. Terry Done (from Puotinen et al. 1997).
<table>
<thead>
<tr>
<th>Year</th>
<th>Cyclone</th>
<th># Sites</th>
<th># Reefs</th>
<th>Region</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>Althea</td>
<td>27</td>
<td>10</td>
<td>Swains</td>
<td>Hartcher 2001</td>
</tr>
<tr>
<td>1990</td>
<td>Ivor</td>
<td>63</td>
<td>33</td>
<td>Cairns -</td>
<td>Cooktown</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Done 1992</td>
</tr>
<tr>
<td>1990</td>
<td>Joy</td>
<td>186</td>
<td>33</td>
<td>Cairns -</td>
<td>Cooktown</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ayling 1991</td>
</tr>
<tr>
<td>1971-</td>
<td>Various</td>
<td>6</td>
<td>1</td>
<td>Heron Island</td>
<td>Connell et al 1997</td>
</tr>
<tr>
<td>1992</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>Celeste</td>
<td>7</td>
<td>6</td>
<td>Whitsundays</td>
<td>DPI 1996</td>
</tr>
<tr>
<td>1997</td>
<td>Justin</td>
<td>54</td>
<td>13</td>
<td>Townsville,</td>
<td>Puotinen 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Whitsundays</td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>Justin</td>
<td>55</td>
<td>35</td>
<td>Swains -</td>
<td>Puotinen 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cooktown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>398</td>
<td>131</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.** Cyclone damage observations available for the Great Barrier Reef.

Moreover, although cyclones track through the far north (between 10-11° S) of the GBR less frequently than elsewhere, there are no sections of the GBR that are completely free of cyclones (Puotinen et al 1997) and that could be eliminated from consideration. In fact, the maximum distance of most reefs in the region to the nearest cyclone from 1969-1997 was within 30 km (**Figure 3**).

Given that studies indicate cyclone damage to reefs is possible up to 100 to 200 km (Done 1992, Connell et al 1997) away from a cyclone’s path, every reef in the GBR has been located within striking distance of at least one cyclone over the past 30 years. Further, researchers have found that the coral larvae produced on one reef can be transported to other reefs by ocean currents, though the spatial extent of this connectivity has yet to be established. This means that the ability of coral species to recolonise a particular reef after a major cyclone disturbance could depend on the extent and severity of disturbance sustained by nearby reefs throughout the GBR.
### Issues and Challenges

The ability to map cyclone disturbance is limited by a general lack of key data sets, as well as high levels of uncertainty in the data that is available (Table 2).

#### Eye Positions

Obviously it is vital to know where a particular cyclone tracked in order to map the disturbance it caused. Cyclones are tracked using a combination of satellite and radar imagery and land and ship-based observations. The timing of the observation varies depending on the proximity of the cyclone to land-based communities. The quality of the observation depends on the combination of methods used. Radar produces the most accurate observations, though many cyclones track outside radar range.

While cyclone eye positions have been recorded in Australia since about 1910, the reliability of these positions is largely unacceptable before the advent of widely available satellite imagery in 1969 (Holland 1981). Researchers at the Australian Bureau of Meteorology Research Centre estimate that errors in initial cyclone positions can exceed 400 km in any direction (Figure 4A), though most are within 100 km (Woodcock 1995).

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**Table 2.** Challenges associated with mapping cyclone disturbance of reefs.

<table>
<thead>
<tr>
<th>Issues</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclone Paths</td>
<td>Cyclone movement between eye positions unknown and presumed linear.</td>
</tr>
<tr>
<td>Cyclone Eye Width</td>
<td>Often difficult to measure, often not recorded, very important to cyclone energy models.</td>
</tr>
<tr>
<td>Cyclone Models</td>
<td>Mesoscale in nature (10s of km) - don't incorporate local scale effects such as rain bands</td>
</tr>
<tr>
<td>Reef damage observations</td>
<td>Very limited number available. Biased towards damaged sites. Measured at a very local scale (meters).</td>
</tr>
<tr>
<td>Reef vulnerability</td>
<td>Very little data exists. Highly variable over short time periods and small distances.</td>
</tr>
</tbody>
</table>
While this does not reveal the level of error remaining in the revised cyclone tracks, it suggests a high level of positional uncertainty.

**Intensity**

The magnitude and extent of the winds and waves generated by a particular cyclone depends largely on its intensity. The central air pressure, in hPa, of a cyclone is commonly used as a measure of intensity. As central pressure falls, the difference in air pressure between the cyclone and the external environment increases, powering the storm. Central pressure is rarely measured directly and is typically estimated using satellite imagery (Dvorak 1975). Initial central pressure measurements have also been found to be in error (Figure 4B), suggesting considerable uncertainty in cyclone intensity estimates.

**Eye Width**

Every cyclone contains a relatively calm region at the centre of the storm circulation called the eye. Wind speeds are near zero within the eye, while they are at their maximum around the boundary, called the eye wall. Defining the diameter of the eye is thus important to accurately reconstructing the cyclone’s energy. However, cyclone eyes can
be very dynamic over short time periods, sometimes with a double eye structure (Willoughby 1990). In addition, the presence of upper atmospheric cloud can make it difficult to measure eye width from satellite imagery (Figure 5). Subsequently, eye width is not always recorded in the tropical cyclone database.

**Figure 5.** Satellite images of tropical cyclone eyes. Though the cyclones are of similar intensity, in B the eye is clearly visible, while in A it is obscured by upper atmospheric clouds.

**Model Scale**
Another problem is that the meteorological models used to estimate cyclone energy are designed to operate across broad spatial scales with a resolution of 1-10 km. The processes that control the finer scale dynamics of cyclones have not yet been adequately modelled.

**Damage Observations**
While basic data about the cyclones that have tracked through the GBR during the last three decades is available, observations of reef damage from these cyclones are very limited in both spatial and temporal distribution (Table 1). Broad scale field surveys were conducted only for cyclones Ivor and Joy in 1990 and Justin in 1997. Some data can be gleaned from crown-of-thorns starfish survey records (Althea in 1971) and from incidental reports (Celeste in 1996). The only long term data set available is a study of reefs near Heron Island over three decades (Connell et al 1997). Field surveys in the marine environment are expensive and time consuming. It is simply not feasible to visit every reef that could have been affected by a cyclone across 100s of square kilometres. Thus, researchers typically target surveys in areas where cyclone damage seems most likely (Table 3). However, this creates a bias in the data, which reduces the potential strength of predictive models that are developed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cyclone</th>
<th>% Surveyed Sites Damaged</th>
<th>% GBR Sites Potentially Damaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>Ivor</td>
<td>75</td>
<td>74</td>
</tr>
<tr>
<td>1990</td>
<td>Joy</td>
<td>63</td>
<td>12</td>
</tr>
<tr>
<td>1996</td>
<td>Celeste</td>
<td>63</td>
<td>8</td>
</tr>
<tr>
<td>1997</td>
<td>Justin - field survey</td>
<td>56</td>
<td>7</td>
</tr>
<tr>
<td>1997</td>
<td>Justin - questionnaire</td>
<td>60</td>
<td>7</td>
</tr>
</tbody>
</table>

**Table 3.** Percentage of field survey observations found to be damaged versus the number of reefs potentially damaged by cyclone waves.

**Reef Vulnerability**
As previously mentioned, the likelihood of cyclone damage to a reef depends just as much on the vulnerability of that reef to impact as it does on the intensity of cyclone energy. Vulnerability is controlled by a range of highly variable factors, such as the history of disturbance at a site and the predominant size and types of corals growing there. This information is poorly known for much of the GBR, most of which has never been directly surveyed (Figure 6). Vulnerability also depends on the relative exposure of sites to waves during a cyclone versus ambient conditions, which can be modelled based on the relative positions of reefs and other wave blocking obstacles such as the coastline and islands. Although the boundaries of the reefs have been mapped as vector polygons, this was done using satellite imagery and was verified by field surveys for only a small fraction of the reefs. Further, the definition of reef that is used, as well as the scale and timing of the observations, can make a big difference to the resultant reef polygons (Spalding and Grenfell, 1997).

In summary, much of the data needed to map cyclone disturbance of the GBR is missing. The data that is available contains unknown, but potentially large, uncertainties in both position and attribute. Further, there is a mismatch of spatial scales between the cyclone data from 1 km to 10 or more and the reef vulnerability data in square metres. Finally, the study area is vast but must be modelled at a high resolution (500 m pixel) in order to adequately depict the basic outlines of most of the reefs.
Figure 6: Location of reefs where at least one (black squares) or at least three (grey squares) surveys were conducted from 1992 to 1999 by the Australian Institute of Marine Science. The grey polygon outlines the GBR Marine Park. The number of reefs that were monitored for each $1^\circ$ of latitude is listed (number of reefs surveyed at least three times are in brackets).

CREATIVE SOLUTIONS

Although the major uncertainties inherent in this project are unavoidable, the work is still worthwhile as long as some estimate of the confidence of the results, and thus how they should be appropriately used, can be made. For example, cartographic visualisation can be used to assess the implications of large uncertainties in the position of the cyclone eye to the modelling based on those positions. The cyclone database records the methods used to estimate each cyclone eye position. They involve direct, radar and satellite observations, or a combination of these. As previously mentioned, Holland (1981) and Woodcock (1995) have estimated the level of potential uncertainty associated with using each of these methods. Although this is not an actual measure of error, it does provide a ‘worst case scenario’ of the maximum error likely in each eye position.

To visualise this potential error, I constructed uncertainty circles around each eye position for cyclones Ivor and Justin, with the radius of each circle equal to the likely maximum positional error (Figure 7). Thus, each cyclone eye position could be located anywhere within its uncertainty circle. Interestingly, eye positions for cyclone Ivor were more uncertain when the cyclone was closer to land. This occurred because it was relatively weak at that stage, and thus was tracked less diligently. In contrast, cyclone Justin’s eye positions were most uncertain when it was located far out to sea. This occurred because it was out of radar range and posed no immediate threat to the Queensland coast at that time.
Figure 7. Uncertainty circles (grey) for each recorded eye position (black dots) of cyclones. A) Ivor (1990) and B) Justin (1997).
Figure 8. Uncertainty zones for the tracks of cyclones: A) Ivor (1990) and B) Justin (1997). Shading indicates the number of times each position was located within an uncertainty circle during the cyclone.
To get an idea of how this uncertainty varied throughout each entire cyclone, I counted the number of times each position across the GBR was located inside an uncertainty circle, and thus could have a cyclone eye passing directly through it (Figure 8). Where the colours are more pink than red, the uncertainty of the cyclone eye positions is low, such as when cyclone Justin tracked southward down the Queensland coast. Where the colours are more red than pink, the uncertainty is high, such as where cyclone Ivor tracked down the coast or where cyclone Justin was located far out to sea. Reefs of interest, such as those for which damage data is available, can be overlaid with the uncertainty zones to assess the confidence with which the relevant cyclone energy measures should be used. For example, uncertainty in the location of cyclone Justin’s eye was highest while the cyclone was located in the middle of the Coral Sea (Figure 8), which is when most of the reef sites surveyed after the cyclone were probably damaged. This suggests that reconstructed cyclone conditions for this period are likely to be in error and that the predictive model for cyclone Justin is likely to be poor. In addition, animated movies of this uncertainty could be used to show how it changes over time.

CONCLUSION

Mapping cyclone disturbance of the GBR is difficult due to a general lack of necessary data and potentially large uncertainties in both the location and attributes of the data that is available. However, it is possible to build a predictive model of cyclone disturbance by linking field observations of reef damage from cyclones to hindcast cyclone energy and reef vulnerability measures. Creative use of cartographic visualisation, as demonstrated in the previous section, is essential for estimating the implications of data uncertainty on the model results and the confidence with which they should be used.

REFERENCES
