Impact of Data Uncertainty on the Spatio-Temporal Distribution of Australian Cyclones, 1906-2006

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EXTENDED ABSTRACT

Tropical cyclones (known elsewhere as hurricanes or typhoons) regularly track through Australia's northern coastal regions (Figure 1).

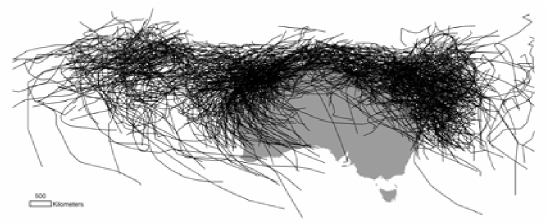

Figure 1. Tropical cyclone tracks (black lines) near Australia (gray polygon) recorded by the Australian Bureau of Meteorology from 1906-2006, reconstructed by the author as of May 2006.

Data documenting the basic characteristics of cyclones in the Australian region is available from the Bureau of Meteorology (BOM) as early as 1906. This data set (freely available in ASCII format at http://www.bom.gov.au) records some 41 attributes (most of which are not complete for the entire time series) for 22,645 individual cyclone eye positions. Because cyclones can cause considerable impact to both marine and terrestrial environments, data sets such as this are widely used to reconstruct past cyclone conditions (for example, see Berz et al 2001, Peduzzi et al 2005, Puotinen 2007) to enable comparisons with what may happen in the future under global climate change (i.e., Webster et al. 2005, Walsh et al. 2004). Because cyclones tend to vary on long time scales (centuries or more), the accuracy of this type of modeling is sensitive to the length of the time series on which the analysis is based (Nott 2003). Thus, long time series are of particular value.

However, inherent in long-term cyclone data for much of the world is considerable positional and attribute uncertainty. For example, in Australia, cyclones that tracked far from populated areas prior to the satellite era (pre-1970) may not have been detected at all, eye positions could be in error by up to 20-500 km in any direction, and storm intensity was likely to be underestimated (Holland 1981). Further, key data fields essential for modeling (i.e., central pressure) are often missing. This makes it difficult to determine whether apparent long-term spatio-temporal trends in cyclone data sets are reliable.

Although the most severe of the potential problems associated with the Australian cyclone database can be avoided by not using records prior to 1970, uncertainties remain in the more current data, particularly with the estimate of storm intensity (Harper and Callaghan 2006). The reliability of methods used worldwide to estimate cyclone intensity has changed considerably over even recent times (i.e., last 30 years). For example, reporting regions within BOM vary in how they have and continue to employ the methods and standards (i.e. Western Australia and Queensland often, but not always, use different methods for particular cyclones – pers comm. J. Callaghan) and no record of this is kept in the cyclone database. In addition, positional uncertainty remains prevalent in the post-1970 data, and varies between cyclones (and between eye positions in a given cyclone) based on the method that was used to pinpoint the eye position (the details of which are only sporadically recorded in the cyclone database). Further, the timing of observations varies from one to 24-hourly depending on the perceived threat of the cyclone to populated areas. If a cyclone is moving rapidly, infrequent estimates result in a large distance between observed eye positions over which cyclone characteristics are unknown.

As a result of the above uncertainties, this paper demonstrates that apparent trends in even the more current data may not be reliable. While calls to upgrade the cyclone database (Harper and Callaghan 2006) are welcome, in the meantime, innovations in uncertainty research can be employed to at least explore their implications for if and how the data can effectively be interpreted.

1. SOURCES OF UNCERTAINTY

The Australian Bureau of Meteorology (BOM) defines a tropical cyclone as a "non-frontal synoptic scale cyclonic rotational low pressure system of tropical origin, in which 10 minute mean winds of at least 17.5 m.s-1 (gale force) occur [with] the belt of maximum winds being in the vicinity of the system's centre" (McBride and Keenan 1982).

Cyclones are rarely measured directly due to the danger posed by high winds and large waves, the tendency of instruments to fail when maximum conditions are reached, and the difficulty of predicting where a cyclone will move. Although it is possible to obtain direct measurements by flying through storms with specially designed aircraft, in Australia this has only been done for two cyclones - Kerry and Rosa in 1978-79 (Lourensz 1981). Meteorologists instead rely on land-based radar, satellite imagery (Dvorak 1975), and observations from ships and remote automatic weather stations to detect and estimate the basic characteristics of cyclones, such as their location, central pressure, and radius of maximum winds (Lourensz 1981). There is considerable positional and attribute uncertainty in the Australian cyclone database due to the lack of direct observations (Davidson and Dargie 1996, Holland 1981), which arises primarily from: 1) locating the cyclone eye, 2) measuring storm intensity, and 3) interpolating between observations.

1.1. Locating the cyclone eye

Tracking the position of a cyclone is generally easier for a more intense storm because the eye is often more clearly defined as the storm strengthens (Figure 2B), though high-level cloud may obscure even a well-defined eye (Figure 2A).

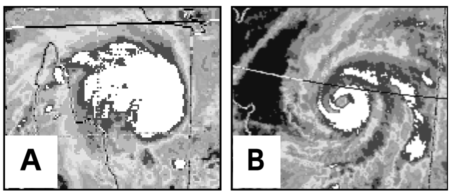

Figure 2: Satellite images of tropical cyclone eyes. Note that though the cyclones are of similar intensity, in [B] the eye is clearly visible, and in [A] it is obscured by upper atmosphere clouds.

Cyclones that track closer to land (within range of coastal radar) can be analysed with greater accuracy. Before 1970, when satellite imagery became widely available, meteorologists had great difficulty in detecting and tracking cyclones beyond radar range. For post 1970 cyclones, Holland (1981) estimates errors in the position of the cyclone eye from ± 20-50 km for storms within 500 km of the coast, and from ± 50-100 km for storms beyond. F. Woodcock, BOM (unpublished data) assessed the difference in cyclone eye position and intensity estimates between initial forecasts and subsequent refinement of the data, which provides a measure of the uncertainty in the data, from 1910 to 1995. He found that the majority of cyclone eye positions were subsequently altered by less than 100 km, although the maximum change was more than 400 km.

The method by which eye position was estimated (position code - another indicator of potential positional uncertainty) was recorded in the cyclone database for just under one-third (7070 of 22,645) of the eye positions - only for cyclones that occurred after 1983 (Table 1).

Table 1: Methods by which Australian cyclone positions are established, the estimated quality of the resultant data, and their relative frequency within the database, 1984-2006.

Position code	Description	Rating	% of those recorded
1	No satellite data, no radar data, no observations.	Very poor	1.7
2	No satellite data, no radar data, observation from ship within 60 nm.		3.8
3	Satellite imagery used; no clear eye visible.	Poor	***67.6***
4	Satellite imagery used; eye clearly defined.	Good	10.3
5	Aircraft radar report.		0.0
6	Land-based radar report.		8.0
7	Combination of #3-6.	Very good	7.6
8	Direct measurement taken from within the eye.		0.1
9	Method used unrecorded / unknown.	-	0.8

Based on this, the positional accuracy of the majority of the data (~73%) is likely to be poor to very poor and less than 10% is likely to be very good. Plotting the point locations of eye positions that fit into the former (Figure 3A) and latter (Figure 3B) categories shows no clear spatial pattern that could be filtered out of the data.

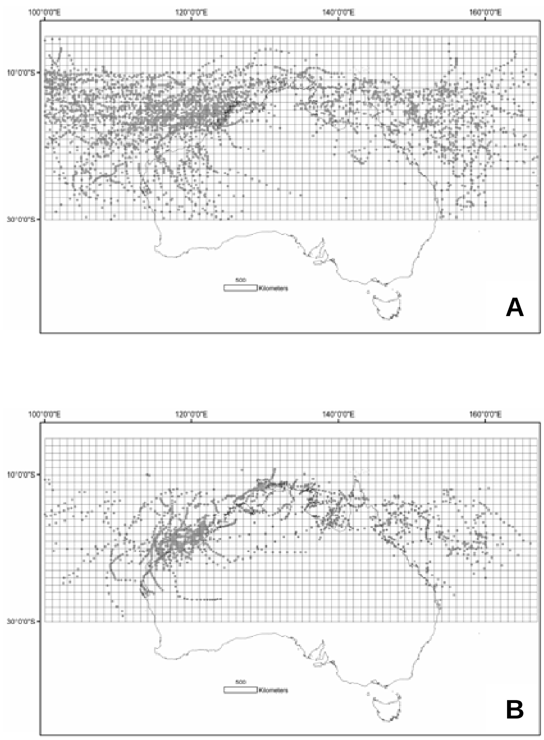

Figure 3: Estimate of positional accuracy (as recorded in the tropical cyclone database) of tropical cyclone eyes crossing a regular grid of one-degree latitude by longitude blocks that spans northern Australia and adjacent waters, based on the nature of the observation method used: A – very poor (position codes 1-2) to poor (position code 3) and B – good (position codes 4-6) to very good (position codes 7-8).

1.2. Measuring cyclone intensity

Cyclones are powered by the difference in pressure between the centre of the storm (central pressure, measured in hPa) and the ambient environment. Since variations in the ambient pressure are typically small, the central pressure alone provides a reasonable indication of cyclone intensity (lower pressure equals greater intensity), though estimates of wind speeds (calculated from satellite imagery) are sometimes also used.

In Australia, initial central pressure estimates are often subsequently reduced by up to 15 hPa (Woodcock unpublished data, Holland 1981), indicating that intensity is often underestimated. This remains a problem even for the most recent data (Harper and Callaghan 2006).

The method by which cyclone intensity was estimated (central pressure code) was recorded in the cyclone database for just over one-third (7632 of 22,645) of the eye positions for cyclones that occurred throughout the time series (Table 2).

Table 2: Methods by which Australian cyclone intensity is measured, the estimated quality of the resultant data, and their relative frequency within the database, 1906-2006.

Central pressure code	Description	Rating	% of those recorded
1	No satellite data, no observations.	Very poor	2.0
2	No satellite data, observation from ship within 60 nm.		4.4
3	Satellite imagery used (Dvorak method).	Uncertain	***45.6***
4	Wind - pressure relationship used.		3.8
5	Methods #3 and 4 combined used.		***34.1***
6	Extrapolation from radar used.		0.2
7	Direct measurement by an instrument.	Very good	9.2
9	Method used unrecorded / unknown.	-	0.8

Central pressure estimates using methods #3-6 are by far the most common (~84%) in the Australian cyclone database, yet are uncertain in quality due to the subjective nature of the approach. Adding to this is the fact that technological advances continue to improve the quality of the techniques, and these advances have been applied unevenly over time and across regions (Harper and Callaghan 2006). For example, meteorologists based in Western Australia, the Northern Territory and Queensland all apply the techniques differently (sometimes depending on the nature of a particular cyclone), and these differences are not recorded in the cyclone database (pers comm. J. Callaghan).

An effort is underway in the United States to re-assess past intensity measurements given the latest technology. Given that models used to reconstruct cyclone wind and wave fields are highly sensitive to intensity estimates (and direct measurements of cyclone winds and waves are rarely available), such an effort would be highly worthwhile for Australia.

1.3. Interpolating between observations

Although cyclone characteristics can vary over short time scales (less than an hour), it is rarely feasible to measure cyclone positions this frequently. Thus, to create a cyclone track, it is necessary to interpolate what likely happened between observations – most wind and wave models require standardisation to a one-hourly interval, a time period within which meteorologists generally assume most cyclones do not make major track changes (Thompson and Cardone 1996). Obviously, positional uncertainty in individual eye positions introduces uncertainty into the track of the cyclone that they define. Beyond this, there is also uncertainty in determining the path between observed eye positions (how to 'join the dots' – typically assumed to be a straight line). When a cyclone moves slowly and its eye positions are observed frequently, the distance between observations, and thus the uncertainty in defining the path, is low. However, eye positions are often estimated infrequently when cyclones track far from populated areas, and cyclones can move at up to nearly 40 km / hour. While the paths of cyclones generally tend to be curvilinear as they track from the tropics to the poles, local scale meanders in the paths follow no standard pattern.

Cyclone observations were recorded by the BOM at time intervals ranging from one-hourly to 24-hourly (Table 3).

Table 3: Time intervals at which Australian cyclone eye positions were recorded and their relative frequency within the database, 1906-2006.

Time step (hours)	% of those recorded	Time step (hours)	% of those recorded
< 1	0.1		
1	1.0	13	0.4
2	1.3	14	0.3
3	***51.6***	15	0.3
4	0.6	16	0.2
5	0.5	17	0.2
6	***31.9***	18	0.7
7	0.4	19	0.1
8	0.3	20	0.1
9	0.8	21	0.2
10	0.3	22	0.4
11	0.5	23	0.1
12	2.9	24	4.9

Of the 22,265 eye positions, the majority (~83%) were recorded at either three or six hourly intervals. Only 1% of them were recorded hourly. There was no relationship between the time step and the speed of the cyclone’s movement (i.e., smaller time steps were not necessarily used when the cyclone was moving quickly, suggesting scope for interpolation uncertainty).

It is important to note that the time step between observations often varies within a single cyclone, and that the values of key attributes like intensity are usually linearly interpolated between these observations, even though it is known that intensity can flux at very short time scales (less than an hour). Thus, cyclone observations spaced a long time intervals introduce attribute uncertainty in intensity, as well as positional uncertainty.

Finally, although a shorter time step is typically used when a cyclone moves near populated coastal areas, this does not produce a clear spatial trend Figure 4) because it also depends on the intensity of the cyclone at the time and its forecast track.

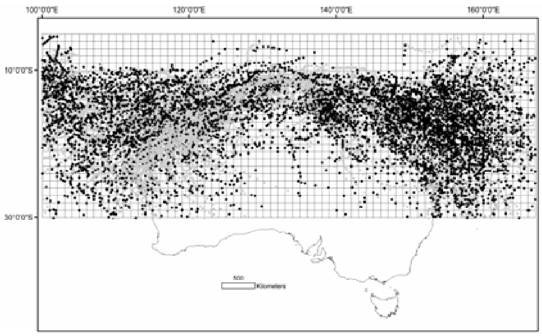

Figure 4: Spatial distribution of time intervals at which Australian cyclone eye positions were recorded (3 hours or less = gray, 4 hours or more – black), 1906-2006.

1.4. Summary

In summary, considerable uncertainties are embedded within the Australian tropical cyclone database due to differences in the effectiveness of the various methods for estimating the location and intensity of cyclones, as well as variation in the time interval at which the estimates are made. A clear improvement in the quality of the typical method applied is apparent post 1970, when satellite imagery became widely available in Australia (Holland 1981). However, uncertainties remain in the post-1970 data, especially with respect to the measurement of intensity.

This paper uses the Australian tropical cyclone database from 1906 to 2006 to illustrate how the uncertainties described above make it difficult to determine whether apparent trends in cyclone frequency and intensity across the region are reliable. It also suggests how recent research in modeling uncertainty could be applied to at least explore the implications of this uncertainty for use of these datasets, especially when the results are to be applied within a decision-making context.

2. NUMBER OF CYCLONES PRE AND POST 1970

Plotting the number of cyclones tracking through one-degree latitude by longitude boxes for the pre (before 1970 – Figure 5A) and post (after 1970 – Figure 5B) eras clearly shows a lower incidence of cyclones off northern Western Australia in the early part of the time series and off northern Queensland in the later part.

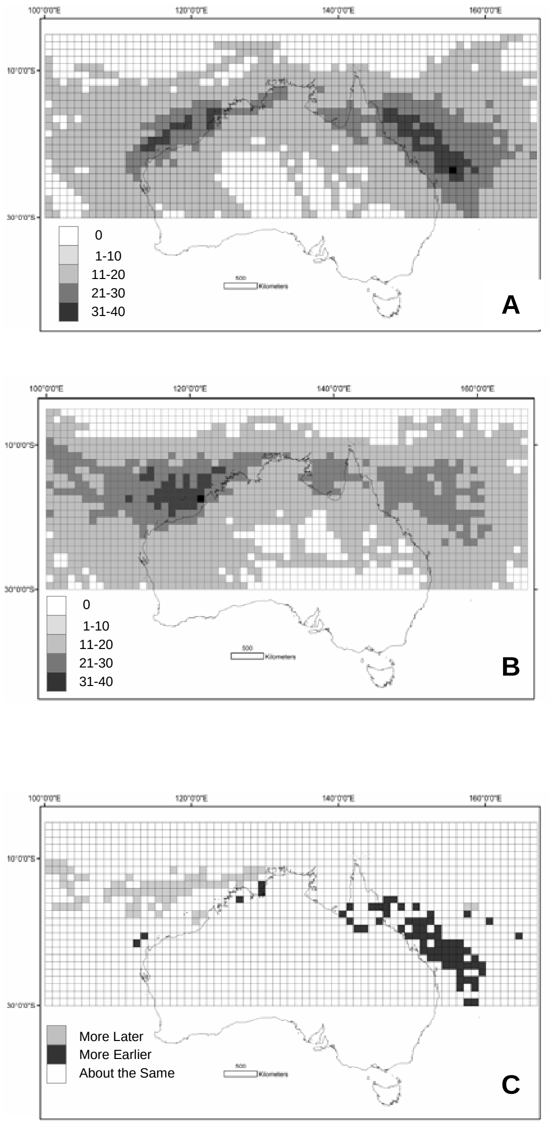

Figure 5. Total number of separate named tropical cyclones crossing a regular grid of one-degree latitude by longitude blocks that spans northern Australia and adjacent waters over the period A – 1906 to 1969 and B – 1970 to 2006; and C – their relative timing (measured by subtracting A from B with differences $\geq$ 10 considered significant).

A quantitative comparison (Figure 5C) highlights this trend. In the Australian region, it is likely that not all cyclones were detected prior to 1970 (before satellite imagery was widely available), particularly if located far from populated areas (Holland 1981). This underreporting seems to have been more severe for Western Australia, where far fewer cyclones were recorded prior to rather than post 1970 despite the greater length of the earlier time series (nearly twice as long).

3. CYCLONE INTENSITY PRE AND POST 1970

Plotting the maximum intensity reached by any cyclone tracking through one-degree latitude by longitude boxes for the pre (Figure 6A) and post (Figure 6B) eras suggests that the prevalence of severe (categories 4 or 5) cyclone intensity has increased considerably in recent times (despite the shorter time series), particularly for Western Australia.

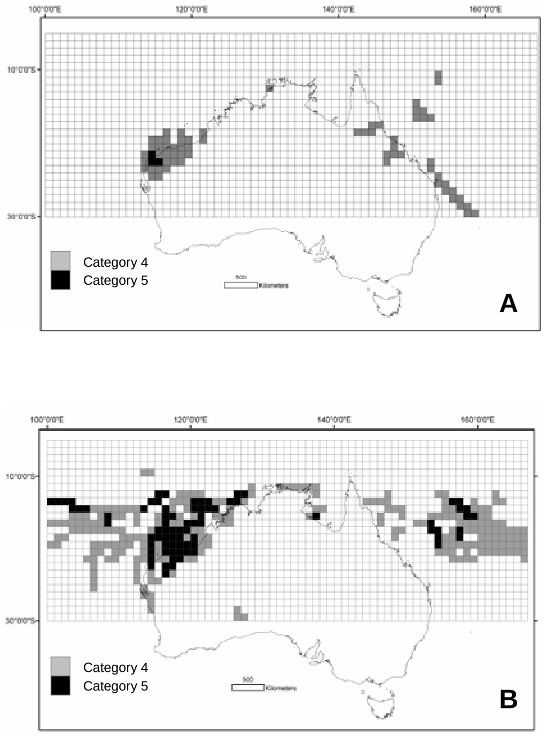

Figure 6. Maximum recorded intensity (as measured by minimum cyclone central pressure in hPa: category 4 = 920-945 hPa; category 5 = 920 hPa or less) of tropical cyclones crossing a regular grid of one-degree latitude by longitude blocks that spans northern Australia and adjacent waters, A – 1906 to 1969 and B – 1970 to 2006.

As is the case for the detection of cyclones in general, it is well recognised that advances in technology have continually improved the ability of meteorologists to estimate the intensity of tropical cyclones where direct measurements are not possible (almost always the case in the Australian region). An assessment of the likely result of uncertainties in the early methods used suggests that intensities were more likely underestimated than overestimated in the past, especially in the pre-satellite era (Holland 1981). Thus, the apparent increase in number of severe cyclones on both coasts over time most likely does not reflect reality. Complicating this is the fact that intensity was not always recorded in the database – it was missing for ~39% of eye positions pre-1970 and ~57% of those post-1970.

4. CONCLUSIONS AND RECOMMENDATIONS

Considerable positional and attribute uncertainties exist in databases that record tropical cyclone positions and characteristics, both in Australia (Holland 1981) and worldwide (Harper and Callaghan 2006). Thus, studies that use this type of data, particularly for the pre-satellite era (for example, Woodley 1992, Treml et al 1997 – Caribbean; Massel and Done 1993, Puotinen 2004, 2007 – Great Barrier Reef; Balling and Cerveny 2003 – North America) should be interpreted with care – at the least acknowledging that apparent spatio-temporal trends may or may not be reliable.

A very simple approach, which would be suitable for visualising the variation of positional uncertainty along individual cyclone tracks, involves constructing 'uncertainty circles' around eye positions using a radius proportional to the level of uncertainty embedded in the method by which the eye position was mapped, and then identifying areas located within the largest number of uncertainty circles as those most likely to have been in the direct path of the eye during the storm (Puotinen 2004a).

Similarly, a range of more sophisticated analyses would be possible for those eye positions for which the method used to map the eye was recorded (for Australia, observations post 1983). Much work has been done over the past decade or so to develop techniques in GIS for modeling data error and uncertainty (for example, in natural resources - Lowell and Jaton 1999, in ecology - Hunsaker et al 2001). Future research should draw upon this well developed literature to devise a technique to identify, for example, the most probable locations of cyclone tracks of given intensities based on a set of simulations constrained by their estimated level of positional and attribute error.

It is also worthwhile exploring more sophisticated techniques (than simple linear methods) for interpolating between cyclone eye positions, particularly those that were taken far apart in time when the cyclone was moving quickly. For example, the 'constrained random walk' technique outlined by Wentz et al (2003) could be adapted for use in generating cyclone tracks and tested for the Australian region as a case study.

Finally, and perhaps most importantly, another option would be to model and then express the risk the level of positional and attribute uncertainty in a given cyclone database poses to decision makers who use the data (or modeling based on it) by adapting procedures described by Agumya and Hunter (2002).

5. ACKNOWLEDGEMENTS

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