JP3.1 AN ENHANCED TROPICAL CYCLONE DATA SET FOR THE AUSTRALIAN REGION

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1. INTRODUCTION

There has been considerable interest in the question of whether or not there is evidence of a significant increase in tropical cyclone activity (e.g. Emanuel, 2005; Webster et al., 2005; Landsea et al., 2006). A necessary prerequisite for rigorous analysis of long-term trends in cyclone activity is the existence of an underlying data set which is homogeneous, that is, one where any changes reflect changes in the underlying climatic conditions, and not influences arising from changes in the way in which the data are observed.

Numerous homogeneous data sets have been produced for surface air temperature over the last 10-15 years, both on the global (e.g. Jones and Moberg, 2003) and national (e.g. Torok and Nicholls, 1996) scale. More recently similar data sets have been produced for other climate variables (e.g. Jovanovic et al., 2007, for pan evaporation).

Until very recently, there had been no comprehensive attempt to develop a homogenised tropical cyclone data set for any region. Kossin et al. (2007) were the first to develop a homogenised global data set for the period 1983-2006, using satellite imagery degraded to a resolution typical of the mid-1980s, and intensity assessments using an automated (Dvorak) technique. There is also a major re-analysis project for the North Atlantic basin in progress (Landsea et al., 2003). No homogeneous data set has been published for the Australian region, although an unpublished (to date) limited-area reanalysis covering the Timor Sea region for the period 1968-2001 has been carried out on behalf of local oil and gas interests (Harper et al., 2008). Holland (1981) documents the quality of the available Australian-region data set to that time.

This paper describes the first stage of a project to develop, as far as possible, a homogeneous tropical cyclone data set for the Australian region. In addition to supporting analyses of observed climate change, such a data set will support more accurate risk assessments for tropical cyclones under the existing climatic regime. Such assessments are of great importance in many engineering and emergency management applications, with a particular focus on the north-west coastal region of Western Australia, the most cyclone-prone part of the Australian coastline, where there are major concentrations of mining and oil and gas production, with 2006 revenues of approximately US$28 billion (WA Department of Industry and Resources, 2007).

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2. THE AUSTRALIAN REGION AND EXISTING DATA SET

Under the World Meteorological Organization's Tropical Cyclone Programme, there are three separate areas of responsibility (AORs) surrounding the Australian continent (Fig. 1), with Tropical Cyclone Warning Centres (TCWCs) in Brisbane, Darwin and Perth having responsibility for the Eastern, Northern and Western Regions respectively. In addition, there is an area (between the Eastern Region and the Equator) for which Papua New Guinea currently has responsibility for issuing warnings, but for which the Brisbane TCWC produces post-analysis tracks, whilst Indonesia will take over responsibility for parts of its area in 2007-08. Combining these areas, the broader Australian region can be considered to cover all areas south of the Equator, between longitudes 90°E (the western boundary of the Western Region) and 160°E (the eastern boundary of the Eastern Region). These boundaries have changed over time and, as will be discussed in more detail later, this has been one source of inhomogeneity in the existing data set.

For the purposes of this paper, the Australian region will be considered as covering the region bounded by 0-40°S, 90-160°E.

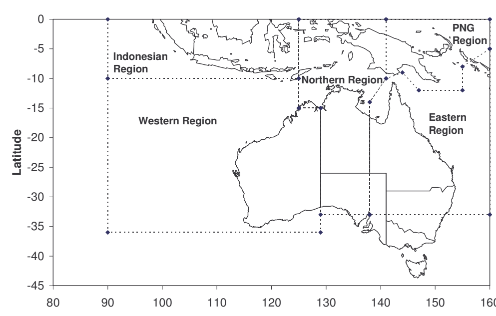

Fig. 1. The broader Australian tropical cyclone region, showing the three Australian sub-regions (Western, Northern and Eastern), and the areas of responsibility of Papua New Guinea (Port Moresby) and Indonesia (Jakarta, from 2007-08).

The principal Australian region tropical cyclone data set, prior to the commencement of this project, was a set maintained by the Australian Bureau of Meteorology (known as the Cycard data set), covering the period from 1906 to 2005. This data set consists of sets of fixed-time observations for each tropical cyclone. In recent years, the observations have normally been at 3-hourly or 6-hourly intervals. For some cyclones, particularly prior to 1960, observations have been only 12-hourly or 24-hourly; conversely, the data set contains numerous observations at times other than the standard 3-hourly or 6-hourly intervals, particularly near the point of landfall.

Each observation contains information, at a minimum, on the cyclone designator (a number, plus a name for systems after the commencement of systematic naming in 1963-64), the time of observation and the position of the cyclone centre. For most cyclones prior to 1939 (and some until about 1950), the only indication of intensity was the estimated minimum central pressure reached. From 1939 to 1984, a central pressure was normally provided at each observation, but no estimates of maximum sustained winds or wind gusts were archived (although there were occasionally records of measured winds and their distance/bearing from the cyclone centre). From 1984 onwards, both central pressures and maximum sustained winds (nominally a 10-minute average) were archived. For some post-1984 observations, information was also available on various size parameters (including radius of gale-force winds and eye diameter – but not radius of maximum winds) and parameters relating to waves and storm surges. Fields notably absent from the Cycard data set, along with the radius of maximum wind, are the maximum wind gust and the Australian intensity category (Table 1). Observations are in either imperial (knots/nautical miles) or metric (ms^{-1}/kilometres) units, with a flag indicating which set of units are used for any given observation.

The principal source for the Cycard data set prior to 1980 was the data set published by Lourensz (1981), which in turn drew on the work of Coleman (1971) and Visher and Hodge (1925), along with additional research. It has been updated since then by annual best-track post-analysis supplied by the three Australian TCWCs. There have also been numerous *ad hoc* additions to the data set as a result of individual research projects or local analyses. In most cases the source of each individual data point is not documented.

3. AUSTRALIAN REGION TROPICAL CYCLONE OBSERVATION PROCEDURES

Satellite observations provide the principal platform for observations of tropical cyclones in the Australian region. These are supplemented by radar observations of cyclone position for those cyclones within radar range. (Approximately 75% of the tropical Australian coastline currently has radar coverage, a proportion which has grown steadily since the first use of radar in the region in 1956).

Surface observations normally only play a minor role in assessments of cyclone position and intensity, as it is rare for the most intense part of a cyclone to be captured by a surface observation; except on the Queensland coast south of Cairns, and in the immediate vicinity of Darwin, surface stations are spaced at a typical interval of 100-200 kilometres. There is no routine aircraft reconnaissance in the Australian region, with the only aircraft data coming from a few research missions, most notably those associated with TC Kerry (1979). Even where surface data exist, they may not be fully comprehensive. As an example, TC George (2007) passed directly over an automatic weather station (AWS) on Bedout Island (19°35’ S, 119°06’ E), with a sustained 10-minute mean wind speed of 54 m s^{-1} at 1000 UTC on 8 March 2007, but as the station only reports hourly, the central pressure within the eye was not measured, nor is it known how close the 1000 UTC observation was to the point of maximum winds within the cyclone.

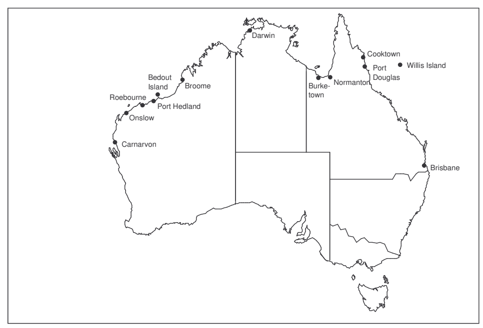

Fig.2. Place names mentioned in the text.

Tropical cyclone intensity assessment in the Australian region is almost entirely based on the Dvorak technique (Dvorak, 1975, 1984; Velden et al., 2006). This technique has been in comprehensive operational use since 1984, with more limited use between 1974 and 1984. The Dvorak current intensity (CI) parameter is converted to a standard 10-minute sustained wind and maximum wind gust (Table 1), using the tables of Dvorak (1975), a standard conversion factor from 1-minute to 10-minute winds of 0.88, and a standard gust factor of 1.40 (Bureau of Meteorology, 1978). This is used by all three regions with only very minor variations, mostly related to rounding (not shown in Table 1). An intensity category of 1 to 5 is also assigned to the system following a scheme introduced in 1989 (which does not match the Saffir-Simpson scheme), although this is not archived in the Cycard data set. The Australian category definitions are formally based on maximum wind

CI Number	Maximum sustained wind (10-min) (ms^{-1})	Maximum wind gust (ms^{-1})	Aust. category	Saffir-Simpson category	ΔP			
					Western	Northern	Eastern (large)*	Eastern (small)*
1	11	16	Tropical low	Tropical depression				
1.5	11	16						
2	13	19			10	10	11	11
2.5	16	22		Tropical storm	13	13	13	13
3	21	28	1		19	19	20	20
3.5	25	35	2		26	25	25	25
4	29	41		1	34	31	35	35
4.5	35	49	3		44	38	45	35
5	41	57		2	56	46	55	40
5.5	46	65	4	3	69	54	70	50
6	52	73		4	83	62	85	65
6.5	57	81	5		96	70	95	75
7	63	89		5	112	80	110	90
7.5	70	99			131	90		
8	77	109			152	100		

Table 1. Relationships between Dvorak CI number, wind speed and central pressure used in the three Australian tropical cyclone regions.

gusts, but are, in practice, derived from the Dvorak CI parameter except on the extremely rare occasions where an accurate measurement of the maximum wind gust exists.

Each of the three sub-regions uses a different pressure-wind relationship to derive estimated central pressures from the CI value and estimated wind. The Western Region follows the method of Atkinson and Holliday (1977), whilst the Northern Region follows a method derived by Love and Murphy (1985), constructed (using a small number of systems) on the basis that Northern Region systems, due to their low latitude and the limited ocean area available for their development, are normally of relatively small size, and hence typically have a higher central pressure for a given wind speed. The Eastern Region has two scales, one for large systems and one for small systems, which correspond quite closely to the systems used by the Western and Northern Regions respectively, except that the Eastern Region scale assumes an environmental pressure of 1010 hPa rather than using the observed environmental pressure as a basis for further calculations. Reviews of the various pressure-wind relationships used operationally in the Australian region (and elsewhere) are contained in Harper (2002) and Knaff and Zehr (2007). There have been minor variations over time since 1984 in the use of the various pressure-wind relationships, and there is also some evidence (Andrew Burton, pers. comm.) that at various times, CI-wind tables may have been in use which were based on 1-minute sustained winds rather than the 10-minute Australian standard.

A variety of pressure-wind relationships were in operational use prior to 1984 (Bureau of Meteorology, 1978; Harper, 2002), but as winds estimated operationally have not been archived in the Cycard data set prior to 1984, this does not affect the data set as it currently stands.

Satellite data coverage over the Australian region improved progressively over the 1960s and 1970s. The first experimental satellite images became available in 1960, the first routine (polar-orbiting) images in 1966, the first routine infrared images in 1972, and the first geostationary images in 1978 (Harper et al., 2008). Radar data also improved progressively from the time of the first radar installation in 1954 (the first Australian tropical cyclone actually observed by radar was in 1956).

After the establishment of standard procedures for recording tropical cyclones by the Bureau of Meteorology in 1955-56 (Bureau of Meteorology, 1955, 1956), there was also some experimental use in the 1950s and early 1960s of observation tools such as microseisms (small seismic disturbances) and sferics (electrical interference to radio signals, caused by lightning), but these were found to be of limited utility in detecting the presence of a cyclone, and little or none in detecting its location, movement or intensity, and were abandoned once satellite data

* The Eastern Region tables assume an environmental pressure of 1010 hPa.

started to become available. Whilst no specific aircraft reconnaissance was undertaken in the Australian region, reports were occasionally available from routine civil and military aircraft traffic, particularly during the Second World War.

In the absence of other observations, information on tropical cyclones was confined to surface data, observed at land-based stations, including those on offshore islands, and on ships. (A significant island station, in this context, was at Willis Island (16°17' S, 149° 58' E), off the Queensland coast, which was established in 1921 for the specific purpose of supporting tropical cyclone warning services). Such surface observations formed the basis for almost all cyclone reports prior to the mid-1950s, becoming progressively less important until being largely supplanted by satellite observations after 1984.

4. WHAT SYSTEMATIC BIASES EXIST IN THE EXISTING AUSTRALIAN REGION DATA SET?

As a result of the various changes which have occurred in observation and archiving procedures, numerous systematic biases exist in the Australian region data set. To a first level of approximation, observation procedures, at least for central pressure, can be considered as reasonably uniform after the introduction of the Dvorak technique to routine operational use in 1984. (Whilst Harper et al. (2008) suggest that the incorrect use of 1-minute rather than 10-minute winds for some post-1984 systems may also have contaminated central pressure data, a recent analysis by the Perth TCWC (Andrew Burton, pers.comm.) suggests that this was not the case).

Nicholls et al. (1998) found an abrupt drop in the frequency of relatively weak tropical cyclones in the mid-1980s, which they attribute to changes in observation procedures. Harper et al. (2008) found a tendency for the Cycard data set to underestimate cyclone intensity in the region (Timor Sea) covered by their study, particularly prior to the mid-1980s. Covering another facet of tropical cyclone behaviour, Buckley et al. (2003) found a marked jump in the number of tropical cyclones reported south of 28°S in the Tasman Sea around 1955, and an equally marked step downwards in about 1977. The latter date essentially coincides with the commencement of geostationary satellite observations, and the consequent introduction of new procedures for distinguishing tropical cyclones from extratropical and subtropical systems (known locally as 'hybrids').

4.1. Intensity

According to the Cycard data set, there has been a dramatic increase in the number of intense cyclones with central pressures lower than 950 hPa (Fig. 3) since 1984. There is substantial evidence of systematic underestimation of cyclone intensity prior to 1984, and particularly prior to 1970. Harper et al. (2008), in their region of interest, conclude that a mean bias in minimum central pressure exists, in the order of 10 to 20 hPa in the early 1970s and about 5 hPa in 2000. (This is based on a quadratic fit to individual storm data which appears to be strongly influenced by a single highly anomalous cyclone, Victor (1998); if Victor is removed the post-1985 bias appears to be minimal). Extending prior to the satellite era, whilst there has not been a systematic evaluation of biases in tropical cyclone intensity, an indicative study was carried out by Holland (1981), in which a number of experienced analysts were provided with surface data in the vicinity of TC Kerry (1979) and asked to estimate its position and intensity, approximately replicating pre-1955 analysis techniques. This study found that the mean of the minimum central pressures analysed using surface data was approximately 985 hPa, whereas the actual minimum (measured by aircraft) was 945 hPa, and occurred four days before the point identified by the majority of analysts as the point of minimum pressure.

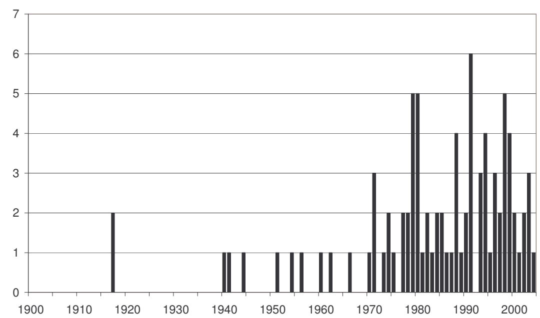

Fig. 3. Number of cyclones per season (July-June, shown by first year of season) with minimum central pressure less than 950 hPa.

It is concluded from the Harper et al. and Holland studies, and from the observed data, that there is a strong tendency towards underestimation of cyclone intensity prior to 1985, which becomes progressively worse further back in the record. Prior to about 1970, the only recorded instances of cyclones with central pressures less than 950 hPa appear to be cases where a pressure of that level was measured. Examples of these include the two 1918 cyclones which made landfall near Mackay and Innisfail respectively, and cyclones in 1941 and 1942 which both made landfall near Port Hedland.

Whilst the post-1985 central pressure data appears to be approximately internally consistent, the lack of ground-truth data means that there has been no systematic evaluation of whether the methods used for estimating central pressure (or wind) are the most accurate available for doing so. As noted earlier, there has been no aircraft reconnaissance of any Australian-region cyclone since 1979, nor is there any instance in that time of a coastal or island station sampling, with sufficiently high time resolution, both the maximum sustained winds and gusts within the eyewall, and the central pressure within the eye, in a category 4 or 5 cyclone. Partial ground truth data does exist for some cyclones, such as George (2007) and Vance (1999) (both with good estimates of maximum sustained winds, but not minimum central pressure) and Larry (2006) (numerous measurements of central pressure at or near landfall, and reasonably reliable estimates of peak wind gusts from damage surveys), but as yet there has been no systematic attempt to use these observations to re-evaluate Australian region procedures for intensity estimation. However, Knaff and Zehr (2007) were critical of the procedures used in the Western and Eastern (but not Northern) Regions and suggest that these may result in systematic errors in their own right.

4.2. Definition of tropical and non-tropical systems

There are indications of strong variations over time in the frequency of tropical cyclones at relatively high latitudes (Fig. 4), especially in the Eastern Region, with Tasman Sea tropical cyclones south of 30°S becoming essentially absent after the late 1970s. Buckley et al. (2003) also identify this change, and trace it to a change in observation practices introduced within the Eastern Region in 1978, following the introduction of geostationary satellite observations. Under these procedures, systems where the maximum winds were well-removed from the centre were considered to be "hybrid" (or subtropical) systems and no longer classified as tropical. Nicholls et al. (1998) discuss the trend over time towards classifying systems as "hybrid" rather than tropical, with particular reference to Wanda (1974), which was classified as tropical (and which resulted in Brisbane's most severe flood of the 20th century), and a similar 1988 system which was not. Buckley et al. (2003) also discuss a March 2001 hybrid system which caused severe flooding in parts of southeast Queensland and northern New South Wales. It should be noted that such systems are included in tropical cyclone counts in some other basins, such as the North Atlantic.

Prior to 1970, a number of clearly extratropical systems have also been included in the Cycard data set for unknown reasons, the most extreme example being a July 1963 system near 40°S in the Tasman Sea. (This system is not included in Lourensz (1981) and the background to its inclusion in Cycard is unknown).

The earlier part of the data set also includes a number of entirely land-based systems. Current policy is not to classify systems as tropical cyclones if they do not pass over the ocean at some stage during their lifetime. There have been some recent systems (such as one over the interior of the Northern Territory in January 2006) which have had some of the characteristics of tropical cyclones, but these have not been officially named, or included in the Cycard data set.

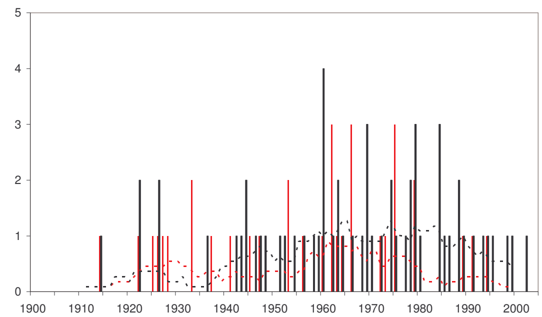

Fig.4. Number of cyclones per season reaching south of 30°S in the Western (black) and Eastern (red) Regions (11-year running means shown as dashed lines).

4.3. Undetected tropical cyclones

Prior to the commencement of systematic satellite observations, it would be expected that many cyclones which did not make, or approach, landfall would have been missed, as the only information available on the occurrence of such cyclones would be observations from ships and offshore islands, or indirect evidence such as large swells at the coast. Ship observations near intense tropical cyclones are likely to have become less frequent over time as improved warning services made ships more able to avoid such cyclones (Holland, 1981), although an opposite influence, at least for weaker systems, was a specific effort by the Bureau of Meteorology to increase the number of ship observations obtained through the appointment of Port Meteorological Agents from 1955 onwards (Buckley et al., 2003).

Holland (1981) makes an assessment of the likely extent of the undercount of oceanic systems, based on the ratio of landfalling to non-landfalling systems (a similar approach was used for the North Atlantic by Landsea (2007)). For systems which did not approach within 500 km of the coast between 105 and 165°E, he estimated an undercount of greater than 50% prior to 1959, and 15-30% between 1959 and 1969. Given the remoteness of much of Australia's coastline, it is also possible that some landfalling systems may have been missed prior to 1960, particularly on the coasts of Western Australia (where only a few small settlements and homesteads existed before the start of large-scale mining in the 1960s) and the north-eastern Northern Territory.

4.4. Inconsistent regional boundaries

As noted in section 2, for the purposes of this study, the boundaries of the Australian region have been set at 0-40°S, 90-160°E, which includes the Western, Northern and Eastern Regions, as well as the Papua New Guinea AOR.

These boundaries have varied over time, both formally and informally. Prior to 1984, the western boundary of the Western Region was 80°E, rather than 90°E. However, Lourensz (1981), a major source for historical data, only considered systems east of 105°E. In addition to the unobserved cyclones discussed in section 4.3 above, it is likely that this has led to a substantial undercount of cyclones between 90 and 105°E, especially prior to 1970. It is likely that this undercount is at least as severe as that identified for open-ocean systems east of 105°E by Holland (1981).

Variations of the eastern boundary of the Eastern Region have also occurred over time, with a boundary of 165°E being used on occasions (including by Lourensz). There were also a small number of systems which stayed entirely within the Papua New Guinea AOR which were not included in the Cycard data set.

4.5. Minimum intensity thresholds

The current definition of a tropical cyclone in the Australian region is that it must have sustained 10-minute winds of at least gale force (17 ms^{-1}) around at least two quadrants. The wind strength criterion (although sometimes without the quadrant requirement) has been in use since at least 1955 (Bureau of Meteorology, 1955). Weaker systems were considered to be 'tropical disturbances'.

Although these sub-gale force disturbances (which were also referred to in publications of the time as 'type A' or 'class 3' cyclones) were not considered to be fully-fledged cyclones, they were nevertheless published in seasonal summaries in the 1957-72 period, and a number of such systems were included in the Cycard data set.

4.6. Duplicate systems

A close examination of the Cycard data set revealed a number of duplicate systems. These most commonly took the form of one of the 'cyclones' containing high-resolution observations near the point of landfall, whilst the other contained less frequent observations over the full track. Less common occurrences were where a single track was broken into two or more parts (often after an overland passage), or where a single cyclone was analysed as having two or three centres in close proximity (often with the assistance of relatively primitive radar and satellite technology), each of which was recorded as a separate cyclone.

4.7. Inconsistent classification of track start and finish

Current practice is to start a track (in post-analysis) at the first point at which an identifiable system develops, and finish it at the point where it dissipates or becomes clearly extratropical. It is also current practice to consider a system to be a single cyclone if an identifiable circulation remains during an overland passage, even if it drops below cyclone intensity over that time.

Both practices have been followed inconsistently in the past, with many systems only being tracked from the point at which a system reached cyclone intensity (Harper et al, 2008). An example of the issues involved is shown by a system in January-February 1996 (Fig. 5). This is currently recorded in the Cycard data set as two cyclones, with one cyclone forming in the Gulf of Carpentaria and making landfall in the Northern Territory (this cyclone was not named at the time and was only upgraded on post-season analysis), and a second (Jacob) which formed in the Timor Sea off the western coast of the Northern Territory and then moved westwards. Further analysis revealed that a circulation crossed the Northern Territory over a period of four days and redeveloped into Jacob on re-emerging over water.

Fig. 5. Unnamed tropical cyclone 27-28 January 1996 (right solid line) and TC Jacob, 1-8 February 1996 (left solid line), with overland track of circulation (dashed line).

5. THE DEVELOPMENT OF AN UPGRADED AUSTRALIAN REGION DATA SET

This paper describes the first stage of a two-stage project. The principal objectives of the first stage are:

- To reconcile all known existing sources of Australian region tropical cyclone data.
- To, as far as possible, develop a data set from existing data sources to which a consistent set of definitions has been applied, with respect to regional boundaries, reaching of cyclone intensity, and tropical/extratropical status.
- To remove gross errors from the data set.

- To comprehensively document the underlying procedures used, and the uncertainties and biases which arise, over time in observing Australian-region tropical cyclones.

The second stage of the project, which is yet to commence, will involve a full reanalysis of Australian region cyclones from original source data (such as satellite images), using a consistent set of procedures and definitions.

5.1. Data sources used in addition to the Cycard data set

In addition to the Cycard data set, a number of additional data sources have been used in the development of the current version of the upgraded data set. These were:

- The Joint Typhoon Warning Center (JTWC) best-track data set from the period 1945-2000 (Chu et al., 2002). This covers the full Southern Hemisphere over that period. Whilst the data set was compiled by JTWC, JTWC did not have responsibility for Southern Hemisphere areas in the earlier part of the 1945-2000 period, and the original source of that data appears to be a data set (TD-9636) compiled by the (U.S.) National Climatic Data Center.
- A limited-area reanalysis, covering the 1968-2001 period in the Timor Sea region, carried out on behalf of Woodside Energy, a major oil and gas company operating in the region (Harper et al., 2008). This will henceforth be referred to as the Woodside data set.
- Local data sets compiled by the Bureau of Meteorology's Queensland and Northern Territory Regional Offices for their respective areas of responsibility. In most cases these closely match the Cycard data set, but they also contain information on local reanalyses of some specific systems which have not been incorporated into the Cycard set.
- The 1909-80 Australian region tracks published by Lourensz (1981), combined with his original working notes, which are held in the Bureau of Meteorology. In most cases the Lourensz tracks closely matched those in Cycard (which is not surprising as they formed the basis for much of Cycard), but there were some deviations of interest. Lourensz's working notes were particularly useful in some cases where they indicated that he had taken a deliberate decision to exclude a system which was reported in one or more other sources.
- Published case histories and seasonal summaries. These were published, either as articles in the *Australian Meteorological Magazine* or as stand-alone documents, from 1957-58 to 1971-72. A regular seasonal summary, covering the broader South Pacific as well as the Australian region, has been published for all seasons from 1978-79 to the present (except 1992-93) in the *Australian Meteorological Magazine* (e.g. McInerney et al., 2006). No case histories were published from 1972 to 1978, except for a few particularly notable cyclones such as Tracy (1974) (Bureau of Meteorology, 1977).

Secondary data sources, which were not used in initial investigations but were drawn on in some cases when further investigating observations flagged by initial checks, included:

- Operational MSLP charts for Australia or for the broader Southern Hemisphere, prepared by the National Meteorological and Oceanographic Centre (NMOC) and its predecessors. (Scanned versions of these charts are available from 1956 to the present, although legibility of many of the early charts is poor, and tropical cyclones were not specifically identified on Southern Hemisphere analyses before 1963).
- Archived hard-copy material on cyclones held on behalf of the various TCWCs. Whilst the material available varies from cyclone to cyclone, it often included copies of warnings issued, print-outs of satellite and radar images, and working sheets for post-event track analysis. The latter were particularly useful in verifying suspected data processing errors.
- Other meteorological data, such as rainfall, wind and pressure observations for specific locations obtained from the Bureau of Meteorology's climate database.

5.2. Internal consistency and error checks

The data were subjected to a wide range of internal consistency checks with those observations failing such checks being flagged for further investigation. These included:

- Irregular observation times. Observations were flagged if they were not made at 00 or 30 minutes past the hour. Many such observations appear to have been included to incorporate a specific wind observation, but in some cases little care was taken in determining other parameters such as the cyclone's wind and central pressure. (There were also some instances where an observation is listed at 01 minutes past the hour, with the apparent purpose of including a second wind observation for the original time).

- Observations less than 60 minutes, or more than 27 hours, apart. These may indicate duplicate observations in the former case or missing observations in the latter.
- Duplicate system check. Systems were flagged for further investigation if two systems occupied the same 1x1 degree box within 24 hours of each other.
- Excessive movement speed. Systems were flagged if their movement speed between two successive observations exceeded 19 ms^{-1} at latitudes north of 22°S, or 28 ms^{-1} further south.
- Erratic movement. Systems were flagged if an observation had a position too far from that obtained by linear interpolation between the preceding and following observations (the exact criteria depended on the time interval involved).
- Extreme values. Central pressures outside a range of 900 to 1010 hPa, and maximum sustained winds exceeding 100 ms^{-1}, were flagged.
- Pressure-wind consistency. Where both winds and pressures were available, an estimated central pressure was calculated, using the operational wind-pressure relationship for the relevant region and assuming an environmental pressure of 1010 hPa. The observation was flagged where the estimated value of ΔP (P_{env}-P) differed from the observed value by at least 25% and 10 hPa. (The most common error detected through this check was the use of metric units for an observation flagged as imperial, or vice versa).

5.3. Intercomparison of Cycard data with other data sources

The Cycard data set was compared with each of the primary data sources listed in section 5.1 above. Substantial differences between data sources were flagged for further investigation, as were cases where a cyclone was in the Cycard set but not in one of the other sources, or vice versa.

The number of data sources available for intercomparison varied depending on the location and year. In ideal circumstances, available data for any one system would include Cycard, JTWC, one or more published tracks, and a regional analysis (either those of the Queensland or NT Regional Offices, or the Woodside set), but for some systems the only available comparison data set was JTWC (after 1945) or Lourensz (before 1945).

The most widely available comparison was between Cycard and JTWC, as JTWC covered the full region for the full period 1945-2000. In the great majority of cases where the two differed, the Cycard data was found to be correct (in particular, 17 cyclones in the JTWC set were found to have dates which were incorrect by one or two days, possibly because of confusion caused by the International Date Line), but JTWC was found to be the more consistent with independent data sources on approximately 5-10% of occasions.

5.4. Further investigation of flagged systems

Where an observation, or a cyclone as a whole, was flagged by any of the checks described in sections 5.2 and 5.3 above, alternate data sets were consulted (including other primary sources and the secondary sources listed in 5.1). A decision was then made based upon all the information available. As a general rule, the most reliable source of information was considered to be the published post-season reports (where available) from the *Australian Meteorological Magazine*, although there were some exceptions made.

5.5. Amendments made to Cycard data set

5.5.1. Additions and deletions of cyclones

A number of cyclones were listed in each of the primary data sources which were not in Cycard. With the exception of systems in the JTWC data set, these were added to the data set unless there were strong reasons to do otherwise (e.g. their non-inclusion in a second independent data set, or evidence of a deliberate previous decision to classify them as non-cyclones).

The JTWC data set contains a large number of systems which did not reach tropical cyclone intensity (40 knots, taking into account JTWC's use of 1-minute rather than 10-minute winds). Furthermore, intensity information is not consistently available in the JTWC set prior to the 1980s. An analysis of post-1983 systems ascertained that:

- No system in the JTWC data set with a lifetime of 36 hours or fewer reached an intensity of 40 knots or greater.
- For systems that did reach 40 knots, the median time of the first 40-knot observation (that is, the point at which the system reached tropical cyclone intensity) was approximately 36 hours after the first observation.

Based on this information, after 1963, JTWC systems were included if they were analysed as tropical cyclones on the NMOC Southern Hemisphere analyses, or identified as cyclones by another source. (Most of these systems were very close to the edge of the current Australian region, including a few which just crossed 160°E before recurving eastwards). Prior to 1963, when the NMOC analyses were not available for this purpose, JTWC systems were included only if they:

- Had a lifetime greater than 36 hours;
- Did not leave the Australian region within 36 hours of formation;
- Were not close enough to the coast for Australian analysts to have been expected to have known about them (with the implication that they would have taken a considered decision to exclude them).

Following these processes, 33 additional cyclones are recommended for inclusion in the new data set. This includes 12 pre-1963 cyclones drawn from JTWC, all near the boundaries of the Australian region (five in the west, seven in the east). Given the probabilistic nature of the criteria above, and the lack of supporting information, it is likely to be impossible to determine definitively that any individual cyclone of these 12 was definitely a cyclone, but it is believed that the criteria used have identified systems that had a greater than 50% probability of having reached cyclone intensity.

Cyclones were automatically deleted from the data set if they did not enter the Australian region at any time, if they were classified as failing to reach cyclone intensity ('class 3' or 'type A' systems) in published seasonal summaries, or if they were not over tropical oceans at any point during their lifetime. The most obviously extratropical systems were also deleted, although a comprehensive reassessment of the tropical/extratropical status of individual cyclones was not undertaken in this stage of the project (see section 5.6 below). Cyclones which were in the Cycard set, but not in one of the other relevant primary data sources, were subject to further investigation, but were generally retained at this point unless there were strong reasons to the contrary, such as documentation of a post-season downgrading (e.g. Coral (1982)). In some cases, Lourensz's working notes indicated a decision to exclude a particular system and this advice was normally followed. A substantial number of systems flagged as potential duplicates were also merged.

As a result of this process, 130 cyclones are recommended for deletion from the new data set, either altogether or through being merged with another system.

5.5.2. Other amendments

A number of other errors or omissions were also identified within the Cycard data set, including erroneous individual data points, parts of tracks which were missing, or parts of tracks which did not correspond to an identifiable system.

Where a data point was identified as erroneous, an amendment was made if evidence existed of the correct value (e.g. working sheets from archival boxes). Otherwise the data point was deleted. Where parts of tracks were missing, these were filled using the most detailed available alternate source, generally the regional data sets or the Woodside data set. Portions of tracks outside the Australian region were maintained, as long as the cyclone was within the Australian region at some point, but no assessment was undertaken of the accuracy of start or end points outside the region.

A small number of cyclones (mainly in Queensland) had their central pressures modified on advice from the Queensland Regional Office, but, in general, amendments to intensity did not form part of this stage of the data set compilation (see section 5.6 below). In particular, the Woodside data set was not used to amend intensity data at this time.

Finally, some minor issues were found with cyclone names, including misspelt names and single systems with multiple names. These were addressed according to the best information available. Where systems had two or more names during their lifetime they are listed in the data set with a hyphenated name, e.g. Beverley-Eva (1970). Current operational practice is that systems which move westwards out of the Australian region are re-named as they enter the new AOR, but that Australia retains the original names for systems which enter its AORs from elsewhere. The new data set does not include renamings of Australian systems, except for a few cases where such systems re-entered the Australian region from the west under their new name.

5.6. What was not done in this stage of the data set development

Whilst this first stage of data set development has resolved many of the inconsistencies in the current Australian region tropical cyclone data set, a number of issues remain to be resolved. It is considered that these issues cannot be resolved adequately without a full reanalysis from original source data, which is planned for the second stage of this project. As such, they did not fall within the brief of the first stage.

- Amendments to cyclone intensity. Except for removal of a few gross errors and a few amendments on the advice of regional staff, changes to intensity were not considered at this stage.
- Inclusion/deletion of marginal systems. Weak systems were not considered for deletion unless there was documented evidence that they had failed to reach cyclone intensity. It is likely that a number of weak systems, especially pre-1985, will be downgraded on reanalysis. (Nicholls et al. (1998) found a systematic decrease in the frequency of weak cyclones after 1985, which they attributed to a likely change in observation procedures). A number of additional marginal systems, not currently in the data set, have also been identified for possible future

inclusion (Ian Shepherd, personal communication).

- Tropical/extratropical status. As discussed in section 4.2, it is likely that some cyclones remain in the data set which would not be classified as tropical cyclones under current criteria. The principal basis for making such a decision is the distance of maximum winds from the system centre, which requires further reanalysis for comprehensive assessment.
- Start and end points of tracks. The intention is that the data set will ultimately contain the tracks of cyclones from the first point at which a system is identifiable to the point at which either there is no longer an identifiable circulation or the system is extratropical. Again, a reanalysis is required for proper assessment of this.

There was also no attempt at this time to use alternate data sets to add higher-resolution data to the Cycard data set at this time. This includes some cases (mostly in the 1940s and 1950s) where Cycard only has data at 12- or 24-hour intervals but the JTWC set is 6-hourly.

6. IMPACTS OF THE CHANGES ON PROPERTIES OF THE AUSTRALIAN CYCLONE DATA SET

Whilst the new data set cannot be considered fully homogeneous with respect to cyclone numbers, due to remaining issues with marginal and extratropical systems noted above (as well as unaddressed, and probably unaddressable, issues with missed open-ocean systems prior to the satellite era), it is nevertheless instructive to compare cyclone numbers, and trends in them, between the new data set and the Cycard data set.

Such a comparison is shown in Figure 6. It may be seen that the major impact of the changes is to substantially reduce the observed frequency of cyclones between approximately 1955 and 1970. Whilst there is still a downward trend in observed cyclone occurrence over both the 1970-2005 and 1955-2005 periods, it is substantially weaker in the new data set than it was using the Cycard data set, with trends of -0.4 cyclones/decade for 1955-2005 (compared with -1.8 in the Cycard set) and -1.7 for 1970-2005 (compared with -2.4). Furthermore, cyclone frequency in the Australian region tends to be reduced in El Niño years (e.g. Solow and Nicholls, 1990), suggesting that the observed downward trend may be at least partly attributable to the relatively high frequency of El Niño events since 1980 (Power and Smith, 2007).

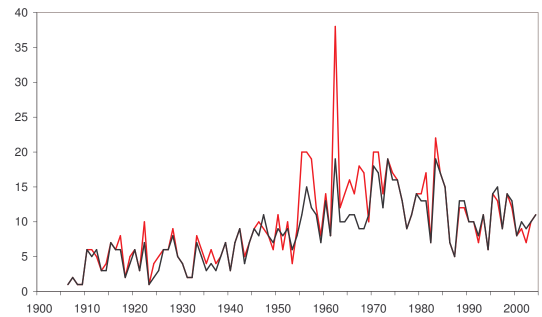

Fig. 6. Number of cyclones per season 1906-2005, in the new (black) and Cycard (red) data set.

7. HOW RELIABLE IS THE NEW DATA SET, AND WHAT MIGHT BE POSSIBLE WITH REANALYSIS?

The new data set can only be considered as near fully homogeneous since the introduction of the infrared version of the Dvorak technique in 1984. However, the new data set greatly improves the homogeneity of the cyclone numbers in the period from the mid-1950s to 1984. After 1970, whilst it is likely that cyclone numbers are slightly inflated by the inclusion of non-tropical (pre-1978) and weak systems, the impact of this on the data set is unlikely to be large. Prior to 1970, these issues are increasingly offset by the non-inclusion of some open-ocean systems. With appropriate caveats on the use of information west of 105°E, it is nevertheless likely that the new data set is a reasonable description, at least to a first order of approximation, of Australian-region tropical cyclone behaviour since 1955. Prior to 1955 it is clearly incomplete, except with respect to coastal crossings in the more heavily-populated areas (which, in the first half of the 20th century, includes the Queensland coast south of Port Douglas, and the immediate vicinity of population centres such as Cooktown, Normanton, Burketown, Darwin, Broome, Port Hedland, Roebourne, Onslow and Carnarvon), and it is unlikely to be possible to further rectify that situation to any significant degree. Intensity data have been left essentially unamended in the first stage of this project and hence can still only be considered as homogeneous and reliable back to 1984.

A reanalysis will allow observations to be homogenised back to the start of the satellite record. As noted in section 2, the first satellite observations occurred in 1960, with full geostationary coverage by 1978. Whilst it is not totally clear how much usable satellite data survives, it is likely that a reanalysis will be possible back into the early 1970s, and possibly the late 1960s. This will allow a thorough assessment of changes in tropical cyclone intensity in the Australian region from about 1970 to the present, matching the information available from several other basins. It is unlikely to be possible to extend intensity data of sufficient homogeneity to allow climate-change assessments prior to, at best, the late 1960s.

8. DATA SET AVAILABILITY

The data set is freely available through the Australian Bureau of Meteorology's climate change website, at http://www.bom.gov.au/climate/change. This includes the raw data and a graphical interface to display cyclone tracks.

9. ACKNOWLEDGEMENTS

The assistance of the staff of the various Australian Tropical Cyclone Warning Centres, and in particular Jeff Callaghan, Ian Shepherd, Andrew Burton and Joe Courtney, is greatly appreciated, as is that of Alan Sharp, particularly in developing some of the original quality control checks, and of Yuriy Kuleshov, for his assistance with the broader Southern Hemisphere data. The assistance of Bruce Harper, and of Woodside Energy Limited, in making data from the Woodside data set available for use in this project is also gratefully acknowledged.

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