A review of historical tropical cyclone intensity in northwestern Australia and implications for climate change trend analysis

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Estimated tropical cyclone intensities for northwestern Australia over the period 1968/69 to 2000/01 obtained from a recent offshore oil and gas industry review are compared with the Bureau of Meteorology official tropical cyclone best track archive, a modified best track archive and another international reference data-set. Potential influences on the accuracy of estimating tropical cyclone intensity over time due to increasing technology, methodology, knowledge and skill are discussed. Historical Bureau of Meteorology practices in regard to estimating tropical cyclone intensity are also outlined and a method is described to potentially rectify the official track data archive to overcome some procedural issues. The methodology of the objective industry review process is then described, together with its expected limitations, and comparisons between the various data-sets are presented.

It is shown that a bias towards lower intensities likely exists in earlier (mainly pre-1980) tropical cyclone central pressure deficit estimates of the order of at least 20 per cent in 1970, reducing to around ten per cent by 1980 and to five per cent by 1985. Inferred temporal trends in the estimated intensity from the original data-sets are therefore significantly reduced in the objectively reviewed data-set. Implications for detecting potential climate-change trends are discussed and recommendations are made for a detailed review of the tropical cyclone data-set for the entire Australian region as well as a call for improvements in the analysis and direct sensing of tropical cyclone intensity.

Introduction

The potential risks to life and property from tropical cyclones (TCs) in northern Australia are significant and the accuracy of historical TC data-sets is of special interest to those involved in the quantitative assessment of these risks, especially in the marine environment. To this end, the offshore oil and gas industry in northwestern Australia has collectively been at the forefront of TC risk monitoring, modelling and risk assessment since the early 1970s. This work has underpinned the extensive investments onshore (pipelines, ports, processing and housing), offshore (pipelines, platforms, floating production systems),

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constructability and operability needs, issues of personnel safety and environmental protection. Woodside Energy Ltd (WEL) has been the principal proponent of research into TC impacts in this area and the study being reported here is typical of many that have been undertaken over the past 30 years. While natural climatic variability alone has always been a sufficiently motivating factor for such research, the increasing concern that anthropogenic climate change may be increasing TC intensity has attracted additional interest over the past decade. Given that typically less than two per cent of all tropical cyclone peak intensities in the Australian region are ever directly measured from instrumented eye passages*, there is a critical reliance on a variety of empirical and remote sensing analyses. The principal issue for industry, therefore, is whether the available TC data-sets are sufficiently accurate for the purpose of refined risk analyses of extreme winds, waves, currents and storm surge to ensure reliability in the design process, which now targets the 10^{-4} annual exceedance probability hazard level (i.e. the 10 000-year Average Recurrence Interval or ARI).

In an attempt to clarify this question of historical data accuracy, the present study describes the results of a comparison between the Bureau of Meteorology (BoM) official TC historical data-set (1968/69 to 2000/01) for northwestern Australia and an explicitly reviewed data-set commissioned by WEL that covers its principal areas of interest. The Neumann, or HURISK, data-set (e.g. Neumann 1999) has, for reasons explained below, also been included in the present comparison. The prime motivation for undertaking the WEL review, completed in 2002, was to address concerns regarding the accuracy and consistency of the official BoM database and to also assemble additional critical storm-scale data, such as radius of gales and eye diameter, that were not available from the official database. The review was undertaken by consulting meteorologists (McCormack and West through WNI Oceanographers and Meteorologists – now Metocean Engineers Pty Ltd), with technical and management assistance from Systems Engineering Australia Pty Ltd (Harper). Although a substantial number of storm track and naming issues were identified during the review process, the present comparisons are limited to mainly issues of the peak intensity estimates of TCs. The WEL-reviewed TC track data-set has been made available to the BoM for general public use and for research purposes.

A subsequent motivation for making the results of this normally proprietary study publicly available has been the extent to which global historical agency databases in general might contain similar biases. Any significant temporal variability in the quality of estimated TC intensities will severely limit their usefulness in detecting possible trends due to anthropogenic climate change. For example, the analyses by Emanuel (2005) and Webster et al. (2005) used global historical best track data-sets for this purpose and respectively hypothesised and hinted at a likely very strong enhanced-Greenhouse related historical intensity trend. Emanuel (2005) compared an annual Potential Destruction Index (PDI) based on the sum of the cube of the six-hourly V_{max} from individual storms of tropical storm strength or above, to an annually averaged sea-surface temperature (SST) for the Atlantic and western North Pacific best track data-sets. That work led to conclusions of a link between increasing SST and TC intensity. Webster et al. (2005), hereafter WHCC, addressed the global best track data-sets and concentrated on the changes in more intense TCs over the past 30 years, presenting evidence of a near-doubling of the proportion of intense storms over this period. These two papers sparked much scientific debate due to questions about the reliability of the globally inhomogeneous historical best track data (e.g. Pielke 2005; Landsea 2005; Pielke et al. 2005; Landsea et al. 2006; Klotzbach 2006). Their publication also prompted an initial disclosure of some of the WEL review outcomes (discussed here) through Harper and Callaghan (2006) and motivated the subsequent fully objective post-Geostationary Meteorological Satellite (GMS) period global analyses by Kossin et al. (2007).

Expected influences on tropical cyclone intensity estimates over time

Tropical meteorology and tropical cyclone science are still very much developing and have benefited greatly from advances in technology, especially numerical modelling and satellite sensing. However, there are a number of other reasons why the overall skill in determining TC intensity in particular has likely changed and improved over the past 30 years.

The BoM 'best track' historical data-set and its equivalent international counterparts (e.g. JTWC, NHC/HURDAT**) are complex products of scientif-

* Assessment based on fewer than 20 reliably instrumented eye passages within the total historical storm database of about 900.

** JTWC is the US Joint Typhoon Warning Center now based in Hawaii; NHC is the US NOAA National Weather Service National Hurricane Center.

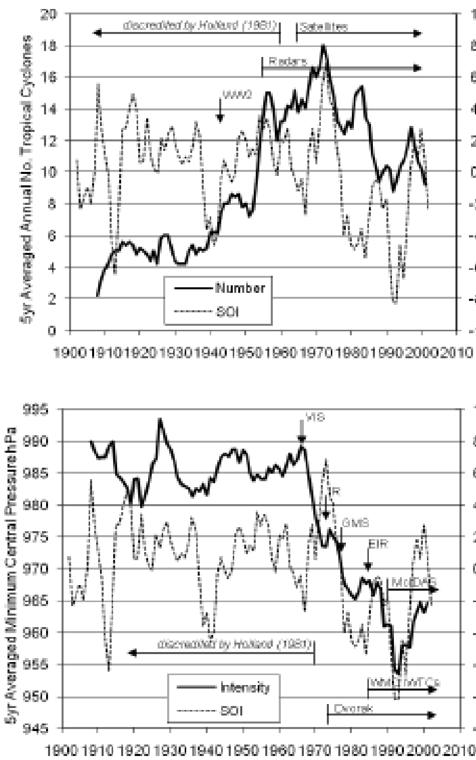
ic and technological advances, combined with increasing skill in detection, interpretation and analysis, and within a background of societal and institutional change (Harper 2004; Landsea et al. 2006). In their raw form, these data-sets provide a very useful indication of the extent and (since the 1960s) frequency of occurrence of TCs throughout the world. However, in terms of intensity estimation, which is still the most difficult parameter to quantify (e.g. DeMaria 2004), the early historical data-sets have been previously assessed as being unreliable for the majority of situations where groundtruth wind and/or pressure observations were absent (e.g. Holland 1981; Landsea et al. 2004). While there have been attempts, principally by Neumann (e.g. Neumann 1987, 1999) who was instrumental in creating the 'best track' concept in the 1960s, to produce globally consistent data-sets by combining individual agency data, even this has proved problematical because of widely differing agency processes and procedures.

While the advent of satellite imaging in the early 1960s is always credited with the onset of significant improvements in TC detection, acceptance of earlier intensity estimates in risk studies has always been influenced by the need to use as much of a relatively short data-set as can be reasonably justified. Even in the USA, which has the enviable record of aircraft reconnaissance since the mid-1940s, the need to critically examine and extend the official HURDAT data-sets was recognised in 1999, when the hurricane reanalysis project was established (e.g. Landsea et al. 2004). The USA review has now progressed from 1851 through to 1920. In the Australian and Pacific region, and as recently as the late 1980s, there are thought to be many instances of significant and systematic underestimation of TC intensity in the official BoM data-set (J. Callaghan, BoM, personal communication). Much debate still occurs even with present-day systems and procedures when accurate groundtruth is unobtainable due to the sparsely monitored Australian continent.

Appendix A provides a (non-exhaustive) list of the many likely influences on the accuracy of TC intensity estimates over time, especially in Australia since the 1960s. It should be acknowledged that much of the progress in knowledge and training has been due to contributions from the WMO Tropical Cyclone Programme (e.g. WMO 2000) and allied WMO Commission for Atmospheric Sciences Tropical Meteorology Research Programme (CAS/TMRP) as well as the influential American Meteorology Society (AMS) series of specialist Conferences on Hurricanes and Tropical Meteorology. Following Harper and Callaghan (2006), Fig. 1 provides some insight into the potential impacts of these changing influences on the frequency of occurrence and also intensity of TCs for the entire Australian region for the period 1906/07 to 2004/05, overlaid for comparison with the Southern Oscillation Index (SOI) (from BoM sources). As annotated on Fig. 1, Holland (1981) was able to largely discredit occurrence statistics prior to 1960 and intensity estimates prior to 1970 (with some caveats). Occurrences in the 1960s are also believed to be inflated by errors and misclassifications of many subtropical and hybrid systems. However, even since the mid-1970s there is compelling evidence that suggested strong trends in climatology could be an artefact of continuing improvements in estimation of intensity. Also, the prolonged El Niño trend (strongly negative SOI) and then its later relaxation over the same period is likely significant.

As noted by Harper and Callaghan (2006), clearly there has been a considerable increase in technology, methodology, knowledge and skill over the past 40 years and the process of information gathering is accelerating. Landsea et al. (2006) addressed many of these issues and provided specific examples of signif-

Fig. 1 Potential influences on the Australian best track database (after Harper and Callaghan (2006); refer Appendix A for details of acronyms).



icant historical storms that have likely been misclassified, especially in the sparsely monitored Indian Ocean. The reliance on satellite interpretation since 1970 is manifest in the Australian region, and some of the critical considerations in respect of that are (refer Appendix A for details of acronyms):

- the early polar-orbiting satellites (1966 to 1978) provided only two images per day (9 am and 9 pm) and the chance of obtaining a well-located view (at nadir) over a TC was small;
- the poor temporal coverage also drastically filtered the dynamic behaviour of the TCs and completely missed the now-recognised time of convective maximum around 4 am local time (e.g. Kossin 2002; Kossin et al. 2007);
- the earlier poor resolution (e.g. 9 km) was unable to detect the type of detail now being made available (e.g. 4 km or 1 km) in convective bands and the eyewall;
- even the readily available three-hourly GMS geostationary infrared (IR) and enhanced infrared (EIR) products from 1978 onwards often suffered from cirrus canopy masking and their higher orbits provide less detail than the lower but less frequently storm-intercepting images from polar orbiters;
- changes in some satellite algorithms and products have created problems, e.g. GMS4 enhancement algorithm in the Man computer Interactive Data Access System (McIDAS) in the early 1990s;
- recent microwave satellites (SSM/I, TRMM, etc.) now allow very detailed imaging that assists in centre and rainband location for the Dvorak method but, being polar orbiters, provide erratic coverage and much of their signatures are yet to be calibrated with *in situ* intensity measurements;
- some technologies (e.g. Advanced Microwave Sounding Unit (AMSU); Brueske and Velden 2003) for directly estimating mean sea-level central pressure (p_c) are very promising but still limited by resolution such that not all TCs can be reliably assessed;
- surface wind estimates from satellite scatterometers have only become widely used since 2000 and, while providing enormous benefit over the outer regions of a TC, remain more limited near the eyewall due to saturation and rainfall contamination.

Bureau of Meteorology best track practices

The official Australian TC historical record maintained in electronic form by the BoM National Climate Centre (NCC) begins in the 1906/07 season. This database derives principally from climatological summaries by Visher and Hodge (1925), Coleman (1972) and later Lourensz (1977, 1981) with annual seasonal updates of best track information from the State-based Regional Offices since that time. The overall quality and consistency of the database were last assessed by Holland (1981), in concert with the Lourensz updates. The clear trends in frequency and intensity statistics identified by Holland could readily be associated with the many changes in observing systems (principally satellites since 1968 but also automatic weather stations (AWSs) since 1966) and the adoption of standardised techniques such as Dvorak (1975). It is 25 years since any comprehensive review, presentation and summary of the Australian region TC climatology has been undertaken.

In spite of the critical importance of the historical TC record for risk analysis or climate trend studies, there is no central or comprehensive source that describes or historically documents BoM best track compilation practice. Due to the BoM's regional structure, each of the Tropical Cyclone Warning Centres (TCWC) at Brisbane, Darwin and Perth developed localised methods over time, albeit with common training seminars since the early 1970s, annual post-season workshops and the exchange of staff (J. Callaghan, personal communication). Parameters of some TCs that traverse more than one region are still typically subject to some debate. Some of these regional BoM practices are summarised in Harper (2002), mainly in respect of the choice of wind-pressure relationships when converting Dvorak (1975, 1984) estimates of maximum sustained surface wind (V_{max}) into associated estimates of the mean sea-level central pressure (p_c). Harper (op. cit.) has documented a regional preference for the Atkinson and Holliday (1977) relationship (hereafter A&H) by Queensland and Western Australia and the Love and Murphy (1985) relationship (hereafter L&M) in the Northern Territory since 1985.

Prior to this time BoM (1978) advocates a variety of techniques based on the accepted literature of the time, especially those arising from the US National Hurricane Research Project (NHRP) from the early 1960s, which proposed various models for wind and pressure fields. For example, in the detailed assessment of winds during TC *Ada* in Queensland in 1970, Wilkie and Gourlay (1971) adopted the Schloemer (1954) exponential pressure profile* as advocated by Graham and Hudson (1960). Likewise, a similar process was used for TC *Althea* (BoM 1972). Assuming that some outer wind and pressure observations were available for an event, the NHRP method is likely to have been the accepted practice for estimating intensity in lieu of

* In hindsight, given *Ada*'s very small size, this was probably not a good choice (e.g. refer Harper 2002).

an actual near-centre observation over the period 1965-1975. The advent of the impressive Dvorak method in the mid-1970s (Velden et al. 2006) then appears to have supplanted the reliance on 'pressure profiles', possibly because of the additional analysis effort needed to extrapolate profiles, as opposed to the new 'objective' cloud pattern recognition system that provided a 'current intensity' or *CI* value on an increasing scale of 1 to 8. This *CI* value was then directly related to V_{max} via an empirical curve. Ironically, as noted by Harper (2004) the simplicity and modest documentation demands of the Dvorak method acted to limit the amount of detail entering the present archive. This oversight in data collection over the past 30 years means that much potentially valuable information, which could have been used to improve such empirical techniques, has unfortunately been lost.

BoM (1978) was a landmark document of its time, attempting to summarise all relevant knowledge and science regarding TCs, and with special relevance to assisting forecasting in the Australian region. Harper (2004) notes that although BoM (1978) was never formally published or updated, it largely survives in spirit as the *Global Guide to Tropical Cyclone Forecasting* (WMO 1993). Of special relevance to this study is that BoM (1978) draws the necessary distinction between US-based so-called one-minute maximum sustained* surface winds (MSSW), which were enshrined in the A&H 1977 wind-pressure relationship, and the WMO standard ten-minute averaged surface winds adopted by Australia. Unfortunately, the supplied 'forecaster check sheets' (e.g. BoM (1978) Fig. 7.28) provided wind-pressure equations that were still one-minute based and required conversion in subsequent steps. The extent to which these one-minute formulae became established, together with the fact that the Dvorak (1975, 1984) CI-V_{max}-p_c tabulations were readily available, is not known but (refer next section) appears to have possibly corrupted some of the historical data-set. For example, BoM (1977) correctly discriminates the wind averaging issue with regard to TC *Tracy*. However in BoM (1979), addressing TC *Joan* that occurred in 1975, the adopted V_{max}-p_c based on the Dvorak (1975) North West Pacific table is coincidently almost identical to the one-minute A&H relationship. By the time of TC *Orson* in 1989 (BoM 1992), the A&H adjusted ten-minute relationship was arguably well established in the Western Australian region, based on the BoM (1978) recommended conversion of V_{600}=0.88 V_{60}. There remains ample scope however for the original p_c values to have been erroneously related to the Dvorak *CI* values.

* The timing and origin of the US 'maximum sustained' one-minute wind standard for hurricanes is uncertain, but may have derived from the use of the 'fastest mile' wind at some time in the mid-1970s and was adopted by A&H in 1977 based on the apparent US military preference (e.g. Sissenwine et al. 1973). Importantly, the one-minute wind in this context is not an average but rather a gust, referenced to an unstated but nominal five-minute reference period. None of the earlier NHRP documentation refers to one-minute winds and even Schwerdt et al. (1979) persist with ten-minute winds, noting a conversion being required for A&H. Notably, Dvorak (1975, 1984) does not explicitly state that a one-minute wind averaging period is applicable to his tabulated CI-V_{max}-p_c values. It is noted that the WMO Tropical Cyclone Programme is currently reviewing wind averaging recommendations.

Bureau of Meteorology data-set processing

The original data-set

The 'original' track data-set here is that obtained from the Bureau of Meteorology internet website, current to the 2002/2003 season, which was the latest available at the time of the analyses. Processing of this data was limited initially to obtaining a contemporaneous set of tracks with that of the revised WEL data-set, given that the reviewed sample was arbitrarily bounded within an active TC region (refer Fig. 3 for spatial context).

Processing of this data-set initially involved retaining only those tracks that:

- represented the period 1968/69 to 2000/01;
- entered within latitude 7°S to 27°S and longitude 100°E to 140°E;
- were in common with the revised WEL data-set, totalling 178 storms.

The primary intensity parameter in the BoM data-set has traditionally been the estimated mean sea-level central pressure p_c, although after matching with the revised data-set, 44 per cent of BoM fixes were found to also provide a V_{max}, ostensibly ten-minute averaged as labelled. The practice of including V_{max} appears to have occurred post-1985 but was apparently not universally applied. However, by cross-plotting the available [V_{max}, p_c] pairs in Fig. 2, it suggests that the BoM data are mostly a mixture of A&H ten-minute (58 per cent) and one-minute (30 per cent) wind-pressure relationships, rather than only the modified ten-minute A&H relationship that might have been expected based on BoM advice.

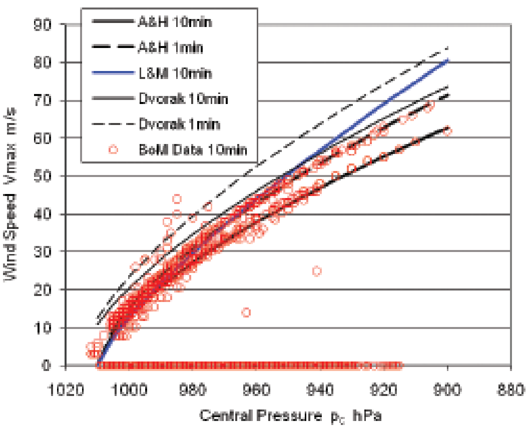
Interestingly, there is no strong evidence here that L&M was being used specifically, but the differences between L&M and the other relationships are only small for weaker storms, and only become substantial for severe strorms, which are less frequent in the NT region. There is also some suggestion in Fig. 2 that

Table 1. The Saffir-Simpson scale vs Western Australian TC category scale and Dvorak (1975).

US Saffir-Simpson hurricane scale			*Dvorak*	*Western Australian TC category*			*Dvorak*
Category No.	p_c *hPa*	V_{60} *m/s*	*(1975)* CI*	*Category No.*	p_c *hPa*	V_{600} *m/s*	*(1975) CI*
-1	Tropical depression	< 17.5					
0	Tropical storm	17.5	2.4	1	> 995	17.5	3.0
				2	985	25	3.5
1	> 980	33.1	3.9				
				3	970	33	4.5
2	980	42.9	4.7				
3	964	49.6	5.3				
4	944	58.6	5.9				
				4	940	47	5.5
5	< 920	69.3	6.7				
				5	< 915	58	6.5

* The Dvorak *CI* is technically defined only in increments of 0.5 (the normally accepted limit of its accuracy) but a continuous approximation is adopted here for conversion purposes.

Fig. 2 Implied wind-pressure relationships in the BOM original data-set.



the Dvorak Atlantic one-minute relationship may have been used in some situations, even as late as 2000, but these winds might be based on specific observations. Because the original Dvorak *CI* values have not been retained, this leaves some degree of uncertainty as to what the originally derived V_{max} was and/or the currency of the retained p_c in the post-Dvorak era (circa 1972).

Because one of the aims of this assessment was to allow direct comparison with WHCC, the approach was to assemble all intensity estimates as V_{60} (so-called one-minute sustained winds) rather than Australian and WMO standard V_{600} (ten-minute average). This allowed ready conversion into USA Saffir-Simpson (Simpson 1974) hurricane categories (Table 1). However, for additional utility, Dvorak *CI* values and p_c values were also analysed and are presented. Note that the US Saffir-Simpson (hurricane) scale essentially begins near 'high category 2' on the Australian scale. This offset in scales necessitates creation here of 'pseudo S-S' scales of 0 and -1 to allow S-S classification of all storms in the Australian data-sets and to generally highlight the fact that there is a significant offset between the Australian and the USA scale systems.

Accordingly, two approaches were taken here, one being to accept the time series of BoM estimates of p_c at face value, assuming that they were derived using an A&H approach and then back-calculating equivalent Dvorak *CI* and V_{60} values. This ignores the fact that the A&H method was strictly not available until circa 1978, but nevertheless provides a suitable reference, given that specific usage of the NHRP approach has not been documented.** This data-set is referred to here as the 'BoM original'. Appendix B summarises the data conversion process used.

** The NHRP method needs to invoke gradient-to-surface wind speed adjustments and the like, which are arguably unknown for specific cases, while the A&H is offered as a surface-wind formula.

A modified data-set

The second and preferred approach was to attempt to 'rectify' the BoM data-set based on the anticipated operational processes of the time. A series of rules were developed to assist in back-calculating what may have been the originally estimated Dvorak *CI* values or what could have been in the pre-Dvorak period. The rules are predicated on the assumption that it was only in recent times (say since 1990) that a strong appreciation of the wind-averaging issues was common amongst all BoM forecasters. Also, as the original NOAA Dvorak CI-V_{max}-p_c tabulations did not refer to wind-averaging issues (e.g. Velden et al. 2006), it was possible that V_{max} and p_c values were being read from the original NOAA report tables rather than from locally adjusted ten-minute versions.

This second (modified) approach is expected to yield a more reliable reconstruction of objective p_c, V_{max} and *CI* values over the original approach. This data-set is referred to here as the 'BoM modified' and the data conversion process is also summarised in Appendix B.

The objectively reviewed WEL data-set

The review methodology

The intent of the WEL review was to recover and review raw storm data (BoM Regional Office files, hardcopy satellite photos, etc.) with the aim of objectively comparing the raw information with the official track commentary contained in storm-specific BoM technical reports and annual summaries, *Australian Meteorological Magazine* season summaries, Lourensz (1981) and the official database itself. The aim was to estimate the Dvorak *CI* number directly, objectively and consistently based on the applicable cloud pattern recognition rules (Dvorak 1984), aided as appropriate by reliable surface observations. Use of the Dvorak method is unavoidable due to the absence of aerial reconnaissance in Australia and the sparseness of the surface-observation network. The review team were specifically cautioned against reverting to the use of potentially more familiar direct metrics such as central pressure, which is subject to a wind-pressure assumption. The latter issues were addressed in Harper (2002) and led to these recommended review procedures.

The revised data-set comprised 183 storms from 1968/69 to 2000/01 seasons that entered the region 5°S to 27°S and 105°E to 140°E as well as 17 storms in the Timor Sea prior to 1968 that had some historical interest. In addition to reviewing the official intensity and track data, a primary intention was also to collate any associated data such as eye diameter, radius to gales, ambient pressure and the like that would be needed for numerical wave modelling studies. The temporal resolution in the revised data-set was not fixed (e.g. unlike the six-hourly US HURDAT) but varied in the same manner as in the original BOM data-set. Data timesteps therefore ranged from one-hourly in situations when the storm was perhaps in the vicinity of a radar installation to 24-hourly during the 1970s when a storm was well out at sea. During the re-analysis some additional data points were included to incorporate information considered important. This might include an additional location point based on an interpretation of the satellite imagery or surface observations, or relate to satellite imagery being available at a non-standard time. Where data were added or modified it was recorded as such using an audit trail.

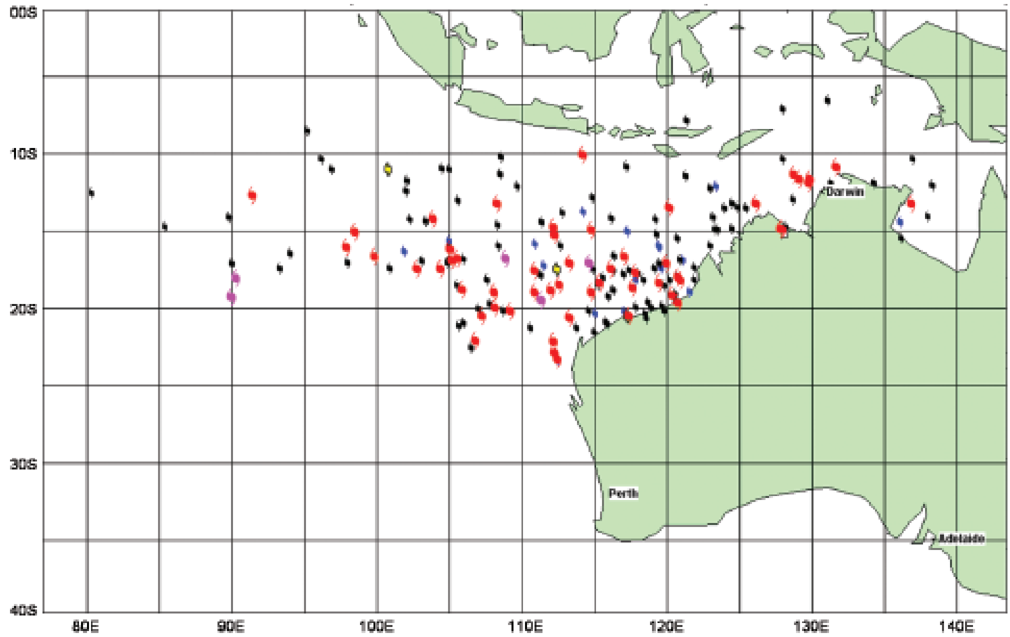
Particular attention was given to ensuring that the beginning and end of each storm's life was as accurate as possible. Soon after the analysis task commenced it became clear that the early development stages of some TCs were not well handled in the original BoM data-set. In most cases where a discrepancy was noted, the system was deemed by the review team to have reached TC intensity earlier than shown in the database. Less frequently, the new interpretation indicated development was delayed. In a few instances the position of the centre of the storm was changed based on a re-interpretation of the observations or from the revised satellite image interpretation.

In summary, the main re-analysis tools used were (process detailed in Appendix B):

- satellite imagery, interpreted according to Dvorak (1984);
- mean sea level (MSL) chart analyses either prepared operationally by the BoM staff or amended during the post-event analysis and containing annotated observations;
- land-based radar imagery, concentrating on centre location.

The resulting WEL-reviewed data-set comprises a total of 8228 positional fixes, 83 per cent of which have positions based on the original BoM fixes, while 17 per cent are new fixes based on either satellite imagery, observations or subjective judgement. Only 22 per cent of the original BoM intensity estimates were retained, with 74 per cent being based on Dvorak interpretation and the remaining four per cent being interpolated or subjective (e.g. over land). This is also an artefact of the precision of the *CI* numbers not being limited to the original 0.5 interval. A more continuous smoothing was attempted to a precision of 0.1. The resulting locations of maximum intensity of all storms in the WEL-reviewed data-set are given in Fig. 3.

Fig. 3 **Location of maximum intensity of tropical cyclones in the WEL-reviewed data-set for seasons 1968/69 to 2000/01 and storms entering the region 5°S to 27°S and 105°E to 140°E. Colour coding compares relative change in US Saffir-Simpson category between the BoM modified and WEL modified data-sets; black is unchanged, red is increased by 1 category and purple increased by 2; blue is decreased by 1 category and yellow is decreased by 2.**



An additional five TCs were added to the WEL-reviewed data-set that did not exist in the BoM data-set. These were *Beverley* (1970), 'Flores Cyclone' (1973), *Linda* (1976), *Tina* (1989) and Unnamed (2001). *Tina* is perhaps the most significant, albeit a sometimes-debated TC event because of its unusual characteristics, notably lacking a demonstrably warm core and having a very large-scale wind field, which created a high wave event on the North West Shelf. The Flores storm in 1973 is significant in the Timor Sea in as much as it seems to have reached TC intensity around latitude 6°S. The remaining new storms were relatively weak and had minor impacts in the region.

Limitations of the review

It can be argued that any subsequent historical review of this type might never have as much information available or as great an appreciation of the developing situations than when it actually unfolded. Hence we are left with skill in interpretation of satellite imagery as the primary discriminator, a reliance on the principal observations being correctly reported and documented but gain an expectation of greater internal consistency. The WEL review was also necessarily done within a context of limited time and resources and, while there is an expectation that the resulting data-set will be superior to the original data-set, it should not be regarded as perfect or not able to be improved upon. Appendix C provides a more detailed critique of the WEL review limitations.

The Neumann southern hemisphere data-set

This is the data-set sourced by WHCC for their Southern Indian Ocean (SIO) region and derives originally from Neumann (1999), whose efforts to assemble consistent best track data-sets from all the relevant agencies has been commendable, identifying many of the data quality issues and lobbying for improvement in best track archives. The data used here are from a southern hemisphere HURISK data-set personally supplied to the principal author by Charles Neumann in 2004. It is considered equivalent to the WHCC data-set for the purpose of these comparisons, although WHCC utilised data only from storms entering their SIO region west of 115°E (i.e. Onslow). However Holland (personal communication) expects that the majority of North West Shelf storm maximum intensities would have been included in WHCC because the full storm tracks were then processed after selection.

Table 2. Comparing the WEL-reviewed data-set peak storm intensities.

Reference data-set	*Percentage of storms changing Dvorak CI intensity by at least 5%*			
	Increased intensity	*Decreased intensity*	*Unchanged*	*Net increased*
BoM modified	44.3	17.5	38.2	26.8
BoM original	47.5	14.2	38.3	33.3
Neumann	58.5	23.5	18.0	35.0

A total of 181 storms were able to be matched with the WEL-reviewed data-set, being three more than the BoM data-set, leaving only Unnamed in 1983 and *Walter* in 2001 outstanding. The original Neumann data-set also contained *Herbie* in 1988, which crossed the Western Australian coast near Denham with some significant impact to the local fishing community. Whether this storm was a TC has been debated over the years, but Burton (BoM Perth, personal communication) advises some portion of its life will likely be admitted, with some caveats, after future reviews.

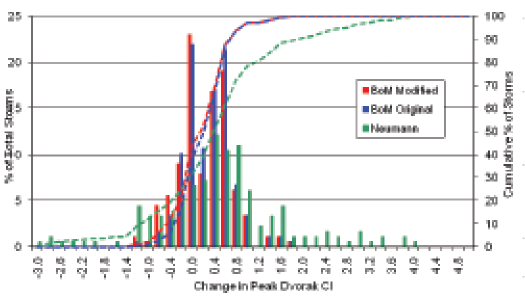
Comparison of the data-sets

There are many different ways in which the various data-sets can be compared. For the purpose of concentrating on issues in regard to intensity change, Table 2 summarises the percentage of all storms that experienced at least a 5% change* in their assessed peak Dvorak *CI* intensity as a result of the WEL review. Of the three reference data-sets, the BoM modified data experienced the least change, confirming the appropriateness perhaps of the adjustment process here, but still with 44.3% of storms having an intensity increase of at least 5%. The next least changed is the BoM original data-set with 47.5% having an intensity increase, followed by the Neumann data-set where 58.5% experienced an increase in intensity by at least 5%.

A more complete picture of the range of changes in the assessed intensities is given in Fig. 4 as a distribution of the changes histogrammed at a 0.2 *CI* interval for each reference data-set. This shows that around 20% of all storm peak *CI* values in the BoM modified and BoM original data-sets increased by 0.6 to 0.8 (the non-zero positive modal value) but only about 10% of storms increased by the same margin in the Neumann data-set because of its much larger variance.

* The 5% threshold also avoids minor rounding issues during application of the various conversions.

Fig. 4 Distribution of changes in peak Dvorak *CI* relative to the indicated data-set.

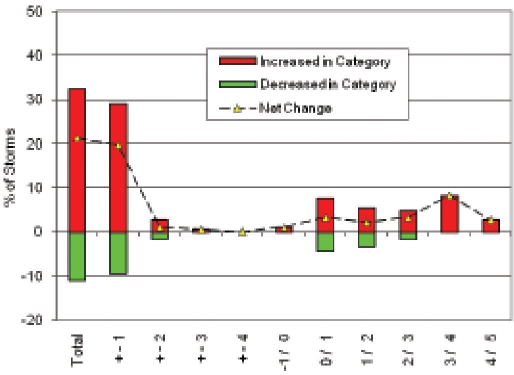


Focusing now on the analysis methodology used by WHCC, Fig. 5 summarises the changes in terms of Saffir-Simpson (S-S) category** whereby 56.8% (104 of the 184 storms) had unchanged peak intensities after the WEL review, 32.2% increased in intensity and 10.9% decreased in intensity. In terms of S-S categories, 29% of all storms (53) increased intensity by one S-S category and 2.7% (5) increased by two S-S categories. Specific information on the moving from one S-S category to another is also provided in Fig. 5 and spatial views of these changes are indicated on Fig. 3.

It can be seen from the above illustrations that, as a result of the WEL review, there has been a significant increase in estimated TC intensity across a wide range of events (net of 21.3% of storms increased), mostly by one S-S category (net of 19.7%). Many of these are at the higher end of the range, whereby S-S Category 3+ changes represent almost 11% of those storms having increased intensities. Analogous comparisons between the WEL-reviewed data-set and both the BoM original data-set and the Neumann data-set show similar differences.

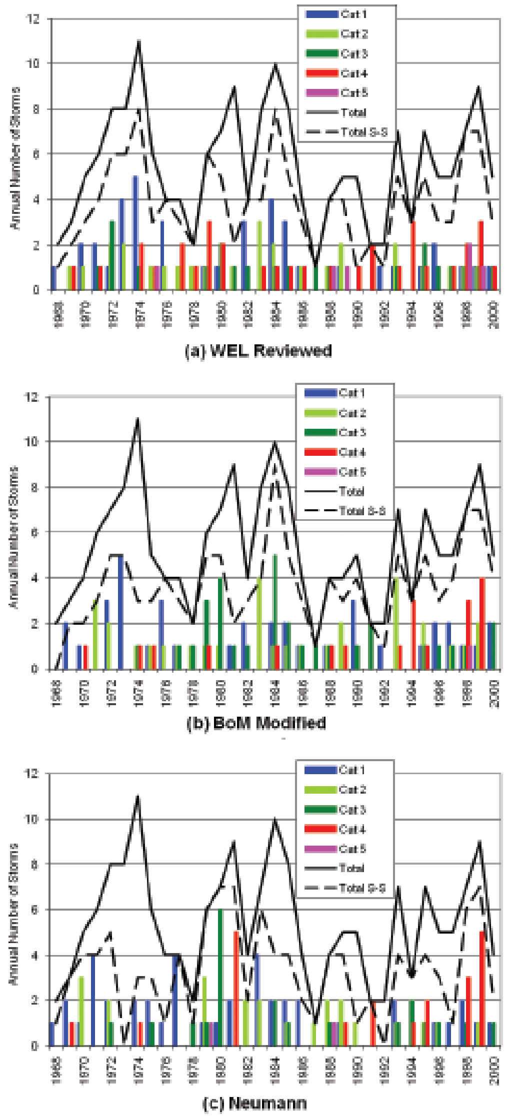
** The slight mismatch in actual storms in-common (183 vs 178) is treated by way of the few unmatched storms being labelled as unchanged.

Fig. 5 **Summary changes in US Saffir-Simpson category between BoM modified and WEL-reviewed data-sets. The left-most column summarises the overall percentages of storms having an increase or a decrease in their original BoM intensity category. The next four columns document the shifts in categories by one S-S number, two, three or four respectively. The right-most four columns document the changes between specific categories, where '0' indicates 'tropical storm' on the S-S scale, or essentially a Category 1 Australian TC.**



A temporal view of the S-S category changes is provided in Fig. 6. This shows a clear increase in category 3, 4 and 5 storms over the early part of the WEL time series (1970s) but also some significant shifts in category classifications across all time periods between the three data-sets. Figure 6 additionally shows the total number of storms in the data-set (solid black) and the total of S-S classified storms (dashed black), whereby a lower proportion of 'hurricanes' can be seen in the early period of the BoM and Neumann data-sets. Figure 7 summarises the magnitude changes of the various intensity estimates (interlinked here according to Eqn B1 to Eqn B5) on a time basis for each individual storm in common between the WEL-reviewed data-set and the BoM modified data-set. Although the changes are seemingly erratic, the quadratic trendlines show a decreasing tendency to apply a change over time. Notwithstanding this, some significant changes are still indicated as late as 2000/01. The linear trend in V_{60} in Fig. 7 is 0.10 m $s^{-1}a^{-1}$, with the quadratic fit having double the R^2 of the linear fit. Table 3 provides a summary of the more significant individual storm changes, ranking those storms that experienced a change in Dvorak $|CI|$ of more than 0.5. The top three storms and the bottom storm (greatest decrease in intensity) are all during the 1970s, while there seems to be a preponderance of mid-1980s storms in the greatest decrease category.

Fig. 6 **Temporal comparison of US Saffir-Simpson intensity category counts by data-set.**

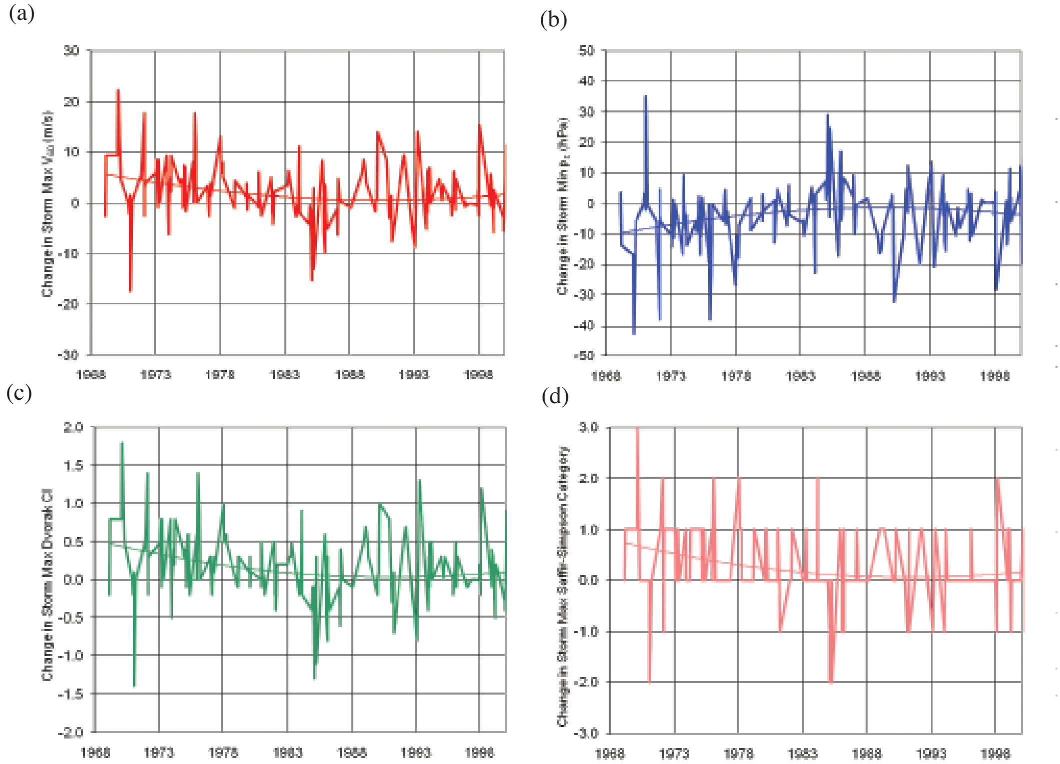


Analysis of trends

Saffir-Simpson categories

For comparison with WHCC a pentadal averaging of intensity trends is presented, beginning in 1969-1973 and continuing until 1994-1998. Figure 8 provides a summary of all the data-sets used here, with numbers and relative percentage of the various S-S categories shown over time, following Fig. 4 of WHCC. The annual maximum V_{60} is also shown in each case, where increasing trends are immediately evident. The differences between the BoM modified and BoM original data-sets are relatively small in this context,

Fig. 7 **Changes in (a) storm maximum V_{60}, (b) minimum p_c, (c) maximum *CI*, and (d) maximum Saffir-Simpson category over time for each storm between the BoM modified and WEL-reviewed data-sets.**



mainly constrained to the latest decade. Both show substantial increases in the combined Category 4+5 class in the final pentad. In comparison, the Neumann data-set shows an arguably steadier rise in the Category 4+5 class and is quite different from the BoM data-sets in respect of the other classes. Finally, the WEL-reviewed data-set shows a very significant suppression in the variability of all classes but with indications still of an increasing trend in Category 4+5 and a decreasing trend in Category 1. By comparison, WHCC obtained a generally steady increase in global percentage occurrence of Category 4+5 from about 16% of the total to about 35% of the total over a 30-year period. The WEL-reviewed data-set is offset from the WHCC global data-set in absolute terms but shows a similar trend in Category 4+5, although clearly much influenced by the first pentad.

Direct intensity changes

Pentadal grouping combined with the arbitrary intensity thresholds of the Saffir-Simpson scale leads to accentuation of the variability and it is more appropriate to consider direct and continuous sampling of the intensity time series, such as trends in assessed Dvorak *CI*. This is presented in Fig. 9 contrasting the WEL-reviewed vs Neumann data-set *CI* values. In each case the averaged annual maximum *CI* in each pentad are plotted. Overlaid linear trendlines are shown for the full pentadal range and then omitting the first pentad 1969-1973. The WEL trendline slope reduces from 0.023 to 0.010 (56% reduction) and the Neumann slope reduces from 0.031 to 0.014 (55% reduction). This indicates that the early 1970s are prima facie contributing a large proportion of this trend effect in both data-sets.

As discussed earlier, lack of adequate imaging prior to GMS satellites in 1978 is likely a significant factor in the intensity trending and is an unrecoverable feature of any TC database review. However, another possible background trend that could be influencing the first pentad in particular is the El Niño Southern Oscillation (ENSO). For example, Broadbridge and Hanstrum (1998) utilised three-monthly mean values of the SOI, together with seasonal trends, to infer a range of TC behaviour in this region. Their conclusion was that a higher percentage of severe TCs (61%) were associated with negative SOI periods compared with positive SOI (38%) peri-

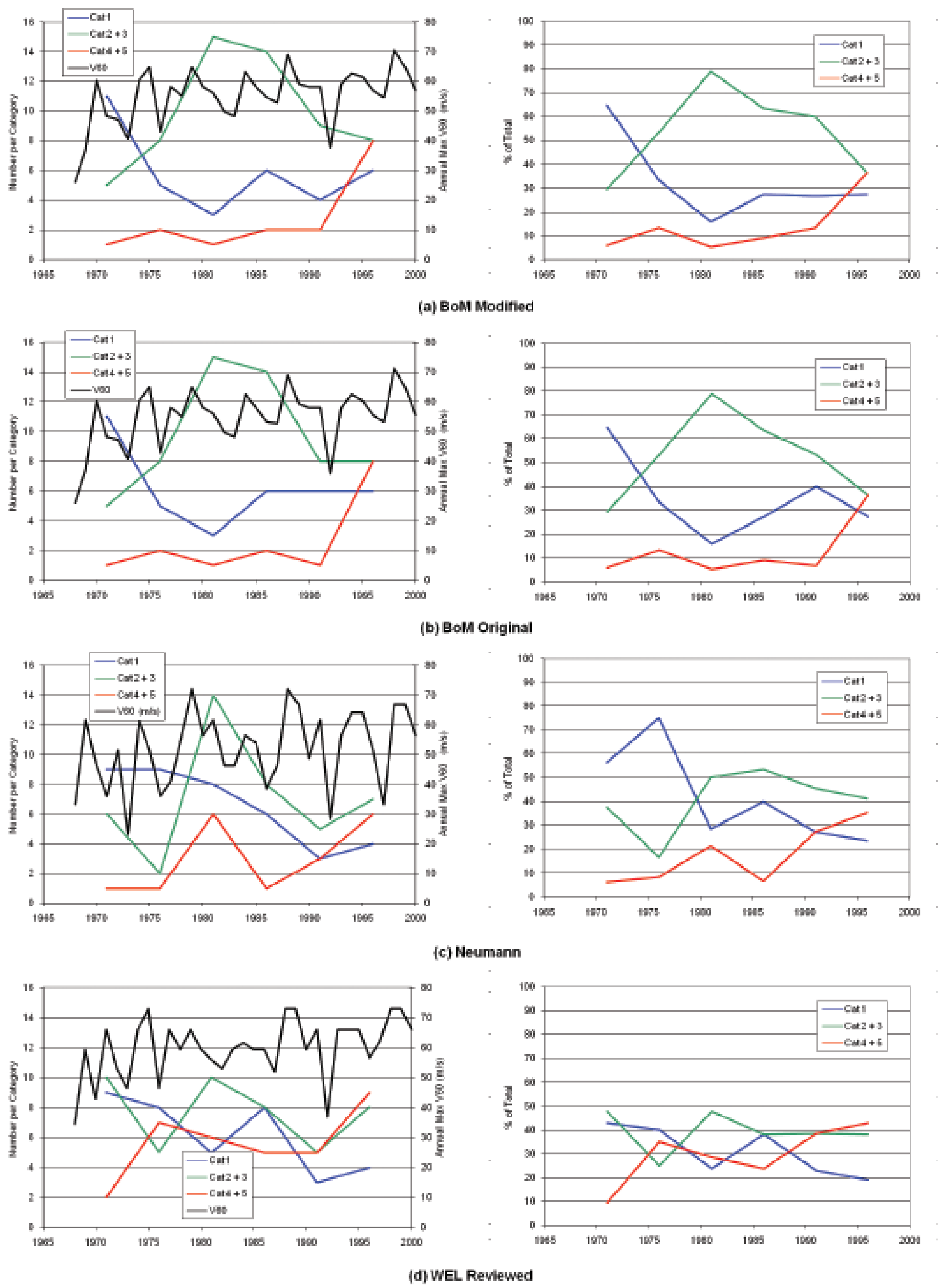
Table 3. Summary of TCs having greatest intensity changes (|CI|>0.5) between BoM modified and WEL-reviewed data-sets.

Storm name	Max intensity Date UTC	Change in value Dvorak CI	S-S	V_{60} m/s	p_c hPa	Final value Dvorak CI	S-S	V_{60} m/s	p_c hPa
Ingrid_1970	15-02-1970	1.8	3	22.2	-42.8	6.0	4	59	927
Tessie_1972	24-02-1972	1.4	2	17.8	-37.9	6.5	4	66	912
Vanessa_1976	23-01-1976	1.4	2	17.8	-37.9	6.5	4	66	912
Monty_1993	10-04-1993	1.3	1	14.1	-20.8	4.2	1	37	971
Victor_1998	13-02-1998	1.2	2	15.3	-28.4	5.5	3	53	941
Trudy_1978	16-01-1978	1.0	2	13.2	-26.8	6.0	4	59	927
Alex_1990	18-03-1990	1.0	1	13.9	-32.0	7.0	5	73	896
Wally_1976	26-02-1976	0.9	1	11.2	-19.7	5.0	2	47	953
Bobby_1984	20-02-1984	0.9	2	11.1	-22.8	6.0	4	59	927
Kirrily_2000	29-01-2000	0.9	1	11.3	-19.8	5.0	2	47	953
Bella_1973	24-03-1973	0.8	1	8.4	-10.4	3.2	0	26	988
Audrey_1969	05-03-1969	0.8	1	9.3	-13.6	4.0	1	35	974
Glynis_1970	02-02-1970	0.8	1	9.4	-16.7	5.0	2	47	953
Maud_1973	29-01-1973	0.8	0	8.4	-12.0	3.8	0	32	978
Ines_1973	21-11-1973	0.8	1	9.4	-16.7	5.0	2	47	953
Jenny_1974	28-03-1974	0.8	1	9.3	-13.6	4.0	1	35	974
Laurence_1990	11-12-1990	0.8	0	8.3	-11.1	3.5	0	29	983
Kirrily_1989	09-02-1989	0.7	1	8.5	-16.4	5.5	3	53	941
Neville_1992	08-04-1992	0.7	1	9.5	-19.7	6.0	4	59	927
Sam_2000	07-12-2000	0.7	1	9.2	-20.4	6.5	4	66	912
Tiffany_1998	26-01-1998	0.6	1	7.5	-15.9	6.2	4	62	921
Clara_1975	22-04-1975	0.6	1	7.1	-10.6	4.0	1	35	974
Kerry_1973	21-01-1973	0.6	1	7.4	-14.0	5.3	3	50	946
Beverley_1975	28-03-1975	0.6	1	7.5	-16.9	6.5	4	66	912
Joan_1975	07-12-1975	0.6	1	8.1	-19.2	7.0	5	73	896
Alby_1978	01-04-1978	0.6	1	8.0	-17.9	6.5	4	66	912
Nicholas_1985	03-12-1985	0.6	1	8.3	-17.3	6.0	4	59	927
Ian_1992	01-03-1992	0.6	1	8.0	-17.9	6.5	4	66	912
Paul_2000	15-04-2000	0.6	1	8.1	-19.2	7.0	5	73	896
Jacob_1985	20-02-1985	-0.6	-1	-8.0	16.1	5.0	2	47	953
Lindsay_1985	09-03-1985	-0.6	-1	-6.9	13.7	5.0	2	47	953
Damien_1987	03-02-1987	-0.6	0	-6.3	9.1	3.2	0	26	988
Gertie_1985	31-01-1985	-0.6	-1	-7.6	12.4	3.8	0	32	978
Isobel_1985	17-02-1985	-0.6	-1	-7.1	13.2	4.6	1	42	962
Terri_2001	30-01-2001	-0.7	-1	-7.0	10.8	3.4	0	28	984
Fifi_1991	18-04-1991	-0.7	-1	-7.6	12.3	3.7	0	31	980
Rhonda_1986	20-02-1986	-0.8	-1	-9.8	17.1	4.0	1	35	974
Lena_1993	25-01-1993	-0.8	-1	-8.7	13.7	3.5	0	29	983
Steve_2000	06-03-2000	-0.9	-1	-10.9	19.6	4.2	1	37	971
Vincent_2001	12-02-2001	-0.9	0	-9.2	13.0	2.9	0	23	992
Margot_1985	14-04-1985	-1.1	-2	-13.1	24.9	4.5	1	40	965
Hubert_1985	14-02-1985	-1.3	-2	-15.4	29.0	4.3	1	38	969
SheilaSophie_1971	03-02-1971	-1.4	-2	-17.5	35.2	4.7	2	43	960

ods. Also shown in Fig. 9, the pentadal SOI variation shows a clear reverse trend to the identified intensity trend, with especially the 1969/73 pentad being influenced by the strong La Niña (+ve SOI) at that time. It can therefore be speculated that the intensity during this early pentad may be SOI-sensitive. However, this conclusion may be a partial artefact of the data-set itself and their specific analysis and conclusions would need to be now repeated for certainty.

Leaving the pentadal averaging to one side, Fig. 10 presents the time history of average annual p_c estimates for the WEL, BoM modified and Neumann data-sets. This presentation highlights the very high level of variability in the annual data-set, whereby the standard deviation is of the order of 16 hPa. A linear trend yields a steady but small increase in intensity (equivalent to a *CI* increase of less than 1.0) over the 30-year period but the quadratic trend-

Fig. 8 **Pentadal fluctuations in Saffir-Simpson categories following Fig. 4 of Webster et al. (2005).**



line, as indicated, is more representative and shows that near-asymptotic behaviour is achieved by the mid-1980s in spite of the enormous variability. The bias between the BoM modified and the WEL-reviewed p_c is of the order of +3 to +5 hPa since 1980 (6% of central pressure deficit; Δp = 1010-p_c). Prior to 1980, the implied p_c bias rises to around +10 hPa by 1968/69 (over 20% Δp).

Fig. 9 **Sensitivity of Dvorak CI data-set trends to analysis period and the simultaneous SOI trend. Solid red and blue lines are the average maximum CI each pentad for WEL and Neumann data-sets respectively; solid purple line is the average SOI each pentad. Linear trends for the full pentadal range 1969 to 1998 shown as long dashed lines, short dashed lines ignore the earliest pentad 1969-1973.**

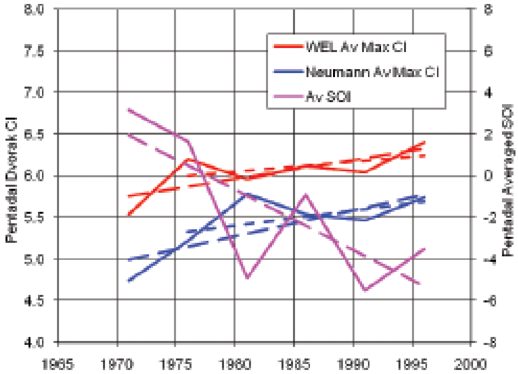


Fig. 10 **Trends in average annual maximum intensity (minimum p_c) for each of the data-sets, together with quadratic lines of best fit.**

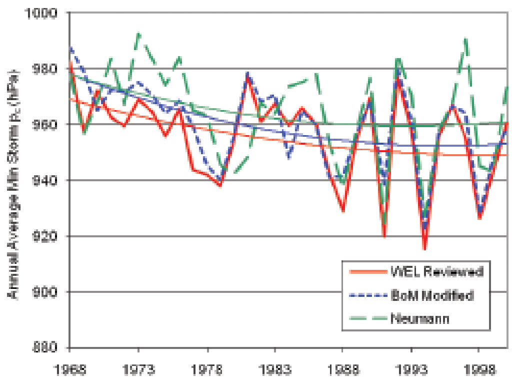
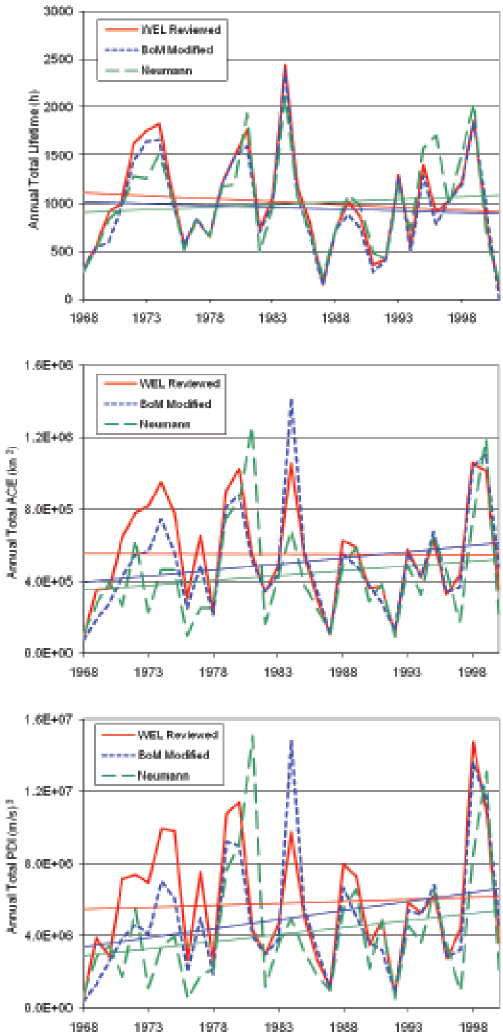


Fig. 11 **Time history comparison of the annual total storm lifetime, ACE and PDI indices.**



Lifetime, ACE and PDI

Next, Fig. 11 provides a comparison between the storm lifetimes and the six-hourly integrated ACE and PDI indices* between the various data-sets. The differences are again significant at various times, the WEL data showing increases over the other data-sets during the 1970s especially. Both the BoM and Neumann data-sets exhibit increasing trends in ACE and PDI, the latter being of somewhat similar magnitude to that presented by Emanuel (2005) in respect of best track derived PDI for the combined Atlantic and NW Pacific basins, which were shown to have nearly doubled from 1970 to 2000. By contrast, the WEL-reviewed data-set shows no trend for ACE and only a very slight increase in PDI.

* ACE is the Accumulated Cyclone Energy index historically used by NOAA, being $\sum V_{60}{}^2$ per six hours in units of kn^2. PDI is the Potential Destruction Index used by Emanuel (2005), being $\sum V_{60}{}^3$ per six hours in units of (m/s)^3. Both are applied over the period when V_{60} exceeds US tropical storm strength of 17.5 m/s or 34 kn.

Conclusions

The results of an objective review of TC intensity in northwestern Australia for the period 1968/69 to 2000/01 have highlighted many important issues concerning the potential reliability of historical TC data-sets within Australia and, by implication, globally. First, consideration has been given to the considerable developmental influences that have occurred over the past 30 years, which can be expected to have affected the way in which TC intensity might be estimated and also the accuracy of those estimates. It is concluded that these changes alone would have tended to create a trend towards increasingly more intense estimates due to the improving technology (increasing sensor resolutions – surface and satellite, time and space) and improving methodologies, knowledge and skill. Second, the review highlights the lack of documentation in regard to the official BoM TC database over the same period and the potential for a variety of analysis techniques to have been applied. Through an assessment of the likely major influences on process and procedures over time, a series of rules were then developed to rectify the original BoM data-set. While these changes had some impact on the overall statistics of the data-set, their application was not significant overall, compared with the changes proposed by the objective WEL review.

Next, relevant background to the WEL review has been included to assist in gauging the veracity of the work and to consider the limitations of time and analyst resources under which the review was conducted. Some of these limitations are seen to be unavoidable, namely the loss of information over time. Notwithstanding this, the resulting data-set has been objectively and consistently reviewed by professional ex-BoM meteorologists who were well experienced and notably expert in the estimation of TC intensity. On this basis it is concluded that the WEL-reviewed data-set, albeit far from perfect, is likely to be of an overall superior quality and consistency relative to any other long-term data-set available for this region. The WEL-reviewed data-set has then been compared with several versions of contemporaneous data-sets, namely the BoM original data-set upon which it is based, a BoM modified data-set here based on the aforementioned rectifying rules and the Neumann data-set as used by Webster et al. (2005). The comparison shows that the WEL-reviewed data-set represents a significant number of changes over the BoM data-set for a range of parameters (peak intensity, time of peak, position of peak, lifetime, etc.). The principal change, though, is an increase in average storm intensities with around 50 per cent of all storms experiencing a non-trivial increase in estimated peak intensity. In Dvorak *CI* terms, the review has lifted annually averaged prior maximum storm intensities by about 0.4 *CI* in 1970, reducing to about 0.10 *CI* in the late 1990s. In p_c terms, this is a corresponding bias removal of the order of +10 to +5 hPa or +20% to +5% in terms of central pressure deficit Δp.

In terms of temporal trends in intensity, it has been shown that there is a trend towards increasing intensity over time evident in each of the data-sets. However, all data-sets also show a tendency for the trend to level out during the mid-1980s. This is consistent with the arguments regarding significant improvements in tools, especially after the GMS satellites became available in 1978 and the Dvorak method became established. If the observed BoM intensity trend prior to the 1980s were to be interpreted purely as ‘instrumental bias’ against a constant climatology, it represents approximately a 35 per cent underestimation at 1968/69, reducing to around 10 per cent underestimation by 1980, relative to the averaged central pressure deficits from 1980 to 2000. On this basis, even the WEL-reviewed data-set shows a 25 per cent ‘instrumental bias’ at 1968/69, suggesting a potential practical limit to recoverability.

Comparing the various data-sets directly with the global analysis by WHCC, whereby changes in S-S category counts are recorded on a pentadal basis, shows that there are very significant differences between each of the data-sets, with only the WEL-reviewed data-set showing a relatively stable temporal behaviour. Notwithstanding this, the reviewed linear trend in Category 4+5 storms is similar to that obtained by WHCC in respect of a global trend. However, the more appropriate comparison here is that the identified WEL-reviewed Category 4+5 trend is significantly less than the trend obtained from the equivalent BoM modified data-set and the Neumann data-set over the same comparison periods. These results therefore suggest that the Neumann data-set (forming the basis of the WHCC analysis in the southern hemisphere) could contribute a significant and unjustified trend of increasing Category 4+5 class percentage changes into the WHCC global analysis.

Importantly, the subsequent objective analysis of the post-GMS period by Kossin et al. (2007) adds confirmation to this conclusion, whereby no trend in intensity in the Southern Indian Ocean was evident over the period 1983 to 2005. Furthermore, analysis of the trends here shows that a significant reduction is achieved by ignoring the earliest and most suspect data pentad 1969-1973. Notwithstanding the arguments in regard to data quality, it is also acknowledged that climatic variability forced by the strong positive SOI during this earlier period may also be consistent with the observed trend. Finally, it has been demonstrated that the original BoM and Neumann data-sets do show a similar and significant temporal trend in PDI as identified by Emanuel (2005) for the Atlantic and Western North Pacific, but that the WEL-reviewed data-set shows only a very minor trend in PDI, and has no trend in ACE.

It is clear from this study that there is a need to similarly review all historical TC intensities across Australia and adjacent areas. If the identified bias of the order of +20% underprediction in central pressure deficit circa 1970 is replicated across other areas it could have an impact on a wide range of existing risk assessment studies. Also, there is an urgent need to standardise and document BoM procedures in respect of the future integrity of the TC database. Greater uptake of the developing Advanced Dvorak Technique (ADT; Olander and Velden 2007) as a routine forecast tool might ensure more consistent intensity analysis into the future but aerial reconnaissance such as that applied routinely in the USA since the 1950s, is a tool capable of demonstrably improving overall accuracy and arguably should be implemented in the Australian region as a matter of urgency.

It is also concluded that there is no prima facie evidence of a potential climate-change induced trend in TC intensity in northwestern Australia over the past 30 years. Moreover, the review has highlighted that there is some danger of empirical techniques such as Dvorak leading to overestimation in intensity as a result of much higher resolution satellite imagery now being available than was used in the development of the original techniques during the 1970s and 1980s (Harper 2002, 2004). This aspect alone warrants further study. Also, as highlighted by Kossin et al. (2007), increasing temporal resolution of satellite imagery has uncovered levels of storm variability that the Dvorak technique never expected and actively acted to suppress. Further comparison of the WEL data-set with Kossin et al. (2007) is planned to provide guidance on adjusting the eastern Australian region historical TC data-set.

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Appendix A

The following is a chronology of significant developments and events in advancing the knowledge of tropical cyclones within Australia. These are further summarised in time aligned categories in Table A1.

1939-45: World War II (WW2) greatly increases regional ship and aircraft reporting;

1954: Weather Watch radars first installed in Australia;

1956: Brisbane Tropical Cyclone Symposium;

1956: US National Hurricane Research Project commences;

1958: First AMS Technical Conference on Hurricanes, Miami (biennially since);

1960: Experimental satellite images become available;

1963: WMO World Weather Watch Programme (WWW) commences;

1966: Routine visible satellite images (VIS) from polar orbiters (two per day only);

1966-72: BoM offshore Automatic Weather Stations (AWS) installed;

1966: WF44 radars first installed in Australia;

1968: WMO/ESCAP (Economic and Social Commission for Asia and the Pacific) Typhoon Committee established;

1968: First objective satellite interpretations of TC intensity started;

1972: Routine Infra-red (IR) satellite images available;

1972: WMO Tropical Cyclone Project established;

1972: Dvorak preliminary methodology for visible satellite images;

1974: WMO Regional Association TC Working Groups established, RA I (Africa), RA IV (North and Central America);

1974: TC *Tracy* devastates the city of Darwin;

1975: Dvorak published a methodology for analysing VIS satellite images;

1977: Atkinson and Holliday wind-pressure relationship published;

1978: WMO Regional Association TC Sub-Committees established, RA I (Tropical Cyclone Committee for SWIO), RA IV (Hurricane Committee);

1978: BoM Tropical Cyclone Forecasting Manual, 1978;

1978: Geostationary VIS and IR satellite images become available (three hourly);

1979: First (and only) aircraft reconnaissance into an Australian TC (*Kerry*);

1979: Perth Tropical Cyclone Symposium;

1980: WMO Tropical Cyclone Programme (TCP) established and supported by the UNDP (United Nations Development Programme);

1980-87: WMO TCP TOPEX (Typhoon Operational Experiment) - 13 reports;

1984: Dvorak published updated methodology for Enhanced Infra-Red (EIR) satellite images;

1985: First WMO/CAS TMRP International Workshop on Tropical Cyclones (IWTC-I), Bangkok, Thailand;

1987: A *Global View of Tropical Cyclones* published by US Office of Naval Research.

1988: BoM regional Severe Weather Sections established, allowing specialisation;

1988: Brisbane Tropical Cyclone Symposium;

1989: Second WMO International Workshop on Tropical Cyclones (IWTC-II), Manila, Philippines;

1989: WMO establishes TC RSMCs (Regional Specialised Meteorological Centres) at Tokyo, New Delhi, La Reunion and Miami with assistance from the UN TCDC (Technical Co-operation among Developing Countries);

1990-99: UN International Decade for Natural Disaster Reduction (IDNDR) accelerates TC-related research and investigation;

1990s: WMO TCP Biennial Training Courses by NOAA and University of Miami;

1990: The Man computer Interactive Data Access System (McIDAS) greatly facilitates interpretation and enhancement of satellite images;

1990-94: WMO TCP SPECTRUM (recurvature) experiments;

1991: BoM South Pacific Forecaster Training Course, Nadi;

1991: Special Sensor Microwave/Imager (SSM/I) passive microwave imaging satellite available but not used for TCs until 1998;

1991: TOPEX/Poseidon satellite altimeter available for significant wave height;

1992: Doppler radar installed at Darwin;

1993: Third WMO International Workshop on Tropical Cyclones (IWTC-III), Hautulco, Mexico;

1993: WMO publishes *Global Guide to Tropical Cyclone Forecasting*;

1994: WMO/BoM first southern hemisphere TC forecaster training course;

1995: WMO publishes *Global Perspectives on Tropical Cyclones*;

1995: Advanced Microwave Sounding Unit (AMSU) satellite sounder available but not used until algorithms available 2000;

1995: ERS-2 satellite altimeter available for significant wave height and wind;

1996: Office of Naval Research Symposium on Tropical Cyclones, Melbourne;

1996: Advent of internet WWW capabilities for accessing satellite data;

1997: Tropical Rainfall Measuring Mission (TRMM) passive microwave imaging satellite TMI sensor available but not used for TCs until 1999;

1998: Fourth WMO International Workshop on Tropical Cyclones (IWTC-IV), Haikou, China;

1998: Development of the Objective Dvorak Technique (ODT);

1998: WMO establishes TC RSMC at Nadi.

1999: QuikSCAT/SEAwinds surface wind scatterometer becomes available;

2000: Advanced Microwave Sounding Unit (AMSU) intensity method;

2000: WMO Tropical Cyclone Programme, Regional Technical Conferences on Tropical Cyclones, Storm Surges and Floods commenced;

2001: WMO establishes TC RSMC at Honolulu.

2002: AMSU-A and -E passive microwave imagers having increased resolution;

2002: AQUA-AIRS satellite sounder available;

2002: Fifth WMO International Workshop on Tropical Cyclones (IWTC-V), Cairns, Australia;

2003: Windsat surface wind and passive microwave imager;

2004: Development of the Advanced Objective Dvorak Technique (AODT);

2005: WMO/CAS TMRP ongoing specialist International Workshops (e.g. Land-falling Processes, Macau; Extra-tropical Transition, Perth);

2005: First hurricane reconnaissance by an Aerosonde UAV (*Ophelia*);

2006: Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI), San Jose, Costa Rica.

Table A1. Timeline of significant events influencing the accuracy of tropical cyclone intensity estimates in Australia.

Year	*Access to technology*			*Methodologies*	*Organisation/ research*	*Education/ training*	*Events*
1954	Weather Watch Radar			Schloemer / Myers			
1955				Fletcher			
1956					US NHRP	Brisbane TC Symposium	TC Agnes
1957							
1958						First AMS Hurricanes Conference	
1959				Graham and Nunn			
1960	Experimental Polar VIS						
1961				Kraft			
1962							
1963					WMO WWW		
1964							
1965							
1966	Routine Polar VIS 9am	AWS installations	WF44 radars				
1967							
1968				HUR 7-97	WMO/ESCAP		
1969				Objective analysis			
1970							TC Ada
1971				Fujita			TC Althea
1972	Routine Polar IR 9am/9pm			Dvorak preliminary	WMO TC Project		
1973							
1974					WMO RA I & IV		TC Tracy
1975				Dvorak VIS			TC Joan
1976							TC David
1977				Atkinson and Holliday			
1978	GMS Geo-stationary 3 h			BoM TC Forecasting Manual	WMO TC Sub-Committees		
1979				Schwerdt, Ho and Watkins		Perth TC Symposium	TC Kerry recon
1980					WMO TC Programme (TCP)		
1981							
1982							
1983							
1984				Dvorak EIR			TC Kathy
1985						IWTC-I Bangkok	
1986							
1987							
1988					BoM Regional SWXs	Brisbane TC Symposium	
1989					WMO TC RSMCs	IWTC-II Manila	TC Orson
1990	McIDAS				WMO TCP SPECTRUM	WMO TCP Training Courses	UN IDNDR
1991		Met Buoys (WA)				BoM SP Training Course	
1992	Darwin Doppler						
1993	ERS-1					IWTC-III Hautulco and 'Global Guide'	
1994						WMO/BoM SH training course	
1995	ERS-2					WMO 'Global Perspectives'	
1996	NSCAT			Advent of Internet WWW		ONR Symp, Melbourne	TC Olivia
1997				NOAA/NESDIS NRL/TC			TC Justin
1998	CIMMS Vapour Winds	AMSU	SSM/I	ODT	WMO RSMC Nadi	IWTC-IV Haikou	
1999	TRMM						TC Vance
2000	QuikSCAT			AMSU	WMO RSMC Honolulu	WMO TCP Regional Technical Conference	TC Steve, Rosita
2001							TC Sam
2002	AMSU-A	AMSR-E	MODIS			IWTC-V Cairns	TC Chris
2003	Windsat			Composite image overlays			
2004				AODT		Intl Conf Storms / WMO TCP Reg Tech Conf	TC Fay
2005	Aerosonde proven			High Res Numerical Models		WMO/CAS TMRP Macau & Perth	TC Ingrid
2006	Brisbane Doppler					IWTC-VI Costa Rica	TC Larry, Monica

Appendix B

Details of the analyses of the tropical cyclone data-sets

The BoM original data-set. This data-set contains central pressure (p_c) data only, which are converted to V_{max} according to the A&H (1977) formula:

$$V_{60} = 3.45(1010 - p_c)^{0.644} \quad \text{...B1}$$

and to *CI* according to the fitted* form of the Dvorak (1984) table

$$CI = (0.186V_{60})^{0.746} \quad \text{...B2}$$

where V_{max} units are m s^{-1}, p_c are hPa and *CI* is unitless.

The BoM modified data-set. To facilitate one-to-one comparisons with the revised WEL data-set, all BoM intensity fixes were converted into *CI*, V_{60}, and p_c based on A&H. The rules adopted here for conversion are as follows:

1. If only a p_c value is available (regardless of fix age), it is assumed that it was based on an unadjusted CI-V_{max}-p_c tabulation, i.e. using a *CI* to obtain a V_{max} and then applying the A&H relationship to obtain the p_c. V_{60} and *CI* are then back-calculated using Eqn B1 and Eqn B2 respectively;
2. If the [V_{max}, p_c] pair lies within 1 m s^{-1} (an allowance for rounding) of the A&H one-minute relationship then the supplied V_{max} is assumed one-minute and *CI* is then back-calculated as above;
3. If the [V_{max}, p_c] pair lies within 1 m s^{-1} of the A&H ten-minute relationship then the supplied V_{max} is assumed ten-minute, adjusted to be one-minute via Eqn B3, and *CI* is then back-calculated by Eqn B2;
4. If the [V_{max}, p_c] pair lies within 1 m s^{-1} of the L&M ten-minute relationship then the supplied V_{max} is assumed ten-minute, adjusted to be one-minute via Eqn B3, *CI* is then back-calculated using Eqn B2;
5. If no p_c value is available, any supplied V_{max} is assumed ten-minute and adjusted to be one-minute and *CI* is then back-calculated using Eqn B3 and Eqn B4.

The additional formulas used for intensity adjustment are then, assuming BoM (1978) open ocean conditions**:

$$V_{60} = V_{600} / 0.88 \quad \text{...B3}$$

and the inverse of A&H (1977):

$$p_c = 1010\ (V_{60} / 3.45)^{1/0.644} \quad \text{...B4}$$

This second (modified) approach is expected to yield a more reliable reconstruction of objective p_c, V_{max} and *CI* values than the original approach. This data-set is referred to here as the 'BoM modified'.

The objectively reviewed WEL data-set. The retrieved parameters of interest to the study were:

- storm id/name;
- centre fix (time UTC, lat., long.);
- Dvorak *CI*.

To facilitate direct comparison with the other data-sets, the following additional parameter was derived, fitted here*** to the Dvorak (1984) table:

$$V_{60} = 5.37CI^{1.34} \quad \text{...B5}$$

together with Eqn B4 to provide an equivalent p_c. Use of A&H here in obtaining p_c estimates is for consistency and convenience only and does not necessarily represent an endorsement of this relationship for future operational use.

The Neumann data-set. As detailed by Neumann (1999), there were considerable difficulties in assembling a southern hemisphere data-set especially in areas remote from land and for storms that traversed more than one agency region. For consistency between the BoM regions, Neumann applied a conversion from BoM-supplied central pressures that was based on an average wind-pressure relationship, as described below for $p < 1010$:

$$\text{W (kn 1-min)} = 6.05*(1010 - p)^{0.682} \quad \text{...B6}$$

where p is in hPa. This incorporated a multiplier of 1.15 to convert between ten-minute and one-minute overwater winds. As noted by Neumann, the averaged relationship was not too different from the A&H relationship. For pressures greater than 980 hPa, there is little difference between the two, whereas, at 920 hPa, A&H gives 122 kn and Eqn B6 gives 130 kn. The resulting winds were further rounded to the closest 5 kn. One exception to this rule was that for winds calculated as 63 kn, rounding was to 60 rather than to 65 kn so as not to create 'hurricanes' when that was not intended. For the present data-set comparisons, Neumann's derived V_{60} winds are used as reference and the central pressure p_c and Dvorak *CI* are back-calculated using Eqn B4 and Eqn B2 respectively.

* A continuous curve is used here although Dvorak anchored the *CI* at a value of 1 for a 25 kn wind.

** This is used for convenience only and does not represent a continuing endorsement of this assumption.

*** As per Eqn B2.

Appendix C

Limitations of the objective WEL-reviewed data-set

The objective review of historical TC data-sets is a demanding and time consuming practice, made more difficult as the years pass. In spite of the above limitations it is believed that the WEL review represented the best that could be achieved with the resources available at the time and that it is likely to be much more homogeneous than the original BoM data-set. To improve upon this review is possible but probably not without at least a doubling of effort and resources.

Some of the specific limitations of this process are:

- not all relevant data could necessarily be sourced for each storm as the archives were not always complete and time did not allow sourcing of original satellite images;
- it is possible that analysts of the day had additional information that was not necessarily retained in the archive or noted in the summary documentation;
- detailed reanalysis time per storm was often simply limited by the available data;
- only two experienced analysts were involved in the majority of re-assessments, hence there is a limited consensus base;
- analyst judgement may still have been influenced by historical BoM operational practices notwithstanding the review team's commitment to objectivity;
- reliance on the Dvorak method is implicit in the vast majority of cases due to the sparseness of observations; no pressure or wind profiling was attempted;
- early satellite imagery suffers from poor temporal and spatial resolution;
- the Man computer Interactive Data Access System (McIDAS), which greatly facilitates interpretation of satellite images could only be used for post-1990 events;
- the number of offshore observations on the North West Shelf increased dramatically in the 1970s due to oil exploration activities and drill ships; from the mid 1980s with permanent offshore platforms, floating production systems; and from the 1990s with onboard AWSs and permanently moored wind and wave buoys;
- critical offshore AWSs on the North West Shelf became available in the early 1970s (Browse I. 1969; Rowley Shoals and Scott Reef 1970; and Adele I. 1972) but operated intermittently through much of the 1970s, 1980s and 1990s due to vandalism, yielding about a 60 to 70 per cent data return;
- the review only utilised observations that had been recorded on the MSL charts – time did not permit sourcing of other original AWS data or consideration of time series records of winds or pressures;
- the available timetable dictated progress, yielding an average of 3.6 storm data-sets being recovered and reviewed each day;
- including management and reporting, overall project progress per analyst-day was approximately 1.7 storms.