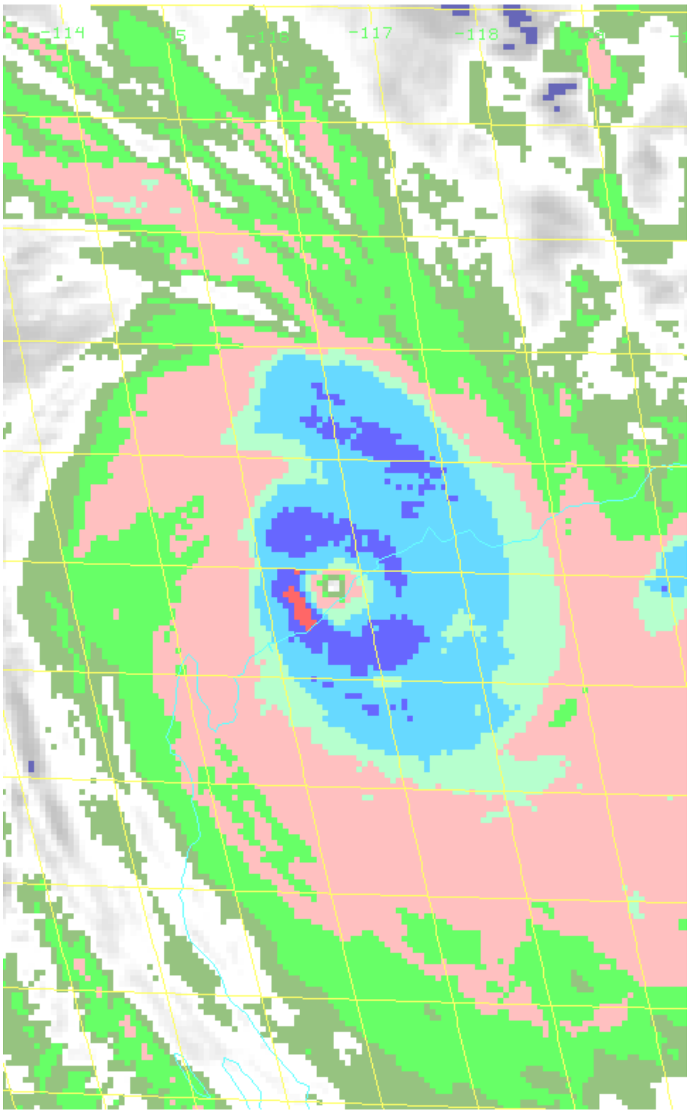
Tropical Cyclone Parameter Estimation in the Australian Region:



Wind-Pressure Relationships and Related Issues for Engineering Planning and Design

A Discussion Paper

November 2002

by

Bruce Harper BE PhD

On behalf of

WOODSIDE
AUSTRALIAN ENERGY

SEA
Systems
Engineering
Australia
Pty Ltd

Cover Illustration:
Bureau of Meteorology image of Severe Tropical Cyclone Olivia,
Western Australia, April 1996.

Report No. J0106-PR003E November 2002

Prepared by:

Systems Engineering Australia Pty Ltd
7 Mercury Court
Bridgeman Downs
QLD 4035 Australia

ABN 65 073 544 439

Tel/Fax: +61 7 3353-0288
Email: seng@uq.net.au
WWW: http://www.uq.net.au/seng

Contents

Tables

Figures

Executive Summary

This discussion paper has been prepared on behalf of Woodside Energy Ltd to facilitate debate amongst relevant professional groups concerned with the estimation of tropical cyclone intensity and related parameters of special interest for the engineering design of offshore and nearshore structures. The discussion has been prompted by a review of historical tropical cyclone data for Woodside's area of interest in Australia (Timor Sea to North West Cape) and the emerging need for consistent parameter estimation methods to be applied to the newly reviewed dataset.

The paper initially sets forth the specific needs for engineering studies, whereby large scale wind and pressure fields are required to drive spectral wave models and/or hydrodynamic models of currents and storm surge to be used in statistical risk analyses. These *hindcast* versus *forecast* needs are then considered within the historical development of meteorological techniques that have been gradually improved over the past 30 to 40 y due to increased sensing and analysis capabilities.

The historical development of techniques focuses on the Dvorak satellite intensity estimation method - the principal forecast tool available in Australia since the early 1970s. In particular, interest is centred on the appropriateness of applying the so-called regional mean wind-pressure relationships available within the Dvorak method to the Australian region. While there are only two "official" styles of wind-pressure relationship (Atlantic or North West Pacific), a number of published and unpublished variants have emerged over the years. The discussion traces the development of these official and variant approaches within the context of increasing knowledge of tropical cyclone structure and behaviour and the increasing availability of more objective data. It is noted that the differences between the various approaches can have significant impact on estimated engineering design parameters for wind, wave and current.

It is concluded that the scientific basis for the presently recommended regional mean wind-pressure relationships for specific tropical cyclone regions is weak. It is argued that some of the principal reasons for apparent regional differences have been caused by regional practices and analysis standards. Specifically, the historical adoption of specific regional methods in the late 1970s very quickly influenced the objectivity of storm datasets and it is likely that strong and persistent biases towards regional outcomes are present in the wide variety of "objective" forecast aids used around the world to this day. This is not to say that there are no regional differences, but that the present data is not sufficiently objective to fully justify their use and is impeding the growth in knowledge.

On the other hand, the sometimes highly variable wind-pressure behaviour of individual storms is emphasised through the examination of some recent, more objective, datasets. Allowance for individual storm behaviour is then argued as being more important than assuming any *prima facie* "mean" regional difference. While the absolute size of a storm is identified as likely to be one of the principal reasons for wind-pressure differences, it is proposed this be considered within a context of *rate of intensification* and *life cycle* rather than scale alone. Using appropriate rules, it is proposed that the Dvorak method could be extended to better allow for dynamic storm behaviour rather than rely simply on assumed mean regional wind-pressure differences.

Recommendations arising from the discussion relate to the great need for standardization of analyses and for improved models of tropical cyclone wind and pressure fields. In particular, methods are required that can account for the observed differences in storm behaviour on a case-by-case basis, but still within the practical satellite remote sensing limitations of a Dvorak-like method. The adoption of improved methods will provide significant improvements in the information available for the safe yet efficient design of offshore structures.

Acknowledgements

This document has been prepared on behalf of Woodside Energy Ltd as part of the *10^{-4} Waves Study*, a comprehensive review of engineering design conditions in the Timor Sea and North West Shelf regions designed to deliver reduced uncertainty at an annual probability of exceedance of 1 in 10^{-4}, or 1 in 10,000 y return period. The project is being conducted under the supervision of Stan Stroud, Principal Metocean Engineer for Woodside Energy Ltd. This particular document forms part of a cooperative review of the tropical cyclone archive by Woodside and the Bureau of Meteorology Regional Offices in Queensland, Northern Territory and Western Australia.

I wish to acknowledge many valuable contributions to this discussion from a large number of colleagues. Principally among these is Jeff Callaghan, Senior Meteorologist, Severe Weather Section, Queensland Regional Office of the Bureau of Meteorology and the support given by the central library in Melbourne. Geoff Garden, Supervising Meteorologist in the Darwin regional Office also provided additional material, together with Jeff Kepert from the Bureau of Meteorology Research Centre. Additionally, I have greatly appreciated the positive encouragement and support of many senior Bureau of Meteorology officers across Australia.

Internationally, James Franklin from the NOAA/NHC Tropical Prediction Center, Hugh Willoughby, Mark Powell, Chris Landsea and Peter Black of NOAA/AOML Hurricane Research Division, and Chris Velden and Timothy Olander from the University of Wisconsin at Madison have also cooperated through the provision of data and exchange of views. Charles Guard and Mark Lander in Guam have also been enthusiastic participants in the discussion. Many others, such as Charles Neumann, have been generous in making available specific unpublished data or drawing attention to relevant published works. Stephen Cocks and William Gray from the University of Colorado contributed advanced copies of material relevant to the discussion and Ray Zehr from CIRA provided helpful input.

Meteorologist colleagues Mike McCormack and Stephen West, acting through WNI Science and Engineering in Perth, have also contributed significantly to the development of ideas and concepts. Credit also goes to David Duncalf from WNI for highlighting many of the initial issues relating to the Timor Sea region.

Greg Holland of Aerosonde Ltd provided valuable comment on the original draft.

Finally, I wish to acknowledge the enormous contribution to tropical cyclone forecasting and analysis made by Vernon Dvorak and his many colleagues who have assisted in the development and refinement of the satellite pattern recognition techniques. I especially thank Vernon for his interest in commenting on an earlier draft of this document and for his encouraging remarks.

Bruce Harper
November, 2002.

1 Introduction

Any attempt to objectively estimate the intensity of tropical cyclones without the aid of direct measurement would seem impossible but for the apparent skill of the Dvorak satellite cloud pattern analysis technique (Dvorak 1972, 1973, 1975, 1982, 1984, 1990; Velden *et al* 1998). Without aerial reconnaissance and with a sparse data recording network, the Dvorak technique has remained the principal tool available to forecasters in the Australian region for the past 30 years (BoM 1978). While improving remote sensing technologies (SSM/I, QuickSCAT, TRMM, AMSU etc), enhanced radar, Aerosonde and increased observation sites hold great promise for the future, there is a critical reliance on the Dvorak technique in underpinning the accuracy of the statistical record. This record in turn is essential in describing the tropical cyclone hazard across the nation and in providing the base information used for the derivation of engineering design conditions (onshore and offshore) and for the safe planning of communities.

Notwithstanding the powerful merits of the Dvorak technique, there remains considerable room for variability in its application without the added knowledge of adequate groundtruth. The extent of this variability is very significant within the context of reconstructing accurate wind and pressure fields across wide oceanic areas and applying these fields to the estimation of extreme waves, currents and storm surge.

The author claims no experience in the application of the Dvorak technique itself in regard to identifying cloud signatures or the associated complex mesoscale processes implicit in the analyses. Indeed, the utility of the overall method and the expertise of those trained and experienced in its application are fully accepted in this context. The purpose of this document is therefore to investigate its development, explore the inherent variability in the technique and the impact of changes in its application since the mid-1970s. These changes are known to have historically influenced the determination of best track intensity parameters across Australia. It is also accepted that some significant differences in application have arisen over time on a regional basis within the Bureau of Meteorology (BoM), supported in principle by BoM (1978) and the need for forecaster judgement. The present initiative is therefore intended to revisit the relevant aspects of BoM (1978) and augment an already established process of review instigated in recent years by BoM (e.g. BoM 1999) but with an engineering design perspective rather than a forecast and warning perspective. Unfortunately the time available for the review has been limited, commencing only in January 2002 and being largely completed by June.

Given that the Timor Sea and North West Shelf track dataset is currently under review by Woodside Energy Ltd (WEL) in association with BoM, it is important that the Dvorak technique be re-applied in an acceptably consistent manner to these revised datasets. By examining the many factors leading to establishment of the final intensity estimates, it is hoped that a new consensus view might emerge leading to a superior set of rules and procedures. While the rapidly expanding knowledge base of tropical cyclone behaviour over the past 20 y is fuelling an increasing interest in re-analysis, the offshore industry also grapples with the demand for greater accuracy in estimating extreme design conditions.

The intended audience is meteorologists familiar with the overall application of the Dvorak technique, and engineers involved in estimating the potential impacts of tropical cyclones. The report begins by outlining some of the issues faced by engineering investigators when attempting to quantify the risks due to tropical cyclones in a coastal and ocean environment.

2 The Need for Reliable Tropical Cyclone Data for Engineering Planning and Design Purposes

It is expected that all persons involved in deriving tropical cyclone intensity and related information will be committed to providing the best possible interpretation from whatever sources are available, leading to the most reliable estimates possible within the normal resource constraints. However, given that the emphasis is initially always on *forecasting* of such events and the issuing of warnings to communities, there is an implicit focus on the conservative estimation of peak surface winds near such communities. Indeed, this is the stated intent of the Dvorak method. In post analysis phases the forecast data may then be reviewed in a more holistic manner and opportunities exist for correction or augmentation of data before entering the historical record.

In many engineering studies, the focus will typically be in regions remote from established communities (e.g. far offshore) that may not have been as carefully considered during the original forecast analyses. This presents a problem in reliably reconstructing the impacts of historical storms where the archived record does not contain sufficient information. Such difficulties include the omission of early or formative portions of tracks, sub or near-threshold events, non-conforming events; poor temporal parameter resolution and an absence of spatial scale estimates. Some of the above omissions will be due entirely to a lack of information; some will be due to a lack of staff and resources; some will be due to administrative processes or even jurisdictional issues. The present reviews of the Timor Sea and North West Shelf datasets aim in part to address these and other issues such as quality control and the like. The reason for raising these matters in the context of the present document is to further emphasise the need for a broad view of each storm event to be reflected in the archive, which in many cases may extend beyond the traditional forecast requirements. This approach in turn highlights the importance of the temporal and spatial lifecycle aspects of each event being represented and retained as much as that is possible.

In spite of the inherent complexities of tropical cyclone behaviour, experience has shown that relatively simple analytical storm models can produce exceptionally accurate recreations of broad scale wind and pressure fields. Such models (e.g. Holland 1980) are typically based on just a few critical parameters and assumptions, *inter alia*:

- The storm central pressure p_c (and associated ambient pressure p_n) at Mean Sea Level ;
- A horizontal scale such as radius to maximum winds R ;
- An allowance for variation of the shape of the radial wind speed profile (typically referred to as the peakedness[1]) B ;
- The speed of forward movement V_{fm} ;
- The storm centre track bearing θ_{fm} ;
- An empirical gradient to +10m surface boundary layer wind reduction factor K_m .

These models in turn are then used to generate surface wind fields to drive spectral ocean wave models and hydrodynamic current and surge models which, when reliable groundtruth is available, can also be shown to perform exceptionally well in many situations (e.g. Harper *et al* 1993). However sometimes results can also be very poor if the storm exhibits highly asymmetric traits or undergoes extreme transformations. Nevertheless, this well-established engineering process permits the quantification of the many potential impacts of a tropical cyclone over extensive regions. The

---

[1] This reflects a specific component of the Holland (1980) model. It is acknowledged that there are many different ways that even a simplified wind and pressure model might be parameterised and that the Holland model is only one option and has its limitations (e.g. Willoughby 1995). Nevertheless it is useful to persist with the Holland model concepts here for illustration of the method etc.

results from many individual model estimates are then considered in statistical assessments that provide guidance for planning and design.

This modelling approach is typically driven by the storm central pressure, with the nationally archived p_c value conveniently assumed to be an objective and reasonably reliable estimate of the intensity of the storm at any time[2]. It is then possible to calibrate such a model to obtain estimates of the (traditionally non-archived) radius and peakedness parameters by taking the track information together with any wind or pressure groundtruth and/or independently retrieved information such as radar. Without such information, the final resort is to assume a climatology of the missing parameters for such storms, perhaps ending with the selection of an estimated mean value. Typically, overseas data for radius is obtained or massaged, based on crude latitude formulations and the like. In the case of peakedness there is no established data source but some US analyses have been done (e.g. Vickery *et al*, 2000; Willoughby 2002) using flight level data. The critical issue here is that any inappropriate pairing of radius and peakedness can have very significant impacts on the modelled wind and pressure fields for the same central pressure value. In terms of the subsequent ocean inertial response, the integrating effect of the spatial and temporal surface forcing then ensures a magnification of any inappropriate pairings of radius and peakedness in respect of predicted wave height, wave period, currents and storm surge over wide areas. This in turn can lead to unacceptably large uncertainty in design criteria. In short, sometimes errors that are (perfectly reasonably) acceptable from a forecasting perspective can be quite unacceptable for hindcasting and lead to large uncertainty in design parameters.

From the above development the concept of cyclone “intensity”, when viewed as cyclone “impact”, can be seen to be a multi-dimensional parameter space. In terms of ocean forcing, for example, the “strength” concept of Merrill (1984) has particular appeal in relating to fetch development for wave modelling. Unfortunately, the principal diagnostic tool available in the Australian region, the Dvorak method, focuses solely on estimation of the maximum surface wind speed V_{max}. While there is an implied discrimination in respect of storm size, the method avoids any direct concept of wind profile peakedness. Furthermore, estimation of the central pressure is relegated to a subsequent empirical step that, over time, has implicitly allowed local or regional variations to be deemed acceptable. Ironically, it is only the resulting central pressure that has been routinely recorded in the Australian archive – the only parameter that could arguably be reconstructed under this approach. Neither the base Dvorak *CI* number, an explicit V_{max} nor radius data (except for eye diameter in later years when available) has been retained. Ideally, each post-storm analysis would invoke an analytical model such as Holland (1980) to verify and reconcile as much as possible of the accumulated data. The full yield of parameter values would then be immediately accessible to post-analysis needs, as well as building into a powerful climatology over time (Harper 1998).

At the risk of appearing to trivialise the representation of what are clearly very complex weather phenomena, it is nevertheless important that any possible improvements be made to the existing analysis processes, that consistency prevails, and that the data archive be populated with all reasonably relevant data. This document aims to highlight some areas where improvements might be possible, concentrating on the concept of so-called mean regional “wind-pressure” relationships as a primary source of uncertainty. However, given the complexity of the subject, many other issues rightfully intrude into such a discussion. Time has not permitted a rigorous pursuit of some of these other important matters and it has been necessary to simply resort to consistency of approach.

---

[2] The critical onset of satellite interpretations in improving the accuracy of the Australian data archive is discussed by Holland (1981). Generally only post-1959/60 data, with reservations, is deemed suitable for statistical analysis.

3 A Brief Overview of Relevant Published Works

3.1 Definitions

The following reviews are presented in chronological sequence to assist the historical development. To simplify the discussion, references to the "Dvorak" relationship will normally mean the Dvorak (1984) Atlantic wind-pressure relationship; references to "A&H" will mean the Atkinson and Holliday (1977)[3] derived wind-pressure relationship for the North West Pacific (NWP). V_{max} here refers to the estimated or measured maximum sustained *10 minute mean* wind speed[4] at +10m ASL surface reference over a rough open ocean (nominal z_0= 0.02m). Where V_{max} has been converted or estimated based on a (stated or implied) maximum sustained 1 minute average surface wind (the US standard), a factor of 0.88 (BoM 1978) has been applied; from a nominal 3 second gust, a factor of 1/1.4 has been applied, which is also consistent with BoM (1978). Flight level winds have first been converted to 1 minute surface winds using the "eyewall" profile from Franklin *et al* (2000), e.g. 0.91 for 700 hPa mean to surface +10 m (refer Appendix E).

The traditional application of the Dvorak method is, through the interpretation of satellite imagery, to initially provide a universal estimate of the storm V_{max} at a specific time. Subsequently, regionally-specific *mean* wind-pressure relationships are applied to convert V_{max} into associated p_c "best estimates". The following development adheres to this general sequence, although in practice it is acknowledged that direct estimations of p_c are often made. The use of such wind-pressure relationships of course significantly pre-dates the Dvorak era, so the Dvorak forms are considered within the context of several other plausible forms.

Almost all of the published empirical wind-pressure relationships have an analytical form loosely based on the cyclostrophic wind relationship, e.g.

$$V_{\max} = C\,(p_{ref} - p_c)^n \qquad (1)$$

where p_{ref} = a reference MSL pressure in hPa (typically p_n)
p_c = estimated MSL central pressure in hPa
C = an empirical constant
n = an empirical exponent (0.5 representing cyclostrophic balance)

Table 3.1 summarises most of the wind-pressure relationships that have been proposed over the past 70 years, together with their best fit coefficients, which using Equation 1 yield the estimated 10 minute average maximum surface wind speed V_{max}. The indicated V_{max} for a nominal 920 hPa is also indicated in each case, yielding an average of 57.8 ms^{-1} and a standard deviation of 6.5 ms^{-1} for all of these variants. This example of the variation of the equivalent 920 hPa winds shows the wide range of possible speeds, with absolute central pressure differences of the order of 15hPa being possible in practice. This can be further exacerbated if the relationships are applied without regard to the implied reference pressure p_{ref} – a practice encouraged historically by the proliferation of tabulated-only values of absolute V_{max} vs. p_c.[5]

---

[3] A&H is used here in preference to the formulation attributed to Shewchuk and Weir (1980) that is referenced by Dvorak (1984) for use in the North West Pacific (NWP). They are the same.

[4] Unfortunately, the vast majority of measured data mentioned in this review is earth-relative, uncorrected for storm motion. Where a clearer distinction is preferred or required, the uncorrected data is referred to as V_{max}'.

[5] The pressure deficit $\Delta p=(p_{ref} - p_c)$ is used here throughout for comparing wind-pressure relationships in preference to absolute central pressure, while $\Delta p=(p_n - p_c)$ is used for individual storms.

Table 3.1 Summary of some previously developed wind-pressure relationships (10 min wind predictors).

Author	Region	Best Fit Parameters for **10min** Wind			V_{max} for p_c=920	Predicted Wind	MSL Pressure	Surface Wind	Comment	Data Period	No. Obs.
		C	p_{ref}	n	m/s						
Takahashi (1939)	NWP	6.08	1010	0.5	58	"max surface"	ships & islands	ships & islands	not reviewed	late 1930s	
Takahashi (1952)	NWP	5.22	1010	0.5	49	"max surface"	ships & islands	ships & islands	not reviewed	1940-1950	
McKnown (1952)	NWP	6.80	1010	0.5	65	"max surface"	aircraft	sea state	for lat=25 deg	1951-1952	230
Myers (1954)	Atlantic	4.90	1010	0.5	46	"max surface"	land	land	not reviewed	1940-1950	
Fletcher (1955)	Atlantic	7.26	1010	0.5	69	"max surface"	aircraft	land	actually used pn	1909-1954	16 - 60
Kraft (1961)	Atlantic	6.35	1013	0.5	61	"max surface"	land	land	almost all Atlantic data	1926-1959	14
Fujita (1971)	Atlantic	3.97	1010	0.569	51	max 10 min +10m			after Black (1993)		
Atkinson & Holliday (1977)	NWP	3.04	1010	0.644	55	max 1 min +10m	aircraft	peak gust	used 50% gust factor (?)	1947-1974	76 storms
Subbaramayya & Fujiwhara (1979)	NWP	5.62	1010	0.500	53	"max surface"	aircraft	sea state	linear also good	1974-1978	510
Lubeck and Shewchuk (1980)	NWP	3.69	1010	0.572	48	max 1 min +10m	best track	best track	used 90% gust factor (?)	1975-1978	
Shewchuk & Weir (1980)	NWP	3.04	1010	0.644	55	max 1 min +10m	best track	best track	maintained A&H	1978-1979	396
Holland (1980)	Generic	$(B/\rho e)^{0.5}$	p_n	0.5	varies	max gradient	land meas	land meas	published data	varies	12 storms
Dvorak (1984)	Atlantic	3.45	1016	0.644	65	max 1 min +10m	various	fitted here to A&H n	1972-1980	1972-1980	
Love & Murphy (1985)	Australia - NT	2.16	1010	0.77	69	max 10 min +10m	land meas	data & argument	1974-1984	1974-1984	5
Crane (1985)	Australia - Qld	2.45	1010	0.7	57	max 10 min +10m	n/a	averaged fit	n/a	n/a	n/a
Guard & Lander (1996)	NWP (midgets)	7.96	1010	0.435	56	max 1 min +10m	island & aircraft	selected storms			
Neumann (1998)	Atlantic GOM	4.82	1013	0.564	62	max 1 min +10m	best track	non-obj composite	1970-1997	1970-1997	664
Neumann (1998)	Atlantic <25°N	5.45	1013	0.534	61	max 1 min +10m	best track	non-obj composite	1970-1997	1970-1997	1033
Neumann (1998)	Atlantic 25-35°N	6.43	1013	0.478	56	max 1 min +10m	best track	non-obj composite	1970-1997	1970-1997	922
Neumann (1998)	Atlantic 35-45°N	7.30	1013	0.433	52	max 1 min +10m	best track	non-obj composite	1970-1997	1970-1997	492
Neumann (2001)	Sthn Hemis	2.74	1010	0.682	59	max 1 min +10m	best track	non-obj composite			
Brown & Franklin (2002)	Atlantic	3.81	1016	0.619	64	max 1 min +10m	aircraft	GPS drop windsondes	1997-2001	1997-2001	456

Figure 3.1 provides a graphical comparison of the relationships in Table 3.1, overplotted in terms of V_{max} versus the absolute pressure difference $(p_{ref} - p_c)$. The central dense region indicates the concentration of proposed Atlantic relationships.

Not all of the works presented in Table 3.1 have been examined for this review and there are also some known omissions from the list. Many of the earliest studies have long since been superseded by the advent of more and better data. The definition of the source surface wind used in the historical analyses has remained relatively uncertain throughout the sequence of development, only recently tending to be described as the open ocean +10m level at a nominal averaging period of 1 minute. Also, it is the storm-relative V_{max} that ideally needs to be isolated and the intrinsic difficulty of measuring the "true" V_{max} in any storm must always be borne in mind (e.g. Sheets and Grieman 1975). Any given storm will exhibit many different time and space scales of motion, making such determination an almost impossible and somewhat meaningless task. Furthermore, all of these published empirical relationships implicitly contain storm forward speed components. Nevertheless, the problem demands a solution which can at least be argued as unbiased in the average sense. Such is the manner in which these types of relationships have necessarily been developed.

The present review is concerned with the post-satellite era and so the discussion here begins towards the late 1960s. It should be noted that, until Black (1993), there has never a functional form specified for any of the very powerful empirical relationships developed by Dvorak. The best fit parameter *C* in Table 3.1 assigned to Dvorak (1984) is in fact derived here by conveniently assuming the same exponent *n* as for A&H, which (interestingly) yields a reasonably accurate fit to the tabulated values for the Atlantic region.

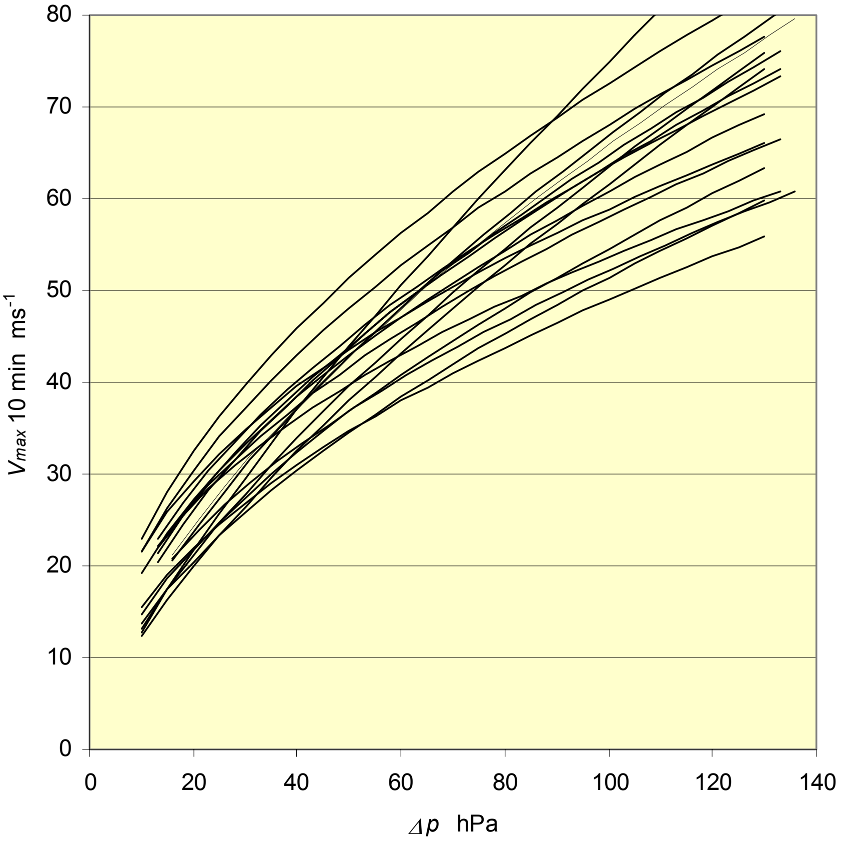


Figure 3.1 Wind-pressure relationships from Table 3.1

3.2 Dvorak (1972,1973,1975) and Erickson (1972)

The Dvorak technique emerged during the late 1960s from a number of separate efforts to utilise the increasing utility of regular and good quality visible satellite imagery. The technique was developed by Vernon F. Dvorak of the Analysis Branch, US National Environmental Satellite Service, and NOAA, based in Washington D.C... The method was based on a conceptual model of tropical cyclone development and decay that uses satellite imagery (initially visual cloud patterns) to identify steps in the storm development. Figure 3.6 in Section 3.9 provides a useful schematic overview of the satellite photograph pattern recognition technique, albeit as it was further refined and described in Dvorak (1984) for EIR imagery. The application of the method is designed to estimate the so-called *T* number (*tropical number*) that represents the increasing storm intensity on a scale of 1 through 8. The *T* number is then further adjusted to a *CI* (*current intensity*) number to allow for inertial lags in the decaying phase of a storm, which is argued to hold the intensity higher while the cloud structure is breaking down (although more recent research questions the extent of this, e.g. Brown and Franklin 2002). The *CI* number is then traditionally converted into an estimate of V_{max} via an empirical relationship, which is largely linear for storms of interest.

The Dvorak technique was in operational use from the early 1970s, but still clearly evolving. Although not located for this review, the earliest internal NOAA reference is Dvorak (1972), followed by an update Dvorak (1973). The later more widely available work Dvorak (1975) notes that parallel work by Erickson (1972) had been influential in suggesting modifications to the original *CI* number and wind speed relationship. Erickson is not only useful in providing essential background and insight into the technique, but also provides the first published set of verification statistics.

The V_{max} - *CI* relationship is one of the most important assumptions of the Dvorak technique and traditionally has always been shown as a tabulation (refer Table 3.2 later also). To better visualise this function it is shown graphically in Figure 3.2, adjusted to the present context of 10 minute winds. The *CI* scale is from 1 to 8, with implied surface wind speeds respectively ranging from 11 ms^{-1} to 77 ms^{-1}. Three relationships are shown, the earliest in 1972 as given in Erickson, followed by the 1973 shift to increase the mid-range intensities and some further very minor changes in 1975. The Dvorak (1975) V_{max} - *CI* relationship has remained unchanged to the present time.

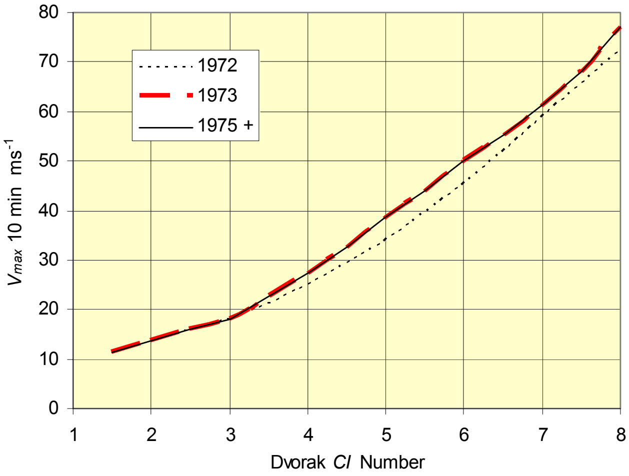


Figure 3.2 The Dvorak V_{max} – *CI* relationship.

Neither Dvorak (1973) nor (1975) provide data in support of the adopted V_{max} - CI relationship, referring instead to the verification study by Erickson (1972). In Dvorak (1973) though it is noted that " *... the relationships were determined empirically with most of the data coming from the North Pacific region*." The only comment made in relation to the link between the CI and V_{max} is that the 40 kt wind had been found to normally enclose the outer limits of the CDO (central dense overcast), the quasi-circular bands or the eye with no CDO. The 30 kt wind is similarly noted as normally enclosing the overcast "feeder bands". The averaging period of the winds is also not stated but has been historically interpreted as a 1-minute average. No other information is offered in regard to more intense winds.

Erickson (1972) provides some of the important detail behind this early phase of development of the Dvorak technique:

- The original 1972 technique was based entirely on NWP data;
- V_{max} was initially the only parameter of forecast interest;
- The early technique tended to underestimate winds from small but intense storms;
- The possible relation between CI and p_c was first addressed in the Erickson experiment and found to be reasonably reliable;
- An experiment was conducted in March 1972 with 11 participants applying the technique to 33 storms over the period 1967-1970;
- The 33 storms covered a full range of intensity with 15 cases each from NWP and Atlantic and 3 from ENP;
- The analyses were limited to storms over the sea and where aircraft data (dropsonde surface pressure and flight level 500m wind adjusted to surface) was available, totalling around 200 classifications of CI versus V_{max} and p_c ;
- It was during this experiment that the first indication of significant physical differences between the NWP and Atlantic became of concern;
- Some biases in the NWP data were recognised as being due to the use of best track data and this resulted in less scatter about the mean;
- It was concluded that CI actually correlated better with p_c than V_{max} ;
- There was a greater degree of error in the mid-range 50 to 100 kt wind intensity band than at either the high or low end;
- It was concluded that different relationships were warranted for the NWP and Atlantic basins.

Some of the results from the Erickson experiment are summarised in Appendix A, where the estimates undertaken personally by Vernon Dvorak (who was one of the participants) are reproduced. The NWP (Figure 1) and Atlantic (Figure 2) data sets are shown separately as a crossplot of the surface *estimated* V_{max} versus the V_{max} derived from the 1972 CI relationship. Each plot shows the 1:1 line between the estimated and measured V_{max} and also a best fit linear and 2nd order polynomial fit. Note that these are nominally 1-minute average winds. Although these plots show that some absolute errors were as much as 40 to 50 kt (or around 50%), Erickson reports the mean absolute error relative to the best fits as being of the order of 11 to 16 kt. The bias discovered between the NWP and Atlantic data sets seems to be exemplified by the fact that for the NWP the 1:1 and best fit linear lines (slope 1.06) are quite close, whereas in the Atlantic set the linear best fit (slope 1.25) deviates quite markedly above the 1:1. Note however that the NWP set also had a much greater proportion of intense storms.

In Dvorak (1973) it is noted that the Erickson experiment prompted changes in the original 1972 V_{max} - CI relationship, as chronicled in Figure 3.2. This does not directly flow from Erickson's conclusions but appears to have been related to concern regarding the scatter in the mid-range intensities for the NWP data, which tended towards underestimation. The NWP data was clearly still regarded as the reference set; the apparent problems with the Atlantic data were then addressed through proposing different wind-pressure relationships, as discussed below.

As previously stated, Erickson presented the first wind-pressure relationship associated with the Dvorak method and gives the impression of having been an advocate of estimating pressure over wind. This is supported by the fact that, although significant differences were found between the NWP and Atlantic V_{max} values, Dvorak's own best fit of CI versus p_c (Appendix A; Figures 5 and 6) during the experiment shows two closely parallel relationships with much less scatter than the V_{max} curves. Strangely, the possibility of different ambient pressures between the two basins was not raised, but if the relationships are plotted in Δp space as per Figure 3.3, using 1010 hPa and 1016 hPa respectively for the NWP and Atlantic cases, they appear very similar[6]. This was undoubtedly apparent to Dvorak when he published the 1973 wind-pressure tabulations, where the indicated difference in p_c between the two basins for a given V_{max} is simply an offset of 6 hPa; the NWP pressures being the lower. Because the $V_{max} - CI$ relationships were also altered, Figure 3.3 shows how the resulting wind-pressure curves changed from being fairly similar to somewhat different.

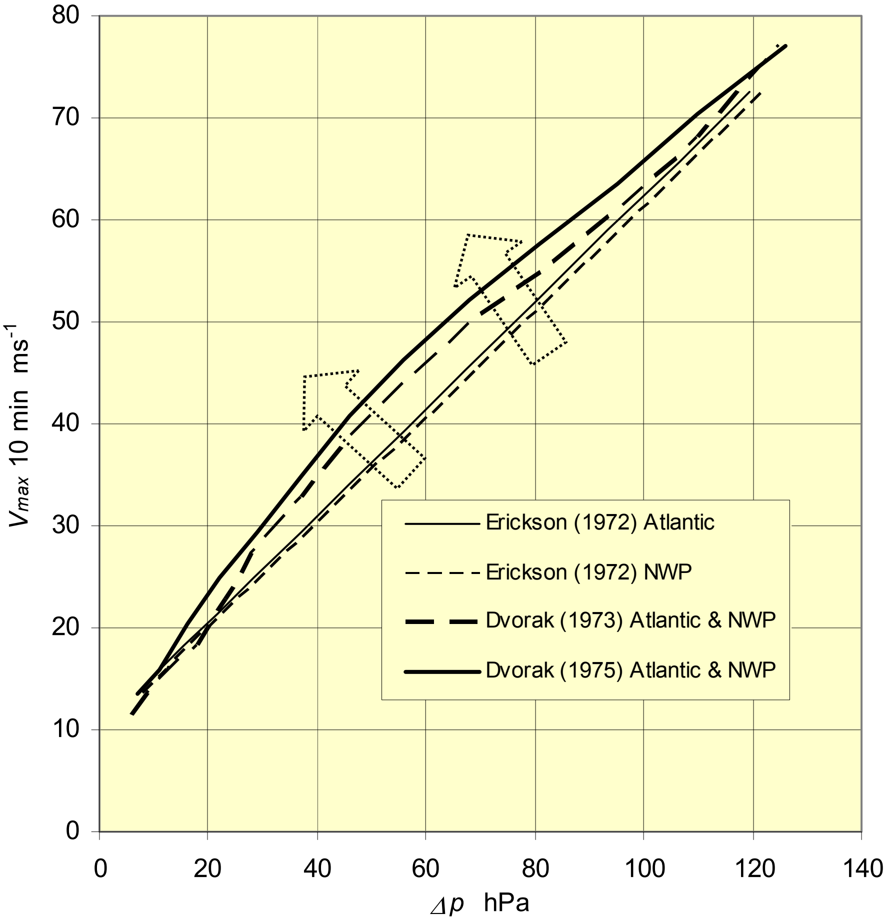


Figure 3.3 The evolution of the early Dvorak wind-pressure relationships.

---

[6] I repeat here the often quoted but not necessarily documented assumptions that the mean ambient pressures p_n of the Atlantic and WNP basins are 1016 hPa and 1010 hPa respectively. Holland (*personal communication*) notes that south of 15-20°N 1005 hPa is generally more appropriate.

One possible conclusion from the Erickson experiment is that it showed that the original 1972 relationship between $V_{max} - CI$ was actually a better proxy for $\Delta p - CI$; i.e. that the cloud pattern recognition system set to its arbitrary scale was a better linear indicator of Δp than of surface V_{max}. Notwithstanding this, Dvorak (1973, 1975) maintained the $V_{max} - CI$ nexus as the principal relationship of interest. The overall technique was then further developed in the mid-1980s, as discussed later, when the apparent inter-basin differences were further accentuated.

3.3 Sheets and Grieman (1975)

S&G was the second major verification study undertaken of the newly developing technique, referencing Dvorak (1973), and making use of data during 1972 - 1973 from the ESSA, ATS and DMSP satellites. The format of the experiment is similar to Erickson (1972) except that storm location and forecasting accuracy are given equal consideration with absolute intensity accuracy. Both NWP and Atlantic datasets were considered, the NWP again being the larger set. It appears that the study was conducted during 1974.

Like Erickson, a strong preference was expressed for using central pressure rather than maximum wind as the intensity measure of the storm. This is based on the range of wind speed measurement techniques that were typically utilised (e.g. sea state, Doppler, inertial systems or combinations thereof), differences in application between crews and also the inherent variability due to convective scale features. Accordingly only central pressures were considered in the analyses.

The results of the S&G experiment are not easy to summarise but the following conclusions about the Dvorak (1973) $CI - p_c$ curve were made:

- for the Atlantic, there was a clear tendency (bias) for the method to overestimate the true intensity by between 5 to 10 hPa;
- for the NWP, strong storms (< 920 hPa) were underestimated by as much as 20 hPa but the combined result was very close to the assumed curve (no bias).

The conclusions by S&G generally supported the earlier view of Erickson that the Atlantic and NWP wind-pressure (by inference from *CI*-pressure) relationships were different. However, it is again not clear that these specific outcomes were translated into the changes made by Dvorak for the 1975 paper, although both activities appear to have been largely contemporaneous[7]. For example, the $V_{max} - CI$ curve was raised across the mid-range from the 1973 to 1975 versions, which would have acted to reduce the NWP underprediction problem. However, the Atlantic overprediction appears to have been considered only through a slight selective raising (1 or 2 hPa) of the Atlantic $V_{max} - p_c$ curve, which equated to little more than smoothing. One is then left with the impression that the emphasis may have been on ensuring the method was *conservative* rather than accurate, which is understandable from a forecast perspective.

3.4 Atkinson and Holliday (1975, 1977)

A&H considers data collected over a 28 year period from 1947 to 1974 by the US Joint Typhoon Warning Centre, representing the most significant climatological review of tropical cyclone intensity of its time for the North West Pacific region. The 1975 and 1977 publications are essentially the same, excepting that A&H (1975) lists the storm data set details. The importance of the A&H study is that its recommended wind-pressure relationship subsequently became adopted

---

[7] Dvorak (1975) was clearly finalised in the latter half of 1974 but Dvorak (1982) is the first to reference Sheets and Grieman, formally published in February 1975. In any case, the Atlantic relationships remained unchanged from 1975 onwards.

by Dvorak (1984) for use in the NWP and, by implication, Australia[8].

A&H includes a review of previous studies in the NWP, dating back to Takahashi (1939), and explores the complexities and difficulties of obtaining accurate data sets of both minimum surface pressure and maximum surface winds. A number of the earlier variants are discussed, principally being stratifications based on latitude, and the operational difficulties are outlined. It is then concluded that a much more systematic study was required to assemble a superior data set that could be better relied upon to estimate actual surface wind speed. By omission, it could be implied that the Erickson (1972) and Sheets and Grieman (1975) aircraft-derived surface data were also not to be relied upon, but this is not stated.

The base data was obtained from a variety of agencies across the whole region, with the main concentrations from Hong Kong, through Taiwan to Japan. The methodology is then presented in some detail, emphasising the data screening process and the fact that only 76 of many hundreds of candidate storms were selected for analysis. This was because the "*selection was restricted to cases where there was a very high probability that the station experienced the maximum winds in the cyclone during its passage*". In support of that objective, only cases where the eye wall cloud had actually past over the station were considered and then almost only including cases that experienced the strong right-hand-front quadrant effects. Furthermore, wind speeds were taken only from sites with recording anemometers. Also, to overcome difficulties in the analysis of mean winds from anemograph charts, it was decided to only utilise the more clearly visible peak gust. A further expected advantage of this method was to reduce the influence of surface roughness effects, even though coastal or island sites were being considered and the analysis was restricted to onshore flow conditions. Methods for reduction of wind speeds recorded at different heights to the standard 10m level were also applied, based on a contemporary study that recommended a power law exponent of 1/16 (0.0625). Furthermore, the height-adjusted peak gusts were then converted to 1 minute sustained wind using a speed dependent gust factor approach. Surface pressures were obtained from station barographs or aircraft reconnaissance.

Although the authors admit that the study stopped short of a detailed assessment of different anemometer types, responses and errors, it would appear that a significant effort was made to ensure only high quality objective data was assembled. The resulting empirical curve fit considered both linear and non-linear fits, concluding that residual errors were similar in both cases, but the non-linear form was adopted in deference to the form of the cyclostrophic balance equation. An ambient pressure of 1010 hPa was adopted as being a reasonable regional reference. It was concluded by the authors that the resulting relationship (refer Table 3.1) was far superior to and resulted in lower V_{max} for a given p_c, than any of the previously used equations for the NWP region. It also yielded a 12% lower V_{max} than Dvorak (1975), as shown in Figure 3.4, which also indicates the actual data used by A&H (from A&H 1975) and also the spread of the data. This shift, at least in pressure terms, was also largely consistent with the conclusion by S&G for the NWP region.

Notwithstanding the considerable effort taken by the authors to screen and process their data it is now possible to consider areas of bias or uncertainty in the A&H analysis. Appendix B presents a number of arguments that would tend to suggest that the resulting V_{max} data is likely to have been overestimated by following the adopted elevation and gust factor adjustments. The degree to which this might have affected the overall analysis is impossible to estimate but a 10% bias might not be unreasonable, where it was applied. The paper also concedes that outcomes were made *deliberately conservative* for forecasting purposes. Balancing this, of course, is the possibility that the sampled

---

[8] Ironically, the original Dvorak (1975) wind-pressure relationship that was initially derived almost entirely from NWP data, survived to become the recommended Atlantic relationship that is still in use today.

winds were never in fact fully representative of the “true” peak winds (e.g. Guard 1998). Nevertheless, the present analysis tends towards the A&H estimated V_{max} being over-estimated rather than under-estimated, thus creating a potentially even larger gap with the Dvorak (1975) curve. One of the principal reasons for this would be the fact that the observed winds were not adjusted for storm forward speed.

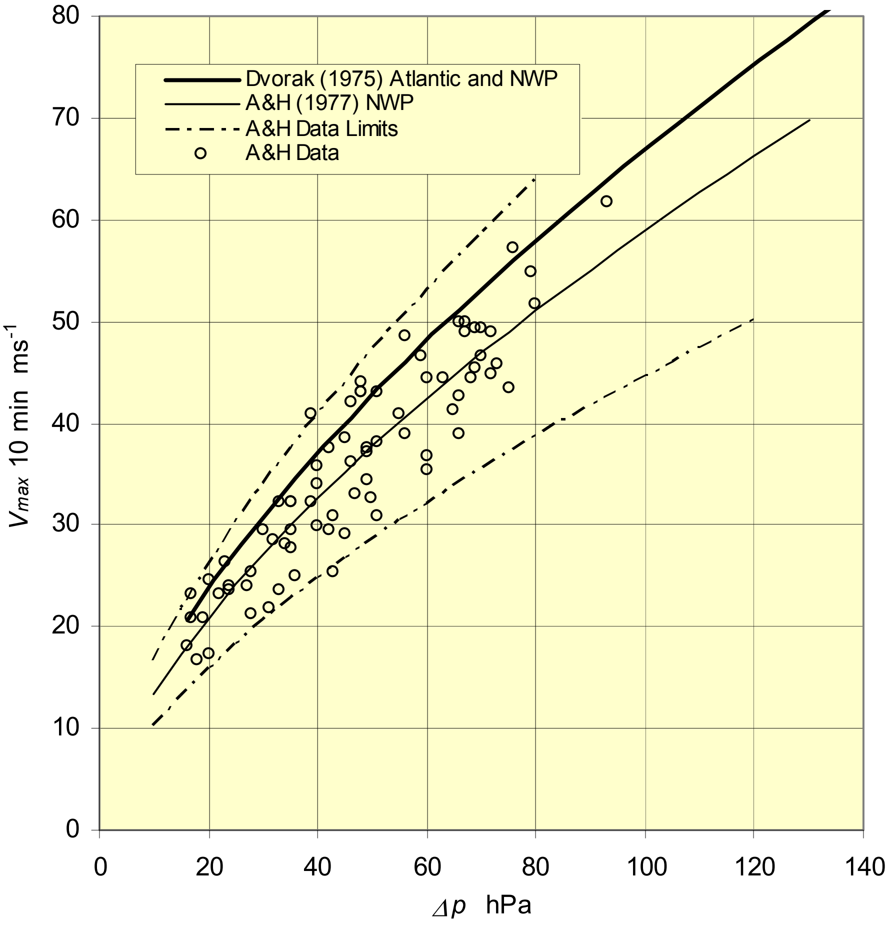


Figure 3.4 A comparison of the Dvorak (1975) and A&H (1977) relationships.

3.5 BoM (1978)

This document contains an excellent summary of Australian data and also worldwide knowledge of tropical cyclones at that time, spurred by the local experiences of *Tracy* and numerous other major storm events during the 1970s. Chapter 7 of the report begins with a simple yet unified view of tropical cyclone structure and considers how best to represent the storm pressure distribution. This leads to the recommendation of one of the many empirical pressure profiles presented by Schloemer (1954) as having the more desirable properties (later to become popularised as the *Holland* profile[9]). It is demonstrated that if a radial pressure profile is available then the requisite empirical parameters (refer later) can be determined and the maximum wind can be directly estimated.

However, in the absence of such data, the development then proceeds to consider resorting to a direct wind-pressure relationship determined empirically from climatology. The report provides a succinct review of the numerous relationships that were available at that time, together with some

---

[9] G.J.Holland was a principal author of BoM (1978).

datasets from Fujita (1971) and Erickson (1972). The relationships discussed at that time are those listed in Table 3.1. Caution is advised by the report in the use of the various relationships, although a preference for the Myers (1954) version is stated. This seems unusual given that it generally produces the lowest wind speed and is based on the criticised Schloemer profile rather than the *Holland* profile. The A&H work is commended also, although there is some reported criticism of the A&H wind correction procedures, which tend to support the present review. It is also inferred that A&H V_{max} allowed for storm forward speed, although there is no evidence to that effect in the original paper.

The report then provides an extensive commentary on the application of the Dvorak (1975) technique, although interestingly, the Dvorak $CI - V_{max} - p_c$ relationship is not considered as merely another wind-pressure variant in this context. There is also advice in Chapter 7 on wind gust factors taken from Spillane and Dexter (1976), which have been adopted also for this review.

3.6 Gaby et al (1980)

This paper summarises the results of 8 years (1971 – 1979) of satellite classification of tropical systems in the Atlantic, Gulf of Mexico and Caribbean Sea. The paper chronicles the adoption of the Dvorak 1972, 1973 and then 1975 methods, as well as including some comparisons between visible and infrared images in 1977-78. It is concluded that the Dvorak technique at the time was capable of providing the maximum surface wind to an accuracy < 10 kt, and as much as < 6 kt in some season summaries. However, it was also emphasised that the best track information used as the benchmark was not fully independent[10].

3.7 Lubeck and Shewchuk (1980); Shewchuk and Weir (1980)

The first of these reports has not been recovered for this review but is understood to have been a re-evaluation of the A&H relationship based on more recent data (Shewchuk and Weir 1980). The 1979 JTWC Annual Report, for example, indicated that ongoing assessment of A&H had not resulted in any changes to the original formulation. Black (1993) also provides insight.

Shewchuk and Weir (1980) is then a verification study of the Dvorak (1975) technique. It uses a 396-case sample from 51 tropical cyclones during 1978-79, covering the full range of intensities. The reference best track data set is acknowledged as having been assembled from both objective and subjective sources, with the A&H relationship being one of the subjective inputs. The report concludes that the mean absolute intensity error was less than one *CI* number and that the developing stages were more accurately estimated than the weakening stages. The final recommendation of the report was that the Dvorak (1975) wind-pressure relationship should be replaced by A&H for the NWP.

The importance of this conclusion is difficult to assess, given that the A&H relationship was an integral input to the best track data set used in the comparison. Also, the report does not demonstrate how replacing the Dvorak (1975) by A&H leads to a better or different mean error outcome. Nevertheless, the A&H relationship was subsequently adopted by Dvorak (1982), although it remains cited as being due to Shewchuk and Weir (1980).

---

[10] Holland (*personal communication*) strongly asserts that the lack of data independence in the Gaby *et al* comparisons renders invalid their conclusions about the accuracy of the Dvorak method.

3.8 Holland (1980)

This landmark paper is a formalisation of some of the concepts arising from BoM (1978). It brings together for the first time an explicit comparison of the empirical wind-pressure relationships of A&H and Dvorak (1975) with a theoretically based argument of cyclostrophic balance, albeit still with recourse to parameterisation. The development begins by considering the functional form of a number of pressure profiles from Schloemer (1954) that were derived from nine Atlantic hurricanes, leading to the adoption of a formula for the axisymmetric radial r MSL pressure variation p:

$$\frac{(p - p_c)}{(p_n - p_c)} = e^{-\left(\frac{R}{r}\right)^B} \tag{2}$$

where all variables are as previously defined and e is the base of the natural logarithm. It can be noted that this reduces to the "Schloemer" equation when $B = 1$.

Assuming cyclostrophic balance at MSL with constant air density ρ (i.e. ignoring the surface layer), the maximum equivalent storm-relative gradient wind speed $V_{g\,max}$ at $r = R$ can be shown to be:

$$V_{g\max} = \sqrt{(p_n - p_c)\frac{B}{\rho e}} \tag{3}$$

which can then be expressed in similar terms to Equation 1:

$$V_{\max} = K_m V_{g\max} = K_m\sqrt{\frac{B}{\rho e}}\,(p_n - p_c)^{0.5} \tag{4}$$

where K_m is an empirical gradient to surface +10m 10 min wind boundary layer reduction factor.

Holland then considered the likely dynamic range of B and concluded from dynamical arguments that a lower limit near 1 and an upper limit near 2.5 appeared reasonable, although these are not necessarily rigid. The model was then demonstrated through application to a selection of Australian storms for which radial pressure data and radar was available, yielding the following set of parameters (ρ assumed 1.15 kg m^{-3}):

Storm	Year	p_n	p_c	R	B	$V_{g\,max}$
		hPa	hPa	km		ms^{-1}
Tracy	1974	1004	950	8	1.5	51.4
Joan	1975	1004	930	40	1.05	49.8
Kerry	1979	1008	958	48	1.4	47.3

While this served to illustrate the utility of the analytical approach for a range of storm types it also highlighted the vagaries of individual storms and the difficulty of measuring the maximum surface wind. For example, *Joan* peak winds were only estimated; *Kerry* remained 20 ms^{-1} underpredicted when compared with reconnaissance data (the only available aircraft data for an Australian storm) because of an unusually large, apparently supergradient, component. *Tracy* was also underpredicted relative to the surface peak gust envelope (an assumed proxy for the gradient wind) by about 10 ms^{-1} (refer Appendix C). This lead to comment by Holland on the difficulty of actually estimating the peak pressure gradient for some storms (a recurring problem mentioned as early as Schloemer 1954). Whereas the barograph for *Tracy* (BoM 1977) indicates a peak gradient of 5.5 hPa km^{-1}, the fitted model only achieved 4.2 hPa km^{-1}. Incorporating the true gradient would allow for a higher B and a higher $V_{g\,max}$.

Finally, Holland considers the general problem of estimation of intensity without adequate spatial data being available and addresses the empirical wind-pressure relationships of A&H and Dvorak (1975) within the context of cyclostrophic balance and the possible role of a B parameter. Unfortunately, since both of the wind-pressure relationships are designed to reflect surface winds, it is not possible to make this comparison without addressing the gradient to surface boundary layer reduction K_m. Like Holland, it is assumed here for the moment that the gradient wind is 1.2 times the surface 1 minute wind (equivalent to a K_m of 0.73 within the present context). Following Holland, Figure 3.5 therefore shows the effective B value implied by each of these empirical relationships[11] when combined with Equation 4. This highlighted the quite significant differences between the two empirical relationships but it also demonstrated that the B value can typically span this dynamic range. Holland speculated that either or both of Dvorak and A&H may be biased, but in deference to that body of data decided only to imply that B might more appropriately lie between 1.5 and 2.5. It should also be remembered that Equation 4 delivers storm-relative winds.

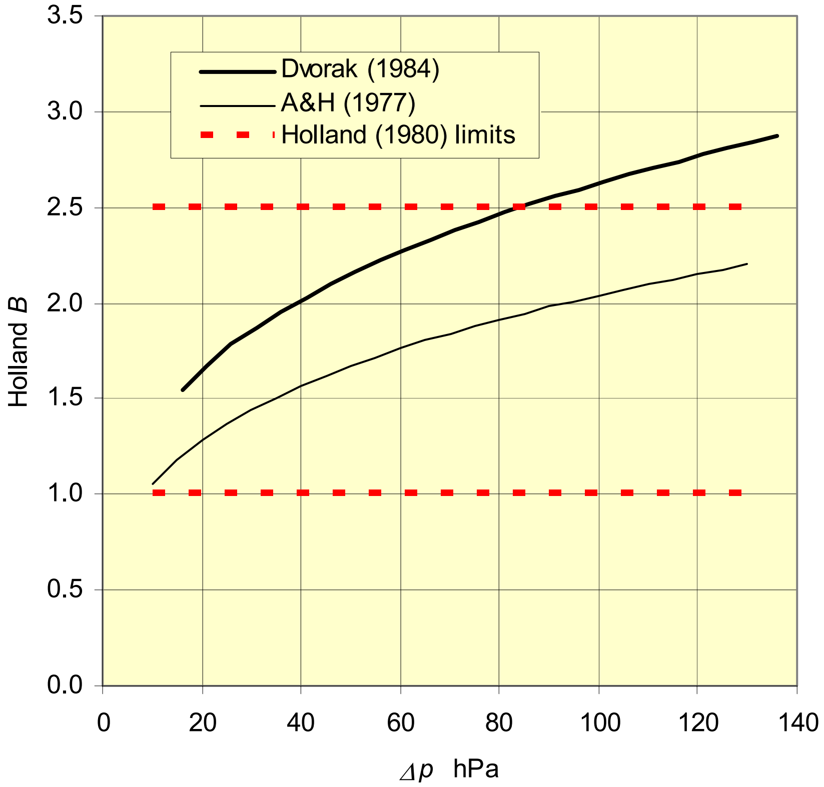


Figure 3.5 The Holland B within a wind-pressure relationship context.

The paper concludes with the assertion that B might be regarded as being a direct function of storm central pressure, the wind profile peakedness increasing with intensity. However, the possibility was raised that supergradient winds may also potentially play a part in this process – a factor now known to be prominent (Franklin *et al*, to appear; Kepert 2002ab).

---

[11] Here the Dvorak (1984) curve (see later) is substituted for the (1973) curve that was used by Holland and it is also assumed that the reference p_n is 1016 hPa rather than 1010 hPa as assumed by Holland.

3.9 Dvorak (1982,1984)

Modifications to the earlier Dvorak technique emerged in 1982 to utilise the availability of enhanced infra-red (EIR) imagery. While there were also a number of analysis rule changes, the present review focuses only on changes to the aforementioned empirical relationships. These changes were confined to the adoption of the A&H wind-pressure relationship for the NWP basin, replacing the original 1975 relationship. The Atlantic curve then largely remained as simply the 6 hPa offset from the original NWP curve but with some minor adjustments. It was set 2 hPa higher at *T2.0*, reducing to less than a 1 hPa difference from the 1973 version over the rest of the range. The tabulated range of the intensity relationships were also changed slightly for both basins, beginning at *T2.0* rather than *T1.5*. Significantly, no further changes were made to the 1975 $V_{max} - CI$ relationship[12]. However, the accuracy of the satellite-based intensity estimates is explicitly discussed for the first time, referring to the verification studies by Shewchuk and Weir (1980) and Gaby *et* al (1980) [9], quoting average V_{max} errors against best track data of less than 8 kt.

In the later Dvorak (1984) update, additional rules were developed for using digital IR data, whereby the temperature difference from the core to an outer cold ring becomes the primary means of estimating the intensity (a proxy for the strength of eye wall convection). In this later report the accuracy from the previously quoted verification studies is claimed to be further improved (7 kt Atlantic, 3 kt NWP). However it is also noted rather candidly by Dvorak that the best tracks themselves *have now become biased* by the application of the technique itself, especially in the NWP region.

Figure 3.6 (actually taken from Dvorak and Smigielski 1990) provides a schematic overview of the final form of the Dvorak technique, showing expected cloud patterns developing over time in relation to the *CI* or *T* number classes and the V_{max} and p_c scales. The straight-line plot indicates the assumed mean relationship (whereby the V_{max} and p_c axes are independently scaled here to produce an overplot) and the curved line illustrates the possible short-term temporal variability from the assumed mean line. Note that the indicated V_{max} on this figure are 1 minute (assumed) surface winds in kt.

Table 3.2 below summarises the final and current form of the recommended Dvorak relationships for relating *CI* to V_{max} and p_c for each basin. These are then plotted in Figure 3.7 in terms of Δp, assuming p_n of 1016 hPa and 1010 hPa respectively for the Atlantic and NWP basins. This shows that, for the same Δp, the mean V_{max} in the Atlantic basin is predicted to be some 13% higher than in the NWP basin. Figure 3.7 is, expectedly, visually identical to Figure 3.4.

The rather significant discrepancy between the Atlantic and NWP mean wind-pressure relationships seems not to have been fully addressed anywhere in the literature from a theoretical viewpoint. Implicitly, though, climatological arguments point to overall differences in storm scale between these two basins (e.g. Merrill 1984), which can be shown to lead to different states of dynamical balance. The problem remains though as to how best to transfer these empirical results to other basins, assuming these results themselves are sufficiently accurate.

---

[12] Dvorak and Smigielski (1990) appears to be the final publication by Dvorak in regard to this technique, taking the form of a forecaster's workbook. It also appears to have been updated over subsequent years (circa 1995) but, apart for some new case studies, does not provide any specific new information on the topics of interest in this review.

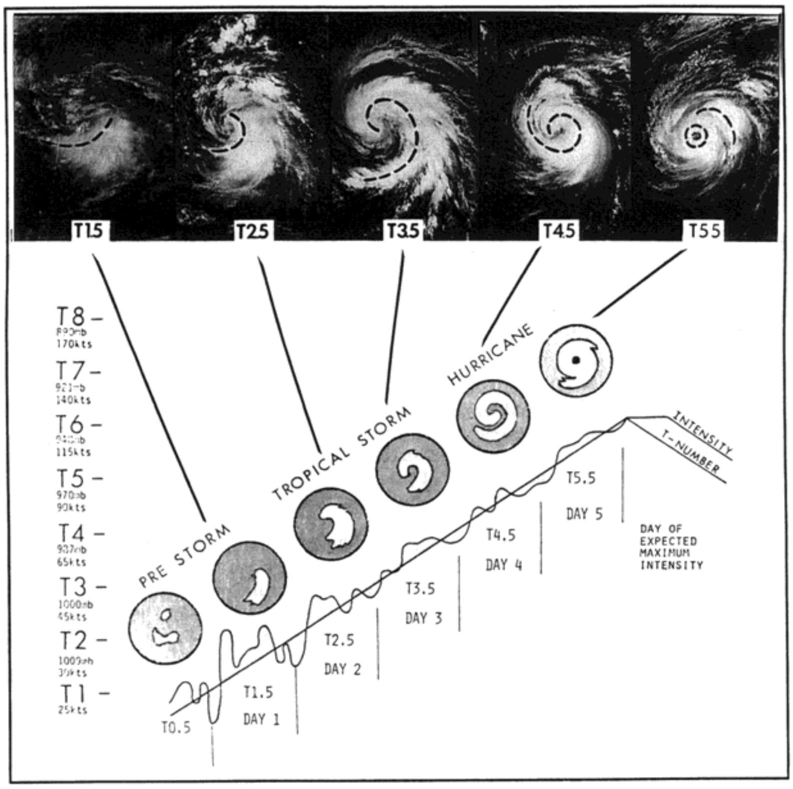


Figure 3.6 Schematic of the Dvorak (1984) technique for the Atlantic basin from Dvorak and Smigielski (1990); 1min winds shown.

Table 3.2 The Dvorak (1984) tabulated relationships.

CI	V_{max} ms^{-1}	*Atlantic* p_c hPa	*NWP* p_c hPa
2.0	13	1009	1000
2.5	16	1005	997
3.0	21	1000	991
3.5	25	994	984
4.0	29	987	976
4.5	35	979	966
5.0	41	970	954
5.5	46	960	941
6.0	52	948	927
6.5	58	935	914
7.0	63	921	898
7.5	70	906	879
8.0	77	890	858

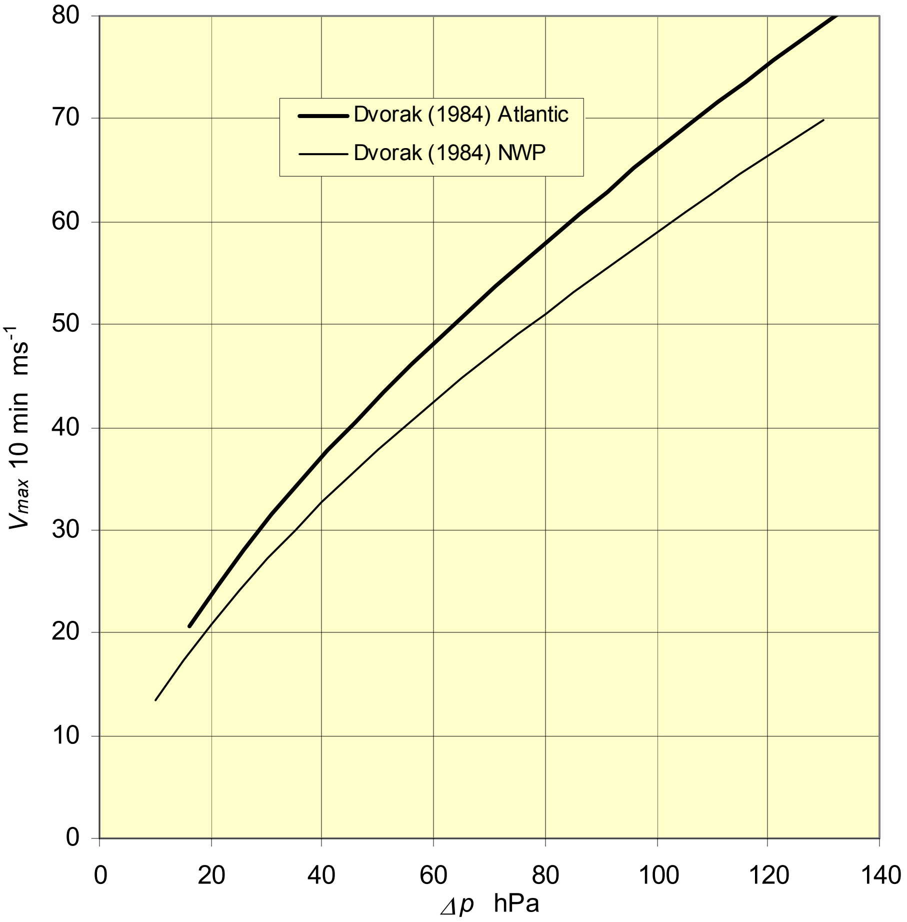


Figure 3.7 Comparison of the Dvorak (1984) Atlantic and NWP wind-pressure relationships.

3.10 Love and Murphy (1985)

This paper (L&M) was prepared by staff from the Northern Territory Regional Office to summarise BoM operational experience in applying the Dvorak (1975) rules to some intense storms in the Darwin region, mainly concentrating on TC *Kathy* (1984) and its very rapid development over the western Gulf of Carpentaria (Murphy 1985, refer also Appendix C here). The paper proposed an alternative wind-pressure relationship to either of Dvorak or A&H for use in the northern Australian region. Some data from TC *Tracy* (1974), *Max* (1980), *Kerry* (1979) and *Joan* (1975) was also presented. Significantly, this form of wind-pressure relationship has been used to characterise the majority of storms in the Northern Region since that time.

Following guidance from Merill (1984), the paper postulated that "In *the Northern Region the relatively small oceanic areas permit the development of cyclones only on the smaller end of the possible size distribution.*" This lead further to the assumption that "*intense cyclones … will tend to be of small eye diameter and have relatively high central pressures*". It was also noted that the ambient pressures p_n in the Northern Region are typically around 1009 hPa which is low when compared with the North Atlantic reference value (1016 hPa as implied by Dvorak), but similar to A&H with 1010 hPa.

A modified wind-pressure tabulation was then presented, reproduced here as Table 3.3. It is noted that the relationship between the *CI* number and V_{max} is identical to the Dvorak relationship. Only the p_c values have been changed to align the *Kathy* 940 hPa value with the assessed value for *CI* of 6.5. While no equation to the tabulated values was presented, the best fit parameters determined here are those listed in Table 3.1 earlier.

Table 3.3 Northern Region wind-pressure relationship proposed by L&M.

CI	Δp hPa	p_c hPa	V_{max} ms^{-1}
2.0	10	1000	13
2.5	13	996	16
3.0	19	991	21
3.5	25	985	25
4.0	31	978	29
4.5	38	972	35
5.0	46	964	41
5.5	54	956	46
6.0	62	948	52
6.5	70	940	58
7.0	80	930	63
7.5	90	920	70
8.0	100	910	77

The paper then presented the Holland (1980) analytical model in some detail, explaining the links between the radius to maximum winds *R* and the model constants *A* and *B* as well as the role played by *B* in the calculation of V_{max}. Some operational experiences in using the Holland model were then described, noting the potentially high variability in *B* when relying only on peripheral pressures remote from the centre. To overcome that difficulty it was then proposed to constrain *B* values to follow a specific relationship as a function of intensity, namely

$$B = 0.25 + 0.30 \ln(\Delta p) \tag{5}$$

which is reportedly derived from a best fit curve of data for *Max*, *Kerry*, *Tracy* and *Kathy*. Although the bases of the calculations of *B* are not presented, the *Tracy* data can be seen to derive from BoM (1977) and *Kathy* data is from Murphy (1985). It is then implied that the adopted *B* formulation should be included with Δp into the Holland calculation to yield an estimate of V_{max}. However, this process seems to have resulted in an underestimation of peak winds for most of the storms considered of from 10% to 23%[13]. The paper then proposed to “factor” the final result to allow for the underprediction but no details were provided.

L&M set out to provide a set of modified Dvorak procedures to better accommodate the style of small and intense storms that appeared to be dominating the Northern Region and causing considerable difficulty for forecasters, at least since *Tracy* in 1974. However, the principal issue seems to have been the problem of the Dvorak rapid intensification rules limiting the maximum daily *CI* changes and the assessed *CI* for *Kathy* being 6.5 for a measured p_c of only 940 hPa. On the recommended Dvorak scales this p_c would indicate either a 5.5 in the Atlantic or a 5.0 in the NWP. Unfortunately, *Kathy* did not produce measured winds commensurate with the assessed *CI* and

---

[13] We can now also attribute some of this apparent mismatch to the likely supergradient component near the eyewall, which demands a higher K_m than the original 0.73 implied at the time. Refer Appendix E for further discussion.

measured p_c. It is not clear therefore how a new wind-pressure relationship was justified based on the cited wind-pressure dataset, all of which were obtained from coastal stations, viz

Storm	Year	p_n	p_c	Δp	CI	V_{max}
		hPa	hPa	hPa		ms^{-1}
Tracy	1974	1004	950	54	5.5	40-43[14]
Joan	1975	1004	930	74	7.0	45[15]
Kerry	1979	1008	958	50		41[16]
Kathy	1984	1005	940	65	6.5	46-50[17]

When these wind-pressure data are plotted against the available relationships in Δp terms, as in Figure 3.8, there seems little justification for a new relationship that would produce a higher V_{max} than even the Dvorak curve. Indeed, both *Tracy* and *Kerry* are midway between the A&H and Dvorak relationships[14,17,18]. Even making allowance for both these V_{max} to be understated because of failure of anemometers (refer Appendix C for storm commentaries) each would be unlikely to exceed the Dvorak curve. By comparison, the proposed L&M curve yields a V_{max} some 17% above the measured value for *Kathy*. This significant mismatch is also evident in the proposed tabulation of Table 3.3.

The L&M attempt to utilise the Holland relationships to explain the observed V_{max} was also unsuccessful, but this can be mostly traced to the imposed assumption of Equation 5. This is represented in Figure 3.8 by the mismatch between the heavy dashed line[19] and the data points.

In hindsight, the assessed high *CI* value for *Kathy* compared with the available groundtruth might now be regarded as simply anomalous or at least representative of the potential inaccuracy of the Dvorak method in some cases. While L&M assessed the *CI* at landfall as 6.5, the landfall *T* number is possibly only 6.0 (J. Callaghan, *personal communication*), consistent with an observed weakening trend over the previous 12 h. This weakening occurred in spite of the normally expected period of maximum diurnal convective activity. There is also the unknown effect of the offshore Sir Edward Pellew island group through which the storm passed in the final 4 h to landfall. The scattered island group is of similar scale to the zone of storm force winds and may have helped initiate rapid weakening. The Dvorak *CI* rule, which works to maintain the pre-existing intensity, therefore appears to have inflated the true intensity at landfall and led L&M to the conclusion that *Kathy* was significantly different from the existing CI - p_c relationships. This potential for over-compensation by the Dvorak rules during weakening phases has also been recently questioned by Brown and Franklin (2002). In conclusion, it now appears very difficult to justify the L&M wind-pressure relationship on the basis of the cited data and present level of knowledge of storm weakening, especially for relatively small circulation systems. It is recommended that the impact of applying this rule to many of the historical storms in the NT region now be reassessed.

---

[14] The V_{max} for *Tracy* is shown here as a range; the lower value of 40 ms^{-1} is that given in BoM (1977) and presumably used by L&M; the 43 ms^{-1} is a revised value proposed here in Appendix C and plotted on Figure 3.8, consistent with a standard 1.4 gust factor from the 60.3 ms^{-1} measured peak gust.

[15] *Joan* is not objective data; V_{max} here extrapolated from Holland (1980) Figure 6; *CI* from BoM (1979).

[16] *Kerry* V_{max} taken here as 0.75 of flight level (540m) maximum wind from Black and Holland (1995), Fig 6c.

[17] L&M quotes V_{max} for *Kathy* as 50 ms^{-1}, which compares with the official anemograph peak gust of 64.3 ms^{-1} from Murphy (1985); the 46 ms^{-1} is a revised value proposed here in Appendix C and plotted on Figure 3.8, consistent with a standard 1.4 gust factor.

[18] BoM (1977) actually used the A&H relationship to support the selection of a V_{max} for *Tracy* of 40 ms^{-1} , which seems to have been overlooked by L&M.

[19] K_m of 0.73, as used by Holland (1980), and ρ of 1.15 kg m^{-3} is also applied in this case.

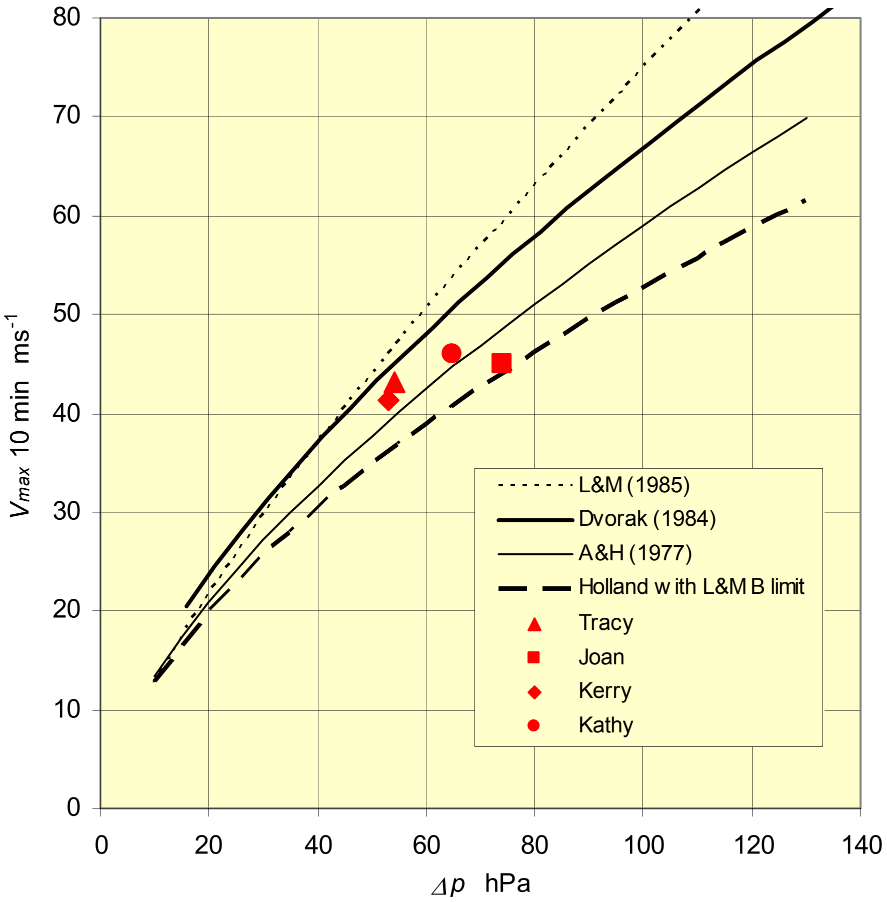


Figure 3.8 L&M relationship compared with data.

3.11 Crane (circa 1985)

This refers to analyses undertaken at the Queensland Regional Office to address concerns that the published wind-pressure relationships (A&H and Dvorak) were not well suited to experiences in Queensland at low storm intensities (G. Crane, *personal communication*). The approach taken was to consider the many published wind-pressure relationships available at that time (BoM 1978) and choose a relationship that appeared to represent an average condition but which also satisfied the local Queensland concerns.

Figure 3.9 summarises the chosen relationship relative to A&H and Dvorak, with the best fit parameters being listed in Table 3.1. While the basis for this curve has not been formally published, the curve itself was tabulated for operational purposes in Queensland from around 1985. The tabulated form is also indicated on Figure 3.9 but, probably due to round-off, does not faithfully follow the parent curve. In essence, the Crane relationship lies between Dvorak and A&H, although is much closer to the latter. This relationship is understood to have been used to characterise the majority of storms in the Queensland Region since that time.

Since the application of the technique has been principally via the tabulated version it is believed that this amounts to essentially an application of A&H.

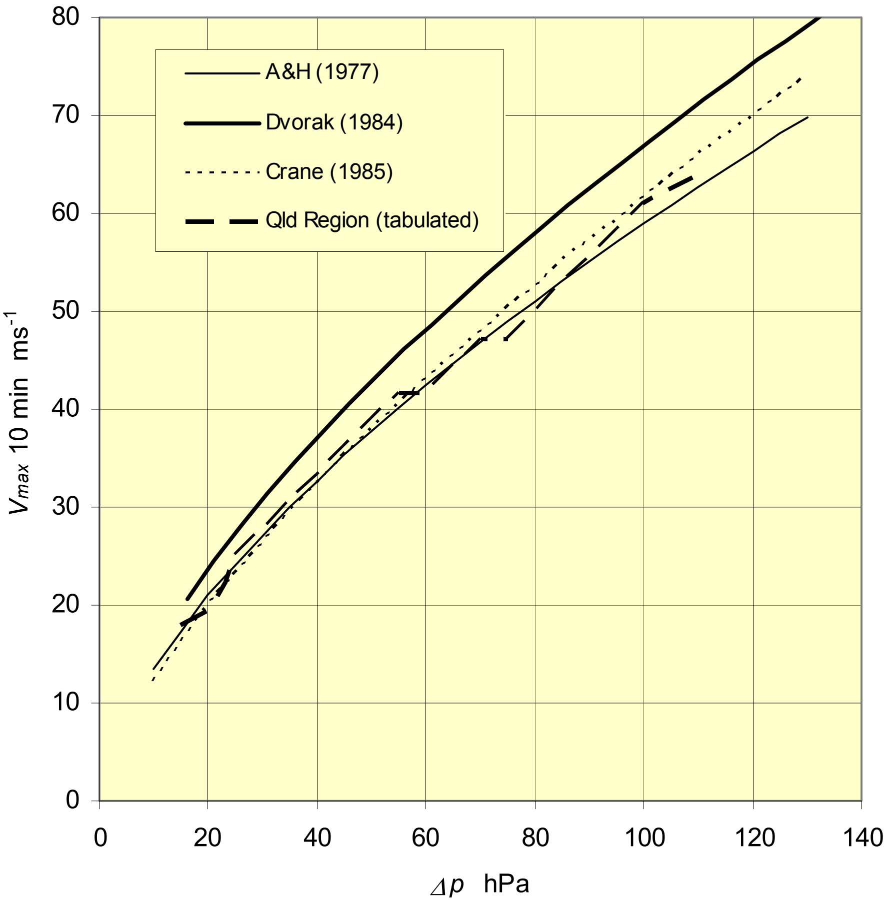


Figure 3.9 Relationship proposed by Crane (1985).

3.12 Weatherford and Gray (1988ab)

This double paper (W&G) represents the first detailed analysis undertaken of NWP reconnaissance data involving Doppler wind radar and consists of over 500 flight missions into 66 tropical cyclones over 337 days during the 3 y period 1980-1982. All of the wind data was derived from the 700 hPa flight level and converted into the storm-relative mean radial profile of tangential winds, averaged over (typically) four radial flight legs. The averaging period of the measured wind was not stated but is assumed to represent sustained 1 minute. The MSL p_c data was either from dropsonde or, more often, derived from the 700 hPa height (which is deemed quite reliable).

The aim of W&G was to examine the so-called *Outer-Core-Strength* (OCS) of tropical cyclones, defined as being between 1° - 2.5° from the centre (111 – 278 km), and the relationship of this zone with the inner-core (<1°). The study examined many potential relationships between inner and outer core strength variables such as latitudinal, seasonal, diurnal, speed of movement and intensity change. The *Inner-Core-Strength* (ICS) parameter was taken as the MSL p_c in preference to the derived flight level winds because of the better accuracy. It was noted that the Doppler wind measurements could sometimes suffer due to rainfall interference but also due to wind-wave velocity shift, which was not accounted for in the measurement. A possible underprediction of 5% to 8% is cited as occurring in worst-case situations. It is estimated that the wind-wave phase error could be of the order of ± 5 ms^{-1} (P.G. Black, *personal communication*) but, in the present author's view, likely to be somewhat randomly distributed across aircraft transects.

The wind-pressure relationship uncovered during the study was not compared with A&H by the authors, but has been compared here in Figure 3.10 based on a scanned data image. To provide an intercomparison, the nominal 1 minute surface wind from A&H has been factored by 1/0.91 to represent mean winds at the 700 hPa level (Franklin *et al* 2000). A visual line of best fit has then been added that is essentially equidistant from the indicated nominal upper and lower data limits. A&H here appears to significantly overpredict the estimated 700 hPa winds by an average of about 25%. Clearly the wind measurement technique used here is not as accurate as present GPS windsondes or SFMR but the W&G analysis represents a large and carefully selected *storm-relative* dataset and it is useful to consider its implications[20].

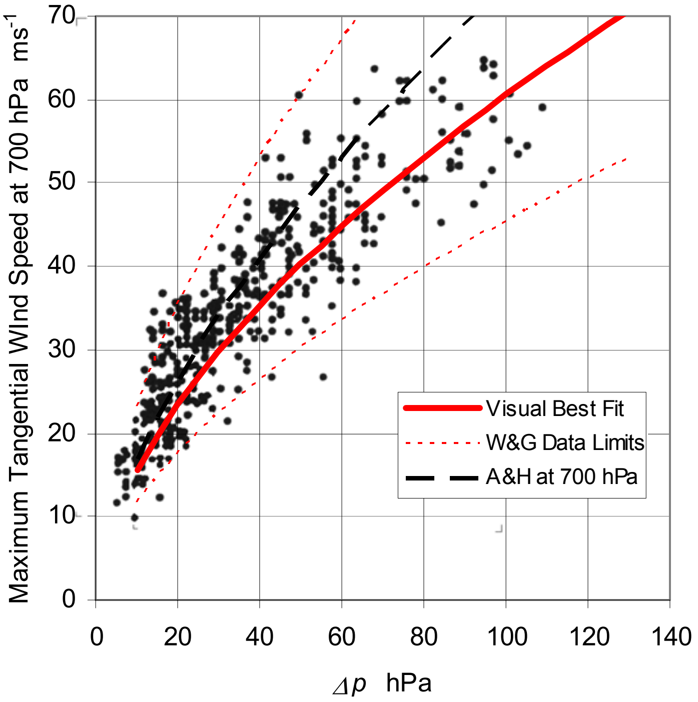


Figure 3.10 NWP data from Weatherford and Gray (1988)

3.13 Gray, Neumann and Tsui (1991)

GN&T is mentioned here within the overall context of validation of the Dvorak technique, although it does not contribute directly to the development in this review. GN&T illustrates the very considerable degree of effort mounted in the late 1980s by many investigators to try and maintain regular aircraft reconnaissance of storms in the Atlantic basin, which had commenced in the 1940s. This flurry of validation against satellite methods was prompted by the decision of the US Department of Defense in 1987 to cease reconnaissance in the NWP region.

The review by GN&T provides a useful comparison of the merits of the many observational platforms and importantly highlights the need for continuing variety in measurement techniques. They noted the sometimes high variability in intensity estimates made using only the Dvorak method and the critical importance of aircraft data for future improvements in that method, as well as many others. It is noted that there are many internal reports referenced in GN&T which relate to the validation of the Dvorak method, but time has not permitted recovering these for the present review.

---

[20] The W&G “best fit” here is also a reasonable fit to the scatter plot from Shea and Gray (1973) for Atlantic storms.

3.14 Martin and Gray (1993)

M&G represents a continuation of the comparison between satellite and aircraft reconnaissance methods but is much more quantitative than GN&T. It considers the last 7 years of North West Pacific aircraft data from 1979 to 1986, consisting of over 200 tropical cyclone cases comprising some 5000 centre fixes. It appears to overlap the last 3 years of the W&G dataset. The analyses consider comparisons in storm position as well as intensity, however the latter is limited to only central pressure p_c rather than V_{max}.

The difficulty of obtaining "independent" data sets of Dvorak *CI* and aircraft intensity measures is discussed by M&G at some length. However, notwithstanding the expected operational interaction between the two methods, it was found that there was still a tendency for the satellite analyses to overestimate the intensity (give lower p_c) for "strong cyclones" relative to the aircraft dropsonde or extrapolated flight level pressure reading. This is thought to have been due to a rigorous application of the Dvorak (1984) NWP rules in spite of aircraft information being available. M&G's statistical analysis of the intensity differences has been re-presented here in terms of $V_{max} - \Delta p$ space to illustrate the impact of removing the apparent bias in overestimation of intensity. Note that at the upper intensity level there were only 5 samples available, compared with 23 at the next highest level.

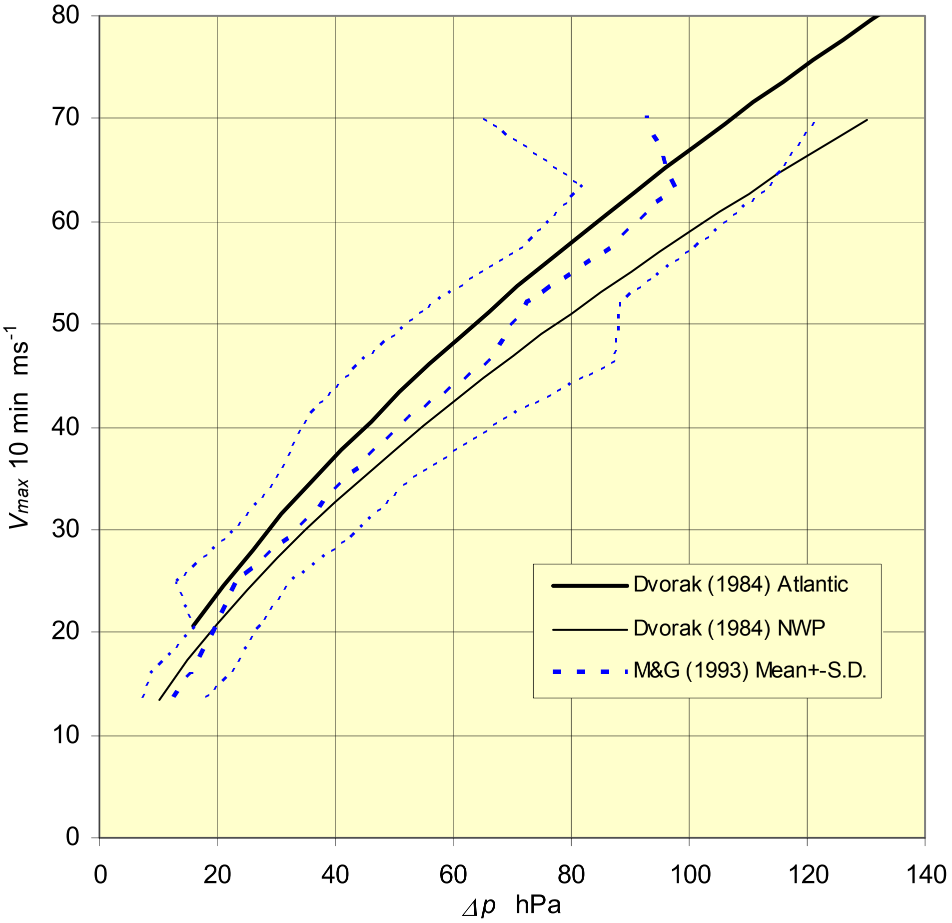


Figure 3.11 Impact of analyses by Martin and Gray (1993)

Figure 3.11 shows the M&G bias-removed mean and standard deviation relationships in $V_{max} - \Delta p$ space compared with Dvorak (1984) for the Atlantic and NWP (A&H). If applied as an operational measure, this adjustment would have had the effect of moving the A&H NWP curve more towards the Atlantic curve. However, this result can equally be interpreted as a bias in the CI - V_{max} or even CI - Δp curves. It should be noted though that there were many occasions when the aircraft-measured intensity fell below the A&H curve. In the present review context, this result is considered as further evidence of the great variability in individual storms and the difficulty of applying a single wind-pressure relationship. It also suggests that the A&H curve is well positioned for Δp up to about 70 hPa. Beyond this point, the M&G sample size halves from about 130 to 65 storm events.

3.15 Black (1993)

Black's study was prompted by a JTWC Annual Report article by Bouchard (1990) subtitled "Where have all the super typhoons gone?", which revealed a significant difference in the apparent mean frequency of occurrence of "super typhoons" from 1959 through to 1988. Black investigated this phenomenon from the viewpoint of changes in intensity estimation methods, and provides very useful historical insight into the development of many of those listed in Table 3.1. He shows that as a result of adoption of new methods, a stepped change occurred in the JTWC best track mean maximum annual wind speed from 33 ms^{-1} to 26 ms^{-1} in 1970, which in turn lead to the apparent changes in numbers of "super typhoons".

In his analysis, Black chronicles the development and use of various intensity estimation methods over the period up until Dvorak (1985). He also offers further insight into the JTWC operational procedures, expanding upon that presented in Atkinson and Holiday (1975, 1977). He then addresses the issue of different wind averaging periods as being one of the principal issues behind the variability in approaches and the spread of results. This leads to an assertion that prior to 1970, the best track wind speeds should be regarded as "peak gusts", whereas after general uptake of the A&H work, they are (approximately) 1 min winds. In support of this he critiques the A&H approach and compares it with the earlier and largely unadopted proposals by Fujita (1971), which included implicit allowance for wind averaging periods. In respect of A&H, Black also finds issue with the method used to reduce measured peak winds to 1 min winds, albeit offering a slightly different argument to that in Appendix A here. He suggests that, as a result, the gust factor used by A&H was probably too low by a ratio of 1.1/1.23 (0.89). This would place the A&H wind-pressure curve lower and approximately along the equivalent Fujita curve.

In summary, Black appears to advocate a mean 1-min wind-pressure relationship applicable to the NWP as being slightly lower than the published A&H curve. By implication though, he also asserts that the Dvorak (1975) wind-pressure relationship refers to "peak gusts". This has essentially survived as the "Atlantic" wind-pressure curve, variously quoted as "1 min sustained".

3.16 Guard and Lander (1996)

In response to the growing experience in detecting very small and often short-lived storms, G&L proposed a variant to the A&H relationship for what they termed Western North Pacific "midget" tropical cyclones. In essence, this development paralleled the L&M intention of some 10 years previously for the Northern Australian region. The G&L analysis was based mainly on island landfall situations but some aircraft observations were used where suitable. They noted that "*Midget TCs have a high intensity inner core where the outer winds are from the inertial spindown of the belt of maximum winds. There is no outer core.*"

Their new relationship is shown in Figure 3.12, compared with Dvorak and A&H. It allows "midgets" to have a higher central pressure than A&H by as much as 10 to 17 hPa when "weak" but tends to merge with A&H for "intense" storms. Also shown is the Holland B=2.2 curve, which follows the G&L curve fairly accurately right up until the more intense class of storms.

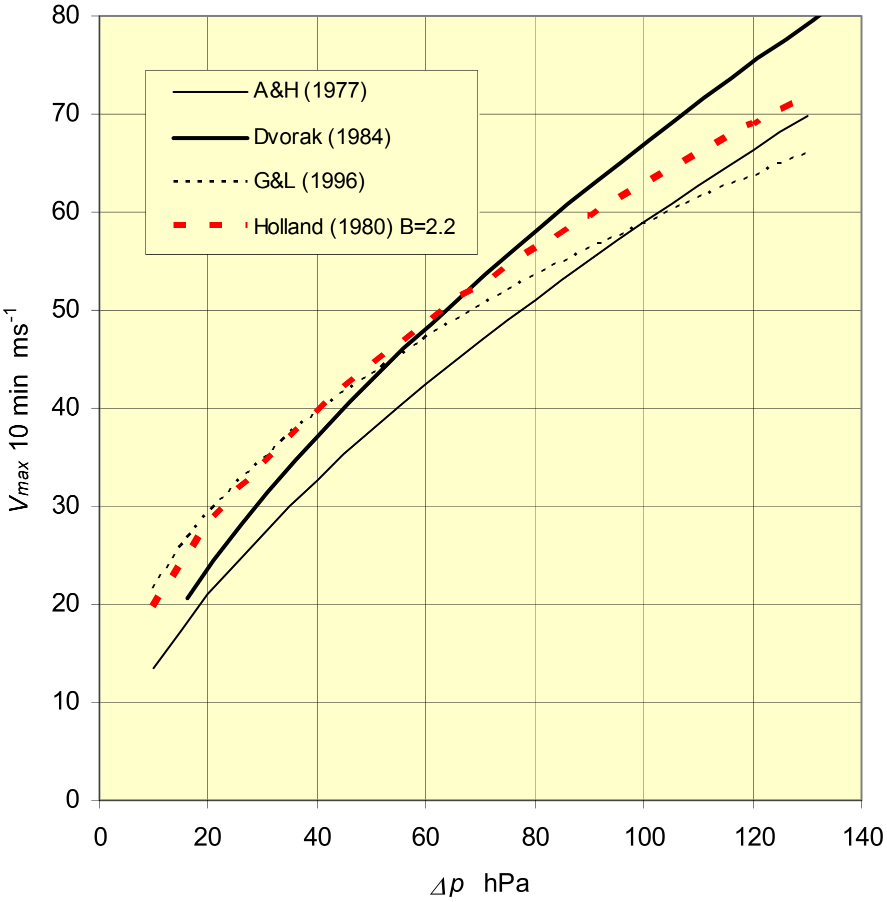


Figure 3.12 “Midget” NWP relationship proposed by Guard and Lander (1996)

3.17 Callaghan and Smith (1998)

This paper (C&S) outlines evidence from a number of case histories of storms to focus attention on some apparent emerging relationships between V_{max} and p_c. This takes the form of a qualitative consideration of both absolute *size* and also forward *speed*. Finally, theoretical considerations are demonstrated to largely explain the observed ranges in behaviour. While the principal effect of *speed* on first-order asymmetry is well appreciated, the paper emphasises the potential for wind-wave coupling also under extreme conditions. Of particular relevance to the present review though is the consideration of *size* as a possible discriminator of the V_{max} - p_c coupling.

Figure 3.13 shows the various data considered by C&S, plotted on the now familiar wind-pressure backdrop. These are essentially as described in the paper, which are a mixture of V_{max} and V_{max}'. The three *Alicia* V_{max}' data points have been extracted from the NHC best track files. Three data points are also indicated for *Gilbert* V_{max} winds from Black and Willoughby (1992). The *Kerry* V_{max} estimate is from Black and Holland (1995)[16]. The data are shown in the various size groupings of *small*, *medium* and *large* as described in the paper. While not necessarily the authors’ intention, the principal outcome of this is perhaps to demonstrate just how widely distributed storm behaviour can be, rather than illustrating any specific tendency for logical groupings by size alone.

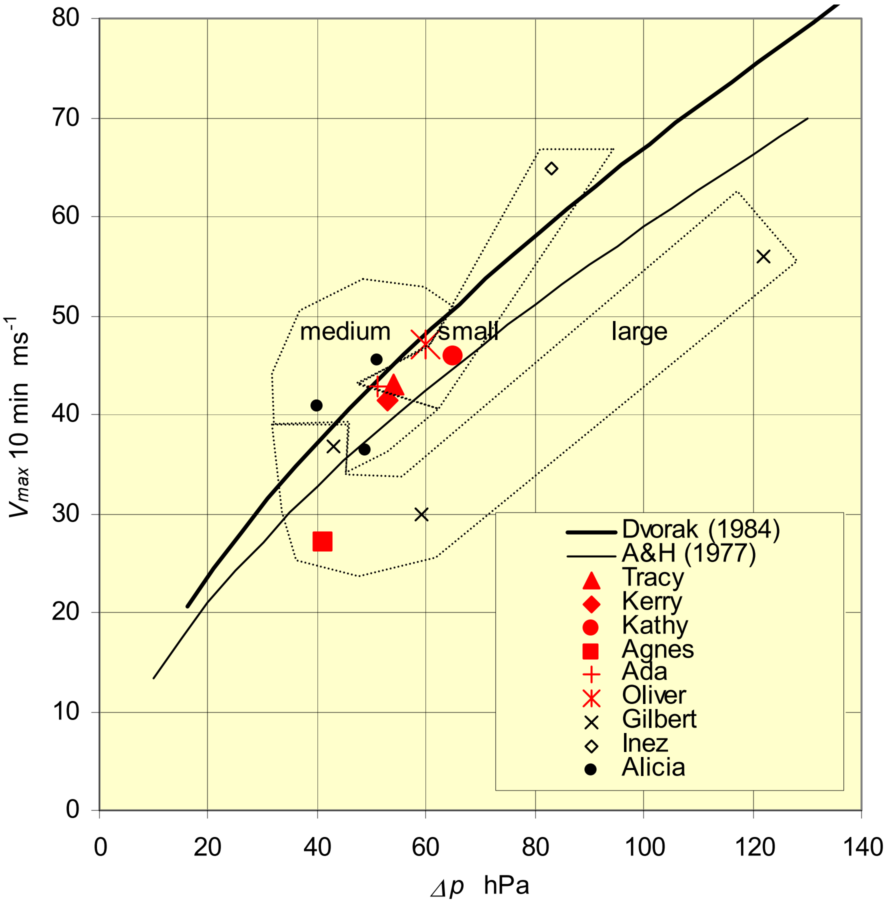


Figure 3.13 Data considered by Callaghan and Smith (1998)

Notwithstanding the wide range of behaviour displayed, the possible reasons for this are then explored in a mathematical context through the development of a simplified gradient balance model, similar to the Holland concept. Unlike Holland, however, the argument does not rely on the pressure gradient to control $V_{g\ max}$ and no "peakedness" parameter is specifically identified. The analysis uses a generalised inner and outer circulation formulation which retains the Coriolis interaction in preference to considering cyclostrophic-only affects. This alone is used to show how, for the same $V_{g\ max}$,the central pressure of smaller scale storms will be higher than for larger scale storms and that there can be no fixed relationship between V_{max} - p_c. This is further expanded by considering the effect of a region of dead calm within a given radius of the vortex core, rather than the solid body rotation assumed by a conventional analysis. This shows a significant impact on the V_{max} - p_c coupling which could play a role in some larger systems (perhaps the "truck tire" phenomenon, e.g. Knaff *et al 2002*). For example, the theoretical analysis indicates the potential for p_c ranging of the order of 15 hPa for a given $V_{g\ max}$ of 50 ms^{-1} and R of 50 km.

The purpose of the C&S paper was to alert analysts to the possible variability in storm behaviour compared with the established wind-pressure relationships routinely applied as part of the forecast process. This is well illustrated even by the small sample of storms considered. However, the evidence shown for *Gilbert* and *Alicia* also points to the temporal variability within storms (especially larger long-lived storms) as being extremely important in influencing wind-pressure variability. The eye-wall replacement cycle (e.g. Willoughby 1995) is clearly a very significant element in that process. In terms of *large* versus *small*, it can be argued from Figure 3.13 that there is something of a tendency for *small* storms to exhibit higher V_{max} than their *large* counterparts, subject to the temporal issues just raised. For completeness though, it should be noted that the *Alicia* data shown here is essentially a random sample from the best track data near the time of peak intensity. For reasons to be more fully developed later, the *Alicia* V_{max} data may well be overestimated here and tending to upset the suggested progression in size implied by the authors.

In respect of the theoretical arguments presented, it appears that these would only be valid in respect of *large* storms, given the dependence on Coriolis. Accordingly, the issue of V_{max} - p_c variability for *small* storms seems to remain more likely related to the Holland model concept of "peakedness".

3.18 Velden et al (1998)

This paper provides a comparison study between the developing *Objective Dvorak Technique* (ODT) and objective p_c dropsonde data from aerial reconnaissance into ten Atlantic storms during 1995 and 1996. The ODT is the further development of the Dvorak (1984) EIR method but using digital infra-red data and automatic computer-based algorithms. This advance is an important use of technology to address the issue of variability in the Dvorak method due to analyst interpretation and experience. The paper notes that no similar study has yet been completed for the NWP, where reconnaissance data is no longer available.

Their comparison of the Dvorak method with the data however is limited to p_c and thus avoids the many vexing issues of a V_{max} comparison. The conclusion from the study, which utilised 346 estimates of p_c, is that the ODT method had a negligible overall bias (0.33 hPa) compared with the reconnaissance data but an RMS error of 8.34 hPa, representing a reasonably large scatter. The most difficult storm in the set was *Opal*, which was also the most intense. It was considered that the ODT was typically accurate to within ±5 hPa for well-defined cyclone structures. Table 3.4 provides a summary of their results.

Table 3.4 Verification results from Velden et al (1998)

Storm	Year	Peak Intensity	Sample Size	Bias Error	RMS Error
		hPa		hPa	hPa
Felix	1995	930	26	2.06	8.66
Iris	1995	972	11	-0.69	5.04
Luis	1995	935	14	0.01	9.82
Marilyn	1995	948	29	-5.11	10.09
Opal	1995	915	20	8.57	13.66
Roxanne	1995	955	38	-0.89	3.18
Bertha	1996	960	34	8.66	9.17
Edouard	1996	935	55	0.21	6.49
Fran	1996	945	73	0.76	7.76
Hortense	1996	935	49	-5.89	8.89

The paper concentrates on the detailed application of the computer-based algorithms but Velden (*personal communication*) confirms that the method still delivers a conventional *CI* number and that the MSL pressure is directly estimated from Table 3.2. The most interesting outcome of this paper for the present review is therefore that the original Dvorak (1975) *CI* - p_c relationship still stands up well, albeit in the *mean*, to some of the best objective data in the Atlantic basin. There is the possibility though that the subtle changes in rules now being applied to the ODT are in fact serving to calibrate it to the existing Dvorak relationship. The considerable scatter in the results may then point not only to the inherent difficulty of the problem, but potentially highlight the limits of some of the base Dvorak storm model assumptions.

3.19 Harper and Holland (1999)

The Holland (1980) radial pressure and wind profile formulation has been widely adapted by ocean engineers as a very useful means of obtaining reasonably realistic wind and pressure fields for the numerical modelling of tropical cyclone winds, waves, currents and storm surge. However, the original paper does not fully describe all that is needed to generate a model wind or pressure field. Harper and Holland (H&H) is a short summary only, but provides additional guidance in terms of the boundary layer reduction of winds and a simple first-order allowance for wind field asymmetry due to the effects of forward motion. It reflects some of the extensive experience gained in the application of the Holland model in the offshore oil and gas industry (Harper *et al* 1989; *WOP* 1990, 1992; Harper *et al 1993*) and the insurance industry (Harper 1999). All of these studies have utilised extensive onshore and offshore datasets comprising wind, pressure, waves, currents and water levels. An important conclusion from this body of work is that the Holland model has sufficient parameter dynamic range to be able to reasonably match wind and pressure profiles from a wide range of storms, and within a consistent *temporal* framework.

Of interest to the present review, is that almost all of these offshore studies also included an assumption regarding allowance for temporal changes in the *B* parameter throughout the life of individual storms. This derives from advice (Holland, *personal communication*) in the late 1980s that, notwithstanding the variability of an individual storm, it is perhaps reasonable to assume that *B* varies in a manner similar to the trends indicated by the Dvorak and A&H formulations in Figure 3.5. This leads to the suggestion in H&H that a simple linear temporal trend of the type:

$$B(t) \quad = \quad 2 \quad - \quad (p_c(t) - 900)/160 \tag{6}$$

could be considered to provide a reasonable variation in wind profile shape. This particular approximation (graphed in Figure 3.14) was chosen to basically follow the A&H relationship as graphed by Holland, respecting the accepted "regional" trends for the Western Pacific basin.

Given that the Australian best track database is largely built on the A&H relationship, the successes of this method is perhaps guaranteed to some extent. However, in practice, this relationship has been considered in the context of a simple family of linear curves, more appropriately arranged thus:

$$B(t) \quad = \quad B_0 \quad + \quad 0.00625\,(p_n(t) - p_c(t)) \tag{7}$$

The constant B_0 is then an intercept value able to be calibrated for an individual storm. Having determined an optimal B_0, the temporal change in *B* is then fixed as a function of the temporally varying pressure drop. This has proven to be a very useful calibration tool where one or more anemometer and/or pressure recording sites are available (e.g. Harper 2001). A high B_0 then characterises the lifetime of a "peaked" storm and a low B_0 characterises a "flat" storm, but both are permitted to vary the absolute value of their "peakedness" *B* as a function of their intensity. Implicitly this approach supports a view that any given storm tends to retain its principal scale characteristics throughout its life even though there is variation about a mean scale.

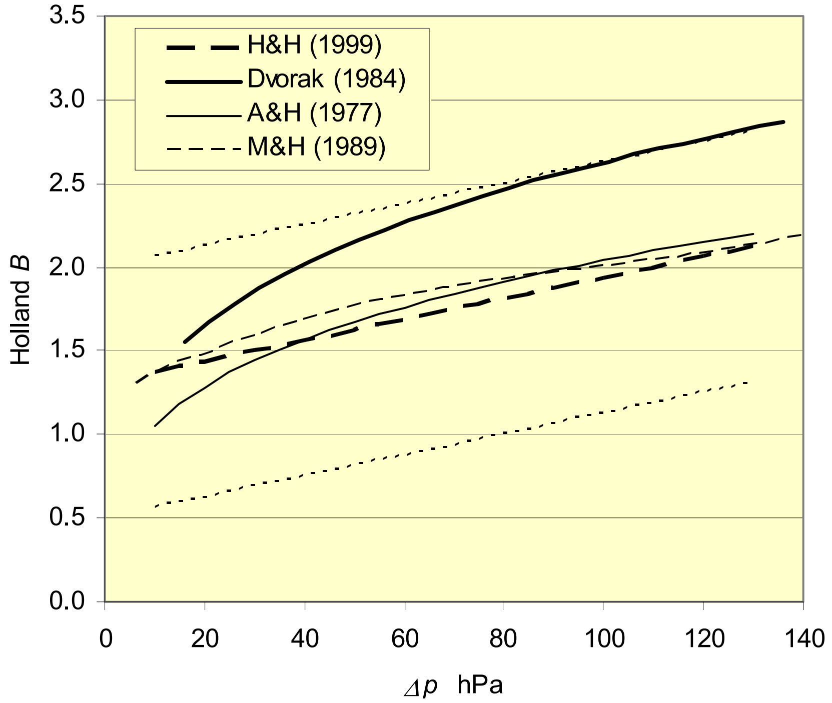


Figure 3.14 Holland B ranges found from calibration studies by Harper.

By the amalgamation of many similar calibrations, regional statistics of values of B_0 have then been utilised in probabilistic modelling studies. The typical envelope range of B_0 obtained from these studies is between 0.5 and 2.0, which is also indicated on Figure 3.14 by the upper and lower dashed lines[21]. This stretches the range of *B* recommended by Holland and but doing so also indicates the influence of many other factors in the calibration process (anemometer exposure, distance from vortex core, synoptic effects etc) as well as the actual vagaries of individual storms. *B* values below 1, for example, typically occur in calibration when the only observed winds are remote (> 5 *R*) from the centre, where the Holland model tends to lose applicability and underpredicts the true wind. Higher *B* values are typically justified by observations closer to the centre. The important issue arising from this data calibration experience is that the ability to describe variability from the *mean* condition is extremely valuable. In essence, this approach serves to reintroduce some of the variance which is suppressed during the best track determination because of reliance on a single fixed wind-pressure relationship such as A&H. Also shown on Figure 3.14 is the Martin-Holland *B* relationship (M&H), as presented by Rupp and Lander (1996), which was developed for use in the NWP. Unlike Equation 7, however, this gives a fixed value for *B* as a function of Δp.

3.20 Landsea et al (2000)

This refers to on-line documentation in respect of the "Atlantic Hurricane Database Re-analysis Project", which is a joint project between (principally) NOAA/HRD, NOAA/CDC and the Florida International University. Of special interest to this review is the series of wind-pressure relationships presented therein based on best track data 1970 – 1997 that are stratified by latitude. It is understood that the best-fit analyses were performed by Charles Neumann (Science Applications International Corporation but a former Head of Research and Development at NHC).

---

[21] These earlier studies actually defined B_o as $B + p_c/160$ with the statistical range being typically 6.8 to 8.3.

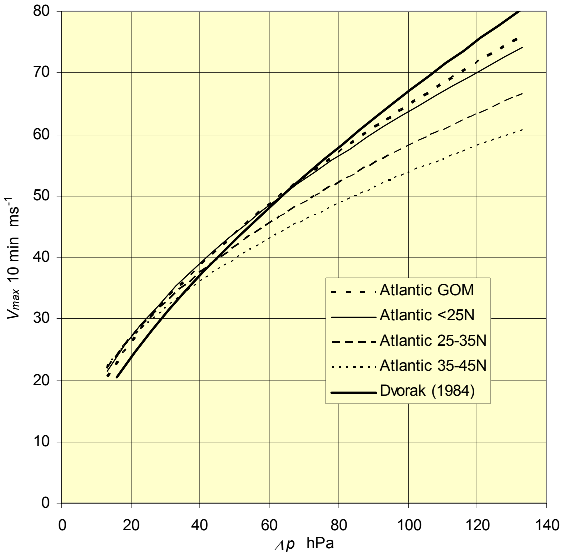


Figure 3.15 Atlantic best track data stratified by latitude after Landsea *et al* (2000).

Figure 3.15 compares these relationships with Dvorak. While not a fully objective set, there is a strong latitudinal separation evident, which suggests that V_{max} for a given p_c weakens with increasing latitude. It is proposed by the authors that this reflects the fact that hurricanes encounter cooler sea surface temperatures as they move poleward and the windfield typically expands outward (flattens) with increasing latitude. These results further emphasise the fact that there can be no "one size fits all" wind-pressure relationship.

3.21 Neumann (2001)

This reference describes application of the HURISK model, originally developed for the Atlantic, to a number of other ocean basins. Although not published therein, Charles Neumann kindly supplied his derived "southern hemisphere" wind-pressure relationship for this review. His curve is an amalgam of the available best track datasets made available to him and hence is in no way objective, but serves as a useful summary of how the southern hemisphere forecasting community is apparently interpreting and applying the Dvorak technique in practice. Not surprisingly perhaps, his relationship (Figure 3.16) forges almost a midpoint between the competing Atlantic and NWP lines.

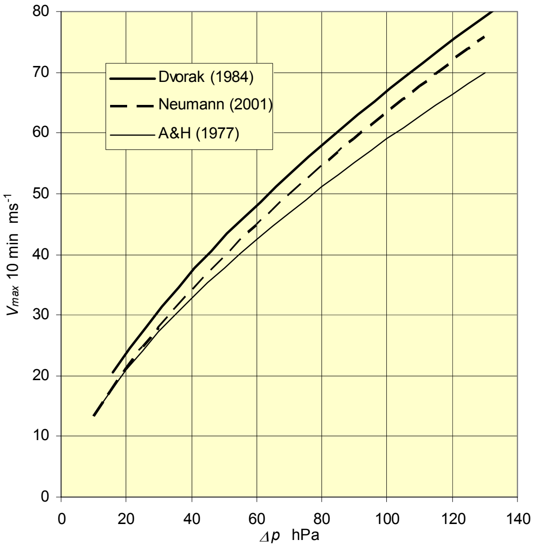


Figure 3.16 The mean Southern Hemisphere practice after Neumann (2001)

3.22 Brown and Franklin (2002)

B&F provides a comparison of 450 Dvorak estimates of surface winds obtained from three different US forecast agencies with measured near-surface GPS dropwindsondes, over the period 1997-2001 in the Atlantic basin (here termed "best track"). Accordingly B&F represents arguably the most complete set of ostensibly objective data yet assembled for comparisons of direct interest to this review.

Figure 3.17 summarises the Dvorak forecasting performance, showing a mean result (solid line) very close to the ideal (dashed) but with some considerable scatter (note that these are 1-minute averaged winds). Overall, 50% of the Dvorak estimates were within 7 kt; 75% within 13 kt and 90% within 20 kt. It is noted by the authors that the Dvorak intensity for weak storms seemed to show a slight low bias, thought to be due to the rule limits on *T*-number changes. At the high end the Dvorak estimates tend too high and this effect is said to reduce if *T*-numbers rather than *CI*-numbers are used, thus implying that the intensity persistence rule may be too restrictive.

The data is then presented in pressure-wind space in Figure 3.18 and the best fit line (refer Table 3.1), labelled as "best track", can be seen to be almost identical to the original Dvorak relationship. This result tends to further support the conclusion by Velden *et al* (1998) that the Dvorak intensity relationship, in the *mean*, still holds true for the Atlantic. In this case the A&H curve, which is also shown, can be seen to be bracketing the upper data points and comment is made by the authors that almost all of the occasions when points lie above A&H are for *Floyd*, regarded as an unusually large hurricane for the Atlantic.

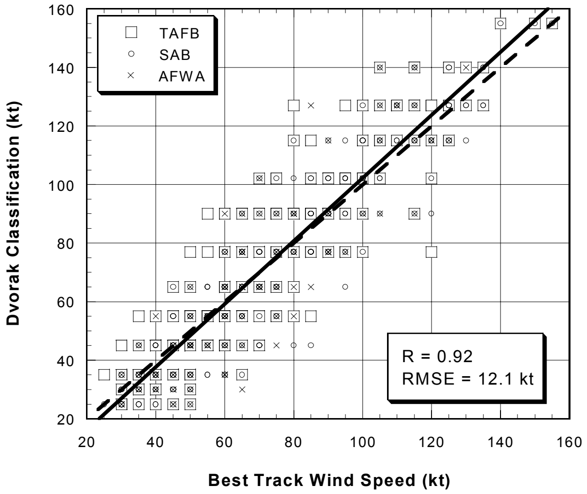


Figure 3.17 Dvorak intensity estimates versus best track data in the Atlantic from Brown and Franklin (2002); 1 min winds shown.

The B&F analysis is a remarkable result given the history of development of the Atlantic wind-pressure relationship and (with due respect to Brown and Franklin) is one that prompts further enquiry. For example, while it is stated that the surface wind estimates are derived from GPS dropwindsondes, a detailed examination of the raw NHC data files (the ATCF files were also kindly provided by J. Franklin) shows that objective wind measurements are not flagged and cannot be readily extracted. This was confirmed by Franklin as a problem in the analysis, which he believes is overcome by only selecting best track data pairs within 1 h of an aircraft fix. However, while the surface pressure is almost certainly based on dropsonde, there are no guarantees in respect of the surface wind. Also, importantly, the data have not been adjusted for likely storm forward speed effects.

Figure 3.18 also indicates the Kraft (1961) relationship, upon which the Saffir-Simpson storm category scale (Simpson 1974) appears to be based. It is considered quite likely that, like the historical tendency for accumulated data to follow the Dvorak relationship, that the operational importance of the Saffir-Simpson scale in the US has also exerted a powerful force on best track outcomes. Recent concerns felt by the NHC in upgrading hurricane *Andrew* from Category 4 to Category 5 status (NHC 2002) highlight the sensitivity to this (albeit arbitrary) scale of potential damage. While such sensitivity is to be expected by any forecast agency concerned with maintaining consistent lines of communication with the public, vigilance is clearly needed to ensure against long term biases appearing in the databases.

Hence, while it is not unreasonable that the maximum surface wind is a somewhat *considered* best track parameter, there remains the possibility that the extensive empirical guidance offered by a wide variety of NOAA forecast models (e.g. CLIPER, SHIPS, SHIFOR etc), which are themselves derived from best track datasets, are continually biasing the adopted surface wind towards a *Dvorak-like* or *Kraft-like* mean outcome. Also, the operational practice of always rounding up estimates to the nearest 5 kt value is highlighted by the stratification evident in Figure 3.17. This works to push the mean position further from A&H. Appendix C also presents several examples of Atlantic hurricane data where the pressure-wind pairings are outside the A&H relationship and Figure 3.18 is also inconsistent with, for example, Figure 3.15, although the B&F dataset might consist of mainly low latitude storms. Finally, like Gaby *et al* (1980), the knowledge of reconnaissance data within the Dvorak assessment process is likely to strongly reinforce the outcome (Holland, *personal communication).* Some of these aspects are further explored in Section 4.3 and Appendix D.

The availability of such a large collection of data also raises a related matter that should be considered when deriving wind-pressure relationships from storm data sets. This is that multiple data pairs from the same storm are not independent. This means that the trend of the temporal behaviour should rightly be considered in the "best fit" for the family behaviour of all storms and this will influence the "slope" of the derived line. Examples of how this might influence the outcome are illustrated by some data comparisons in Appendix D.

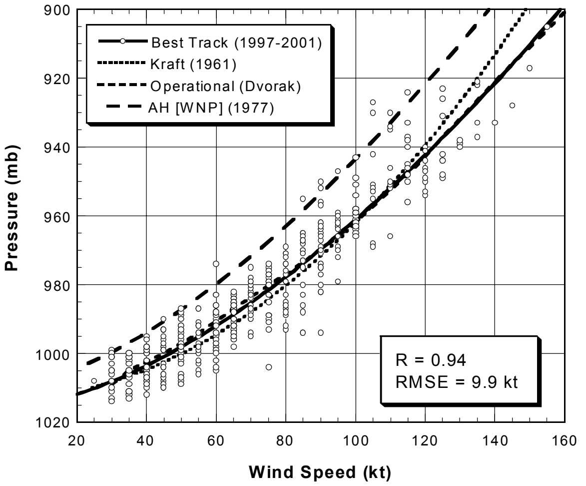


Figure 3.18 Pressure – wind relationships based on best track data in the Atlantic from Brown and Franklin (2002); 1 min winds shown.

4 Discussion

4.1 The Dvorak Technique

The Dvorak technique is the result of some 15 years of active experimental development (1969 – 1984) that was based on a variety of data from several hundred tropical cyclones in both the NWP and Atlantic basins. During the period of its development there were continuing improvements in the quality of satellite imagery, the accuracy of objective estimates of the central pressure and, to a lesser extent, the measuring of maximum wind speeds in tropical cyclones. Analysts also became more proficient in its application. At least four significant verification studies were undertaken during the development period, all generally confirming the accuracy of the method to be at least within 0.5 *CI* number for each of the NW and Atlantic basins (i.e. < 10hPa and < 5 ms^{-1}). Following the period of active development a number of other comparison studies were done.

Notwithstanding the above, it is clear that the empirical development and verification of the method has to a large extent been unavoidably influenced by a lack of truly objective data. This has led to performance measures being made against datasets largely preconditioned by the method itself. Even in the present era, where much more objective data has become available, operational procedures could still be acting to bias best track data towards expected outcomes.

This should not detract from the great utility of the technique, but certainly presents problems in assessing its absolute accuracy and in transferring the technique to other basins.

4.2 Some Provocative Questions

The review has highlighted some of the critical phases of the development of the Dvorak technique that are important when considering its present and future application, *viz*

1. The method was designed to provide conservative (i.e. unlikely to be exceeded) estimates of V_{max} ;
2. The procedures were developed on NWP data, modified by later Atlantic and NWP;
3. The *CI* - V_{max} relationship has remained fixed since 1975;
4. The original NWP V_{max} - p_c relationship was replaced by A&H (1977);
5. The Atlantic V_{max} - p_c relationship is the old NWP relationship offset by 6 hPa;
6. Contemporary verification studies in the Atlantic show very good agreement, in the mean, with apparently “objective”[22] data.

On the basis of the above development:

How likely is it that the base relationships developed in 1975 were as accurate as they now appear?

> This question is posed with due respect to the developer of the method. It aims to elicit debate on whether self-calibration has not become a serious problem that could be restricting future progress in this area.

How conservative is the governing CI - V_{max} *relationship?*

> Anecdotally at least, there has been much debate between forecasters and engineers in the US as to the true magnitude of wind speeds, the engineers asserting that forecast and best track

---

[22] V_{max} inferred from flight level remains problematical but dropsonde pressure data is normally regarded as objective.

> winds are often too high compared with platform and/or buoy observations. This debate has focused on the claimed distortion of the Saffir-Simpson/Kraft wind scale from its original intention of describing gust wind speeds to now being used to describe 1-minute average winds. On the other hand, *the maximum* wind is rarely known to have been observed and even if it has, the true convection-free mean storm-relative component is still an unknown.
>
> The original CI - V_{max} relationship was developed at a time when less attention was focused on the averaging period and applicable height of wind estimates.
>
> A&H showed how a significant difference in estimated wind speed could be made through a more careful reassessment of measured winds. M&G suggests that A&H is quite reliable at least up to a Δp of about 70 hPa.
>
> W&G flight level data, which is storm-relative, seems to suggest that A&H is already over-estimating, perhaps supporting the critique in Appendix B. Black (1993) also suggests A&H is slightly high and that Dvorak (1984), now used in the Atlantic, predicts peak gusts.

Given the above mixed parentage and doubts in regard to accuracy, is it reasonable to continue to assert that either of the presently adopted V_{max} - p_c *relationships are justifiably unique to their respective basins?*

> In the earliest comparison by Erickson, the basic difference between the Atlantic and NWP data sets seemed readily explained by a difference in ambient pressure. Subsequent development of the method seemed content with a separation of the ways. From a reading of the literature it is conjectured that this split may have had as much to do with politics as with science. The original NWP method is now applied to the Atlantic.

In summary, the Dvorak method as it stands should not be regarded as a "sacred cow" but as an insightful, cost-effective and very powerful observational base that can and should be continuously developed. The ongoing development of the ODT technique (Velden *et al* 1998) clearly has such an objective in mind and is being most enthusiastically received and encouraged by those without reconnaissance capability. However, methods like the ODT (e.g. Kidder *et al* 2000) will have lessened value if they remain merely calibrated to an existing empirical method. Ironically it will only be through the increasing availability of more objective data from aerial reconnaissance and advanced surface wind speed sensors that the Dvorak method will be improved.

4.3 Evidence of Best Track Bias in the Atlantic Dataset

One of the more significant observations made during this review was the potential for systematic bias of best track information towards existing *Dvorak-like* wind-pressure relationships in both the NWP and Atlantic best track datasets. Accordingly, access was sought to these datasets to enable an assessment to be made. Atlantic National Hurricane Center (NHC) data was provided by James Franklin of the NOAA Tropical Prediction Centre, while Tim Olander from the University of Wisconsin was also able to provide ODT analyses for the Atlantic seasons prior to 2001. Surface wind analyses for select storms were then also referenced from the NOAA Hurricane Research Division (HRD) web page. No NWP datasets of comparable detail have been obtained.

A simple comparison was then undertaken to determine if any systematic bias in adopted best track information might be evident from some of the recent hurricanes where more objective data was available. In this context, to avoid the ambiguity faced by B&F in having to choose best track data within 1 h of a known dropsonde or other objective wind measurement, the HRD surface analysis records of V_{max} are taken as “objective”. Based on Mark Powell’s advice, the indicated V_{max} is objective within the context of the mean boundary layer model used by HRD, but due to changing analysis methods, only storms during the past three years were considered to ensure the highest accuracy.

Due to a lack of time, only four events were considered. These are listed in Table 4.1, being selected subjectively on the basis of their intensity, good availability of measurements and range of size etc. The analysis method firstly consisted of simply comparing the time history of p_c, V_{max} and R as retained in each of the Atlantic operational “best track” (or NHC) and HRD data sets. These are shown in Appendix D, which provides some additional detail of the method. A comparison of the time history graphs in Appendix D shows that the p_c data are essentially the same between the two datasets. This is to be expected since both claim to be based on the same dropsonde data[23]. However, a comparison of the V_{max} data shows a tendency for the NHC data to be higher than the HRD. A visual comparison of the R data shows reasonable concurrence but there remain instances of some very significant differences, which may be due to the presence of rainband features casting doubt on the most representative value for R in some cases. The data were then transformed into V_{max} - Δp space and trend lines constructed as presented in Appendix D. It should be noted however that the wind values at this time are not storm-relative and a more careful analysis might alter these shapes slightly. Notwithstanding this, the differences between the two sources seem clear – the NHC sequence lies closer to the Dvorak curve in each case, regardless of whether the initial data starts above or below the Dvorak curve. Table 4.1 presents a brief summary of the findings from this limited review.

Table 4.1 A comparison of some recent NHC Atlantic best track and HRD data sets.

Storm	Year	Δp	NHC/HRD V_{max} Ratio			NHC/HRD R Ratio		
		hPa	Av.	S.D.	#	Av.	S.D.	#
Floyd	1999	86	1.07	0.11	27	0.97	0.41	27
Keith	2000	53	1.07	0.13	9	1.42	0.55	9
Iris	2001	62	1.02	0.10	8	1.49	0.57	7
Michelle	2001	71	1.09	0.13	15	1.67	1.65	9
		Overall=	**1.07**	**0.11**	**59**	**1.26**	**0.93**	**52**

It is concluded that there is *some evidence* of a systematic overestimation of V_{max} in the Atlantic best track data set when compared with the (deemed here) more objective HRD surface wind analyses. Based on the summary analysis of the ratios of NHC/HRD V_{max} for these 59 data pairs, the average ratio is 1.07 with a standard deviation of 0.11. While this small offset might be considered reasonable, the summary plots in Figure 4.1 allude to a more systematic bias. Also, the difference between A&H and Dvorak is 13%, and when the potential bias for rounding-up to 5 kt is included, this adds a further 6 to 2% depending on the wind speed. There is also evidence of possible significant overestimation of R by NHC which should be considered if best track radii are used in other studies. It is also conjectured that more recent NHC data may tend to be less biased than the historical data over the past 30 y due to the incorporation of the more objective data[24].

It is concluded that there is a reasonable basis for considering amalgamation of the so-called NWP (A&H) and Atlantic (Dvorak 1984) wind-pressure relationships into a new universal mean relationship. However, the utility of just using a mean relationship seems counter-productive given the inherent spread in the data even within the lifetime of individual storms.

---

[23] One notable exception is for *Iris* where the NHC p_c estimate differs from HRD due to their assessment that the dropsonde was not successfully located in the centre of this very small storm. Refer Appendix C for details.

[24] Vickery *et al* (2000b) present a best fit relationship for B derived from HRD flight level data that yields a mean B of about 1.42 for R values between 20 and 40 km; this mean line lies below the A&H line in wind-pressure space.

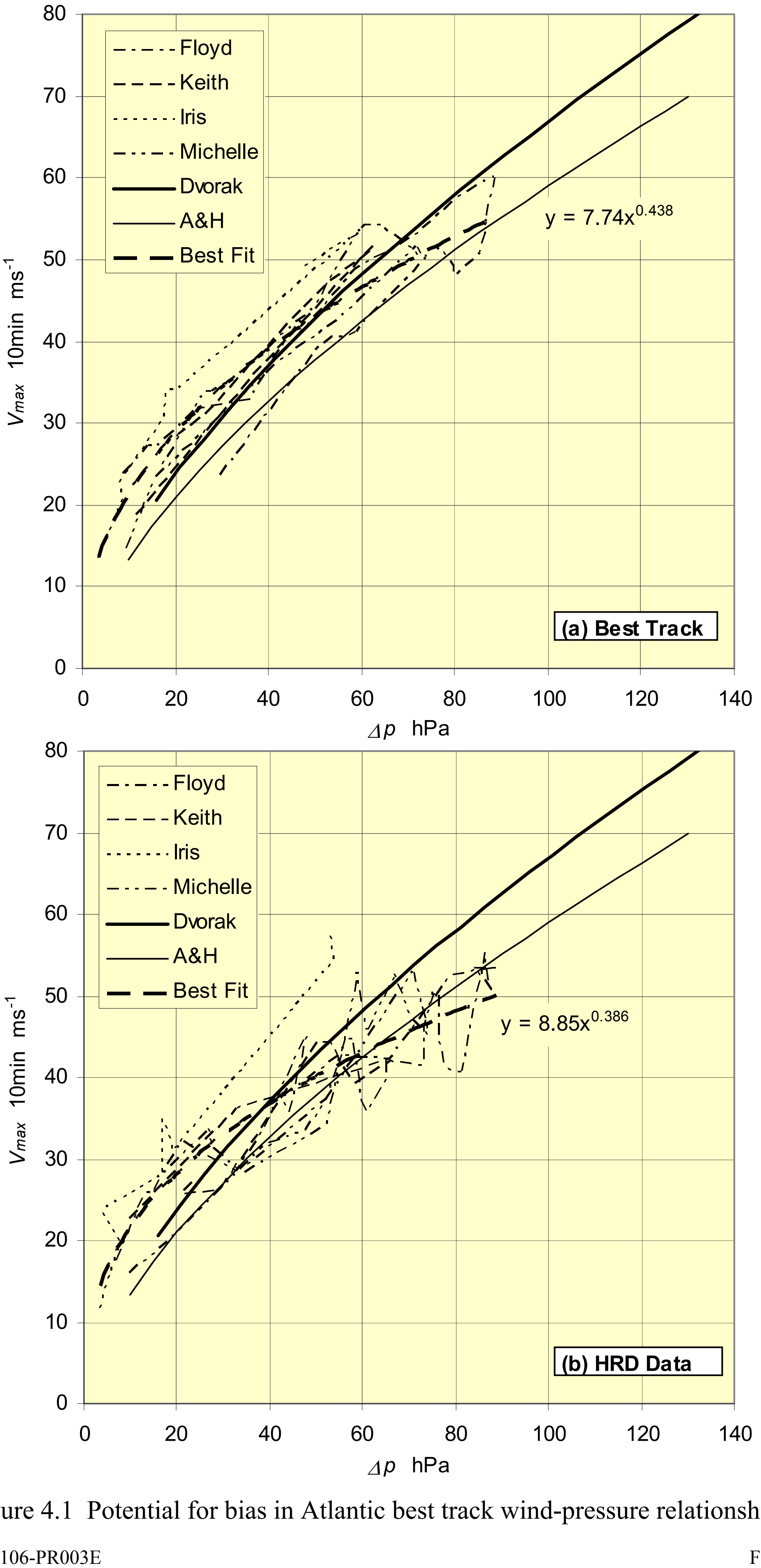


Figure 4.1 Potential for bias in Atlantic best track wind-pressure relationships.

4.4 Storm Structure, Dynamics and the Apparent Influence of Size

The principal differences in application of the Dvorak method across Australia (and the NWP and Atlantic) have been predicated on the basis of regional differences in storm scale, accommodated through regionally-based empirical wind-pressure relationships.

Much of the earliest information on storm structure derived from the US National Hurricane Research Project (e.g. Colón 1963) and landmark studies by Shea and Gray (1973) but Merrill (1984) was the first to encapsulate observed lifecycle structural changes in tropical cyclones in terms of some relatively simple yet fundamentally useful concepts, i.e.

- "*intensity*" being an "inner-core" or "inner-vortex" p_c or V_{max}
- "*size*" being the averaged radius to V_{gales} (or, alternatively, R_{OCI})
- "*strength*" being an average "outer-vortex" wind speed

These are illustrated in Figure 4.2 on a typical spatial baseline scale out to a 500 km radius (say 5°) from the storm centre. The solid line conceptually describes a steady-state starting point while the dashed inner and outer lines illustrate typical intensification and growth processes respectively.

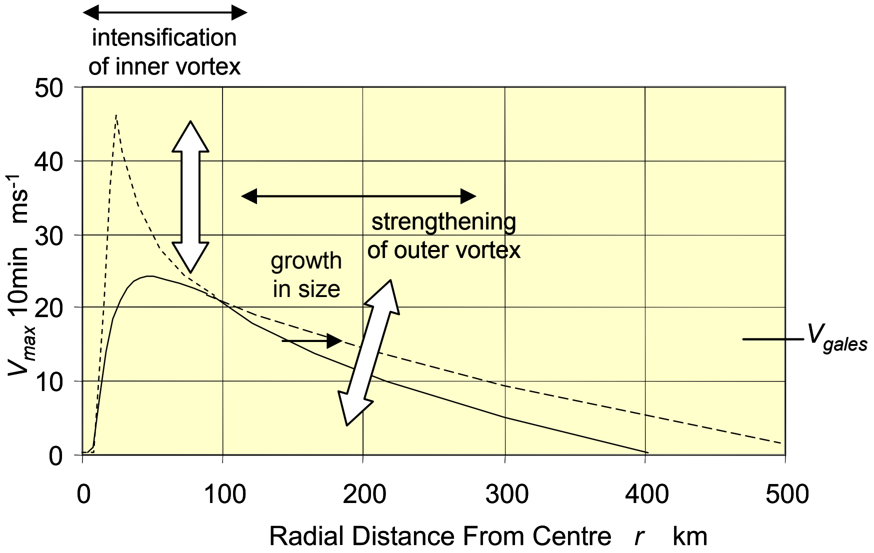


Figure 4.2 A simplified model of changes in tangential wind structure after Merrill (1984).

These simple classifications were used to stratify NWP and Atlantic data sets at the time to determine if any of these parameters exhibited useful correlations. It was found that correlations of sorts did seem to exist for broad categories of storms but, perhaps more critically, some parameters were not correlated. This approach began an important consideration of "inner" and "outer" vortex concepts. Weatherford and Gray (1988), for example, continued the investigation by specifically examining wind profiles between 1° - 2.5° from the centre (111 – 278 km) and found little correlation of this "outer-vortex" *strength* with the "inner-vortex" *intensity*. Meanwhile, a much more recent study by Croxford and Barnes (2002) considered the nearer 65 – 140 km region from the centre, which suggests a linear correlation between this "inner-vortex" *strength* and the "inner-vortex" *intensity*. Clearly the closer one examines to *R* the more likely that a correlation will emerge, but these studies emphasise the fact that there is a "region" where the "inner" and "outer" vortex influences tend to meet and/or overlap. Merrill (1984) explored this concept in terms of the angular momentum requirements of storms of different size and found significant differences based on *size* and also *intensity*.

Willoughby (1995) re-presents much of this earlier material within a more universal concept of dynamic structural changes, the role of "convective rings" and eye-wall replacement cycles. It is argued that any tropical cyclone may exhibit traits of *intensification*, growth in *size* or *strength* depending on the particular stage of its development. Unlike Merrill, the influence of *size* alone is discounted in this process to simply a proxy for lifecycle phase. Like Merrill though, it is acknowledged that *intensity* changes require much smaller angular momentum imports into the storm than changes in *strength* or *size*. This implies that the time-scale of *intensification* is therefore significantly less than that for the other changes and that this effect alone causes the apparent de-coupling of the *inner* and *outer* vortex domains. The convective ring phenomena then perhaps remains as the restabilising mechanism that acts to realign the inner and outer vortex modes.

Notwithstanding the individually complex situations occurring within any given storm at any given time, the present discussion is concerned with how best to describe that behaviour in such a way as to enable a reasonably accurate reconstruction of the storm's impacts. It would be of lesser value, for example, to *know* the complex behaviour without the means to *identify* it objectively and then *describe* it in a succinct and practical manner.

4.5 Use of the Holland B Parameter for the Inner-Vortex Balance

The apparent utility of the Holland (1980) analytical pressure and wind profile has been demonstrated earlier and its extensive use in successful hindcasting is well established elsewhere (albeit not necessarily in the open literature). However, by definition, the Holland model embodies no relationship between absolute scale (i.e. R) and the inner-vortex *intensity* (refer Equation 4). On the other hand it does provide a very useful function in encapsulating the basic cyclostrophic balance relationship whereby the local pressure gradient dp/dr dictates the local wind speed. This is well illustrated by the sequence of radial wind profiles in Figure 4.3 having an identical V_{max} (45 ms^{-1}) but, due to differing B parameters, significantly different p_c.[25] The simple concept of "peakedness" of the wind profile provides significant flexibility in this context although it should be noted that B also influences the shape of both the inner and outer profiles. It can be seen that very high B values force an annulus of complete calm in the eye; a feature similar to the C&S discussion.

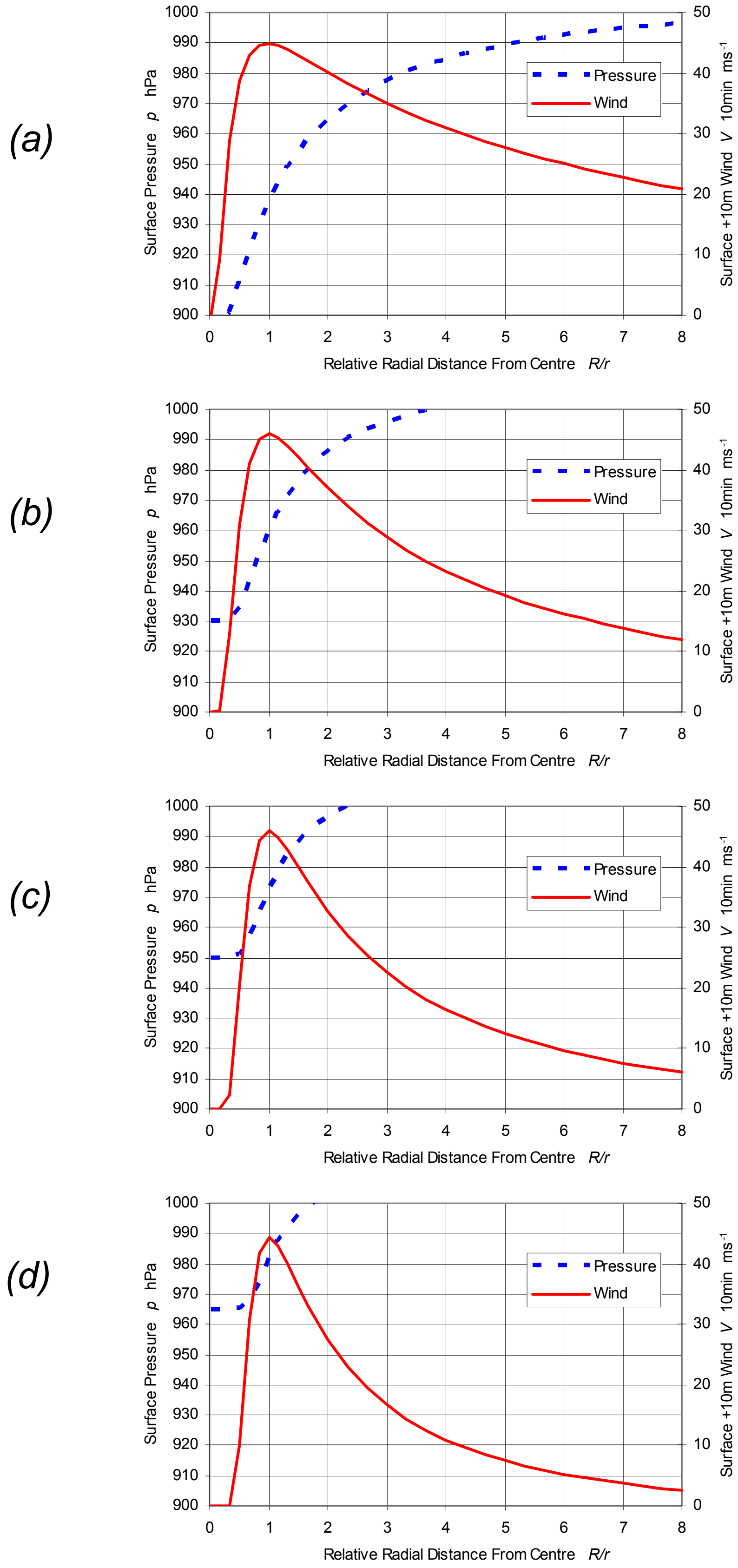
If a means could be found to identify storm "peakedness" through some intrinsic relationship between (say) deep convection and the intensification process, then the Holland model B seems well suited to being able to span the necessary dynamic range. The B parameter would then need to be calibrated against the intensification proxy with its midpoint established relative to a "universal" *mean* wind-pressure relationship proposed earlier. For example, Figure 4.4 illustrates the significant dynamic range offered by the B parameter in modulating V_{max} for any given p_c. The top graph compares a number of the relationships discussed thus far, while the lower graph shows some selected data[26] comparisons against nominal Holland B values of 1.0, 1.75 and 2.5. The Holland model B performance appears very promising in this overall context.

It is proposed that the Holland B parameter be adopted as a practical means of characterising the inner-vortex intensification state and local cyclostrophic balance. A satellite-derived peakedness proxy needs to be developed and verified to achieve this as an extension to the Dvorak assessment process, possibly using the existing "D", "S" and "W" development status. Such a technique would permit estimation of storm-relative wind-pressure pairings that naturally deviate away from a "universal" mean relationship on a temporal basis, and also be independent of absolute storm size.

---

[25] The Holland model V_{max} in this section is completed by assuming K_m=0.75 as per Appendix E, and ρ=1.15 kg m^{-3}.

[26] Refer Appendix C and Table C-1 for details of the data points shown, including storm-relative adjustments etc. For example Typhoon Rammasun, a recent storm of opportunity over Miyako-jima, shows the wind-pressure relationship can be extremely widely spread.



V_{max} = 45 m s^{-1}
p_n = 1010 hPa
K_m = 0.75
ρ = 1.15 kg m^{-3}

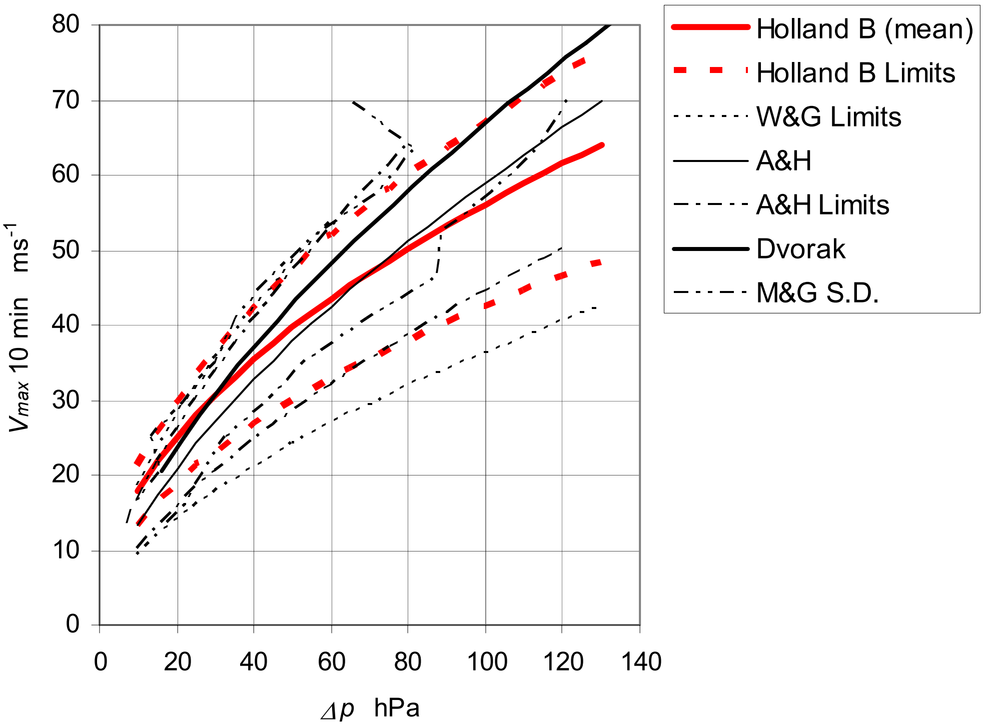
B = 1.0
p_c = 895 hPa
Δp = 115 hPa

B = 1.5
p_c = 930 hPa
Δp = 80 hPa

B = 2.0
p_c = 950 hPa
Δp = 60 hPa

B = 2.5
p_c = 965 hPa
Δp = 45 hPa

Figure 4.3 Example wind-pressure profiles using the Holland model.



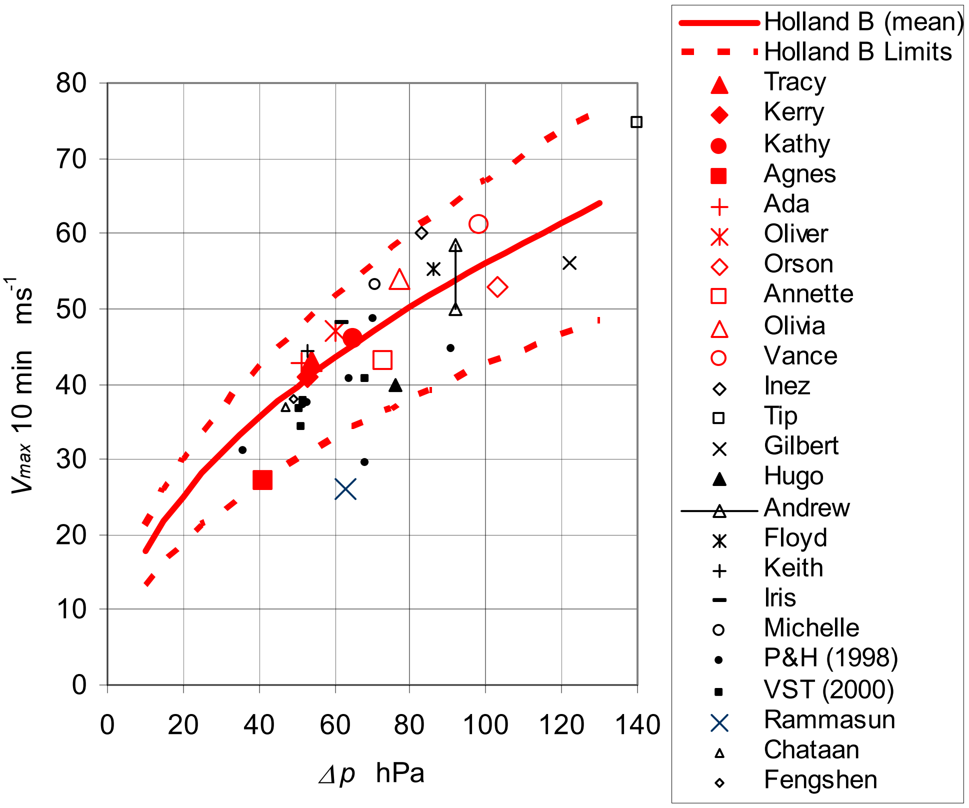


Figure 4.4 The Holland *B* parameter performance in wind-pressure space.

4.6 The Outer-Vortex Problem

An often reported drawback with the Holland model wind profile is its tendency for underprediction of winds at larger radii (say > 5*R*). Accordingly, a separate or non-continuous Holland model is desirable to simultaneously represent the (proposed decoupled) outer-vortex profile behaviour from the inner-vortex. There is a reasonable expectation that outer vortex parameters could be related empirically to R_{gales}, or R_{OCI} and that regional differences will emerge.

For example, Rupp and Lander (1996) combined a Holland inner-vortex model with a modified Rankine outer vortex ($V_g r^x = k$; $x = 0.50$) based on Weatherford and Gray (1988) composite data. The Rankine profile was merged with the Holland profile beyond 3*R*. A similar effect can be provided through the use of a composite Holland profile such as that proposed by Thompson and Cardone (1996) and utilised by McConochie *et al* (1999) . Here the normal Holland radial pressure profile is linearly combined with an additional outer vortex parameterised by $\Delta p_c'$, B' and with scale R'.

Aspects of the proposed piecewise approximation model by Willoughby (2002) may also be suitable in this regard. This profile is the culmination of work instigated by NOAA/HRD some 4 years ago, partly in response to discussions (Harper, Holland and Willoughby) regarding options for developing a practical successor to the Holland parametric model using the NOAA flight level dataset. The new Willoughby wind model is a piecewise continuous radial profile made up of separate inner and outer vortex formulations. The transition across the radius of maximum wind from the inner to outer profiles is accomplished with a smooth polynomial ramp function. The maximum wind region is claimed to be much sharper than that provided by the Holland profile and could well be preferable for use in the inner-vortex region. However, the use of a separate outer profile that overcomes the tendency of the Holland model to underpredict at large radii is of special interest in this context. Details of the method are still to be published, together with parameter statistics based on the Atlantic dataset.

It is proposed that a separate Holland-like model be utilised to represent the outer-vortex profile, scaled against the (normally) readily determinable estimate of R_{gales}*. Merging with the inner-vortex profile will be required at some nominal relative storm radius. A minimum of one or two parameters will be required to complete this description of the outer profile. A statistical approach may be beneficial to examine and make use of broader scale (e.g. latitudinal) and other regional trends.*

4.7 Towards a Universal Method that also Considers Size

There are only two separately "verified" technical choices as to how to apply the Dvorak method for determining estimates of p_c from V_{max} – either the NWP or the Atlantic method. In the Australian context the NWP approach has dominated the Queensland and Western Australian approaches. While this original choice may have been based on a crude geographical and climatological affinity, it has clearly been supported by ongoing experience, feedback and the like amongst the professional meteorological community. However, the Northern Territory experience in particular has led to a shift towards what is probably more like the Atlantic method[27].

The wind-pressure relationships discussed thus far have been based on the *mean* location of many hundreds of separate wind-pressure pairings, very few of which can be regarded as fully objective,

---

[27] Notwithstanding the L&M relationship is theoretically "more severe" than the Dvorak (1984) Atlantic relationship, the practical application has been limited by storm opportunity to the extent that the Northern Territory archive over the past 20 y possibly resembles the Atlantic approach.

accurate or independent[28]. It is clear that there is a continuum of possible wind-pressure pairings across a broad parameter space and that individual storms will exhibit a particular developmental path and this results in the large degree of scatter found in the many observational studies. Therefore, the evidence for claiming that these preferred mean relationships for the separate basins are different is assessed here as rather weak when considering the potential for bias in the historical record and the history of development of the technique. This is not to say that there are not preferred means, but that the present data is not sufficiently reliable to justify the present choices.

These two approaches have been (loosely) supported by the apparent mean difference in scale of the NWP and Atlantic storm systems as, for example, illustrated by Merrill (1984). While size differences are certainly consistent in principle with the dynamical concepts of gradient balance, the present review suggests that the actual derivation of the two empirical methods is not sufficiently pure to be beyond reproach. It is further argued that some of the significant scatter in many wind-pressure datasets might be further reduced by the simple matter of converting the individual storm data pairings to Δp. Also, some of the earliest reported aircraft reconnaissance studies that predate the uptake of the Dvorak method, such as Colón (1963), highlight the wide variability in storm characteristics observed within a single basin – the Atlantic. It is proposed therefore that the inherent scatter in wind-pressure pairings is *much greater* than the difference in the likely true *mean* values on a regional basis.

In a seemingly separate development, there is general agreement that "small" storms, typically characterised by short lives, rapid development and decay, seem to consistently display characteristics of "high" wind speeds and relatively "high" central pressures (low Δp) which we now associate with "peakedness" of the inner-vortex profiles. One of the most recent studies to consider variability in storm size (Cocks and Gray 2002), shows a very clear relationship between size and central pressure in the NWP. The rapid development of small storms appears to be related to the low angular momentum requirement and thus their short inertial response. However, there is also evidence of the inner-vortex of "large" storms showing similar behaviour during intensification cycles and/or with the succession of *convective rings*.

It is then hypothesised that there is a natural scale at which a storm begins to act more as a "large" rather than a "small" storm and then is less likely to consistently display a "peaked" wind profile. This scale could arguably extend to what is typically regarded as the inner-vortex region of a "medium" sized storm. Hence, decoupling of the inner and outer vortex strengths can lead to "small" storms within "large" outer circulations at various stages of development.

Assuming the maximum mean surface wind in the inner-vortex responds in cyclostrophic balance to the developing surface pressure differential, the shape of the radial pressure profile within an individual storm inner-vortex directly determines the local maximum sustained wind speed. For simplicity, this feature is referred to as the "peakedness" of the wind profile. It is then proposed that the peakedness of profiles can be specifically related to the observed *rate of intensification*, which can often be assessed from the degree of deep convection seen on satellite imagery. In short, it may be useful to describe "small" storms as tending towards a constant state of intensification, as opposed to "large" storms which, given favourable conditions, will typically reach an initial steady-state, followed by possible bursts of intensification and periods of strengthening. On this basis, "small" storms might be reliably classified as "peaked", while "large" storms may exhibit a wider range of variability depending on their stage of development, which is facilitated by their generally longer life cycle.

---

[28] Ideally, the "best fit" mean line should also be based on the slope trend of each storm's development cycle.

4.8 An Example Storm

By way of example of how the *B* parameter could be tracked usefully in time and wind-pressure space, HRD HWIND data for hurricane *Michelle* (October 2001) is presented in Figure 4.5 and Figure 4.6 respectively. The track of *Michelle* is shown in Appendix C; the HRD data commencing around 0000 01-Oct-2001 (day 0 here) after the embryonic storm moved northwards off the coast of Nicaragua and into the Caribbean Sea. It should be noted that the V_{max} presented here are not storm-relative and so the forward speed V_{fm} is also considered to assist interpretation. Dvorak *CI* data is taken from the ATCF fix file and sometimes consists of more than one value per timestamp because of estimates being obtained from different forecast agencies (SAB, TAFB, KGWC etc).

Figure 4.5 shows the time history development of the storm in terms of V_{max} and Δp, Dvorak *CI*, *B* and V_{fm}, and various scale changes (R, R_{hurr}, R_{storm}, R_{gales}, R_{OCI})[29]. The storm moved slowly northwards and gradually deepened over the first 3 days, accompanied by increases in *strength* as noted by the increasing scale radii of R_{storm} and R_{gales} but with little change in *R*. During the third day there is a significant change in *B* reflecting an intensification of V_{max} relative to Δp. This then relaxes over the next 12 h but is followed by two further intensification pulses over the next 24 h in spite of the falling pressure deficit, just before the storm eye suffers disruption by crossing Cuba and is accelerated to the north-east. The NHC official report on *Michelle* remarks that "*A notable aspect of Michelle was that the aircraft-reported winds and pressures appeared to be somewhat out of phase*." During the period of pulsed *intensification* though there are also clear reciprocal increases in *strength*, while *R* remains reasonably constant until the filling phase begins. The inner and outer vortex behaviours therefore exhibit some of the characteristics previously discussed.

Figure 4.6 concentrates on the wind-pressure context, plotting the evolution of the storm using V_{max} and Δp. The top panel shows the complete time sequence with the recommended Holland *B* limits of 1.0 and 2.5 and the Dvorak and A&H relationships. *Michelle* can be seen to start by following the A&H curve reasonably closely for 2 days, then dipping below it just before the period of initial intensification. It then crosses the A&H line over the next 12 h and sits just above the Dvorak line, before dropping back below A&H at times during the period of pulsing. In the final intensification pulse it just exceeds the Holland 2.5 limit before dropping back below A&H once again. In the filling stage it still manages to move back towards the Holland 2.5 limit but this is reflective of the high V_{fm} and not the true vortex-balanced winds. A line of best fit through the complete HRD sequence is also shown. The bottom panel considers the deepening and filling legs of the event separately, showing the possible differences in best fit curves as a result.

It is proposed that there is scientific merit in routine tracking of the *B* parameter and in retaining wind-pressure best fit trends in this manner as opposed to continued use of regional mean wind pressure relationships. In this case, *Michelle* exhibits a range of behaviour, which during deepening is closest to A&H but at other times is similar to Dvorak. The overall limits of its behaviour can be seen to be well described by the Holland *B* limits, even without allowance for forward speed.

The challenge remains to determine a forecast method that might detect these intensification cycles and so provide a basis for modulating *B*. Ongoing detailed analysis of the most objective data available (e.g. US reconnaissance data) combined with detailed Dvorak *CI* reassessments will assist in developing theoretical structural and/or statistical descriptions of this behaviour, which could be transferable to other locations and basins.

---

[29] The scale radii here are taken directly from the HRD data and so represent radii to the relevant 1 minute wind rather than the 10 minute wind.

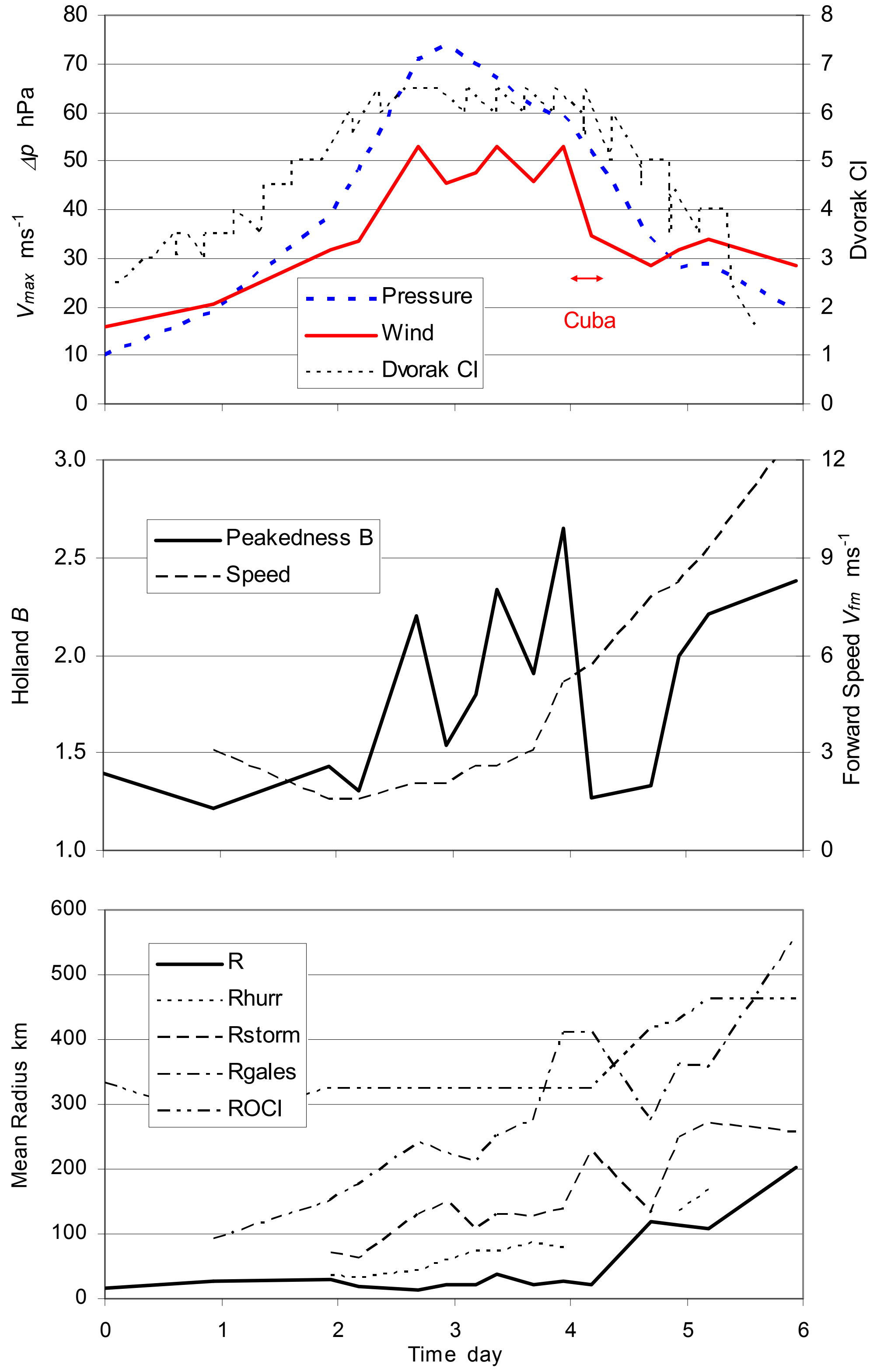


Figure 4.5 Time development of Hurricane *Michelle*, October 2001.

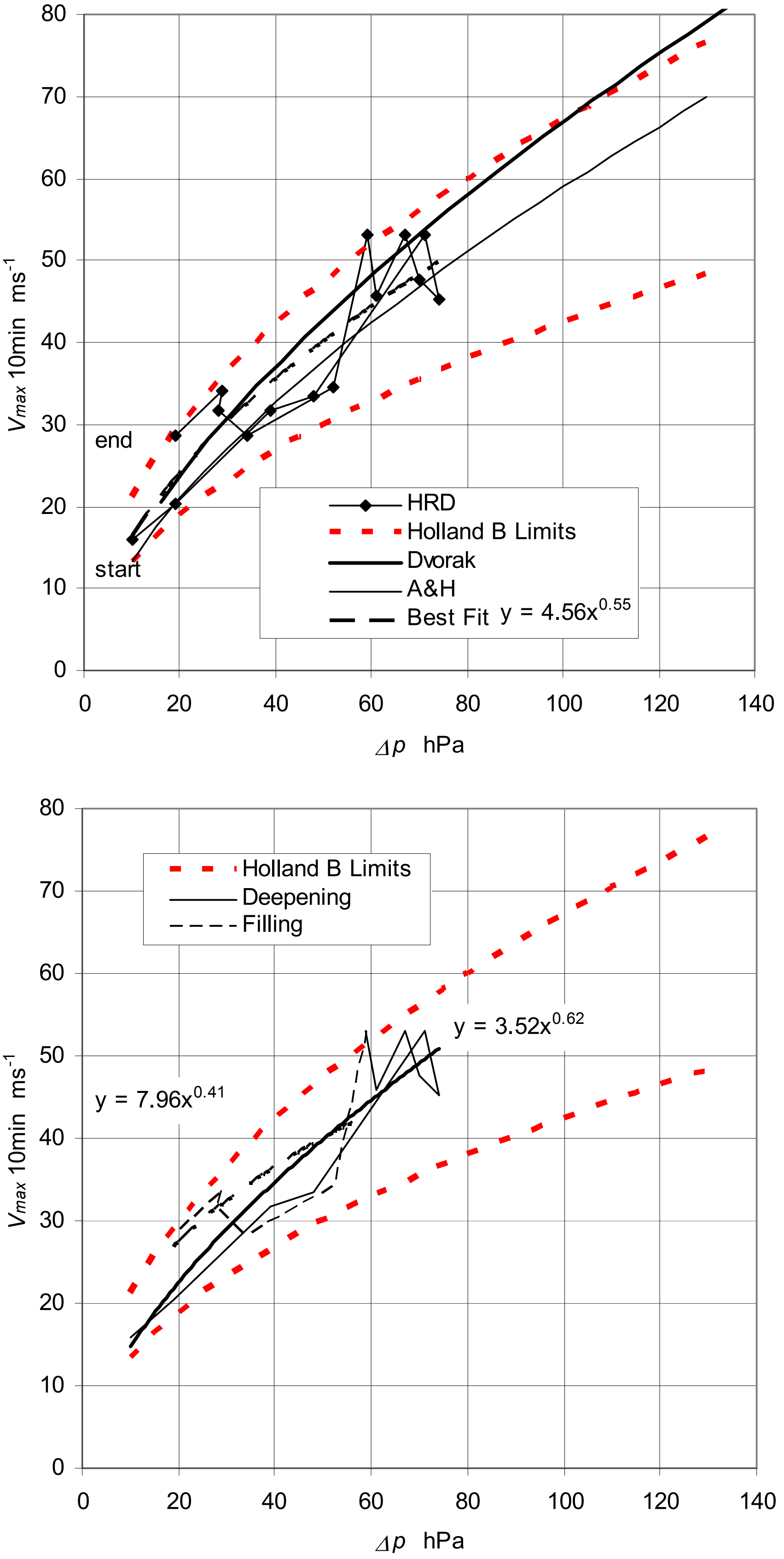


Figure 4.6 Wind-pressure development of Hurricane *Michelle*, October 2001.

4.9 Concluding Discussion

It has been demonstrated that, over time, it is likely that standardised practices by regional forecasting agencies may have contributed to much of the continuing scatter evident in measured wind-pressure datasets and that some of these practices probably have resulted in significant biases being programmed into best track datasets. In spite of more objective data becoming available these practices may be continuing.

The simple matter of accounting for the ambient pressure p_n in wind-pressure comparisons would reduce scatter and eliminate the need for artificial (nominal) regional reference pressures. The extent to which the ambient pressure is universally ignored by operational agencies is evidenced by it rarely being recorded at all. For example, it does not appear in official Atlantic or NWP or indeed Australian “best track” files and is not an included parameter in the recommended WMO standard format. While the variability in this parameter is small relative to the central pressure, it could readily be retained, thus providing a better basis for exploring the underlying broad scale wind-pressure balance.

Some allowance for forward speed asymmetry is also *essential* for reducing scatter observed in wind-pressure datasets. With no adjustment, regional datasets of $V_{max} - p_c$ will simply remain contaminated by regional speed differences and provide biased estimates of the storm-relative winds. This bias will typically be of the order of 10 to 15%, given that the majority of peak winds are thought to be found in the poleward forward quadrant of a moving storm.

It is also appropriate that the various time and space scales affecting the observations of surface winds be explicitly considered when developing any new technique. Not only should the storm-relative wind be considered but there should be allowance for convectively-driven local wind components. The statistical nature of the latter should be considered, for example, when compiling “best track” archives, where it may be a significant contributor to bias. The practice of consistently rounding-up wind estimates using a nominal increment should be discontinued in favour of a statistical sampling approach that aims to be unbiased. Undoubtedly some of these subjective decisions about the accuracy of individual measurements and instruments are made routinely by experienced forecasters; however a lack of transparency in this regard will not serve the best interests of the *science*. As previously mentioned, the fixed “5 kt rounding-up” practice introduces a consistent 2 to 6% bias in V_{max}.

Other areas which are equally deserving of treatment include re-examination of some specific Dvorak rules (e.g. S. West, *personal communication*; Brown and Franklin 2002), wind gust factors and boundary layer shape. This latter subject is emerging as probably the most important issue needing to be addressed. The possibility of significant spatial variability (radially and azimuthally) in the gradient-to-surface boundary layer reduction factor emerging from the latest numerical modelling (e.g. Kepert and Wang 2000) needs to be merged with the now extensive database of dropwindsonde measurements (e.g. Franklin *et al* 2000) to determine the extent of variance which might now be explained by such features alone (refer Appendix E also). This factor could result in the need for a major review of previous surface wind estimates estimated from flight level data.

The foregoing arguments neglect many other important aspects of the tropical cyclone problem and represent a gross simplification of complex processes. However, they would seem to provide a more expansive basis upon which to further develop the Dvorak technique and ensure that its application results in increased accuracy.

5 Recommendations

In the absence of objectively measured data and notwithstanding the increasing value of advanced numerical modelling, the Dvorak technique remains the essential and principal Australian tool for forecasting and classifying the intensity of tropical cyclones. Its continued development and improvement to take advantage of emerging satellite technologies (e.g. SSM/I, TRMM, AMSU) should be regarded as a national priority for Australia.

This review has traced the implementation of the Dvorak technique over the past 30 y, together with its application in Australia. The accuracy of some of the early empirical relationships has been questioned relative to later and most recent experience. Evidence of possible bias has been found in some of the “best track" datasets that have been used to underpin its verification and that these biases may have become entrenched into the so-called regional wind-pressure relationships for the NWP and Atlantic. As a result, it is questioned whether there is sufficient scientific basis to continue to recognise these specific regional differences or if a more universal approach should not be adopted for Australian use that additionally recognises other important storm characteristics. The review also casts doubt on the use of the so-called Northern Region wind-pressure relationship, which has been in use by the Bureau of Meteorology since the mid 1980s for classifying Timor Sea and other storms in northern Australia.

The specific role of absolute storm scale on the wind-pressure issue has also been examined. It is clear that individual storms will exhibit differences in wind-pressure balance (termed “peakedness” here) due to many separate influences throughout their life. However, since most of the pressure drop occurs within the inner-vortex, this wind-pressure variability appears to be largely explained by the rate of intensification near the storm centre. For “small” storms, typically with low angular momentum and short inertial timescales, reaction to intensification (or decay) is rapid and it is hypothesised that such storms are usefully described as being in a “constant state of intensification”.

There is also evidence that “large” storms, with very high angular momentum and large inertial timescales, can experience a decoupling of the inner and outer storm vortex strengths during periods of inner-vortex intensification. An objective method that can classify storms as “small” might also then be used to objectively identify “peakedness”. For “large” storms the problem is more complicated but “peakedness” may be possibly assigned to the rate of intensification as indicated by deep convection. If a suitable dynamic model can be proposed then there is much available data that could be used to calibrate a more universal analytical approach to the wind-pressure problem.

Notwithstanding the above, by itself, the Dvorak technique of assigning a single V_{max} and p_c is not sufficient to fully describe the characteristics of tropical cyclones to the extent that their effects can be accurately specified and hindcast over wide spatial domains. Information on storm scale of both the inner and outer storm vortex domains is essential for being able to reconstruct representative radial wind and pressure profiles. The accuracy of the outer wind profile is of critical importance for the hindcasting of ocean waves, storm surge and currents.

A simplified operational model of tropical cyclone structure and behaviour that can be routinely applied to forecasting and hindcasting would provide significant benefits for both the meteorological and engineering communities. Such a model would provide a method of documentation of each storm event at a level that far exceeds the value of a simple data archive. It should include allowance for storm motion and convective wind components.

The following recommendations are offered in the operational Australian context:

- The magnitude of V_{max} in the Dvorak $CI - V_{max}$ base relationship be viewed in the context of it being an "upper envelope" condition, probably a peak gust and almost certainly embodying storm motion and local convective wind components;

- All wind-pressure relationships be expressed in terms of Δp and that analytical formula be used operationally in preference to tabulations;

- The Holland model B parameter be considered for describing and parameterising the variability of inner-vortex wind-pressure balance as a replacement for the present A&H and Dvorak regional *mean* wind-pressure relationships;

- The Dvorak method be extended or adapted to identify intensification cycles so that the Holland B parameter may be estimated objectively for storms regardless of absolute size;

- That an absolute storm scale related to R_{gales} be proposed to classify "small" tropical cyclones, leading to a preferred "peaked" wind-pressure regime based on the Holland B;

- The Holland radial wind and pressure profile model be adopted to describe the inner-vortex shape ($0 < R/r < 3$);

- That an outer-vortex wind profile model be adopted ($R/r \geq 3$), spatially scaled by R_{gales}, to merge with the intensity scaling from an inner-vortex model, so that a complete wind and pressure field approximation can be constructed;

- To provide consistency in application, a composite radial wind and pressure field model be developed for operational use in forecasting and classifying tropical cyclones that will satisfy the above requirements and incorporate basic storm geometry such as forward motion asymmetry and inflow angles;

- Post-analysis "best track" determinations should ideally be undertaken independently from the responsible forecast entity and/or be subject to routine analyst peer review to ensure objectivity and the retention of all relevant information for the scientific record;

- That the national data archive be expanded to include the Dvorak T and CI numbers, and to incorporate all other necessary model parameters (e.g. B, p_n, R, R_{gales} etc);

- That, failing further development and in the absence of any better method, the Dvorak Atlantic relationship be used for demonstrably "small and intense" storms but that the A&H NWP relationship be used in all other situations to provide a consistency in application;

- That the effects of applying the so-called Northern Region wind-pressure relationship to storms in the Timor Sea, Arafura Sea and Gulf of Carpentaria national archive be examined.

Feedback and comment on this document and its conclusions and recommendations is invited and would be appreciated.

6 References

API 1993: Recommended practice for planning, designing and constructing fixed offshore platforms – load and resistance factor design. *American Petroleum Institute*, ANSI/API RP2A-LRFD-93.

Atkinson, G.D. and Holliday, C.R., 1975: Tropical cyclone minimum sea level pressure – maximum sustained wind relationship for western North Pacific. FLEWEACEN Tech. Note: JTWC 75-1, US Fleet Weather Central, Guam, 20pp.

Atkinson, G.D., and Holliday, C.R., 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the Western North Pacific. *Mon. Wea. Rev.,* 105, 421-427.

Black, M.L. and Willoughby, H.E., 1992: The concentric eyewall cycle of hurricane Gilbert. *Mon. Wea. Rev.,* 120, 6, 947–957.

Black, P.G., 1993: Evolution of maximum wind estimates in typhoons. Proc ICSU/WMO Int. Sym. on Tropical Cyclone Disasters, Beijing, China. International Council of Scientific Unions, 104-115.

Black, P.G. and Holland, G.J., 1995: The boundary layer of tropical cyclone Kerry. *Mon. Wea. Rev.,* 123, 2007-2028, July.

Black, P.G. and Marks, F.D., 1991: The structure of an eyewall meso-vortex in Hurricane Hugo (1989). 19th Conf. on Hurr. and Trop. Meteor., AMS, May 6-10, Miami, FL, 579-582.

BoM, 1970: Report by Director of Meteorology on cyclone *Ada*. June, 38pp.

BoM, 1977: Report on cyclone *Tracy* December 1974. AGPS, Canberra, 82pp.

BoM, 1978: Australian tropical cyclone forecasting manual. Preliminary edition, *Bureau of Meteorology*, Melbourne.

BoM, 1979: Cyclone *Joan* December 1975. Bureau of Meteorology, July, 40pp.

BoM, 1992: Report on cyclone *Orson* April 1989. Bureau of Meteorology, June, 39pp.

BoM, 1999: Report on tropical cyclone system review conference and user's forum. *Bureau of Meteorology*, Darwin, 11-13 August (unpublished).

BoM, 2000: Severe tropical cyclone *Vance* 16 March 1999 – 23 March 1999. Commonwealth of Australia, March 2000, 13pp.

Bouchard, R.J., 1990: A climatology of very intense typhoons or: where have all the super typhoons gone? In: Joint Typhoon Warning Center Annual Tropical Cyclone Report, 266-271.

Brown, D.P. and Franklin, J.L. 2002: Accuracy of pressure-wind relationships and Dvorak satellite intensity estimates for tropical cyclones determined from recent reconnaissance-based "best track" data. *Proc. 25th Conf Hurricanes and Tropical Meteorology*, AMS, San Diego, 458-459.

Callaghan, J. and Smith, R.K., 1998: The relationship between surface wind speeds and central pressure in tropical cyclones. *Aust Meteorological Magazine,* 47, 191-202.

Cocks, S.B. and Gray, W.M., 2002: Variability of the outer wind profiles of Western North Pacific typhoons: classification and techniques for analysis and forecasting. *Monthly Weather Review*, 130, Aug, 1989-2005.

Cole, E.K., 1977: Winds of fury, *Rigby*.

Colón, J.A., 1963: On the evolution of the wind field during the life cycle of tropical cyclones. NHRP Res. Rep. No. 65, US Weather Bureau, US Dept Commerce.

Crane, G., 1985: Unpublished. *Bureau of Meteorology*, Queensland Regional Office, Brisbane.

Croxford, M. and Barnes, G.M., 2002: Inner core strength of Atlantic tropical cyclones. *Monthly Weather Review*, 130, Jan, 127-139.

Dunion, J.P. and Powell, M.D., 2002: Improvements to the NOAA Hurricane Research Division's surface reduction algorithm for inner core aircraft flight level winds. *Proc. 25th Conf Hurricanes and Tropical Meteorology*, AMS, San Diego, 581-582.

Dunnavan, G.M. and Diercks, J.W., 1980: An analysis of super typhoon *Tip*. *Mon. Wea. Rev.,* 108, 1915-1923, Nov.

Dvorak, V.F., 1972: A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures*. NOAA Technical Memorandum, NESS 36,* June, 15pp.

Dvorak, V.F., 1973: A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures*. NOAA Technical Memorandum, NESS 45,* Feb, 19pp, (Revision of NOAA TM NESS 36).

Dvorak, V.F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.,* 103, 420-430.

Dvorak, V.F., 1982: Tropical cyclone intensity analysis and forecasting from satellite visible or enhanced infrared imagery. *NOAA National Earth Satellite Service,* Applications Laboratory Training Notes, May, 42pp.

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data*. NOAA Technical Report NESDIS 11,* 45pp.

Dvorak, V.F. and Smigielski, F. 1990: Tropical clouds and cloud systems observed in satellite imagery*. NOAA Technical Report NESDIS.* (updated to 1995)

Erickson, C.O., 1972: Evaluation of a technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures. *NOAA Technical Memorandum,* NESS 42, Sept, 28pp.

Franklin, J.L., Black, M.L. and Valde, K., 2000: Eyewall wind profiles in hurricanes determined by GPS dropwindsondes, *Proc. 24th Conf Hurricanes and Tropical Meteorology*, AMS, Fort Lauderdale, 448-449. See also http://www.nhc.noaa.gov/aboutwindprofile.html

Franklin, J.L., Black, M.L. and Valde, K., (to appear): GPS dropwindsonde wind profiles in hurricanes and their operational implications. Submitted to *Weather and Forecasting*, May, 2002.

Gaby, D.C., Lushine, J.B., Mayfield, B.M., Pearce, S.C. and Torres, F.E., 1980: Satellite classifications of Atlantic tropical and subtropical cyclones: a review of 8 years of classification at Miami. *Mon. Wea. Rev.*, 108, 5, 587-595.

Gray, W.M., Neumann, C. and Tsui, T.L., 1991: Assessment of the role of aircraft reconnaissance on tropical cyclone analysis and forecasting. *Bulletin of American Meteorological Society*, 72, 12 , 1867-1883.

Guard, C.P., 1998: *Personal Communication*. University of Guam.

Guard, C.P. and Lander M.A., 1996: A wind-pressure relationship for midget TCs in the Western North Pacific. In: 1996 Annual Tropical Cyclone Report, *Naval Pacific Meteorology and Oceanography Centre / Joint Typhoon Center*, Section 7.9, p 311.

Guard, C.P. and Lander M.A., 1999: A scale relating tropical cyclone wind speed to potential damage for the tropical Pacific Ocean region: a user’s manual. WERI Tech Rep No. 86, *University of Guam*, May, 60pp.

Harper, B.A., Lovell, K.F., Chandler, B.D. and Todd D J, 1989: The derivation of environmental design criteria for Goodwyn 'A' platform, *Proc. 9th Aust Conf. Coastal and Ocean Engin.*, Institution of Engineers Australia, Adelaide, Dec.

Harper, B.A., Mason, L.B. and Bode, L., 1993: , Tropical cyclone *Orson* - a severe test for modelling, *Proc. 11th Australian Conf. on Coastal and Ocean Engin.*, Institution of Engineers Australia, Townsville, Aug, 59-64.

Harper B.A., 1998: Parametric wind fields, In: Topic Chairman and Rapporteur Reports of the Fourth International Workshop on Tropical Cyclones, *World Meteorological Organisation*, Tropical Meteorology Research Program (TMRP) and Commission for Atmospheric Sciences (CAS), Report No. 59, Haikou, China, April 21-30, WMO/TD No. 875.

Harper B.A., 1999: Numerical modelling of extreme tropical cyclone winds. APSWE Special Edition, *J. Wind Engineering and Industrial Aerodynamics*, 83, 35 - 47.

Harper, B.A. and Holland, G.J. 1999: An updated parametric model of the tropical cyclone. Proc. 23rd Conf. Hurricanes and Tropical Meteorology, *American Meteorological Society*, Dallas, Texas, 10-15 Jan.

Harper B A (ed.), 2001: Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - stage 1, Report prep by Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, *Queensland Government*, March, 375pp.

Hawkins, H.F. and Imbembo, S.M., 1976: The structure of a small, intense hurricane – *Inez* 1966. *Mon. Wea. Rev.*, 104, 4, 418-442.

Hock, T.F. and Franklin, J.L., 1999: The NCAR GPS dropwindsonde. *Bulletin of the American Meteorological Society*, 80, 3, 407–420.

Holland, G.J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.,* 108, 1212-1218.

Holland, G.J., 1981: On the quality of the Australian tropical cyclone data base. *Aust. Met. Mag., 29*, 169-181.

Ishizaki, H., 1983: Wind profiles, turbulence intensities and gust factors for design in typhoon-prone regions. *J. Wind Engin. and Indust. Aerodynamics*, 13, 55-66.

ISO 1996: Proposed ISO code, preliminary draft. In: Petroleum and natural gas industries — specific requirements for offshore structures — Part 1: Metocean design and operating conditions, Annex A.6. ISO TC 67/SC 7 N 277A.

Kepert, J. 2001: The dynamics of boundary layer jets within the tropical cyclone core - part I: linear theory. *Jnl Atmospheric Sciences*, 58, Sept, 2469-2484.

Kepert, J. 2002a: The impact of landfall on tropical cyclone boundary layer winds. *Proc. 25th Conf Hurricanes and Tropical Meteorology*, AMS, San Diego, 335-336.

Kepert, J. 2002b: An analysis of some tropical cyclone boundary layer wind observations. Proc. 25th Conf Hurricanes and Tropical Meteorology, AMS, San Diego, 615-616.

Kepert, J. and Wang Y. 2001: The dynamics of boundary layer jets within the tropical cyclone core - Part II: nonlinear enhancement. *Jnl Atmospheric Sciences*, 58, Sept, 2485-2501.

Kidder, S.Q., Goldberg, M.D., Zehr, R.M., DeMaria, M., Purdom, J.F.W., Velden, C.S., Grody, N.C. and Kusselson, S.J., 2000: Satellite analysis of tropical cyclones using the Advanced Microwave Sounding Unit (AMSU). *Bulletin of the American Meteorological Society*, 81, 6, 1241–1260.

Knaff, J.A., Kossin J.P. and De Maria, M. 2002: What are annular hurricanes? *Proc. 25th Conf Hurricanes and Tropical Meteorology*, AMS, San Diego, 609-611.

Kraft, R.H., 1961: The hurricane's central pressure and highest wind. *Mariners Weather Log*, 5,155.

Landsea, C.W., Anderson, C., Charles, N., Clark, G., Fernandez-Partagas, J., Hungerford, P., Neumann, C. and Zimmer, M. 2000: The Atlantic hurricane database re-analysis project documentation for 1851-85 addition to the HURDAT database. *http://www.aoml.noaa.gov/hrd/hurdat/Documentation.html*.

Love, G. and Murphy, K. 1985: The operational analysis of tropical cyclone wind fields in the Australian northern region. *Bureau of Meteorology,* Northern Territory Region, Research Papers 1984-85, Nov, 44-51.

Lubeck, O.M. and Shewchuk J.D., 1980: Tropical cyclone minimum sea level pressure maximum sustained wind relationship. NOCC/JTWC 80-1, USNOCC, JTWC.

McConochie, J.D., Mason, L.B. and Hardy, T.A., 1999: A Coral Sea cyclone wind model intended for wave modelling. *Proc. 14th Conf. Coastal and Ocean Engineering, IEAust*, Perth, April, 413-418.

McKnown, R. *et al* , 1952: Fifth annual report of the typhoon post analysis board. Anderson AFB, Guam M.I.

Martin, J.D. and Gray, W.M., 1993: Tropical cyclone observation and forecasting with and without aircraft reconnaissance. *Weather and Forecasting*, 8, 4 , 519-532.

Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.,* 112, 1408-1418

Murphy, K. 1985: Cyclone *Kathy* at landfall. *Bureau of Meteorology,* Northern Territory Region, Research Papers 1984-85, Nov, 52-60.

Myers, V.A., 1954: Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. *U.S. Weather Bureau*, Hydrometeor. Rept. No. 32, March 1954.

Myers, V.A. 1957: *Bulletin of American Meteorological Society*, 38, 227-228.

Neumann, C.J. 2001: The Atlantic HURISK model: adaptation to other tropical cyclone basins. *Proc. 24th Conf Hurricanes and Tropical Meteorology*, AMS, 549-550.

NHC 2002: Hurricane Andrew Reanalysis - Minutes of the best-track change committee meeting, 08 August 2002. http://www.aoml.noaa.gov/hrd/hurdat/HurricaneAndrewReanalysis.html

Powell, M.D., 1980: Evaluations of diagnostic marine boundary-layer models applied to hurricanes. *Mon. Wea. Rev.,* 108, 757-766.

Powell, M.D., 1982: The transition of the hurricane Frederic boundary-layer wind field from the open Gulf of Mexico to landfall. *Monthly Weather Review*, 110, 12, 1912–1932.

Powell, M.D. and Black P.G. 1989: The relationship of hurricane flight level wind measurements to winds measured by NOAA’s oceanic platforms. *Proc. 6th US Nat. Conf. on Wind Engin*., March.

Powell, M.D., Dodge, P.P. and Black, M.L., 1991: The landfall of hurricane Hugo in the Carolinas: surface wind distribution. *Weather and Forecasting*: 6, 3, 379–399.

Powell, M.D., Houston, S.H. and Reinhold, T.A., 1996: Hurricane Andrew’s landfall in South Florida. Part I: Standardizing measurements for determination of surface wind fields. *Weather and Forecasting*, 11, 3, Sept, 304-328.

Powell, M.D. and Houston, S.H., 1996: Hurricane Andrew's landfall in South Florida. Part II: Surface wind fields and potential real-time applications. *Weather and Forecasting*, 11, 3, Sept, 329-349.

Powell, M.D. and Houston, S.H., 1998: Surface wind fields of 1995 hurricanes Erin, Opal, Luis, Marilyn, and Roxanne at landfall**.** *Monthly Weather Review*, 126, 5, 1259–1273.

Reardon, G. and Meecham, D., 1993: U.S. Hurricanes of 1992 - An Australian perspective. *Proc. Symp. Hurricanes of 1992*, ASCE, Miami, Dec, ISBN 0-7844-0046-6, 642-651.

Reardon, G. F., Henderson, D. and Ginger, J., 1999: A structural assessment of the effects of cyclone Vance on houses in Exmouth WA. *Cyclone Structural Testing Station*, Tech Rep 48, James Cook University, Townsville, July, 65pp.

Rupp, J.A. and Lander, M.A., 1996: A technique for estimating recurrence intervals of tropical cyclone-related high winds in the tropics: results for Guam. *J. Appl Meteorology*, May.

Schloemer, R.W., 1954: Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida. *Hydromet. Rep.,* 31, Dept of Commerce, Washington D.C., March, 1954, 49pp.

Shea, D.J. and Gray, W.M., 1973: The hurricane's inner core region. I. Symmetric and asymmetric structure. *J. Atmospheric Sciences*, 30, 8, 1544–1564.

Sheets, R.C. and Grieman, P.G., 1975: An evaluation of the accuracy of tropical cyclone intensities and locations determined from satellite pictures. *NOAA Technical Memorandum,* ERL WMPO-20, 36pp.

Shewchuk, J.D. and Weir, R.C., 1980: An evaluation of the Dvorak technique for estimating tropical cyclone intensity from satellite imagery. *NOCC/JTWC 80-2*, USNOCC, JTWC, 25pp.

Simpson, R.H. (attributed) 1974: The hurricane disaster potential scale. *Weatherwise,* 27, pp 169 and 186.

Spillane, K.T. and Dexter, P.E., 1976: Design waves and wind in the Australian tropics. *Aust Met Mag*, 24, 37-48.

Standards Australia, 1989: SAA loading code, part 2 wind loads. *Standards Australia*, AS1170.2 – 1989.

Subbaramayya, I. and Fujiwhara, S., 1979: A note on the relationship between maximum surface wind and central pressure in tropical cyclones in western north pacific. *J. Meteor. Soc. Japan*, 57, 4, 358-360.

Takahashi, K., 1939: Distribution of pressure and wind in a typhoon. *J. Meteor. Soc. Japan*, Ser. 2, 17, 417-421.

Thompson, E.F. and V.J. Cardone, 1996: Practical modelling of hurricane surface wind fields. *J. Waterways, Port, Coastal and Ocean Engineering*, ASCE, 122, 4, 195-205.

Trollope, D.H. (Ed), 1972: Cyclone Althea - Part 2: Effects on buildings*, James Cook University*, Townsville.

Velden, C.S., Olander, T.L. and Zehr, R., 1998: Development of an objective scheme to estimate tropical cyclone intensity from digital geostationary satellite infrared imagery. *Weather and Forecasting*, 13, Mar, 172-186.

Vickery P.J., Skerlj P.F., Steckley A.C and Twisdale L.A., 2000a: Hurricane wind field model for use in hurricane simulations. *J. Structural Engineering*, ASCE, 126,10, Oct, 1203-1221.

Vickery P.J., Skerlj P.F. and Twisdale L.A., 2000b: Simulation of hurricane risk in the U.S. using empirical track model. *J. Structural Engineering*, ASCE, 126,10, Oct, 1222-1237.

Weatherford, C.L. and Gray, W.M., 1988a: Typhoon structure as revealed by aircraft reconnaissance. Part I: data analysis and climatology. *Mon. Wea. Rev.*, 116, 1032-1043.

Weatherford, C.L. and Gray, W.M., 1988b: Typhoon structure as revealed by aircraft reconnaissance. Part II: structural variability. *Mon. Wea. Rev.*, 116, 1044-1056.

Willoughby, H.E., 1995: Mature structure and evolution. *Global Perspectives on Tropical Cyclones,* R.L. Elsberry, Ed., WMO Tech Doc. WMO/TD-No. 693, Rep. TCP-38, 21-62.

Willoughby, H.E., 2002: A new parametric model of hurricane wind profiles. *Proc. 25th Conf Hurricanes and Tropical Meteorology*, AMS, San Diego, 553-554.

WOP, 1990: Basis for definition of Goodwyn 'A' environmental design criteria. *Woodside Offshore Petroleum Pty Ltd*, Ocean Engineering Group, WOP Doc A9640RH005, March.

WOP, 1992: Wanaea hindcast preliminary studies. Report prepared by Blain Johnson - PPK for *Woodside Offshore Petroleum Pty Ltd*, Offshore Engineering Dept, Sept.

Appendix A Example Figures from Erickson (1972)

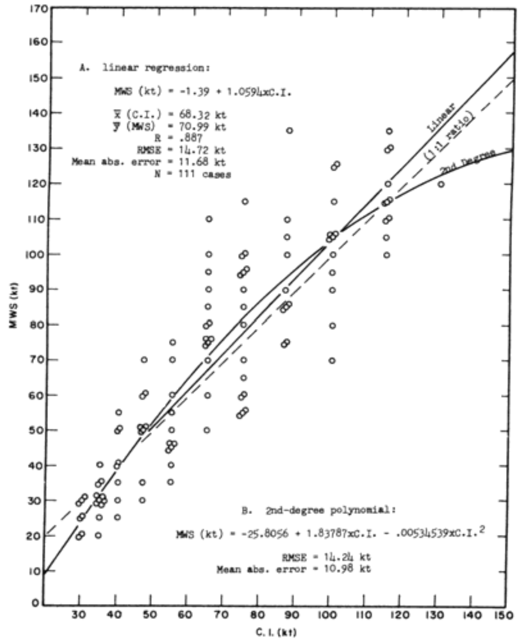


Figure 1 V_{max} from CI : WNP : Dvorak data only.

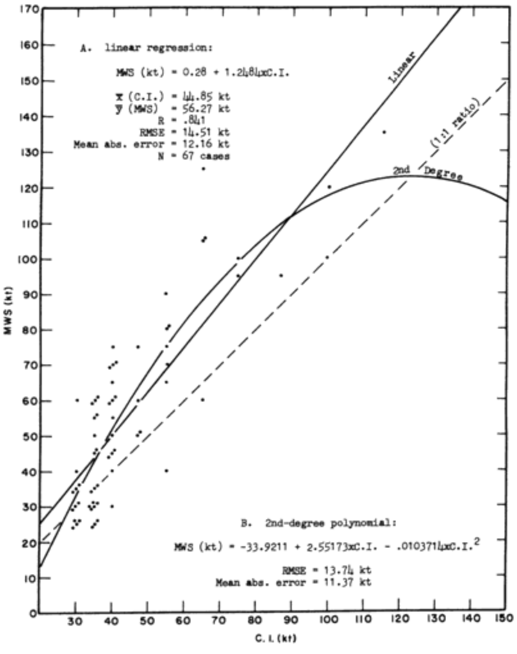


Figure 2 V_{max} from CI : Atlantic : Dvorak data only.

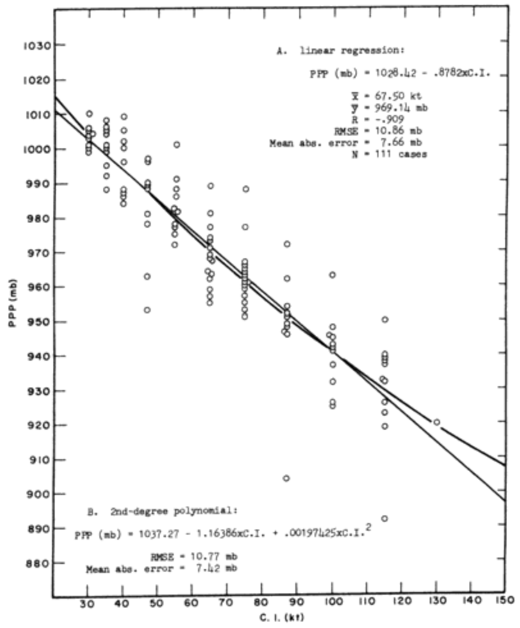


Figure 5 p_c from CI : WNP : Dvorak data only.

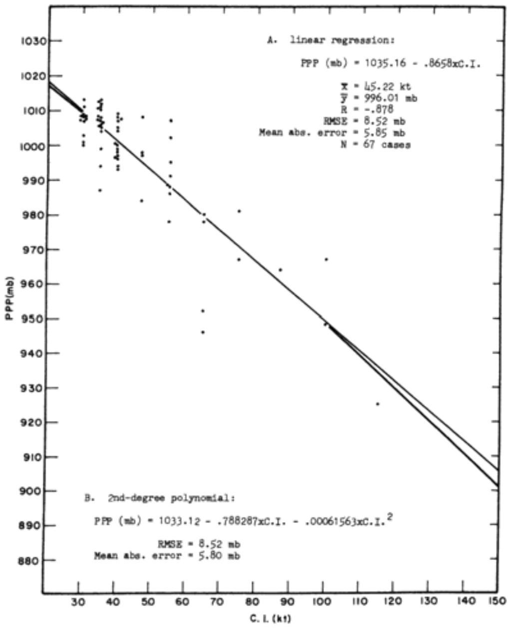


Figure 6 p_c from CI : Atlantic : Dvorak data only.

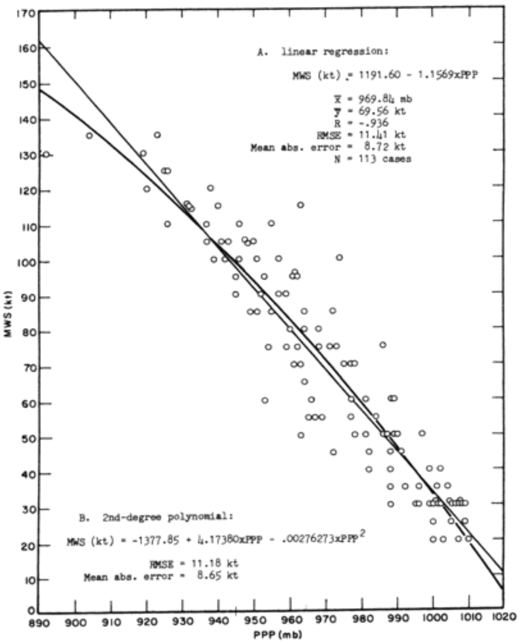


Figure 7 V_{max} vs p_c : WNP : data.

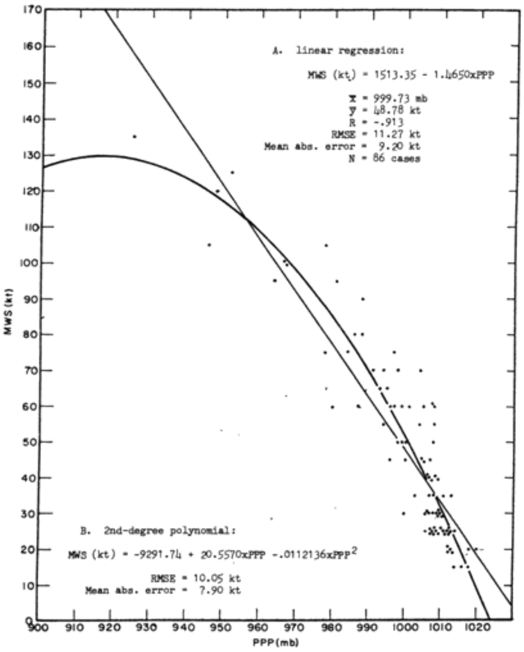


Figure 8 V_{max} vs p_c : Atlantic : data.

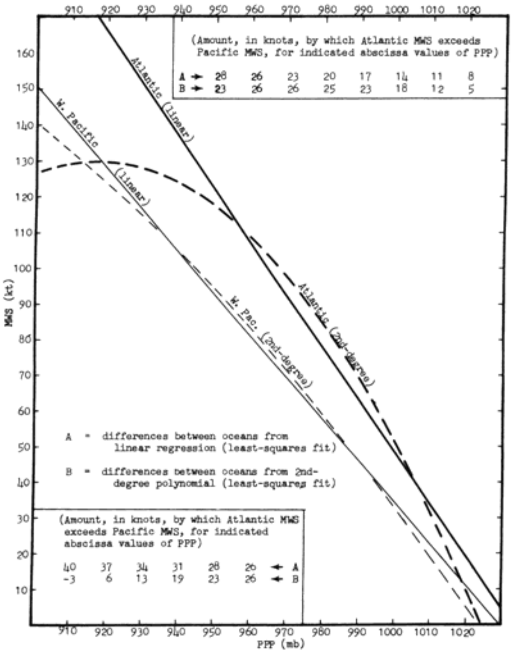


Figure 11 Comparison of the NWP and Atlantic best fit wind-pressure curves.

Appendix B A Critique of the Atkinson and Holliday (1977) Near-Surface Boundary Layer Assumptions

Notwithstanding the considerable effort taken by the authors to screen and process their data it is now possible to consider a number of areas of bias or uncertainty in the Atkinson and Holliday (1975, 1977) analysis:

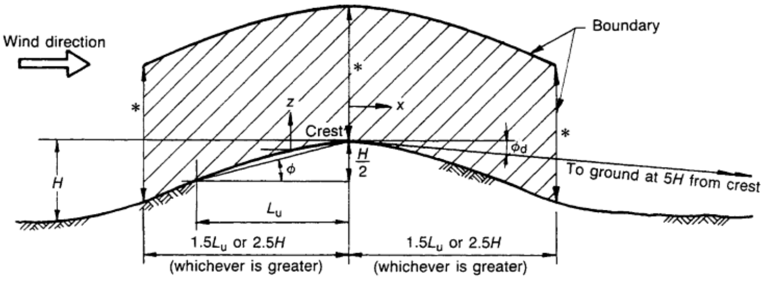
1. Given that the data selection targeted encounters with the right-front quadrant, there remains the strong possibility that the V_{max} data was consistently biased high by some reasonable proportion of the forward speed V_{fm}, say, 5 ms^{-1}.

2. The height correction process was apparently applied not just to masts but also to elevated terrain. The example quoted in the paper indicates an adjustment of wind gusts from a 4m mast at Anderson AFB on Guam, itself at an elevation of 191 m. This ignores the possible topographic effects at such a site, which could contaminate measures of the incident wind gust speed at that elevation. For example, Standards Australia (1989) indicates potential wind speed factors ranging up to 1.5 depending on the steepness of the hill sides and location of the anemometer (refer Figure B-1). Powell and Houston (1998), for example, discuss similar issues in regard to mountainous terrain effects in the Caribbean. The proportion of anemometer sites that were at high elevations is not stated, but each site would need to have been individually assessed in some detail (probably wind tunnel modelling or local calibrations) to determine such influences. Hopefully, although used as an example, such sites were in the minority and that airport locations near sea level might form the majority of cases. It is noted though that many of the islands in the chain enclosing the East China Sea from Hong Kong to Japan are mountainous. Unfortunately it is not possible to draw any conclusions about the possible bias of this effect without reanalysing the original data from A&H (1975) in conjunction with station details of the period. It is noted that the average height reduction applied was 1.12 but was as high as 1.25 in about 10 instances.

3. The form of the adopted power law relationship for the elevation adjustment is significantly different from the accepted procedure in AS1170.2 (Standards Australia 1989) for the wind gust profile variation with height in a free stream environment (refer Figure B-2). Considering the example cited, the difference in reduction factor for a free stream elevation at Anderson AFB would be 1.2 versus 1.4, i.e. A&H overpredicting the +10m value by 17%. Again, this ignores possible local topographic effects.

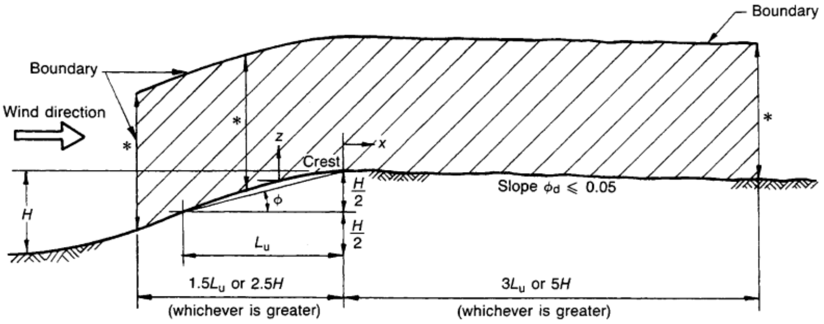
4. Finally, the published speed dependent gust factor used to convert surface gust wind speeds to 1 minute mean winds is also at variance with, for example, Ishizaki (1983) for the same region (refer Figure B-3). A peak turbulence intensity (*Iu*) of 0.6 has been found to agree reasonably well with measured tropical cyclone winds in the Australian context (Harper 1999) and is in broad agreement with BoM (1978). This would lead to the A&H procedure giving a 5% overestimate of V_{1min} at 50 ms^{-1} and about an 8% overestimate at 70 ms^{-1}. The paper concedes that the conversion factors are lower than those used operationally by the JTWC, but were made *deliberately conservative* for forecasting purposes.

Whilst the very substantive nature of the A&H work is acknowledged, it is possible that some of the surface wind speed estimates at elevated sites are in error (inflated) due to topographic influences and that there is an increasing overestimation of surface winds for increasing wind speed (decreasing central pressure).



* L_u or 1.67H (whichever is greater) ▨ Local topographic zone

FIGURE 3.2.8.1 HILLS AND RIDGES



* L_u or 1.67H (whichever is greater) ▨ Local topographic zone

NOTE: Figures 3.2.8.1 and 3.2.8.2 are cross-sections through the structure site for a particular wind direction

FIGURE 3.2.8.2 ESCARPMENTS

TABLE 3.2.8

TOPOGRAPHIC MULTIPLIER AT CREST (x = 0) FOR GUST WIND SPEEDS

Upwind slope (ϕ)	Topographic multiplier (M_t)	
	Escarpments $\phi_d \leqslant 0.05$	Hills and ridges $\phi_d \geqslant 0.10$ (see Notes 1 and 2)
0.05	1.04	1.09
0.1	1.08	1.18
0.2	1.16	1.36
$\geqslant$0.3	1.24	1.54

LEGEND:

ϕ = the upwind slope, calculated from $\phi = \frac{H}{2L_u}$

ϕ_d = the average downwind slope, measured from the crest of a hill, ridge or escarpment to the ground level at a distance of 5H

H = the height of the hill, ridge or escarpment, in metres

L_u = the horizontal distance upwind from the crest to a level half the height below the crest, in metres.

NOTES:

1. An escarpment has a value of downwind slope (ϕ_d) $\leqslant$ 0.05. A hill or a ridge has a value of downwind slope (ϕ_d) > 0.05. The values given in Table 3.2.8 are applicable only to those hills and ridges with downwind slope $\geqslant$ 0.10.
2. For hills and ridges with downwind slope 0.05 < (ϕ_d) < 0.10, linear interpolation between the M_t values for escarpments and, hills and ridges in Table 3.2.8 is permitted.
3. For intermediate values of upwind slope (ϕ) and downwind slope (ϕ_d), linear interpolation is permitted.

Figure B-1 Topographic adjustments recommended in AS1170.2 (1989).

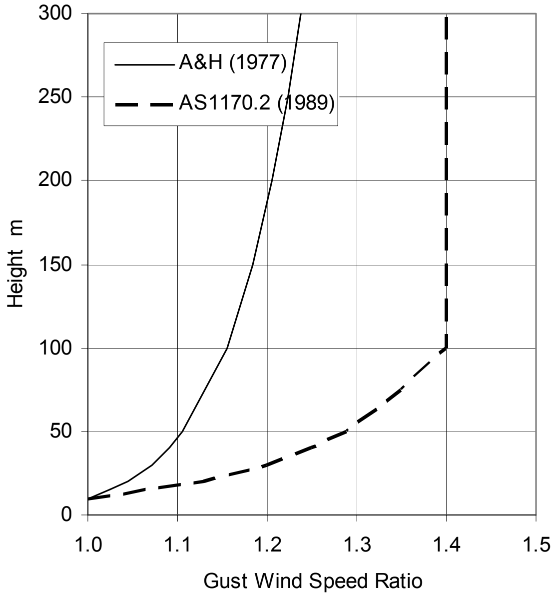


Figure B-2 Differences in elevation adjustment of peak gust speeds.

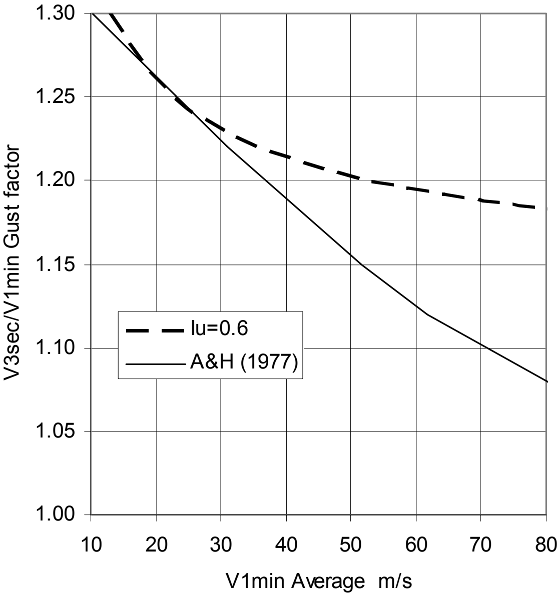


Figure B-3 Differences in surface wind adjustment of gust wind speeds.

Appendix C Selected Storm Data and Commentaries

A number of sets of storm parameters are mentioned in the report and variously plotted. Due to time limitations for this review, the selection offered is one of opportunity rather than any rigorous attempt to gather together a comprehensive sample. Accordingly there is some variability in the bases of the estimates. To provide transparency in this regard, Table C-1 summarises the actual values used, together with their referenced source and any modifications applied here to the source data. Some of these modifications are expanded upon in the storm-specific text that follows.

In Table C-1, V_{max} is reserved for the best estimate of the *storm-relative* 10 minute +10 m sustained surface wind; V_{max}' for the uncorrected earth-relative surface wind speed estimate; V_{1min} for a stated 1 minute +10 m surface wind estimate; V_3 for a stated peak 3 second surface gust estimate; V_{fl} for the reported flight-level wind, which can vary in elevation (refer text). Actual values shown dashed (′) indicate earth-relative speeds, as far as that can be determined. Generally, where the maximum surface wind has been measured during an eye passage, no storm-relative adjustment has been made.

Flight level mean to surface adjustments are based on the “eye-wall” profile from Franklin *et al* (2000). Surface wind averaging period adjustments are fixed as $V_3/V_{max} = 1.4$; $V_{1min}/V_{max} = 1/0.88$. The Holland B is calculated from Equation 4 assuming ρ=1.15 and K_m=0.75 (refer Appendix E).

Figure 4.3 also shows V_{max}' data from Table 2 in Powell and Houston (1998) (labelled as P&H 1998) and Figure 7 in Vickery *et al* (2000b) (labelled as VST 2000). While the individual storms are not labelled on that figure, each data pair used from those sources is summarised in Table C-1.

The following selected commentaries are not intended to provide a detailed description of each of the storms mentioned in the report but rather to address some specific issues directly relevant to the discussion. As a general comment, it is accepted that winds obtained from landfalling storms will be less reliable than those measured offshore, at least in terms of the identification of the base wind-pressure relationships of interest here. For example, Powell (1982) and Kepert (2002a) show that marked changes in surface winds at landfall are likely caused by stepped changes in moisture flux and, depending on the terrain, surface roughness, convergence etc. Also, the Dvorak pattern recognition technique becomes more confused in proximity to landfall. Nevertheless, landfalling storms of note are included here for comparison.

The selected storm commentaries are listed in the tabulated chronological order, with Australian storms grouped first, followed by international storms.

Table C-1 Selected storm data used for illustration.

										Measured or Estimated				
Storm	**Year**	***CI***	**p_n**	**p_c**	**Δp**	**V_{max}**	***B***	**Wind Source**	**$V_{max'}$**	**$V_{max'}$**	**V_{fm}**	**V_3**	**V_{fl}**	**V_{1min}**
			hPa	**hPa**	**hPa**	**ms^{-1}**		**Reference**	**Method**	**ms^{-1}**	**ms^{-1}**	**ms^{-1}**	**ms^{-1}**	**ms^{-1}**
Agnes	1956	4.0	1002	961	41	27	1.0	Callaghan and Smith (1998)	V_3/V_{max}	27.1	7.6	38′		
Ada	1970	5.5	1011	960	51	43	2.0	Estimated here.	V_3/V_{max}	42.9	2.7	60		
Tracy	1974	5.5	1004	950	54	43	1.9	BoM (1977)	V_3/V_{max}	43.1	1.7	60.3′		
Joan	1975	7.0	1004	930	74	45	1.5	Holland (1980); BoM (1979)	estimated	45.0	-			
Kerry	1979	5.0	1008	955	53	41	1.8	Holland (1980); Black & Holland (1995)	$V_{1min} = V_{fl}$ x 0.75	41.0	1.5		55	
Kathy	1984	6.0	1005	940	65	46	1.8	Murphy (1985)	V_3/V_{max}	45.9	3.6	64.3′		
Orson	1989	6.5	1008	905	103	53	1.5	Harper et al (1993)	Adj. from 62.3 ms^{-1} @ +36.4m	53	7.0			
Oliver	1993	6.5	1010	950	60	47	2.0	Callaghan and Smith (1998)	AWS direct	46.0	1.2			
Annette	1994	5.8	1006	933	73	43	1.4	BoM WA	V_3/V_{max}	43.1	-	60.3′		
Olivia	1996	6.0	1002	925	77	54	2.1	BoM WA / WNI	AWS direct	54.0	7.5	74.2′		
Vance	1999	6.3	1008	910	98	61	2.1	BoM (2000)	V_3/V_{max}	52.8	8.3	74′		
Inez	1966	6.8	1010	927	83	60	2.4	Hawkins and Imbembo (1976)	$V_{1min} = V_{fl} x 0.91$	64.9	4.1		81′	74′
Tip	1979	7.8	1010	870	140	75	2.2	Dunnavan & Diercks (1980)	$V1_{1min}/V_{max}$	74.8	3			85′
Gilbert	1988	7.5	1010	888	122	56	1.4	Black & Willoughby (1992)	$V_{1min} = V_{fl} x 0.91$	56.1			70	64
Hugo	1989	6.0	1010	934	76	40	1.2	Powell *et al* (1991)	$V1_{1min}/V_{max}$	52	12			59
Andrew	1992	6.5	1014	922	92	50	1.5	Powell and Houston (1996); NHC	$V1_{1min}/V_{max}$	58.1	7.7			66′
						58	2.1	NHC (2002)	$V_{1min} = V_{fl} x 0.90$	66.1	7.7		83.4’	
Floyd	1999	7.0	1010	924	86	55	2.0	HRD Surface Analysis; NHC	$V1_{1min}/V_{max}$	55.3	6.2			63′
Keith	2000	6.3	1008	955	53	44	2.1	HRD Surface Analysis; NHC	$V1_{1min}/V_{max}$	44.4	1.0			50′
Iris	2001	6.0	1010	948	62	48	2.1	HRD Surface Analysis; NHC	$V1_{1min}/V_{max}$	58.0	9.8			66′
Michelle	2001	6.5	1008	937	71	53	2.2	HRD Surface Analysis; NHC	$V1_{1min}/V_{max}$	53.0	2.1			60′
Erin	1995	5.0	1010	974	36	31	1.5	Powell and Houston (1998)	$V1_{1min}/V_{max}$	36	5.0			41’
Luis (1)	1995	6.0	1010	940	70	49	1.9	Powell and Houston (1998)	$V1_{1min}/V_{max}$	53	4.9			60.7’
Luis (2)	1995	6.0	1010	946	64	41	1.4	Powell and Houston (1998)	$V1_{1min}/V_{max}$	45	4.0			50.7’
Marilyn	1995	5.3	1010	957	53	37	1.5	Powell and Houston (1998)	$V1_{1min}/V_{max}$	41	3.8			46.8’
Opal (1)	1995	6.5	1010	919	91	45	1.2	Powell and Houston (1998)	$V1_{1min}/V_{max}$	53	8.5			60.4’
Opal (2)	1995	5.5	1010	942	68	29	0.7	Powell and Houston (1998)	$V1_{1min}/V_{max}$	40	11.0			46’
Roxanne	1995	5.5	1010	958	52	37	1.5	Powell and Houston (1998)	$V1_{1min}/V_{max}$	42	5.0			48.1’
Frederic	1979	6.0			68	41	1.4	Vickery *et al* (2000b)	$V_{1min} = V_{fl} x 0.83$	41			56’	
Elena	1985	5.0			51	34	1.3	Vickery *et al* (2000b)	$V_{1min} = V_{fl} x 0.83$	34			47’	
Emily	1987	5.0			52	38	1.5	Vickery *et al* (2000b)	$V_{1min} = V_{fl} x 0.83$	38			52’	
Gustav	1990	5.0	1012	961	51	41	1.8	Vickery *et al* (2000b)	$V_{1min} = V_{fl} x 0.83$	41			56’	
Rammasun	2002	5.5	1008	945	63	26	0.6	Nagata (JMS)	AWS direct	26		47		
Chataan	2002	5.5	1008	961	47	37	1.6	Lander (UOG)	V1min/Vmax	29	7.7		40’	
Fengshen	2002	4.5	1008	959	49	38	1.6	Edson (Anteon)	V1min/Vmax	38			43.7’	

Ada Whitsunday Islands, Queensland, January, 1970.

Ada was a very small but intense tropical cyclone which caused considerable destruction in the Whitsunday Islands region of the central Queensland coast (BoM 1970, Callaghan and Smith 1998). At the time of maximum destruction it is estimated to have had an eye diameter of only 20 km, with radius to gales of only 55 km. The minimum central pressure near Airlie Beach is reasonably reliably estimated by C&S as 960 hPa, with an ambient of 1011 hPa.

There are no instrumented wind records but observers estimated 50 ms^{-1} (gusts) at Hayman Island (9 km off track) where the level of damage to tourist accommodation was very extensive. Based on the Guard and Lander (1999) scale, this is consistent with the broken and twisted palm trees indicated in photography. Daydream Island experienced eye passage and accommodation units were completely destroyed, while similar damage was experienced at nearby South Molle where a life was lost when cabins were destroyed.

Without a wind speed record it is difficult to assess the maximum winds during *Ada*. While the building damage was extensive, the standard of construction would have been similar to that at Townsville in 1971 (e.g. Trollope 1972), which was found deficient in a number of basic areas. It is therefore possible to compare the reasonably extensive damage to tourist-style accommodation during *Althea* at Magnetic Island with that at Daydream Island. For example, the maximum estimated peak gust at Magnetic Island during *Althea* was assessed as being about 60 ms^{-1} and so *Ada* was probably of similar or slightly greater magnitude. Using the standard 1.4 gust factor, this would indicate a V_{max} of about 43 ms^{-1}. Due to the poor quality of satellite imagery and the small size of *Ada* it is not practical to attempt to classify the Dvorak *CI* number (J. Callaghan, *personal communication*).

Tracy Darwin, Northern Territory, December, 1974.

The impact of *Tracy* on the City of Darwin remains the most significant natural disaster in Australian history. Its widespread destruction forced the evacuation of 30,000 inhabitants and rebuilding took over two years (Cole 1977). Approximately 8,000 houses were rendered uninhabitable.

Given the very high level of destruction created by *Tracy* and the fact that the anemometer was destroyed by flying debris just before entering the eye, there will always remain some doubt as to the best estimate of the peak wind speed for this event. There is no doubt that the MSL central pressure was 950 hPa, with an ambient of 1004 hPa, and that the eye diameter was about 12 km. The airport Dines anemometer was well located in flat open terrain about 3 km from the coast and within 500 m of the assessed storm track centreline. The storm *CI* was assessed reasonably confidently in BoM (1977) as being 5.5 at landfall. However, given the relatively poor satellite imagery by present standards combined with the very small eye, it is conceivable that this estimate is too low (J. Callaghan, *personal communication*). It is recommended that this aspect be reviewed.

From an engineering viewpoint, the high level of destruction alone should not necessarily be used to justify the presence of significantly higher winds than were measured, i.e. an assessed peak gust range of 60 to 67 ms^{-1} (BoM 1977). This is because of the very poor strength of the majority of the domestic housing that was affected (e.g. Reardon and Meecham, 1993) and the high level of uniformity of this construction in close proximity to the airport location. By comparison, very few structural failures were noted for engineered buildings, where design allowance had been made for winds of even less than 60 ms^{-1} (D. H. Lloyd FIEAust RPEQ, *personal communication*)[1]. While the presence of tornadoes cannot be completely ruled out, the level of destruction was sufficiently high and widespread that tornado paths could have been masked. No tornadoes were reported.

The Dines anemometer, nominally rated to 67 ms^{-1}, failed 40 minutes prior to the full calm being experienced at the site but only 10 minutes prior to the passage of the accepted period of maximum winds based on observer logs. The highest wind gust recording deemed reliable was 60.3 ms^{-1}, which occurred 5 minutes before total loss. The radar evidence suggested the band of maximum winds had passed the site within 5 minutes after the failure or 10 minutes after the highest reliable reading. During this time the storm forward speed was around 1.7 ms^{-1}, indicating a radial travel over 10 minutes of only about 1 km. Also, detailed analysis of the pressure record indicated a radius for R of about 7 km when fitted to a Holland profile and the storm centre was estimated as being 7 km from the site at the time of the peak measured gust.

In support of possibly higher winds occurring, Callaghan and Smith (1998) observes that the eastern/southern RADAR eyewall (sampled by the Dines just before failure) was relatively clearer of rain echoes than the northern eyewall, which seemed to coincide better with the regions of major housing damage. However, the absence of similar housing south-east of the airport at the time, which could have been used as a comparison, leaves this finding open.

For some, there remains the issue of an “electrical failure” which occurred just prior to physical loss of the instrument, which resulted in an off scale value (77 ms^{-1}) being recorded on the anemograph. Whether this indicates a true gust in full or in part will remain a mystery but the mean wind during this time was confidently assessed as being around 39 ms^{-1} and the nearby trained observers did not note a significant burst at that time. The BoM (1977) peak gust range is therefore predicated on the lower limit of the most reliable record obtained (60 ms^{-1}) and the upper limit of the rated anemometer speed (67 ms^{-1}), which permits some subjectivity in regard to the “electrical failure”. The official estimate of the mean wind was then given as a range from 39 ms^{-1} to 41 ms^{-1}, although this seems to have been based on a combination of observer notes and a favourable comparison with A&H. It is proposed below that the better estimate of the mean wind would be obtained by factoring from the measured gust.

When considering the best estimate of the “over water storm relative” mean wind speed, both the forward speed and the surface roughness at the anemometer site must be considered. As the forward speed was relatively low and the anemometer was very close to the track centreline, no adjustment for that factor is deemed necessary. Regarding surface roughness, the airport site is very well exposed and is actually on a slightly mounded and elevated region. The overland streamline at the site would have been of the order of 6 km over a landscape predominantly represented by scattered trees and long grass, say Terrain Category 2.5 or z_0=0.06 mm (Standards Australia 1989). This may have reduced the overwater mean wind by some 5%. However, given that the mean wind is difficult to estimate from the anemograph anyway and the airport site is slightly raised relative to its surrounds, it is proposed to simply base the estimate of the overwater mean wind on the measured peak gust of 60.3 ms^{-1} adjusted by the standard overwater gust factor of 1.4. This yields an estimated V_{max} of 43 ms^{-1}.

---

[1] It is not possible to be unequivocal here in the sense that engineered structures were not as well represented in the housing areas as they were in the industrial region to the west of the airport. However, the types of failures examined were deemed to be due to poor structural detailing or post-construction changes rather than due to the wind speed being in excess of design levels.

In the final analysis, therefore, in terms of a critical $CI - V_{max} - \Delta p$ data tuplet directly relevant to this review, *Tracy* yields a score of 5.5 - 43 - 54. This places *Tracy* between the A&H and Dvorak relationship, with an assessed Holland *B* value from Equation 4 of 1.9, placing it within the "peaked" profile category. Taking the official mean V_{max} of 40 ms^{-1} would place it squarely on A&H, as argued in BoM (1977).

Kerry Coral Sea, Queensland, February 1979.

Kerry is the only Australian region storm ever examined with reconnaissance aircraft (refer Black and Holland 1995). The quoted 540 m elevation tangential winds are sourced from B&H Fig 6c for 21/02 in preference to 22/02. This is to avoid the apparent inconsistency in the quoted central pressures on 22/02 between B&H and Holland (1980), i.e. 965 versus 955 respectively. The pressure has been inferred from B&H Fig 1 as 955 hPa on 21/02. The ambient pressure in Holland is also inconsistent but 1008 appears likely. The speed is from B&H and no adjustment was made.

Kathy Port McArthur, Gulf of Carpentaria, March 1984.

Kathy was a rapidly developing and very intense storm affecting a remote section of coast on the western side of the Gulf of Carpentaria (Love and Murphy 1985; Murphy 1985). Shortly before landfall at 221600 UTC, EIR imagery clearly indicates a *T* number of 7.0, based on a white surround and off-white eye (J. Callaghan, *personal communication*). Over the next 5 h the storm moved onshore and encountered the Sir Edward Pellew island group, with the EIR imagery indicating steady weakening in spite of the normally expected period of maximum diurnal convective activity. The eye passed over a temporary Dines anemometer site on Centre Island about 1 h before crossing the nearby coast. Callaghan estimates the *T* number near landfall as possibly no greater than 6.0, whereas Love and Murphy (1985) reports an assessed *CI* of 6.5. Unfortunately, it is almost impossible to accurately estimate the eye temperature from the available archived grey scale enhancement. With present knowledge of the diurnal convective cycle, the potential effects of the islands and the possible Dvorak over-compensation of *CI* during weakening, a more reasonable estimate of *CI* for *Kathy* at landfall could be 6.0. It is recommended that this aspect be reviewed by a panel of experienced Dvorak users.

As reported in Murphy (1985), the instrumentation recorded a minimum MSL pressure of 940 hPa and a maximum gust of 64.3 ms^{-1} (125 kt) just before the tower "blew down"[2]. The ambient pressure was assessed as 1005 hPa, the forward speed as 3.6 ms^{-1}, and the eye diameter as 10.8 km. Using a Holland pressure profile, the radius *R* was then estimated to be 12.7 km, which agreed well with the other information. A storm surge of approximately 4.2 m was also observed.

Whether the anemometer measured the peak winds in the storm is of interest to the present study. The tower failed approximately 40 min prior to the reported onset of calm, which lasted for about 50 min. This would place the eye wall some 9 km distant of the site at the time of failure, with peak winds approaching the site over water from the south-east along the strait between Vanderlin Island and the coast. This compares with the assessed *R* of almost 13 km and the observation by Murphy that "*gusts recorded during the final 20 minutes show a tendency to flatten out*". The temporary nature of the facility may have contributed to a fatigue-induced failure of either the foundations or supports, rather than the loss being due simply to an extreme wind gust. Accordingly, it appears reasonable to assume that the peak winds were probably sampled. Based on a standard gust factor of 1.4 this yields an estimated V_{max} of 46 ms^{-1}. The anemometer was apparently well located on a site just 6 m above MSL and at standard 10m height.

---

[2] Callaghan and Smith (1998) erroneously reports the maximum recorded wind during *Kathy* as being 71 ms^{-1}.

The best estimate of the *Kathy* $CI - V_{max} - \Delta p$ data tuplet is then 6.0 (6.5?) - 46 - 65. This places *Kathy* only slightly above the A&H (1977) relationship, with an assessed Holland B value of 1.8, placing it in the "peaked" profile category. In order to intersect the Dvorak (1984) wind-pressure curve it would require a further 4 ms^{-1} of mean wind, which seems unlikely based on the evidence.

Orson North Rankin 'A' Platform, April, 1989.

Orson was one of the most severe tropical cyclones to approach the Western Australian coast and holds the present record for the lowest recorded central pressure in the Australian region (905 hPa). The storm is documented in BoM (1992) in considerable detail and results of numerical modelling are presented in Harper *et al* (1993).

The minimum MSL pressure and maximum wind speeds attributed to *Orson* were measured at the North Rankin 'A' oil and gas production platform (NRA), located 130 km NW of Dampier on the West Australian coast. The storm eye passed directly over the platform which, based on recorded wind directions, was about 4 km from the vortex centre. The platform is operated by Woodside Energy Ltd and the onboard environmental monitoring system at the time consisted of dual Skyvane propeller/vane anemometers located with good exposure at an elevation of 36.4 m MSL[3]. Pressure, temperature and humidity were also logged continuously from a standard enclosure and wave and current measurements were also made (refer Harper *et al* 1993). One anemometer failed near the time of peak winds during the first passage through the eyewall; the second failed during eyewall re-entry.

The peak 10 minute average wind speed recorded at anemometer height was 62.3 ms^{-1} with a non-coincident peak 3 second gust of 76.4 ms^{-1}. However, at the time of these analyses, some significantly higher gusts were discounted and these are now being re-examined in the light of the possibility of mesoscale vortices (e.g. Black and Marks 1991). These peak values were adjusted to +10m values of 45.6 and 55.9 ms^{-1} respectively by a roughness-dependent boundary layer adjustment factor used for hindcast studies at the time (WOP 1992) and these are the published values in Harper *et al* (1993).[4] Although newly measured vertical wind profiles at NRA[5] are supportive of this magnitude of reduction (1.4), it is considerably at odds with established practice (e.g. API 1993, ISO 1996). Accordingly, until the new data has been fully analysed, a reduction factor of 1.17 is applied, yielding a V_{max} of 53 ms^{-1}. The ambient pressure p_n was assessed as 1008 hPa and the radius to maximum winds R as 30 km. The storm was moving relatively quickly (7 ms^{-1}) over NRA but due to its positioning does not warrant significant adjustment of the measured peak winds.

At the time of eye passage over NRA the BoM (1992) assessed Dvorak CI number was 6.5, giving the best estimate of the *Orson* $CI - V_{max} - \Delta p$ data tuplet as 6.5 – 53 - 103. This places *Orson* well below the A&H (1977) relationship. The assessed Holland B value is then 1.5. If the lower wind speed estimate proves more reliable, it will push O*rson* towards the limit of the "broad" profile category.

---

[3] B. Harper was Chief Ocean Engineer with Woodside Energy Ltd at the time of the storm, with responsibility for the analysis of data collected by the environmental monitoring system on North Rankin 'A'.

[4] BoM (1992) quotes the peak anemometer wind speeds correctly but estimates the peak surface gust as around 70 ms^{-1}, which may be derived from an earlier erroneous estimate provided by Woodside before instrumentation checks were completed. Also, their Figure 16 plots the recorded anemometer wind trace at +36.4 m, but incorrectly label it as being at +10m.

[5] Winds at various levels from +10 m to +100 m have been captured at NRA during tropical cyclone conditions over the past few years and are currently being analysed in detail by Woodside Energy Ltd.

Oliver Lihou Reef AWS and Marion Reef AWS, February, 1993.

Oliver was a medium-size storm in the Coral Sea that passed, very slowly, over the Lihou Reef AWS (Callaghan and Smith, 1998). The AWS anemometer is located at +10m above the (flat) cay surface, which is 6m above MSL. It records 10 minute average winds, but only once each hour. The passage over Lihou Reef was also monitored by radar from Willis Island, 220 km to the WNW, which showed a clearly defined eye.

C&S reports a V_{max} of 46 ms^{-1} and p_c of 950 hPa from the Lihou Reef passage, with a forward speed of only 1.2 ms^{-1}. The AWS was located on the weak side of the storm and so the recorded V_{max} could be increased marginally to represent the storm-relative peak value. The radius of maximum winds R was estimated as 28 km and the ambient pressure p_n was 1010 hPa. Using the Holland model with a K_m of 0.75, C&S obtained an estimated B of 1.96, thus placing *Oliver* well towards the "highly-peaked" category.

The storm was apparently at its most intense during the passage over Lihou Reef and the assessed Dvorak T number was 6.5 (J. Callaghan, *personal communication)*. The best estimate of the *Oliver* $CI - V_{max} - \Delta p$ data tuplet at this time is then 6.5 - 47 – 60, which places it only slightly below the Dvorak (1984) Atlantic relationship in wind-pressure space but with V_{max} some 11 ms^{-1} below the $CI\text{-}\ V_{max}$ curve. Notwithstanding the disadvantage of the hourly 10 minute wind sample, the slow movement of the storm and the excellent exposure of the anemometer mean that *Oliver* is probably one of the more reliable "groundtruth" measurements yet made of a severe tropical cyclone in the open ocean environment. *Oliver* also passed directly over the Marion Reef AWS some 36 h later, at a reduced intensity, but this data has not yet been fully analysed.

Olivia Varanus Island, Western Australia, April 1996.

A peak wind gust of 74.2 ms^{-1} was recorded during eye passage at a WNI weather station on Varanus Island, offshore Western Australia. The peak measured 10 min wind was 54 ms^{-1} with a central pressure of 925 hPa. A more detailed analysis of *Olivia* is planned.

Vance Exmouth, Western Australia, March 1999.

Vance made landfall at the base of Exmouth Gulf on 22nd March (BoM 2000), having passed between two automatic weather stations at Learmonth and Onslow, separated laterally by about 100 km. The storm passed only about 30 km east of Learmonth, which recorded a peak gust of 74 ms^{-1} on the airport Dines anemograph (a mainland wind speed record for Australia)[6]. The anemometer was located on flat open terrain 3 km from Exmouth Gulf, which is about 30 km wide at this location. The eye diameter is estimated to be around 34 km, placing Learmonth close to the radius of maximum winds. The minimum recorded MSL pressure at Learmonth was 937.8 hPa and the estimated central pressure was 910 hPa (BoM 2000). Ambient pressure is assumed as 1008 hPa.

Applying the standard gust factor of 1.4 then yields a $V_{max'}$ of about 52.8 ms^{-1}. However, since Learmonth was located on the weak side of the storm, it is considered reasonable to consider adding the considerable forward speed of 8.3 ms^{-1} to the calculated mean wind, yielding around 61 ms^{-1}. A more detailed analysis of *Vance* is planned.

---

[6] A further two cup-based anemometers completed a rare trio of observations that were separated horizontally by only about 20 m at Learmonth. The cup anemometers recorded peak gusts during *Vance* of about 64 ms^{-1}. This significant difference is the subject of ongoing analysis and is being pursued in light of the progressive replacement of Dines pitot-tube sensors with cup anemometers by the Bureau of Meteorology. "Objective" measurements remain an elusive goal.

Inez Caribbean, September 1966.

The data here is from Hawkins and Imbembo (1976), which reports a minimum pressure of 927 hPa and a maximum windspeed of 157 kt or 81 ms^{-1} (10 s average at 750 hPa). This was early on 29/09/66 (refer H&I Fig 7) on the eastern side of the storm while it was travelling 277° at 14 kt. This value derives from Doppler winds which did not account for the movement of the sea surface (i.e. similar to W&G results). While it is argued in H&I that these winds may be 5 to 10% low as a result, the complex surface currents and wave directions under a moving cyclone could not justify a simple addition. However, no guidance has been found on how to convert the stated 10 s average flight level winds to the (apparently more routine) equivalent 30 s average . Finally, given that the reported wind was in the rear of the storm it has not been adjusted for storm movement. The ambient pressure could not be determined from the reference and 1010 hPa has been assumed, but given the midget storm condition, this could be too low. Taking all these into consideration it is likely that the *Inez* data has a slightly inflated *B* value.

Tip Western North Pacific, October 1979.

The quoted data is from Dunnavan & Diercks (1980) for 0600 UTC 12/10/1979. The sea level pressure of 870 hPa is termed *recorded* , while the maximum (surface?) wind of 85 ms^{-1} is termed *estimated* but the nature of the estimation is not stated. At best, it is likely a 1-min surface adjusted value from an earth-relative aircraft Doppler reading at a flight level of 700 hPa, and this has been assumed. The storm forward speed is quoted as "between 6 and 13 km h^{-1}", taken here as nominally 3 ms^{-1}. As there is no information on where the max wind estimate was taken, plus the relatively slow movement indicated, no adjustment has been made to the quoted value. The ambient pressure of 1010 hPa has been inferred from their Fig 6.

Gilbert Caribbean, September 1988.

The quoted values are mean tangential 700 hPa winds on 13/09 from Black and Willoughby (1992) Fig 4b with pressure from their Table 1. The ambient pressure has been estimated only and the forward speed is presently unknown.

Hugo South Carolina, September 1989.

The quoted values are from Powell *et al* (1991) for 0400 UTC 22/9, with *CI* taken from the NHC ATCF fix file (which shows estimates varying between 7.0 and 6.0 during this time). The ambient pressure could not be located and is estimated only. The assessed 1-min surface wind at landfall was around 59 ms^{-1} in the northern eyewall. This has been converted to a 10 min wind and the forward speed of 12 ms^{-1} has been subtracted.

Andrew Florida, September 1992.

The assessed peak 1-min surface wind at landfall in Powell and Houston (1996) was 66 ms^{-1} in the northern eyewall when, based on NHC ATCF data, the central pressure was 922 hPa and the storm was moving west at about 7.7 ms^{-1} within an ambient pressure of 1014 hPa. The best track 1-min wind speed at landfall was originally 125 kt (64.4 ms^{-1}) but subsequently increased by the NHC on 8/8/2002 to 145 kt (74.7 ms^{-1}), on the basis of applying the (newly accepted) mean dropwindsonde reduction factor of 0.9 from the aircraft sampled 162 kt winds at the 700 mb level. This change in the best track wind represents a very large increase in the surface sustained wind estimate that seems somewhat at odds with the detailed analysis of anemometer data. Both values are reported here. The assessed V_{max} values have been reduced by the forward speed after conversion to 10-min.

Floyd Caribbean, September 1999.

Data is from HRD surface wind analysis graphic at 0130 UTC 14/09, augmented by ATCF ambient pressure. Although the storm was moving at 6.2 ms^{-1}, the indicated peak 1-min surface wind was in the left rear quadrant. This may have been due to redistribution of momentum at the time and, to avoid debate, the peak wind has not been further adjusted here for forward speed.

Keith Caribbean, September 2000.

Data is from HRD surface wind analysis graphic at 2230 UTC 1/10, augmented by ATCF ambient pressure. The storm was only moving at 1 ms^{-1} and the peak wind has not been adjusted.

Iris Caribbean, October 2001.

Data is from HRD surface wind analysis graphic at 0130 UTC 09/10, augmented by ATCF ambient pressure, but using the NHC estimate of the central pressure. The NHC storm discussion argues that the very small eye prevented a centre dropsonde at this time and the central pressure was assessed as being 9 hPa lower than measured. The storm was moving at 9.8 ms^{-1}, with the indicated peak 1-min surface wind in the right front quadrant. Therefore the peak wind has been adjusted for forward speed.

Michelle Caribbean, November 2001.

Data is from HRD surface wind analysis graphic at 1300 UTC 03/11, augmented by ATCF ambient pressure. Although the storm was moving at 2.1 ms^{-1}, the indicated peak 1-min surface wind was in the left rear quadrant and therefore the peak wind has not been adjusted for forward speed.

Powell and Houston (1998), Table 2.

The wind-pressure parameters for a selection of 1995 hurricanes were conveniently summarised by P&H (1998) and have been included here. The available $V_{max'}$ speeds have been reduced by the storm forward speed as estimated from the track plots. Ambient and central pressures from ATCF.

Vickery *et al* (2000b), Figure 7.

Figure 7 in VST (2000) presents a series of 850 hPa flight level wind and pressure graphs derived from HRD data. Pressure deficits were taken directly as quoted, while wind values were manually digitised from the graphs, retaining the largest speed in each profile. It is assumed that the indicated speeds are not storm relative but no attempt has been made to adjust them at this time. The adjustment from flight level to surface is based on a ratio of 0.91/1.1 from Franklin *et al* (2000). The VST quoted best fit *B* values were based on gradient rather than cyclostrophic winds but, allowing for digitising and adjustment errors, agree well here except for *Emily*.

Rammasun, Chataan and Fengshen (2002)

These data of opportunity have been taken from “Tropical Storms Mailing List” contributions during 2002, with assistance from Jeff Callaghan (BoM Queensland).

Appendix D Selected Atlantic Data Comparisons

The following analyses were made possible through the provision of selected ATCF data files by James Franklin at the NOAA Tropical Prediction Center in Miami.

The ATCF files comprised three different data sets, the parameters of interest being distributed across the various files, e.g.

A (aids) File:	Contains (amongst many prognostic products) p_c, p_n, R, R_{OCI} etc
B (best) File:	Contains conventional "best track" parameters: date, time, lat, lon, V_{max}, p_c
F (fix) File:	Dvorak *T* and *CI*

The HRD HWIND surface wind analyses at http://www.aoml.noaa.gov/hrd/data_sub/wind.html were accessed via internet and the parameters of interest were manually extracted and recorded. Since the ATCF files do not explicitly include objective surface measurements from GPSdropwindsonde or SFMR and the like, the HRD indicated V_{max} was taken as the best "objective" estimate of the surface wind value.

ODT data was also supplied by Tim Olander from the University of Wisconsin, Madison, but time was not available to consider an in-depth comparison with either the NHC or HRD data sets.

Since the use of recent data (within the past 3 years) was expected to yield the best surface wind estimates (M. Powell, *personal communication)* and time was limited, only four recent hurricanes have been considered:

- Floyd, September 1999
- Keith, October 2000
- Iris, October 2001
- Michelle, October 2001

The analysis method firstly consisted of simply comparing the raw time history of p_c, V_{max} and R as retained in each of the Atlantic operational "best track" (or NHC) and HRD data sets. It should be noted that none of the data is storm-relative. The V_{max} - p_c data was then converted to 10 minute V_{max} - Δp to compare the two separate descriptions in wind-pressure space using the ambient pressure p_n from the NHC **A** files.

The two datasets are not contemporaneous, the NHC set being strictly 6 hourly, while the HRD set is dependent upon the reconnaissance schedule. The comparisons shown here are therefore based on a subset constrained by the availability of the HRD surface wind analyses and linear interpolation in time between the closest NHC records. This is not normally a problem since the reconnaissance is typically around the time of maximum intensity. The ODT data, where available, is presently offered without comment.

Trend lines were then constructed for each version of the storm's V_{max} - Δp space to explore the possibility of biases that might be trending the NHC "best track" data towards the Dvorak (1984) curve. This limited comparison of results is meant merely to draw attention to the potential effect of systematic overestimation in best track datasets that, however small, will adversely impact storm intensity statistics and make regional comparisons more difficult.

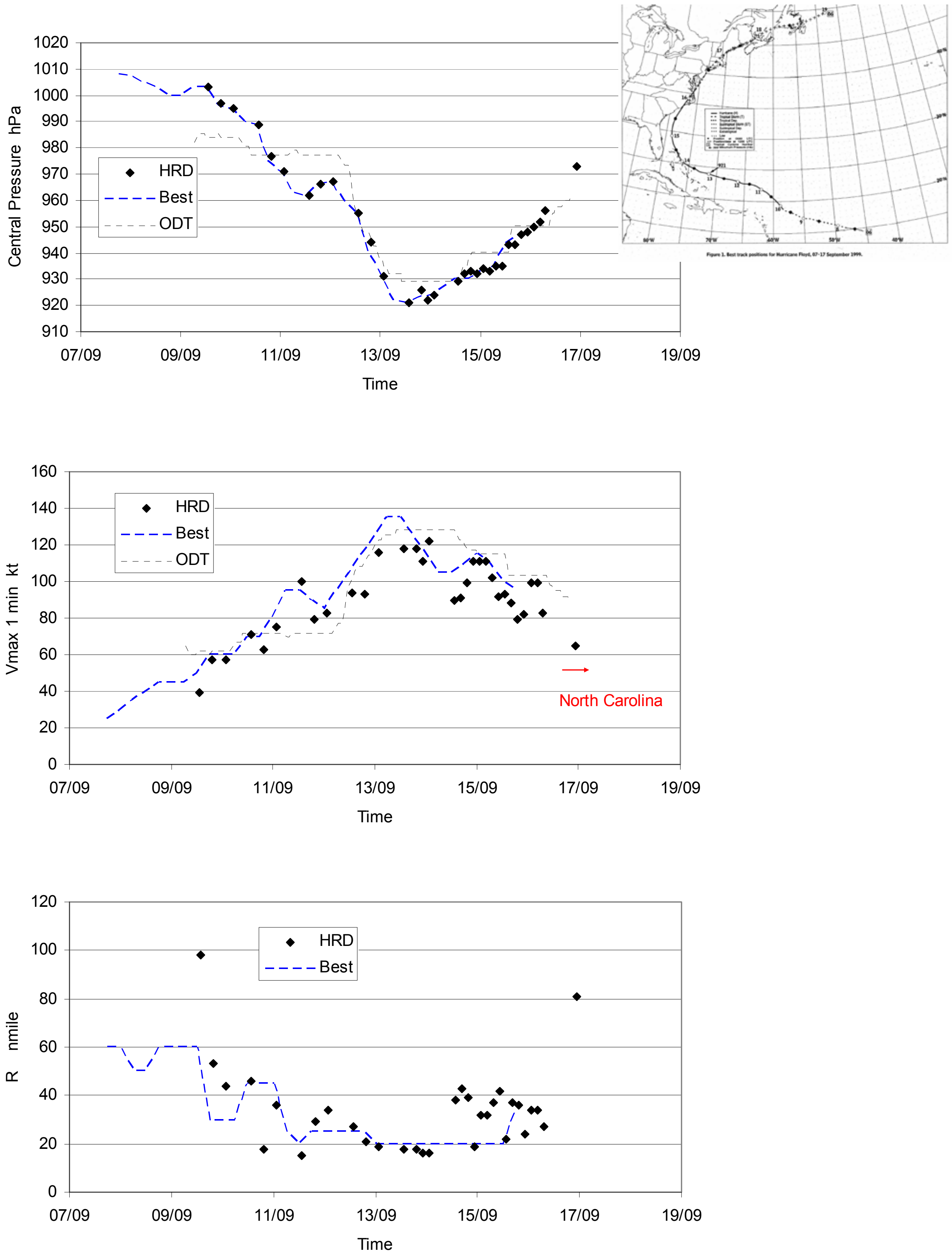
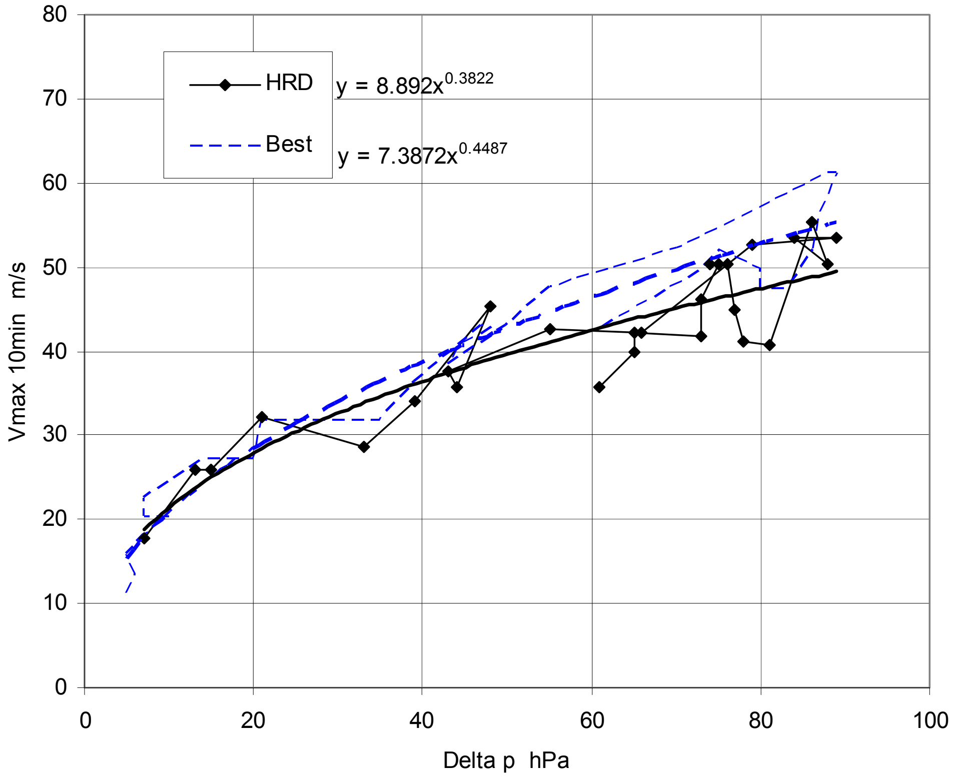


Figure D-1a Hurricane *Floyd* September 1999.



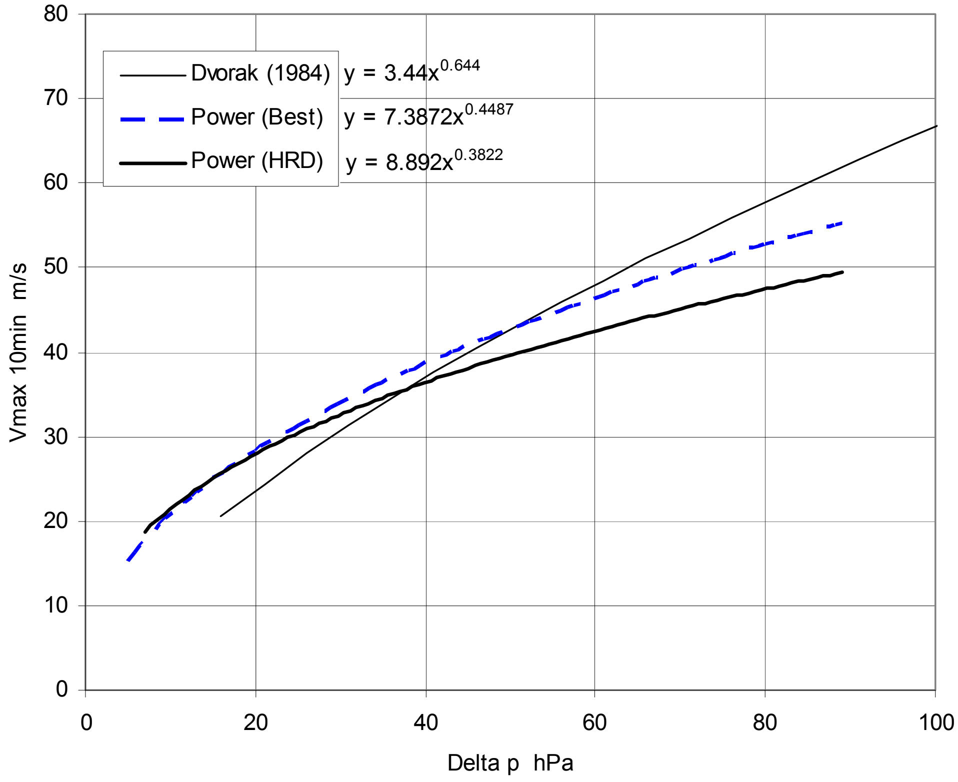


Figure D-1b Hurricane *Floyd* September 1999.

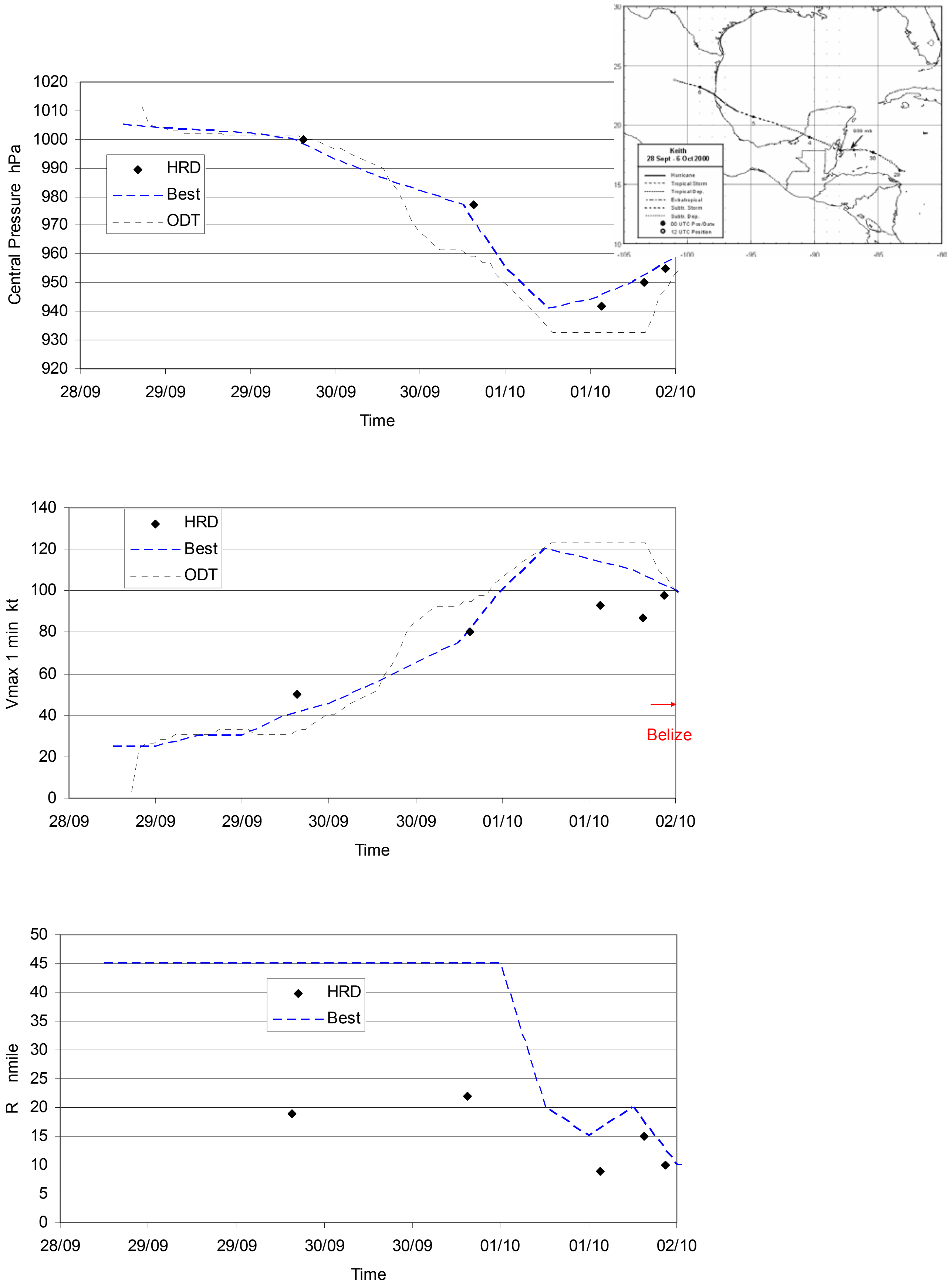
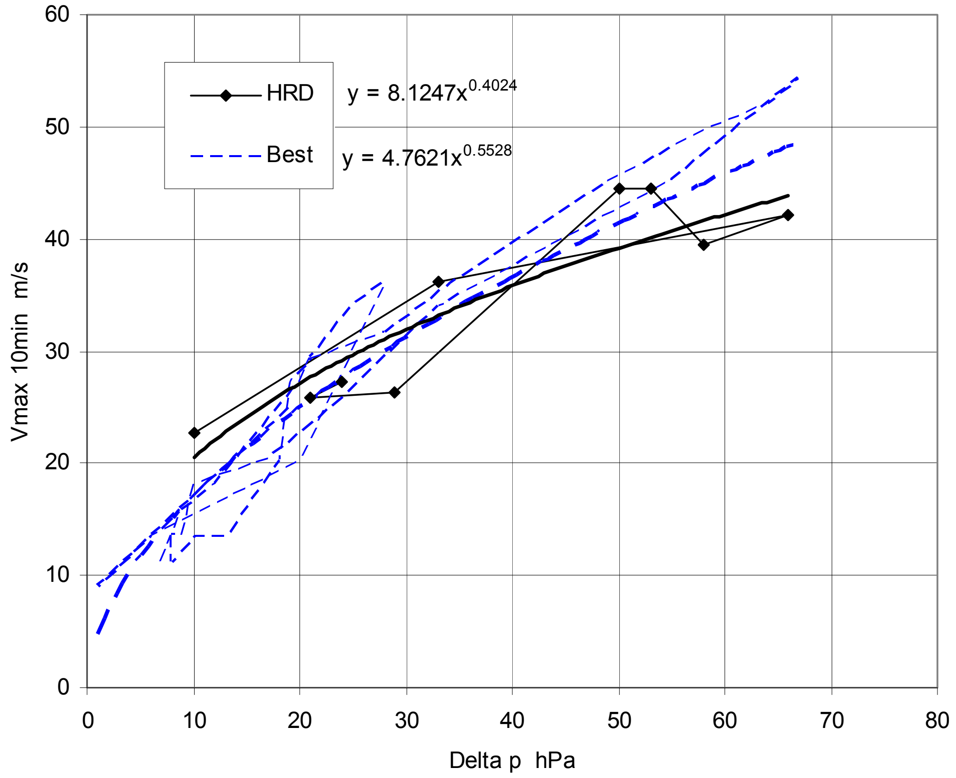


Figure D-2a Hurricane *Keith* October 2000.



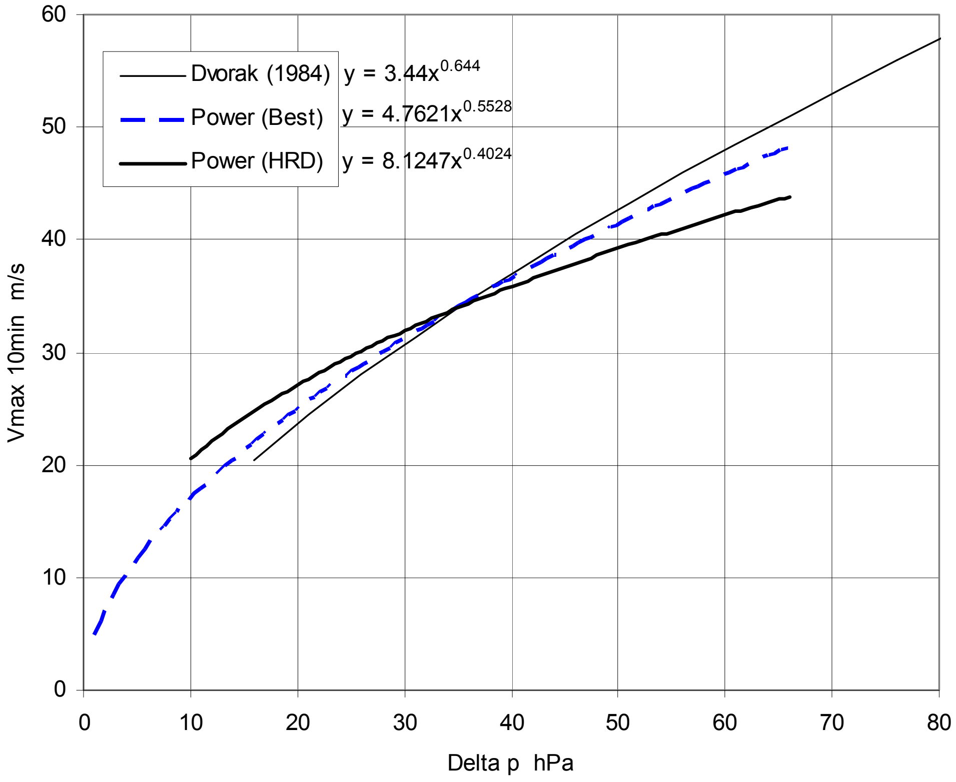


Figure D-2b Hurricane *Keith* October 2000.

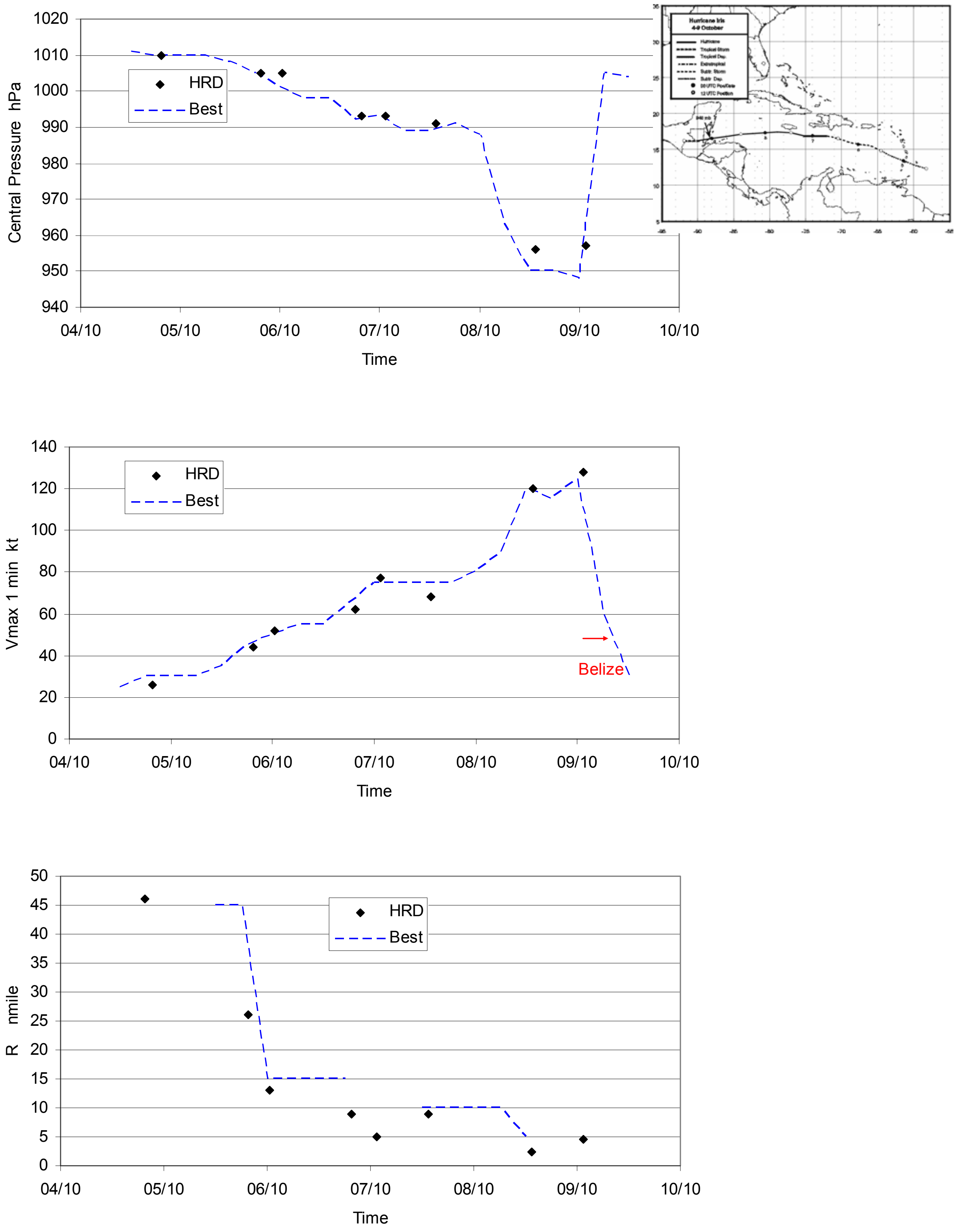
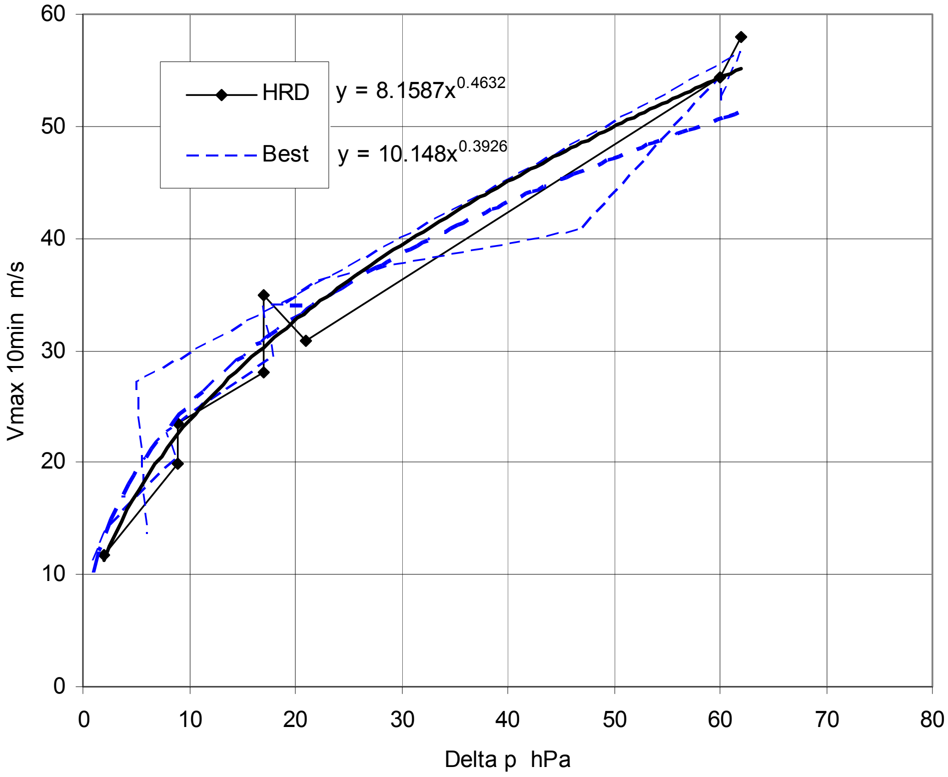


Figure D-3a Hurricane *Iris* October 2001.



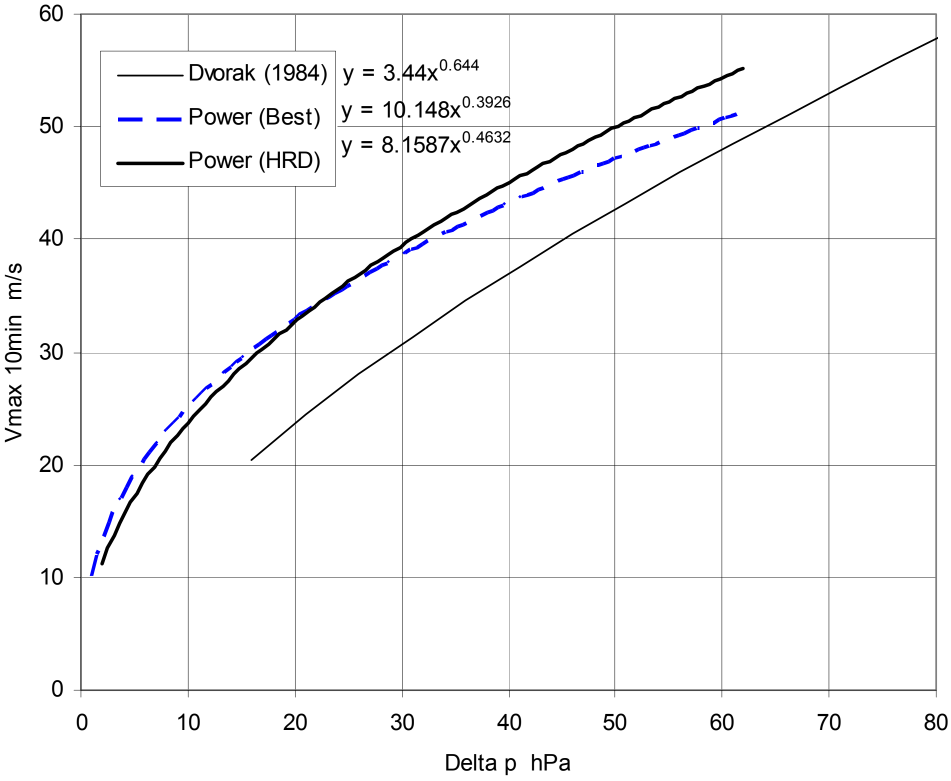


Figure D-3b Hurricane *Iris* October 2001.

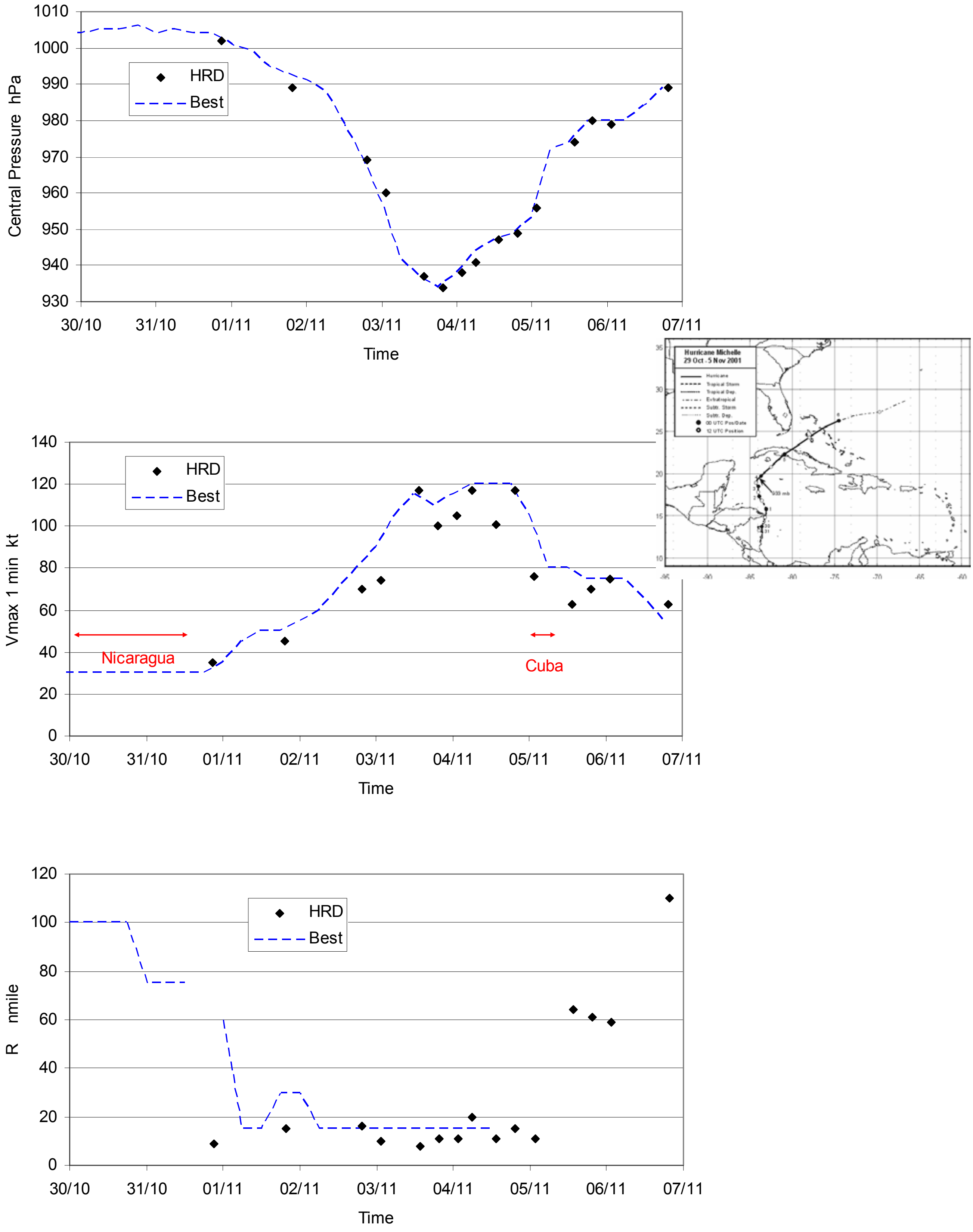
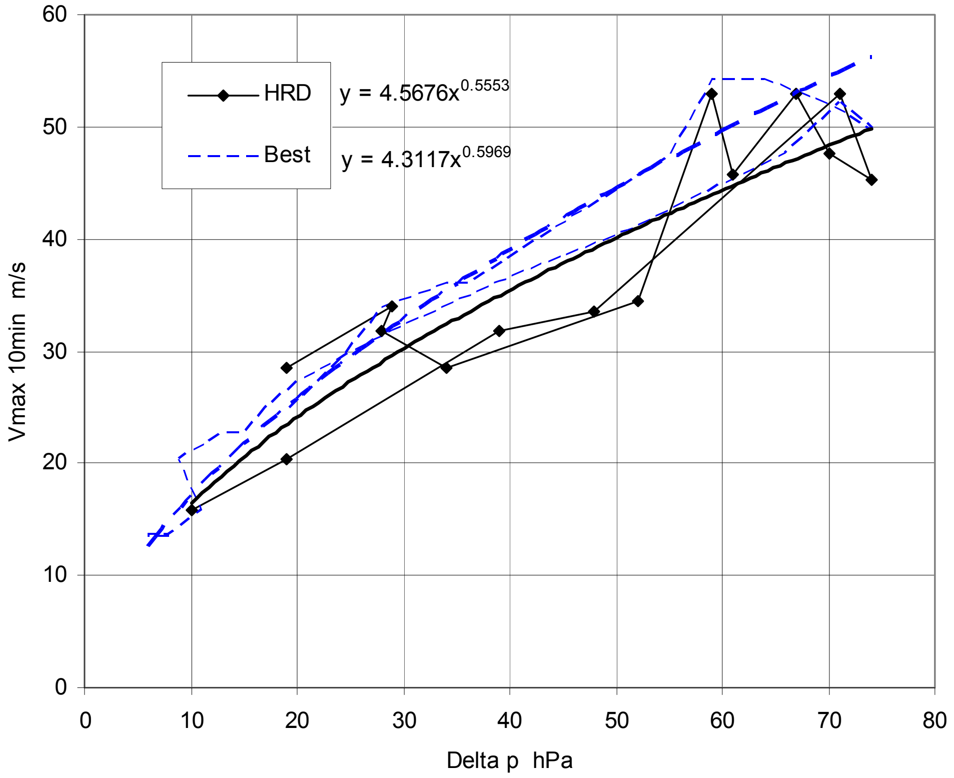


Figure D-4a Hurricane *Michelle* October 2001.



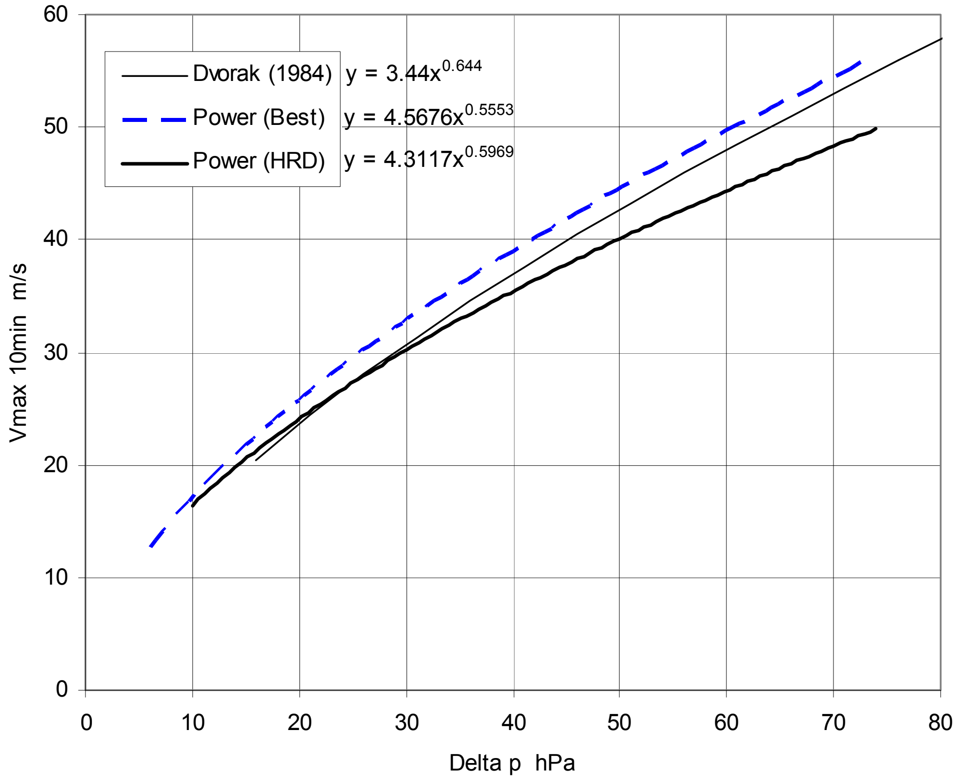


Figure D-4b Hurricane *Michelle* October 2001.

Appendix E Notes on Vertical Wind Profile Assumptions

E.1 Background

Previous assumptions about the vertical wind profile within tropical cyclones have been based on a variety of theoretical approaches (e.g. Powell 1980) considering the relationship between aircraft measured data at various levels and surface winds, combined with accumulated surface data measurements (e.g. Powell and Black 1989). These and other influential studies have led to increasing sophistication in the treatment of estimates of surface winds from a range of sensor inputs (e.g. Powell *et al* 1991, Powell and Houston 1996). One of the important aspects of this development has been the attention given to the need to adjust the many different wind estimates to a standardised exposure and averaging period framework (e.g. Powell *et al* 1993, 1996). While the case of landfalling storms perhaps represents the greatest challenge, the present focus is on open ocean conditions where a more homogeneous surface condition can typically be assumed. Notwithstanding this, the ocean surface responds to the imposition of high winds by presenting a time-varying roughness, about which knowledge is still rapidly increasing.

The relatively recent availability of GPS dropwindsondes (Hock and Franklin 1999) has significantly improved the vertical spatial (approx. 5 m) and temporal (2 Hz) resolution of wind soundings within tropical cyclones. Data from the first three years of deployments (Atlantic hurricane seasons 1997-1999) was presented by Franklin *et al* (2000) and the implications from those initial analyses have been used to amend the earlier surface wind analysis algorithms used by the US NOAA Hurricane Research Division (Dunion and Powell 2002). A more detailed analysis of these data sets has been submitted for publication (Franklin *et al*, to appear) and an advance copy was kindly provided by James Franklin of the NOAA Tropical Prediction Center to assist in this review.

GPS dropwindsondes are small expendable cylindrical sensor packages (70 mm diameter; 410 mm length; 400 g) containing a range of thermodynamic sensors and with GPS (Global Positioning System) spatial locating capability. They can be rapidly deployed from aircraft at a variety of levels (typically at or below 3000 m or 700 hPa level) and descend under parachute control at a rate between 10 to 12 ms^{-1}. The GPS position sampling enables calculation of vertical and horizontal position, speed and acceleration. The speed is adjusted for the inertial lag of the instrument and various quality control checks are applied (refer Hock and Franklin 1999). The claimed absolute accuracy of the wind measurement is 0.5 to 2.0 ms^{-1}, with the ability to measure speed within the last 10 m before surface splashdown (although actual near-surface data yields are much reduced).

The importance of the vertical wind profile assumptions to this review are:

(a) to enable a consistent adjustment of selected aircraft flight level data to the surface, and
(b) to provide the basis for selecting a suitable gradient-to-surface wind adjustment factor K_m

E.2 GPS Dropwindsonde Data

The 3 years of data are presented in some detail by Franklin *et al* (to appear), representing 630 vertical profiles from 17 tropical cyclones in the Atlantic and Eastern Pacific regions. About 68% of the profiles are classified as being within the hurricane eyewall region, the remainder within 300 km of the storm centre. A number of examples of single profiles are presented to illustrate the variability that is possible within an individual storm, sometimes within quite close launch times. This is explained partly by the spatial separation of sondes at launch as well as the turbulent scales of motion, the long drop path and also the inward sloping eye wall ($r<R$). To eliminate some of

these spatial alignment and smaller time scale effects and provide a reasonable basis for generalised reasoning, the eyewall profiles were further stratified to remove inner-eyewall cases and then averaged separately for the eyewall and outer vortex cases. This reduced the data set by about 50% overall and the results were then normalised by the 700 hPa level wind speed (either obtained from aircraft or the sonde itself). The results of this analysis are shown in Figure E-1, sourced from the version of Franklin *et al* (2000) accessible from the internet.

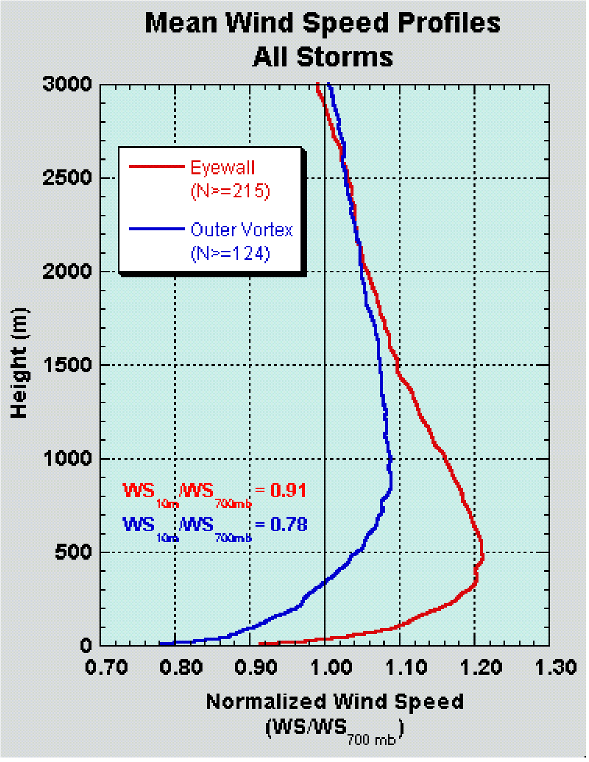


Figure E-1 Mean vertical wind speed profiles (from Franklin *et al* 2000)

The results show that for the eyewall class, the maximum wind occurs at around 500 m above the surface and takes the form of a pronounced "jet-like" feature which is about 20% stronger than the reference winds at 700 hPa (or 2900 m). In contrast, the outer-vortex class shows a much broader, slightly higher (1000 m) peak which is about 10% stronger than the reference speed. Importantly, the +10 m "surface" reduction factor differs from 0.78 for the outer-vortex case to 0.91 for the eyewall case. It is concluded by the authors that the outer-vortex results are consistent with the recommendations arising from earlier studies (e.g. Powell 1980; Powell and Black 1989) where the datasets were predominantly from non-eyewall situations. The increased surface winds possible within the eyewall, however, represent a mean 17% higher condition within this narrow region of highly-destructive winds.

E.3 Adjustment of Flight Level Winds to Surface

The implications of these results for the present review are that Figure E-1 has been used to adjust all flight-level reported winds to equivalent surface values, based on the eyewall case. The majority of the quoted wind measurements are from the 700 hPa level but some other levels are also used. The eyewall class is used because all the measurements of interest here purport to be attempts to measure the maximum wind speed in the storm. In addition to application of the height adjustment, it has also been necessary to interpret the applicable averaging period of Figure E-1. This is a contentious issue from a number of viewpoints. Franklin *et al* (to appear) implies that the GPS dropwindsonde analysed-wind represents an averaging period of not longer than about 5 s (over a 50 m vertical sample). They acknowledge that any individual wind measurement from the sonde therefore "*should not be interpreted as a sustained (e.g. 1-min mean) wind*". However, Figure E-1 is the product of considerable averaging of these individual profiles from different storms and James Franklin (personal communication) suggests that "*the mean eyewall profile in the paper describes the mean relationship of winds from level to level, irrespective of the averaging time*". While a not unreasonable description, this also implies constant gust factors being experienced by the sondes over the vertical, which is not likely. Secondly, in terms of the practical application of Figure E-1, it is not always clear from some publications what the aircraft level wind averaging period is, although 10 s averages and 1 minute means are the most typically quoted and/or inferred. Also, the physical wind measurements by aircraft and fixed anemometers are not the same (refer for example Powell *et al* (1991) for some discussion etc).

The method developed at the NHC to rationalise these issues is to average any individual sonde's (5 s) wind speed over the lowest 500 m and call this the *Mean Boundary Layer* (MBL) wind, which has an implied averaging period of about 45 s, or nominally the 1 minute average. The *mean* ratio of the 10 m level (5 s) wind to this MBL wind obtained from all the data (0.80) is then used to perform the final adjustment for each storm, although the lowest 150 m is also considered separately. This compares to a ratio of 0.75 (0.91/1.21) taken across the MBL region directly from Figure E-1, implying an averaging conversion through this process of 0.94 (0.75/0.80).

The approach adopted here is to accept Franklin's advice, i.e. to enter the profile with flight level 1 minute averaged winds and adjust these to the surface as the 1 minute average. A nominal conversion of 1/0.88 is then applied to obtain the estimated 10 minute sustained surface wind.

E.4 Gradient to Surface Adjustment

Finally, Figure E-1 is interpreted in terms of the most appropriate gradient-to-surface wind reduction factor K_m for use in adjusting cyclostrophic winds to the surface via Equation 4. Together with an assumption of representative air density, this enables a Holland B value to be calculated for a given $V_{max} - \Delta p$ pairing, such as shown in Table C-1 and as plotted on Figure 4.4. This reduces to deciding what vertical level in the eyewall profile of Figure E-1 is representative of gradient balance and taking K_m relative to that level.

Franklin *et al* (to appear) implies that gradient balance exists immediately above the position of the low level maximum (nominally 500 m). However, the numerical modelling analyses by Kepert (2001) and Kepert and Wang (2001) argues that such low level jet features near the eyewall are implicitly super-gradient and that gradient balance is typically not restored until around 1.5 times above this maximum (Jeff Kepert, personal communication). It is useful therefore to consider the implications of these two approaches. For example, Figure E.2 reproduces Fig 10d from Kepert and Wang (2001), hereafter K&W, which shows the numerically modelled gradient-to-surface (+22.5 m ASL layer) reduction factor for the case of a nominal 970 hPa[1] northern hemisphere storm moving to the left at 5 ms^{-1}. This is the only result presented by K&W of a moving storm, but represents a typical average speed and intensity that could be reasonably representative of the Franklin *et al* dataset. Figure E.2 indicates a very significant radial and azimuthal variation in this factor, which reflects the correspondingly large changes in the K&W modelled vertical wind profiles. Franklin *et al* do not provide details of azimuthal variability in the sonde profiles but comment that the left-

---

[1] K&W apply a Holland pressure profile as the upper boundary condition to their model; taking p_n = 1010 hPa, at gradient level this was equivalent to Δp = 40 hPa, V_{gmax} = 39.3 ms^{-1}, R = 40 km, B = 1.3, λ = +15°.

right eyewall differences in the 700 hPa to surface factor were only about 4%, with greater differences in the outer-vortex region. The asymmetry is noted to be at least consistent with K&W, having a higher factor on the left-hand side.

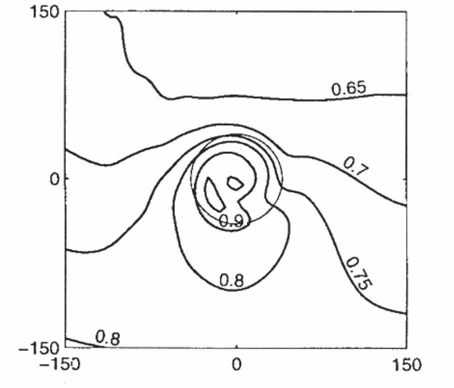


Figure E.2 Modelled example gradient-to-surface reduction factor from Kepert and Wang (2001). The storm is moving to the left at 5 ms^{-1} within a 300 km square domain. The centre circle indicates the radius of maximum winds of 40 km. The contours show the modelled surface-to-gradient wind reduction factor applicable to the lowest modelled layer of +22.5 m ASL.

In order to compare the K&W results with the Franklin *et al* data, it is appropriate to take an average reduction factor from Figure E.2 that could be considered to capture the likely “eyewall” class of sonde data. While Franklin *et al* do not give explicit limits to their eyewall class, it is perhaps reasonable to assume $0.8 \leq r/R \leq 1.2$. Taking the azimuthal average over this range from Figure E.2 (via a linear interpolation of the digitised surface) yields a factor of 0.825, which is quite similar to the azimuthal average at $r=R$. Since the model delivers a +22 m surface wind a further reduction of 0.90[2] is assumed to reduce to a nominal 10 m level. This results in an “average” K_m of 0.743 from the model results broadly applicable to the region sampled by Franklin *et al*. It should be noted that the K&W result near the sea surface is sensitive to the adopted Charnock coefficient, which is not well known in these extreme conditions.

By way of comparison with the dropsonde data, using this K_m in Figure E.1 to estimate the level of gradient balance yields WS/WS_{700} of 0.91/0.743 = 1.22. This is functionally equivalent to the Franklin *et al* definition of the gradient balance level being at the top of the jet maximum, i.e. a K_m of 0.91/1.21 = 0.752. The fact that these two approaches yield a similar estimate in this case makes the decision easier but is otherwise regarded as coincidental.

Accordingly, a nominal mean value for K_m of 0.75 is assumed here when relating gradient level to surface winds, although it is acknowledged that the K&W results suggest values as high as 0.8 are possible in specific regions of the eyewall. This value is somewhat higher than the speed-dependent range of 0.73 to 0.67 that has been used historically in Woodside hindcast and calibration studies (e.g. WOP 1990, 1992). All things being equal, use of a higher K_m will lead to lower *B* values being obtained during calibration studies.

---

[2] ISO (1996) yields 0.92 for 33 ms^{-1} at +22m; AS1170.2 (1989) yields 0.88 from +20m to +10m, Category 1-2, Regions C&D.