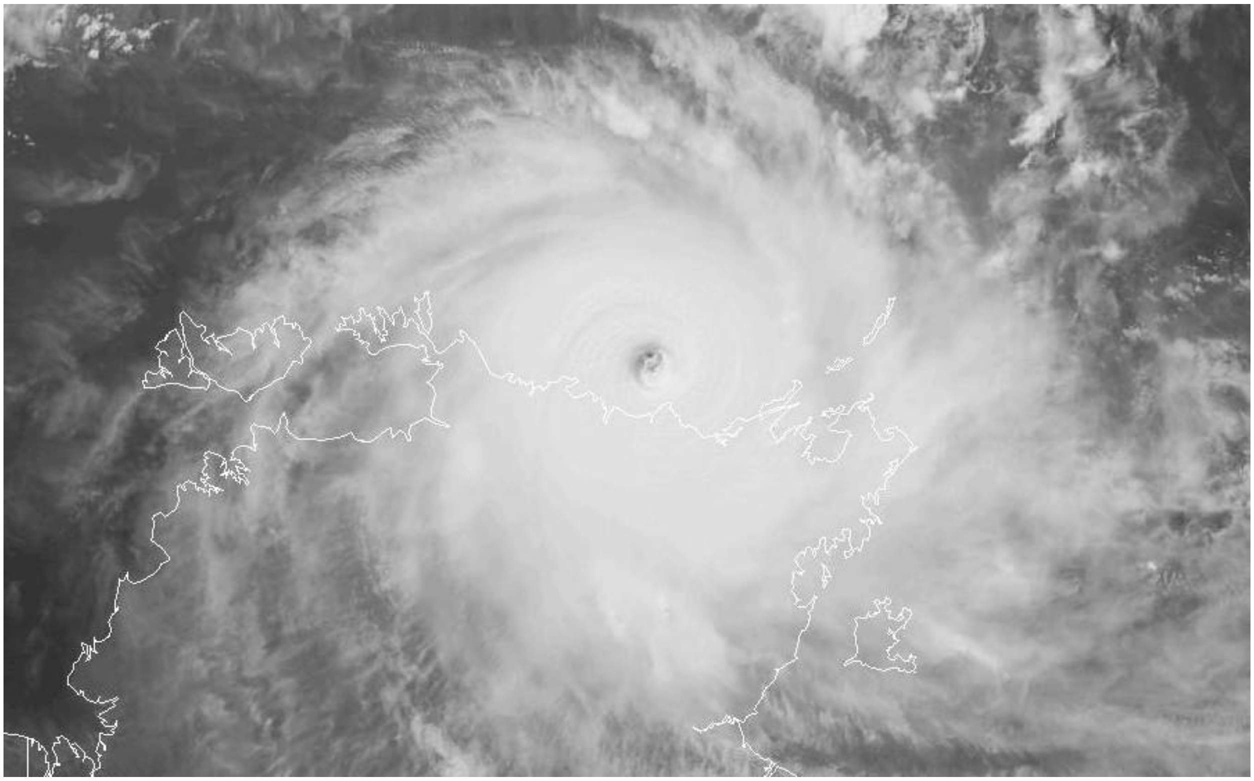
REVIEW OF NT CYCLONE RISKS



Cyclone Monica at 2 PM on 24th April 2006
Image Source   https://www.yoko.npmoc.navy.mil

A REPORT

Prepared by Mike Nicholls for:

Community Group for the Review of NT Cyclone Risks Inc.

March 2007

ACKNOWLEDGEMENTS

Thanks are given to the many people who have assisted with the project. Particular mention is made of the assistance provided by Mr. Geoff Garden and Mr. Ian Shepherd of the Bureau of Meteorology, Darwin; by Prof. Robert Wasson at the Charles Darwin University and Dr Patrick Baker at the Monash University.

Much credit must also be given to the members of the Community Group of the Review of NT Cyclone Risks Inc, who have attended meetings, assisted with administration and provided invaluable assistance in reviewing and editing the final report.

COPYRIGHT

DISCLAIMERS

The Group and the Australian Government make no representations about the suitability of the information contained in this document or any material related to this document for any purpose. The document is provided ‘as is’ without warranty of any kind to the extent permitted by law**.** The Group and the Australian Government hereby disclaim all warranties and conditions with regard to this information, including all implied warranties and conditions of merchantability, fitness for particular purpose, title and non-infringement. In no event shall the Group or the Australian Government be liable for any special, indirect or consequential damages or any damages whatsoever resulting from the loss of use, data or profits, whether in an action of contract, negligence or other tortious action, arising out of or in connection with the use of information available in this document. The document or material related to this document could include technical inaccuracies or typographical errors.

The views and opinions of the writer of this report do not necessarily state or reflect those of individual members of the Group or of the contributors of Appendices J and L of this report. (Appendix J was contributed by Dr Patrick Baker of Monash University. Appendix L was contributed by Prof. Robert Wasson of Charles Darwin University.)

The opinions, findings and recommendations contained in this report are not, and should not be taken to be, those of the Australian Government. The Australian Government should not, through its funding of this project, be taken to endorse or support any aspect of this report. The Australian Government had no role in the development of this report other than funding it through Australian Government Local Grant Scheme (2005 – 2006)

CONTENTS

Page

APPENDICES

FOREWORD

This report deals with the likelihood of an intense cyclone occurring but not the physical consequences of or measures required to mitigate the effects of such events. It questions the currently accepted methods used to determine the risk for the NT coast from intense cyclones. As a result, it concludes that the risk of an intense cyclone impacting Darwin is seriously underestimated. It recommends that the risk values currently used be urgently reviewed in the light of the above findings. If this conclusion is confirmed then current building standards for dwellings and shelters and disaster response plans will require substantial review. The main report is a presentation of the conclusions and includes supporting arguments. The appendices provide more detailed technical discussions in support of the arguments in the main report.

The results presented in this report are 'ball park' estimates using raw data and then common sense is used to arrive at the conclusions. Engineers routinely use such 'back of the envelope' calculations to check that results arrived at using more complex methods do in fact make sense. (I recall that when electronic calculators came into common use, rough manual calculations were often utilised to make sure that the electronic results were realistic). This approach can be quite useful to identify potential flaws in the methods and assumptions used in more complex methods - as this report amply demonstrates.

The report suggests there may be flaws in:

- Elements of the records used;
- The interpretation of the record; and,
- The current understanding of cyclone behaviour and characteristics in the Darwin Region.

Also, the period of record commonly used for determining the risks is very limited. It is suggested that natural and cultural records (tree rings, sediment analysis, contemporary written & anecdotal evidence, etc.) be used to extend this record. This approach may identify a more realistic pattern of intense cyclone frequency and severity along the NT coast.

It is further suggested that current government funding for studies and mitigation measures is woefully small compared to the potential costs associated with an intense cyclone strike on the NT coast in general and Darwin in particular. It recommends a significant increase in funding.

I am convinced that the evidence presented in this report supports the conclusions reached. Sufficient doubts have been raised to support the call for a comprehensive review of risks and the allocation of adequate funding to conduct the recommended investigations and research programs.

Herman Mouthaan

16th March 2007

1. INTRODUCTION

1.1 Project Background

This report was prepared by the Community Group for the Review of NT Cyclone Risks Inc. The object is to review cyclone risk for Top End coastal communities in terms of the likelihood of an intense cyclone impacting any particular locality. The detailed consequences of such an impact are not examined in this report.

KEY FINDING

The review has found that that the risk of a Category 5 cyclone impacting Darwin, or another NT coastal community, may be much higher than is currently provided for in government building codes and regulations.

Measures taken by governments to minimize or mitigate the immediate impact of a cyclone are obviously important. However the only aspect of mitigation examined here will relate to the further research that is necessary to make realistic estimates of the likelihood of a Category 5 impact. Furthermore, only the risks resulting from high winds or storm surge are reviewed**.** Flooding of major rivers in the Top End is also normally caused by cyclones but it is not examined here.

There are thirty-two coastal towns and communities and many more small out-stations along the Top End coastline. Their combined population is more than 150,000.

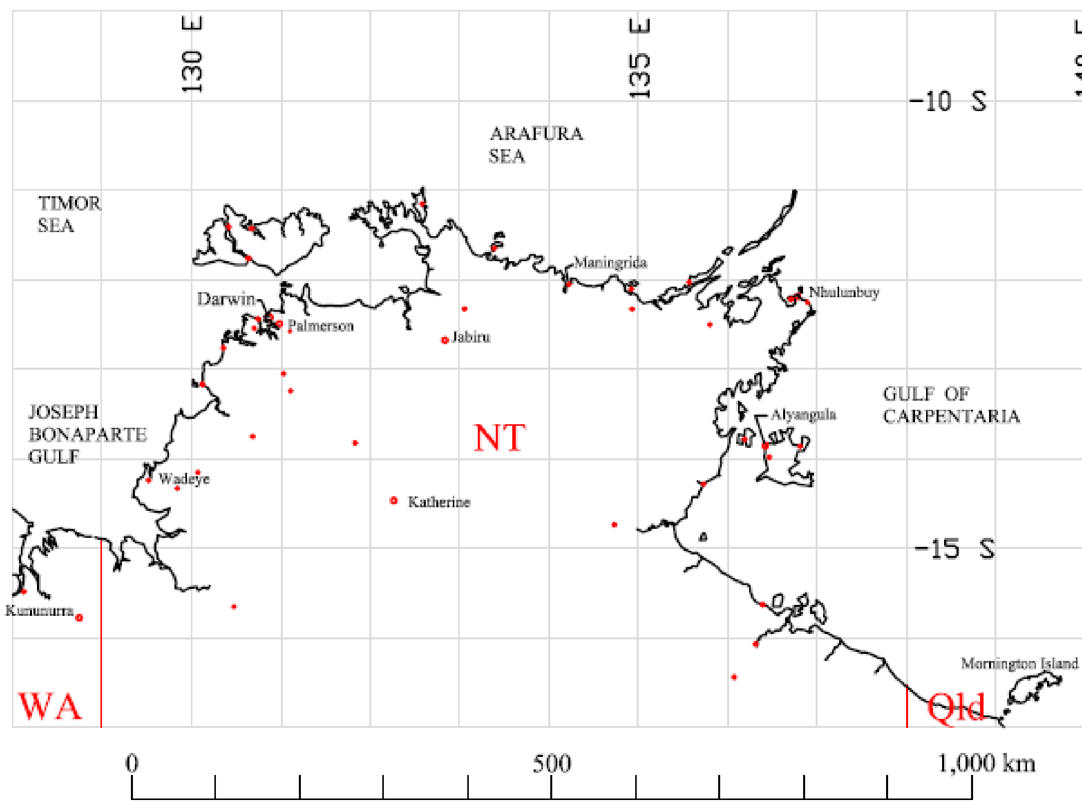


Figure 1.1 The Top End of the Northern Territory and adjoining coastlines of Western Australia and Queensland. Dots are towns & communities – those with populations more than 2,000 have been named.

The Greater Darwin Region has a population of 125,000 and this has meant that the report focuses mainly on that region. However, most of the findings will apply to all of the other coastal communities. In some cases, these communities are at greater risk than Darwin because of their more exposed locations geographically and their reduced standards of building maintenance.

Production of this report was stimulated by the recent succession of category 5 cyclones Thelma Ingrid and Monica. When Cyclone Monica made landfall near Maningrida last year, the maximum gusts were estimated at 350 kph. This intensity is higher than any ever previously estimated or recorded for a cyclone at landfall in Australia – such winds are completely beyond the capacity of buildings designed to the current building regulations.

This review does not claim to be a rigorous, scientific examination of all facets of the subject. It is presented with the objective of stimulating public and political support for the funding of a wide-ranging and in-depth research effort by government agencies, universities and consultants into resolving the issues of concern drawn attention to in this report.

The long term objective is that such research would resolve many of the issues and, if found necessary, lead to changes in policy and standards to better mitigate cyclone risk. Needless to say, such changes are better introduced in preparation for, rather than as a reaction to, an impact from an intense cyclone.

KEY RECOMMENDATION

The review recommends that for the next few years, Federal, NT and local governments jointly provide funding of at least $6 million per year to fully research the likelihood of a Category 5 cyclone impacting cities and coastal communities along the NT coast.

(It is only after that likelihood is determined with some confidence that other appropriate mitigation measures can be brought into effect with the full knowledge that the costs involved will be justified.)

Report Structure

Part 2 of the report examines records for the Top End which indicate that coastal communities will be impacted by very high wind speeds at much more frequent intervals than the building regulations provide for. In brief, the hazard appears to be under-estimated.
Part 3 is a compilation of the various recommendations made in previous sections of the report.
Part 4 is the bibliography.
Appendices A to O give more detailed and technical coverage of various issues.

1.2 Community Group for the Review of NT Cyclone Risks Inc.

The Community Group for the Review of NT Cyclone Risks Inc. (the Group):

- comprises twelve long term Darwin residents, most of whom had their houses collapse around them during cyclone Tracy. Several in the group have expertise in various fields related to this report.
- shares a concern that cyclone risk in the Top End may be under-estimated by the authorities and that consequently, public safety is being compromised.
- was formed in July 2005, and in April 2006, obtained a grant of $50,000 through the Australian Government's Local Grants Scheme to prepare and publish this report.

The writer of this report sub-contracts to the Group as its Project Manager. He is also the Group's Secretary.

1.3 The writer's background

The writer was a structural engineer but is no longer practising as such. For the fields of meteorology, climatology, paleotempestology and computer modelling for storm tide or wind risk the writer admits to being nothing more than an amateur. However he has spent at least twenty of the last thirty-five years taking an active interest in these various fields and in the last few years has read hundreds of peer-reviewed papers relating to them.

His first foray into trying to warn the public on cyclone risk was in 1974 when he co-authored a paper issued by the Darwin branch of the Institution of Engineers, Australia which sought funding from the government to research on and improve the then current provisions relating to cyclone risk in Darwin (Gamble et al, 1974). The report reached the minister for the Northern Territory under the Whitlam government one month before cyclone Tracy. The writer was subsequently involved in the official structural investigations following cyclone Tracy and in initiating the Deemed to Comply standards for Darwin

His second report on the matter was issued on his own initiative in 1990 following a decade-long absence from Darwin (Nicholls, 1990). The report reflected his concerns that lessons learnt from Tracy were being forgotten. It was a crude attempt at changing official attitudes and achieved little.

This third report on the subject was stimulated by a succession of category 5 cyclones which have affected Top End coastal communities, **T**helma in 1998, **I**ngrid in 2005 and **M**onica in 2006 - the "TIM" cyclones. These cyclones have brought realization that the chance of an impact from a category 5 cyclone has much higher probability than was previously only feared and that consequently the strategies to mitigate cyclone risk are even more inadequate than the writer warned was the case in 1974 and 1990.

1.4 Intended readership and method of presentation

To achieve the desired support for research funding, this report aims to inform and alert the public and politicians as to what is known and what is not known about cyclone risks and on the possible defects in current strategies to counter or mitigate the risks. The report is intended to be readily understood by the layperson and for that reason some liberties have been taken with the language. Also the units of measurement used in this report are those in common usage and are not normally those used by experts in the various fields.

For instance, structural engineers measure wind speed in metres per second. Amongst themselves, meteorologists measure wind speed in either knots or metres per second. This report will refer only to wind speed in terms of kilometers per hour (kph). Unless stated otherwise, the wind speed will be the maximum wind gust speed used by the **Bureau of Meteorology** (**BoM**) in their warnings and as used by structural engineers for building design. These maximum gusts are defined as those lasting only two or three seconds and which occur at a height of 10 m over water or flat, open land.

Other examples of the writer taking liberties in this report are:

- The Australian/New Zealand Standard which provides the minimum wind loads to be used for the structural design of structures will be called the "wind code". Its official title is "Structural design actions - Part 2: Wind actions AS/NZS 1170.2:2002"

- Some meteorologists think it is important to say "tropical cyclone" rather than just "cyclone". Here the "tropical" is implied in all references to cyclones

Cyclones are extremely complex and unpredictable phenomena - many aspects of their behaviour are only partly understood by meteorologists and climatologists. This report attempts to unravel some of the complexity and highlight the uncertainties. The more detailed and technical aspects of various subjects have been placed in Appendices. Where appropriate, these appendices are referenced within the main report so that the interested reader or an expert in the field can make a judgement on the validity of some of the findings.

One frustrating aspect of trying to understand cyclones is that the terminology and units of measure vary between different countries. In particular there are several different ways of defining wind speed and cyclone strength categories. Appendix A of this report gives conversion factors to convert the various ways that cyclone intensities are measured around the globe. The Australian media could usefully refer to such tables when they report on hurricanes in the USA. If they did, their reported wind speeds and strength categories might actually mean something to the average Australian.

Even the adjectives for cyclones, such as severe, strong or intense, create confusion:

- BoM define a "severe" cyclone as one having Australian Severity Category 3, 4 or 5
- A "strong" cyclone does not mean much at all – for instance it could refer to a very large sized Category 3 cyclone or a very small Category 4 cyclone
- **This report will only concern itself with "intense" cyclones - defined here as those having maximum gusts greater than 250 kph.** (It is a convenient demarcation in that 250 kph is the current design wind speed for most buildings in coastal areas of the NT. In Australian parlance, it corresponds to mid level category 4 upwards and in US parlance to base level category 4 upwards.)

Appendix B is a glossary of the technical terms and acronyms which by necessity will have to be used in this report. Where a technical term or acronym is used for the first time in the main report it will be in bold font. For instance **Sea Surface Temperature** (**SST**) introduces the acronym and the term being in bold font indicates that it will be briefly defined in the glossary. A more extensive definition of such bold-font terms will often be found by a search at http://en.wikipedia.org/wiki/Main_Page

1.5 What is meant by Risk?

(The answer to this question is more fully developed in Appendix C – the following is a summary of that Appendix.)

Risk is part of life but the word means different things at different times to different people depending on their beliefs, circumstances and life experiences. The risks we are concerned with in this report are those resulting from the impact of cyclones of various levels of intensity (the hazards) on any particular community. This risk can be thought of as having two parts:

- the likelihood of the hazard occurring
- the consequences of the occurrence

Engineers commonly measure the likelihood of a hazard occurring in terms of the **Average Recurrence Interval** (**ARI**). If the ARI = 100 years, then we have the 1 in 100 year flood or cyclone impact or whatever. (ARI used to be termed the "Return Period" but the new loading codes replaced the term because it gave the false impression that there was some regularity in the occurrences.)

To confuse things further, the **Building Code of Australia** (**BCA**) measures the likelihood of occurrence in terms of the **Annual Probability of Exceedance** (**AEP**).

Fortunately, AEP and ARI are really the same thing – one is just the reciprocal of the other so that AEP = 1/ARI. If for example, a hazard has an ARI of 100 years, then it will have an AEP of 1/100 per year or 1% per year or 0.01 per year – however one wants to express it. (In this report AEP will always be expressed as a fraction. Many people prefer to think in terms of the Average Recurrence Interval (or Return Period) and the relevant figure remains in view if a fraction is used.)

To include the consequences of the hazard into the notion of risk, requires a definition such as given at http://www.ga.gov.au/urban/factsheets/risk_modelling.jspf by Geoscience Australia:

RISK = Hazard * Elements at Risk * Vulnerability

As the formula makes clear, the consequences of a hazard occurring can be considered as the product of the two terms, 'elements at risk' and 'vulnerability'. It should be noted that in order to reduce 'vulnerability' in a cost effective manner it is necessary to know the likelihood of the hazard occurring. Many of the recommendations in this report have that objective.

This formula is used in Appendix C to illustrate how:

- persons or communities in the Top End could be at 20 times the risk of death or injury from Category 5 winds compared to their equivalents in Port Hedland, WA or Townsville, Qld

- Because at least half of the NT population is at risk from Category 5 winds, on a state or territory wide basis, the risk for the NT as whole is at least 100 times greater than it is for WA or Qld.

These figures are alarming but they need to be kept in perspective. Socially accepted things such as tobacco smoking and road vehicles are many times more dangerous to us than cyclones. Historically, there have been 50 deaths on land from cyclones in the NT in the last 50 years - the number of fatalities from traffic accidents in Darwin and the other NT coastal communities in the same period would be more than 20 times that number. And if death from disease is included into this morbid survey, the biggest single preventable cause of death which we should worry about is tobacco smoking - it kills more than 19,000 Australians each year.

Cause of preventable or accidental death in Top End coastal communities.	Estimated average deaths per 100,000 population / year
Cyclones with "adequate" mitigation	1
Cyclones with current mitigation	3
Road accidents at current levels	10
Tobacco smoking at current levels	100

Table 1.1 Estimated future, average fatalities per year from cyclones, road accidents and tobacco smoking in Top End coastal towns and communities.

As already stated, this report will concentrate on the risks from cyclones to persons rather than property. But at the same time, it is realized that it is the adverse effect that natural disasters have on the economy rather than issues relating to public safety that tend to determine how much money governments will spend to mitigate the risk of natural disasters. Tables C3 and C4 in Appendix C give the relative, historic costs in Australia for the seven main natural disasters – cyclones, floods, severe storms, earthquakes, bushfires, landslides and tsunami. The tables show:

1. In the last century, for the whole of Australia, cyclones caused 32% of the total building damage from natural disasters, the next worst were floods, severe storms and bushfires which each caused approximately 20% of the total damage (RiskFrontiers – Macquarie Uni.).

2. For the NT, for the period 1967 – 1999, the annual average damage cost from <u>cyclones</u> was $134 million. (Economic Costs of Natural Disasters in Australia, Bureau of Transport Economics, Canberra 2001). This was 94% of the cost of all NT natural disasters. River flooding, which usually stems from cyclones anyway, caused most of the remaining 6%. (Bureau of Transport Economics, 2001)

3. For the period 1967 – 1999, the average <u>annual</u> cost of all natural disasters was:
   - For the whole of Australia: $1,087 million or $54 per capita.
   - For the whole of the NT: $143 million or $713 per capita

   This also means that 13.2% of Australia's natural disaster costs occurred in the NT.

1.6 Initiatives by governments to mitigate natural disaster risks

In the following discussions, it should be borne in mind that there are two phases to mitigation. The first phase is to make realistic assessments of the likelihood of the hazard occurring. The second phase is to implement a range of practical measures to reduce the consequences of the hazard if and when it occurs. As stated on page 1, this report is primarily concerned with the first phase of mitigation – however in the following, 'mitigation' will refer to both phases.

In recent years there has been increasing awareness of the need to reduce the unnecessarily high cost of natural disasters to the Australian economy and on the need to coordinate the various departments and agencies at all levels of government which are involved in the management of natural disasters.

In mid 2001, the **Council of Australian Governments** (**COAG**) commissioned a wide-ranging review of natural disaster relief and mitigation arrangements in Australia. The recommendations contained in ***Natural Disasters in Australia: Reforming Mitigation, Relief and Recovery Arrangements, August 2002***, (**COAG Review Report**) were endorsed in principle by COAG in December 2003. The COAG Review Report recommended fundamental structural reform and a new approach to natural disaster management in Australia. Central to the new approach is a systematic and widespread national process of disaster risk assessments and a fundamental shift in focus towards cost-effective, evidence-based disaster mitigation – a shift beyond disaster response and reaction, towards anticipation and mitigation. The report is available for download at: http://www.dotars.gov.au/disasters/publications/pdf/natural_naturaldis.pdf

The Australian Government aims to achieve this reform with a range of initiatives, of which the **Natural Disaster Mitigation Program** (**NDMP**) is a key component. All three levels of government may be involved with the funding under this program with the Australian Government generally contributing one third of approved project costs. A reduction or waiver of the local agency contribution may be made where low capacity councils or remote indigenous communities would otherwise be precluded from participating in the program. (Given the small budget of the local government councils in the Darwin Region in comparison with the NT government budget, it would seem that the Darwin Region should also qualify under these provisions for cyclone related projects.)

NT government departments, local governments and indigenous community councils having responsibility for disaster management and disaster mitigation works are eligible to apply for funding under the NDMP. Approved projects predominantly encompass: disaster risk assessments; nationally consistent data and research; disaster mitigation strategies; resilient infrastructure; and community awareness and warnings.

The NDMP is a five year program which got under way in 2003/2004 and will end in 2007/2008. Over this period, the NT government will have received about 3.5% of the Australian Governments total funding under the scheme – significantly less than the 13.2% mentioned previously as being the NT's proportion of national disaster costs in the period 1967 - 1999.

In the NT, the NDMP operates in conjunction with the older, Regional Flood Mitigation Program (RFMP). Over the period, 2003 – 2008, approximately $7 million of combined government funds will have been expended in the NT on disaster mitigation programs under combined NDMP/ RFMP funding. About $5.5 million has been spent on river flood mitigation projects and the remainder on a bushfire management project for seven remote communities. Amazingly, even though on average cyclones cause more than 90% of natural disaster costs in the NT, nothing has been spent on cyclone (wind + storm surge) mitigation projects.

How much should governments spend annually on cyclone mitigation for the NT?

One way of obtaining an estimate is to assume that spending to mitigate disasters should be proportional to the cost of the disasters and use some of the figures from the preceding page:

- Expenditure by all levels of government on all natural disaster mitigation in the NT over the five year period of combined NDMP/NFMP funding will be about $7 million or an average of $1.4 million per year

- These amounts represent about 3.5% of the national totals. But, on average, the NT contributes 13.2 % of Australia's natural disaster costs

- Cyclones have contributed 94% of the NT's natural disaster costs.

Therefore, combined government expenditure on cyclone (wind + surge) mitigation in the NT should be: $1.4 million x 13.2/3.5 x 94/100 = **$5 million per year.**

Another way of obtaining an estimate is to assume that the amount spent by governments to mitigate cyclones in the NT should be proportional (on a disaster cost basis) to the amount spent by governments to mitigate natural disaster nation wide:

- The combined state, territory and commonwealth expenditure on natural disasters for the years 1999 -2001 was $1,828 million with 40% being spent on relief & recovery, 47% on preparedness and response and 11% on mitigation. (1)

(1) Derived from Table 1 of the COAG report, *Review of Natural Disaster Relief and Mitigation Arrangements – Government Expenditure Analysis (1999/00 and 2000/01*).
http://www.dotars.gov.au/disasters/research/coag_report/pdf/govt_expenditure_analysis.pdf

- From the second paragraph on page 6, the annual average damage cost for NT cyclones over the period 1967 – 1999 was $134 million. For this exercise, it is assumed that in the future, half of this average annual damage cost will be met by expenditure by governments and half by the private sector.

Therefore, combined government expenditure on cyclone (wind + surge) mitigation in the NT should be: 11/100 x $134 million x ½ = **$7 million per year.**

From the two sets of calculations above, it seems that combined government spending to mitigate cyclones in the NT should be about $6 million per year.

If the annual amount should be about $6 million, how much is being spent?

As stated on the previous page, it would appear that nothing has been spent under the NDMP. However government funds are being applied in other ways, for instance last year:

- this review project was funded through the Australian Government's Local Grants Scheme
- a report was commissioned to review the storm tide risk in Darwin harbour
- another report was commissioned to study the structural adequacy of Darwin's public cyclone shelters

Also about $3 million per year is spent by the NT government to fund NT Emergency Services but this amount covers mitigation and preparedness-response for all types of natural disaster.

The writer estimates that the annual amount spent on mitigation for cyclone (wind + surge) effects (i.e. excluding river floods) from all levels of government in the NT would be **less than $300,000.**

Why the shortfall in funding?

If the somewhat dire findings in section 2 of this report are verified by subsequent research, the practical mitigation measures such as more and stronger public cyclone shelters, stronger houses etc, will be costly. But dollar for dollar, cyclone mitigation projects will provide more local jobs for a longer period than many of the big glamour projects that the NT has funded over the years. And, unlike things like the new parliament house or the railway line, there will actually be a positive financial return on the money spent.

It is sometimes said that every one dollar spent on mitigation will save four dollars when the disaster strikes. The problem with that saying is that we may have to wait 50 years for the pay-off. A more direct estimate of the return is given on page 24 of the COAG Review Report which states:

> *Additional investment in natural disaster mitigation by all three levels of government is conservatively estimated to provide a rate of return of 15 per cent.*

The prime objective of this report is to significantly increase present levels of government funding on researching cyclone risk. Many of the recommendations in this report lend themselves to be projects under the National Disaster Mitigation Program or its successor program. Hopefully, within a short space of time, the total annual expenditure by all levels of government on this first research phase of cyclone mitigation in the NT will be at least $6 million per year.

A significant proportion of this money should be directed toward basic research on cyclones in the lower latitudes and this would possibly be channeled through the Bureau of Meteorology Research Centre.

1.7 Past and current studies by NT government on cyclone risk

Although there appears to be a severe shortfall in the amount spent on cyclone mitigation, the NT Government has nevertheless been mindful of cyclone risk from wind and surge and over the years various government departments and the Territory Insurance Office have commissioned studies to examine different aspects of it. The reports of most of these studies are available at the NT Public Library but there are some that have never been released to the Public.

An important review of the structural adequacy and debris impact resistance of public cyclone shelters for the Darwin Region and for the coastal communities has been recently completed. The report is currently under review by the NT Department of Planning and Infrastructure. It is not known if or when the report will be made public.

Two of the most authoritative reports relating to the hazard component of risk were written by Dr Peter Georgiou.

- "Tropical Cyclone Storm Surge Risk for the Greater Darwin Region", (*VIPAC,1994*)
- "On the Probability of Darwin being struck by a Category 5 Cyclone"; Environment and Climate Risk Assessment (*Georgiou, 2000*)

Both of these reports are available for view at the NT Library. In general the findings were reassuring in that the surge risks for Darwin were more or less as indicated by previous surge studies and the risks from extreme wind speeds were close to the values assumed in the current wind code. Georgiou's risk study is referred to in various sections and appendices in this report and is examined in some detail in Appendix I

There has been a recent review of the storm tide risk (1) in the Darwin Region by SEA Pty Ltd of Brisbane (*SEA. 2006*). The study was commissioned by the NT Emergency Service. A written request for the Group to be involved in an interim review process for this study was refused. The report has been made public and presumably a copy will be placed in the NT Library. The SEA study found that storm tide risk in the Darwin region is significantly less than found in the1994 VIPAC report. This report presents evidence which indicates that the SEA report under-estimates the wind hazard and hence the surge hazard. The SEA study is referred to in various sections and appendices in this report and is examined in more detail in Appendix I.

It is recommended that all reports to government relating to cyclone risks in the NT should be made available for public inspection and be in a format enabling easy access and comprehension.

(1) Storm tide is the level reached by the <u>combination</u> of the storm surge height produced by the cyclone and the astronomic tide level. Storm tide is measured as an elevation relative to the ***Australian Height Datum*** *(**AHD**) whereas storm surge is simply a height measured in metres.*

2 PROBABILITY OF AN INTENSE CYCLONE OCCURRING

2.1 Engineering Estimates

(a) Summary
(b) From written records – 1824 to 2006, within 50 km of a settlement
(c) From satellite era records – 1974 to 2006 within 500 km of Darwin
(d) From the Wind Code used for building design
(e) From two recent reports to the NT Government
(f) Conclusions and Recommendations

2.1(a) Summary

This section will present four different, engineering estimates for the probability of an intense cyclone impacting any single building in the Darwin region. The estimates are given in terms of either the AEP or the ARI for maximum wind gusts. (refer Section 1.4 for definitions)

The estimates in parts (b) and (c) are the writer's "ball-park" estimates (also known as back-of the-envelope calculations) which scientists and engineers should routinely make to provide a reality check on their results derived by complicated, computerized calculations.

The estimates in parts (d) and (e) are what could be termed the "official" engineering estimates. Part (d) describes the estimates as given in the wind code. Part (e) examines the estimates in the two most recent reports to the NT government relating to risks from extreme winds and from storm tide inundation in the Darwin region.

Part (f) concludes that the writer's estimates are near the mark and recommends ways of resolving what is a critical issue in the safe design of buildings and cyclone shelters in the NT and in the correct estimation of the risks from storm surge.

Tables 2.1.1 (a) and (b) following give the pessimistic and optimistic AEPs for the wind speeds impacting a single building as derived from the written records and the satellite era records for the Darwin region. The values are compared with AEP values from the wind code as detailed in part (d) following. (The current wind code has Darwin in Region C. Region D encompasses the coastline from Carnarvon to Port Hedland in Western Australia where design wind loads are 60% higher than for Region C.)

Probability as estimated by:	AEP for maximum gust speeds (Vg)		
	Vg >= 250 kph	Vg >= 270 kph	Vg >= 290 kph
the writer from the 'written record'	1/40 to 1/60 (1)	1/60 to 1/80	1/120 to 1/210
Wind code (Region C)	1/500	1/1,350	1/4,000
Wind code (Region D)	1/70	1/120	1/220

Table 2.1.1 (a) The AEP for three different maximum gust speeds as estimated by the writer from the 'written record' and as given by the wind code.

Note (1) The ranges 1/40 to1/60, 1/60 to 1/80 and 1/120 to 1/210 represent the ranges between optimistic and pessimistic scenarios – refer page 18 and Appendix G.

Probability as estimated by:	AEP for maximum gust speeds (Vg)		
	Vg >= 290 kph	Vg >= 324 kph	Vg >= 357 kph
the writer from the 'satellite era record'	1/160 to 1/800	1/240 to 1/1,200	1/470 to 1/2,300
Wind code (Region C)	1/4,000	1/37,000	1/600,000
Wind code (Region D)	1/220	1/650	1/2,200

Table 2.1.1 (b) The AEP for three different maximum gust speeds as estimated by the writer from the 'satellite era record' and as given by the wind code.

The findings of this section 2.1 are that Darwin should be in the wind code's Region D. The various tables showing this are summarised graphically in Figure 2.1.5 on page 27

2.1(b) Estimating from written records for the Darwin Region – 1824 to 2006

The details used to derive the estimated AEPs in Table 2.1.1 (a), page 10, are given in Appendix E. This part summarises the Appendix E methods and findings.

Only cyclones that affected settlements in the Darwin Region have been examined. The earliest written record is for the 1827 cyclone which devastated the newly established settlement of Fort Dundas, (at what is now Pirlangimpi), Melville Island.
The records from four, small settlements which were attempted prior to the establishment of Darwin in 1869 are included in the analysis. This inclusion means that there are effectively 158 years of records for cyclones that have come within a "single settlement".

Settlement	Location latitude, longitude (degrees)	Period	No. of cyclone seasons
Fort Dundas	-11.4, 130.4	Sep 1824 – Feb 1829	4.5
Fort Wellington	-11.3, 132.4	Jun 1827 – Aug 1829	2
Victoria	-11.3, 132.2	Nov 1838 – Nov 1849	11
Escape Cliffs	-12.1, 131.3	Jun 1864 – Jan 1867	2.5
Palmerston (now called Darwin)	-12.4, 130.9	Feb 1869 – Jun 2006	138

Table 2.1.2 Details of the five 'single settlements' included in the analysis of cyclones that have come within 50 km of such places in the Darwin region since European settlement.

Some people, scientists and statisticians in particular, have a problem with using records from five different locations to derive an AEP for a single location. The writer maintains that it is acceptable because:

- the AEPs for given gust speeds will be essentially the same for all five settlements
- these are engineer's "ball-park" estimates

The issue is further discussed in Appendix E. The writer maintains that the analysis is rigorous enough for its intended purpose – the only fault being the minor one that there were effectively two "single settlements" for the entire 1827/28 cyclone season and for the first half of the 1828/29 cyclone season.

The basic assumption in the analysis of the historic records is that an intense cyclone would have been detected and recorded if its centre came within 50 km of a settlement.
(In this report, an "intense" cyclone generates maximum gusts greater than 250 kph.)

To maintain parity, cyclones which would have required radio, aeroplane or satellite technology to detect have been precluded from the dataset.

The records in Big Blow Up North (*Murphy, 1984*) and subsequent BoM records indicate that there have been 14 cyclones coming within 50 km of a single settlement in the 158 years of record – on average, about one such cyclone every 11 years. However, if we consider only the intense cyclones, there were six in the first 90 years or say 1 in 15 years but only one (Tracy) in the last 70 years. These figures suggest that a significant, multi-decadal shift may have taken place circa 1940 in the climatic conditions that govern the frequency of intense cyclones.
The seven intense cyclones occurred in 1827, 1839, 1897, 1915, 1919, 1937 and 1974.

In Appendix E, the probable tracks of these cyclones are plotted and reasons given for denoting them as being either:

- mid-level Category 4 with gusts greater than or equal to (>=) 250 kph
- high-level Category 4 with gusts >= 270 kph
- low-level Category 5 with gusts >= 290 kph

Date	Category	Estimated Max. Gusts (kph)	Distance of cyclone centre from "single settlement" (km)
03/04/1827	Mid - Cat. 4	250	50
25/11/1839	Low - Cat. 5	290	15
07/01/1897	High - Cat. 4	270	45
23/12/1915	High - Cat. 4	270	25
06/03/1919	Low - Cat. 5	290	45
11/03/1937	Mid - Cat. 4	250	38
25/12/1974	High -Cat. 4	270	10
	Averages:	**270**	**33**

TABLE 2.1.3 Estimated maximum gust speeds and proximities of the seven intense cyclones that have come within 50 km of Darwin or its proxy "single settlement".

Derivation of Wind Speed – AEP relationships

To derive the AEPs in Table 2.1.1 (a), it was assumed that for all cyclones, the gusts being considered extended out to a radius of 19 km only. Two scenarios were proposed as representing the likely range for the frequency of intense cyclones entering the 50 km radius circle around Darwin:

- Optimistic Scenario: The Table 2.1.3 arrivals can be averaged over 158 years
- Pessimistic Scenario: Only the arrival frequency of the first six cyclones in Table 2.1.3 will represent arrivals into the immediate future – say over the next 50 years

As explained in greater detail in Appendix E, the above assumptions allow very simple, "ball-park" estimates to be made of the probability of a maximum gust impacting a single building. For example, for gusts >= 250 kph:

- AEP = 7/158 x 19/50 = 1/60 /yr for the optimistic scenario
- AEP = 6/90 x 19/50 = 1/40 /yr for the pessimistic scenario

The AEP estimates for wind gusts of 250 kph, 270 kph and 290 kph are given in Table 2.1.1 (a) and compared with the AEPs given by the wind code for Regions C and D.
Fig. 2.1.5 on page 27 presents the results graphically.

In Appendix E, the simple calculations used above are modified to allow estimation of the AEP for an impact on the whole of Darwin rather than on a single building. This was on the basis that Darwin (not including Palmerston) can be encompassed by a 7 km radius circle. The results for optimistic and pessimistic scenarios are summarised in the following table.

Target Area	AEP for maximum gust speeds (Vg)		
	Vg >= 250 kph	Vg >= 270 kph	Vg >= 290 kph
Single Building	1/40 to 1/60	1/60 to 1/80	1/120 to 1/210
Darwin (7 km rad.)	1/60 to 1/90	1/90 to 1/130	1/190 to1/330

Table 2.1.4 AEPs for impact on a single building and for all buildings in the whole of Darwin.

Track Directions and Storm Surge

Appendix E also examines the track directions of the twelve cyclones that have come within 50 km of Darwin. Track directions are important because of their effect on the surge heights produced in Darwin harbour. In general terms, cyclones heading into the south-east sector can produce surges between 30% and 70% higher in Darwin harbour than those heading into the south-west sector.

The most recent report to the NT government on storm surge (SEA, 2006) examined the tracks of all cyclones that have come within 500 km of Darwin between July 1959 and June 2006. Of the 100 cyclones examined for direction, only 4% had an easterly component in their heading when closest to Darwin. This probability was incorporated into the analysis as one of many components that produce estimated risks for the various storm tide inundation levels in Darwin harbour.

A previous report to the NT government on storm surge (VIPAC, 1994) examined the tracks of all cyclones that have come within 300 km of Darwin between July 1957 and June 1990. Of the 41 cyclones examined for direction, only 15% were heading into the south-east sector when closest to Darwin whereas 80% were heading into the south-west sector. These probabilities were also incorporated into the VIPAC analysis to estimate the risks of various surge levels in Darwin harbour.

The records of the 12 cyclones that have come within 50 km of Darwin since 1859 show a distinctly different trend to that assumed for the surge studies. All of the five intense cyclones had an easterly component in their track directions compared with five of the seven non-intense cyclones having a westerly component. A similar trend is found between pre-1940 cyclones (most tending to head easterly) and post-1940 cyclones (most tending to head westerly).

It is possible that the historic track directions related to a multi-decadal cycle which influenced both steering effects and cyclone intensity. The good news is that the last four intense cyclones that have come within 500 km of Darwin (Neville in 1992, Thelma in 1998, Ingrid in 2004 and Monica in 2005) were all tending westerly when nearest to Darwin.

Because of the direct correlation with surge risks, the possibility that the track directions and intensities of intense cyclones approaching Darwin may be influenced by multi-decadal cycles deserves in-depth research by meteorologists and climatologists.

The 1937 Cyclone

To demonstrate the way new information can be extracted from old records, the writer made a detailed study of the 1937 cyclone. Full details of that examination are in Appendix F. Briefly, the findings were:

- BoM's official track for the cyclone's approach to Darwin is almost certainly wrong
- the cyclone was slightly more intense than previously estimated by BoM
- the relevant chart in the VIPAC report and the writer's best track data indicates that the surge at Fanny Bay would have been about 1.9 m. However, eyewitness reports of inundation levels indicate that the surge was about 3.4 m
- the SEA report indicates that the observed inundation level equates to a 1 in 500 year event

Discussion

A caveat on the results obtained in Appendices E and F is that the estimation of the intensities for the cyclones can be questioned. Certainly, all seven cyclones require more extensive investigation than could be applied for this report. In particular, the observed surges for the 1839, 1919 and 1937 cyclones should be hindcast using modern surge simulation programs. The results should give a very good indication of the intensities of these three cyclones. If the computer runs fail to reproduce the observed storm tide levels then it may also give indication that the programs fail to accurately predict storm tides in the localities where the levels were measured.

Refer 2.1(f) for recommendations for future research.

2.1(c) Estimating from satellite era records for the Darwin region, 1974 to 2006

The details used to derive the estimated AEPs in Table 2.1.1 (b), page 11, are given in Appendix G. This part summarises the Appendix G methods and findings.

Data was extracted from a publicly available database (cyclones_newformat) provided by BoM at http://www.bom.gov.au/climate/how/ to derive a dataset of 49 named tropical lows and cyclones ('storms') sorted into three intensity groups. Because this report is only concerned with intense cyclones, the three groups were: tropical lows, non-intense cyclones [gusts < 250 kph] and intense cyclones [gusts >=250 kph, (above mid Cat 4 and Cat 5)].

The dataset gives details of each storm at its most intense stage of development when within 500 km of Darwin for the 32 year period July 1974 to June 2006. (Tropical lows that are inland for the whole time when within 500 km of Darwin have been omitted as not representing any sort of wind risk to Darwin.) July 1974 was chosen as the start date because, although the incidence and track locations of all systems were fairly reliably detected after about 1959, the current intensity estimates in the database are not considered even reasonably reliable until after 1974 when BoM began using the Dvorak technique.

The Dvorak technique allows experienced practitioners to estimate the maximum wind speed of a cyclone by analyzing distinctive cloud patterns and other data obtained from satellites. The endpoint of the satellite analysis is to obtain a so-called **Current Intensity** (**CI**) number. A good explanation of the technique and CI numbers can be found at http://en.wikipedia.org/wiki/Dvorak_technique

The intensity of a cyclone can be measured in terms of the pressure drop (ΔP) between the ambient pressure and its central pressure, or the wind speeds generated in the eye wall or its Severity Category number; or its Dvorak CI number. In the NT, the CI number is nearly always the basic measurement from which the other intensity measures are estimated. For this reason, most of the Appendix G analysis is in terms of CI numbers.

The relationship between CI numbers, the three intensity groups and gust speeds is:

- CI 1.5 to 2.5 = tropical lows with maximum gusts between 56 kph and 79 kph
- CI 3.0 to 5.5 = non-intense cyclones with maximum gusts between 103 kph and 234 kph
- CI 6.0 to 8.0 = intense cyclones with maximum gusts between 262 kph and 390 kph

(It should be noted that the mid-value between CI = 5.5 & 6.0 is 248 kph, so the above grouping is close to the previous definition of intense cyclones as having maximum gusts >= 250 kph.)

A histogram plot of occurrences against CI numbers for the 49 storms is shown Fig. 2.1.1 next page. The plot is significant because it does not accord with the theories normally used by engineers to relate intensity with frequency of occurrence. These theories assume that, given enough data, the line connecting the top of the bars in a histogram such as Fig. 2.2.1 will reach a peak and then taper off in a nice curve down to zero (or near zero).

The fact that the number of occurrences for the non – intense cyclones in the histogram is nearly constant at 5 and the number for the intense cyclones is nearly constant at 1 suggests that the probability distributions used by engineers may not reflect the distributions in nature.

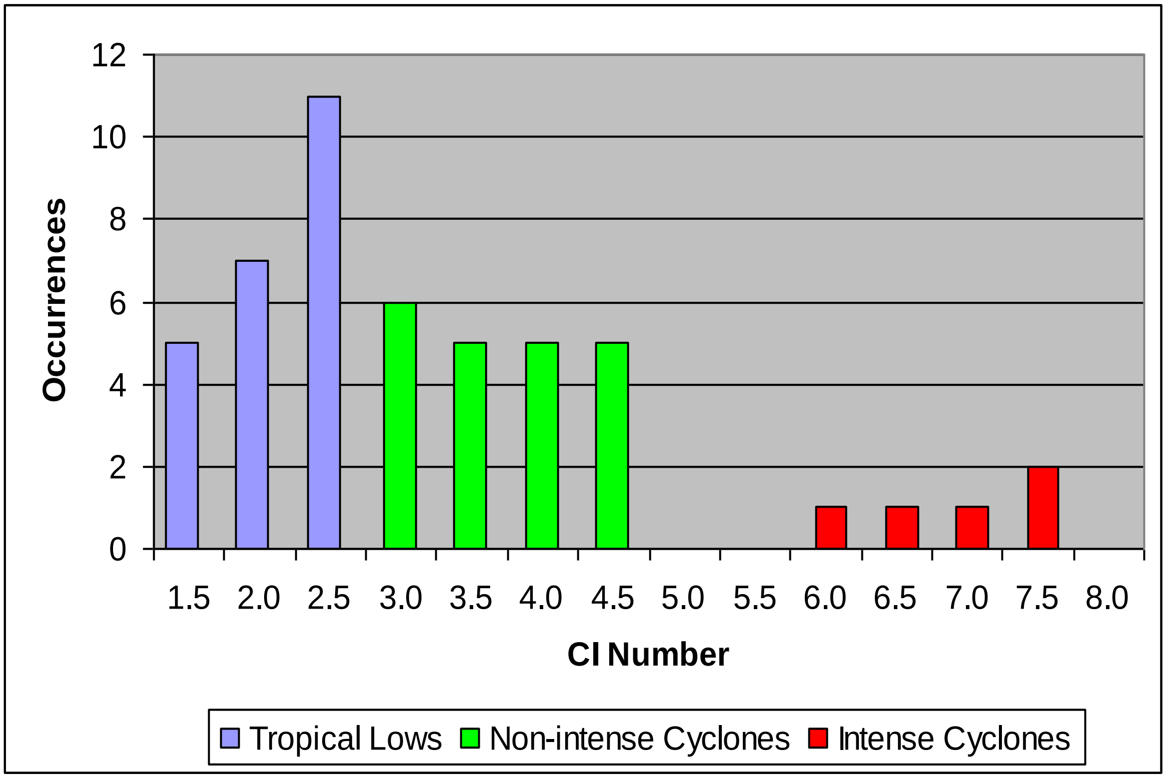


Figure 2.1.1 Histogram of Occurrences vs. CI Number for the 49 tropical lows and cyclones that have come within 500 km of Darwin over the 32 years between July 1974 and June 2006.

To analyse large sets of data, engineers and scientists use statistical functions called Probability Distributions which go by names such as the Lognormal Distribution, the Gumbel Distribution, the Weibull Distribution and the Pareto Distribution. These are all examined in Appendix G but the first two in much greater detail because:

- the report to the NT government that found that Region C in the wind code was appropriate for Darwin (Georgiou, 2000) assumed the intensities followed a Lognormal Distribution;
- the most recent report to the NT government on storm tide risk (SEA, 2006) assumed that the intensities could be obtained using a Gumbel analysis.

Appendix G goes to some lengths to demonstrate that because all of the conventional distributions assume a tapered "tail", then none of them will fit the data derived for this report. This is particularly the case for the Lognormal and Gumbel distributions. The use of an appropriate distribution is not just an academic debate – it is has a decisive effect on the results obtained by the computer model that will use it.

If for instance we are wanting to model the frequency that cyclones with CIs = 6.0, 6.5, 7.0 and 7.5 will impact some location and one distribution predicts that each has a 25% chance of occurring while another (one of the conventional, tailed distributions) predict 45% chance for a CI = 6.0 tapering down to say 10% chance for a CI = 7.0 then obviously very different risks will be obtained by the computer model.

The next question is - Why won't conventionally used distributions fit the writer's data ? There are several possible explanations:

.

1) The BoM "cyclones_newformat" database could be defective. It certainly is defective and needs fixing (see recommendations) but it is not the reason for the lack-of-fit. If anything, fixing the BoM database will make the problem worse because the revisions will tend to increase the intensities of the cyclones on record.

2) The writer's derivation of CI values from the BoM pressure data could be defective. The writer's data has not been checked but it should be accurate – it certainly will be for the intense cyclones.

3) The period of record could be too short to draw any definite conclusions from the data. This is the case regardless of the distribution used to model intensities. For this report, the writer attempts to overcome this difficulty by using the data to derive an optimistic and a pessimistic scenario so that the hazard presented by a given wind speed is presented as a range rather than a single figure.

4) The intense cyclones could belong to a different statistical population to the non-intense cyclones. Recent research indicates that this is the case (Emanuel, 2003). A study of the data obtained from GPS dropsondes (Powell et al, 2003) also provides a possible physical explanation for the fact that there are no cyclones with CIs = 5.0 or 5.5 in Fig.2.1.1.

5) There are some other statistical distributions which will fit the data for intense cyclones. There is and that distribution is apparent in Fig. 2.1.1 – namely that in the Darwin region, there is an equal chance of a cyclone attaining a CI = 6.0, 6.5, 7.0 or 7.5. This rather obvious conclusion was verified in a study of 56 North Atlantic hurricanes post 1958 and 73 western North Pacific hurricanes post 1970 (Emanuel, 2000). That study also predicted that there will be an equal (but greater) chance for occurrences for non-intense cyclones – also as indicated in Fig. 2.1.1.

Derivation of Wind Speed – AEP relationships

To derive the AEPs in Table 2.1.1 (b), on page 11, it was assumed that for all cyclones the gusts being considered extended out to a radius of 19 km only.

Two scenarios were proposed as representing the likely range for the frequency of intense cyclones entering the 500 km radius circle around Darwin:

- Optimistic Scenario: an intense cyclone will enter on average once every 11 years
- Pessimistic Scenario: a category 5 cyclone will enter on average once every 3 years

As explained in greater detail in Appendix G, the above assumptions allow very simple, "ball-park" estimates to be made of the probability of a maximum gust impacting a single building. For example, for gusts >= 290 kph:

- AEP = 19/500 x 50/100 x 3/44 = 1/800 for the optimistic scenario
- AEP = 19/500 x 50/100 x 3/9 = 1/160 for the pessimistic scenario

The AEP estimates for wind gusts of 290 kph, 324 kph and 357 kph are given in Table 2.1.1 (b) on page 11 and compared with the AEPs given by the wind code for Regions C and D. Refer also to the graphical representations in Fig. 2.1.5 on page 27.

Discussion

Without further research, there is really no way of knowing whether the writer's optimistic or pessimistic estimates will prove to be more accurate in the long term. Two conclusions are:

- Even the optimistic scenario above predicts wind speeds for a given AEP which are well in excess of the values predicted in the wind code for Darwin and in the most recent studies for the NT government relating to design wind speeds and storm surge inundation heights for the Darwin region

- Until further research throws light on the matter, the pessimistic scenario should be assumed for decisions relating to emergency management and provision of cyclone shelters.

2.1(d) Estimates in the current Wind Code (AS/NZS 1170.2:2002)

This part will examine:
1) the different wind regions in the wind code and the design wind speeds for Regions C & D
2) how the design wind speeds have been derived and how the they have varied over the years
3) how design loads have varied over the years for typical houses in Darwin
4) how the wind code allows for weakening after landfall and recent research on the subject

Topic 1) is examined in some detail on the following three pages.
Topics 2) and 3) are demonstrated only briefly on pages 22 to 24 but are examined in detail in Appendix D.
Topic 4) is examined briefly on pages 24 and 25 and in detail in Appendix H.

It is obviously desirable that the design wind speeds used in the wind code are equivalent to the wind speeds that meteorologists use in their public cyclone warnings. BoM call their speeds "maximum gusts" and the wind code refers to them as **Regional Wind Speeds** (**RWS**) but they both refer to maximum gust speeds at 10 m height over water or over open terrain such as large airports. The only minor difference is that meteorologists refer to the gust duration as being two seconds whereas the current wind code refers to three second gusts. That one second difference makes only a 2% or 3% difference in theoretical values – the difference will be ignored in this part.

For the following, it will be assumed that there is equivalence between BoM speeds and the wind code speeds.

1) The Wind Speed Regions (RWS) and typical values for Regions C and D

Region A covers all of Australia except for some strips running around the northern 2/3rds of the coastline. In region A the maximum winds generally come from thunderstorms and possibly gales in Tasmania. (The code specifically excludes consideration of tornados because they only cause very narrow swathes of wind damage and usually occur in only sparsely populated areas.)

Region B is an intermediate zone which is mainly the 50 km wide strip inland from the "cyclonic regions" but it is also a 100 km wide coastal strip that extends some distance south of the cyclonic regions. It is particularly important because it includes Brisbane. The winds in Region B are caused by cyclones but are of reduced strength and are not referred to as being "cyclonic".

Regions C and D are termed the "cyclonic regions". Region D is the 50 km wide coastal strip that extends up the WA coast from Carnarvon to Port Hedland. Region C is the 50 km wide coastal strip that extends from just north of Port Hedland all the way to Darwin and on around Cape York and down to Bundaberg on the Queensland coast. Region C also extends adjacent to Region D from 50 km to 100 km inland.

As far as the wind code is concerned, over a given period, everywhere in a particular region is at an equal risk of being impacted by winds of a certain strength assumed to be typical for that region. As one might expect, the wind speeds increase in strength from Region A to D.

The RWS for different values of the ARI are given in Table 3.1 of the current wind code. The values are in accordance with a formula which takes the form:

$$V_{(ARI)} = F \times [C_1 - C_2 \times (ARI)^{-0.1}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

(Values for F, C_1 and C_2 are given in the wind code – they vary from region to region.)

The BCA and AS/NZS 1170.0:2002 (General Principles) establish the minimum ARIs that must prevail for different types of loads (wind load, earthquake load, etc.) for different types of buildings and different periods for the design working lives.

To keep things simple here, consideration will be given to the RWS for only four types of building with only a 50 year design life in only the two cyclonic regions and assuming that the minimum value of the ARI permitted in the regulations has been selected for the designs.

Building Types	Minimum required ARI for the RWS (years)	RWS (kph)	
		Region C	Region D
Farm Sheds	200	230	285
Houses, apartments, etc.	500	250	317
Major Hospitals, etc	2,000	276	356
Public Cyclone Shelters (1)	10,000	305	394

Table 2.1.5 ARIs and Regional Wind Speeds from the BCA and Part 2 of AS/NZS 1170. *(corrected)*

Notes

1. According to the current codes, designated post-disaster Emergency Shelters should have the same ARI as major hospitals. At present there is no official ARI for designated mid-disaster Public Cyclone Shelters but moves are in hand to follow US practice and have an ARI of 10,000 years incorporated into the Australian codes (Peter Mullins, pers. comm.)
US practice is to also use an ARI of 10,000 years for private, in-house cyclone shelters. The writer considers this should also prevail in Australia but at time of writing is not aware of any proposals of that nature for the Australian codes.

*2. The percentage probability (P) that the RWS will be exceeded within the **50** year lifetime of any of the above building types is closely obtained from P = (**50** x100) /ARI This means that for houses, apartments, etc. the authorities consider it reasonable that there is 10% probability of the RWS being exceeded within a 50 year life time. That probability used to be 5% - the risk was doubled (it seems without public consultation) with the introduction of the new loading codes in 2002.*

3. It needs to be emphasised that the mandated ARIs (and the matching RWS values) are *minimums.* *Structural engineers should probably advise their clients of the fact that for a slight increase in cost they could obtain greater safety by designing to some higher value of RWS for their new house. However the only problem with that approach is that most buildings are not designed to resist debris impact so this strategy is only assured if the neighbouring houses are also designed and built to the same (or higher) RWS value.*

4. Anyone wanting to check the values in Table 2.1.5 should be warned that they will need to refer to three separate codes and be prepared to evaluate that formula on page 20 involving the ARI being raised to the minus 1/10th power.

5. It is surprising that a farm shed 50 km inland from Port Hedland should be designed for wind speeds that are considerably higher than should be used for a new hospital in Darwin near the coast – but if they are to both have a design life of 50 years then that is what the current codes direct.

Comments

As is well known, wind loads increase as the square of the wind speed. Consequently, the current building codes require the design loads for a house in say Port Hedland (Region D) to be $(317/250)^2 = 1.61$ times or 61% higher than for an identical and similarly exposed house anywhere along the NT coast.

Fortunately, the structural component is only a minor element in the total cost of a house and this significant increase in design loads does not translate into dramatically increased housing costs.

House prices in Region D in WA have now sky-rocketed because of the mining boom, but indications of the minimal effect on costs can be obtained from house prices before the boom. The following figures are for houses built for the Department of Housing & Works in WA circa 2004/2005 and demonstrate how other factors such as transport costs can have greater impact on costs than the design wind speeds (*Steve Blower, pers. comm.*).

- Port Hedland (region D) costs were 50% greater than Perth
- Broome (region C) costs were 45% greater than Perth,
- Kununurra (region C) costs were 70% greater than Perth

Values of $V_{(ARI)}$ from formula (1) on page 20 and the appropriate constants given in Table 3.1 of the wind code have been plotted in Fig. 2.1.5 on page 27 for Regions C and D. This plot enables direct comparison to be made with values derived in parts 2.1 (b) and 2.1 (c) of this section.

Fortunately, houses built to earlier versions of the wind code and those that are a fair distance inland built to any code are better placed than is indicated by Fig. 2.1.5. These aspects are examined on the following pages.

2) Derivation of the RWS over the years and how its value has varied

The derivation of the various values used for design wind loads for Darwin housing and an examination of how those values have varied over the years is given in Appendix D.
The following is a brief summary of the Appendix D findings.

The writer studied the provisions in the six major versions of the wind codes that have been in effect in Darwin since 1952. The six codes were in force from 1952 to 1971, 1972 to very late in 1974, 1975 to 1983, 1984 to 1989, 1990 to 2002 and 2003 to … sometime into the future. After allowing for changes in units and calculation methods used, the basic design speeds used in those codes have been converted to values which can be directly compared with the RWS as defined in the current wind code.

These values are plotted in the Figure 2.1.2 following. The sloping lines between the different values are merely an attempt to show that some engineers take longer than others before incorporating the rules of a new code into their calculations.

At first glance, it looks like there have been major changes in the values but this is just an artifact of the vertical scale used to make the plot. The 'RWS' from 1975 to 1989 of 279 kph was what some believe was an over-reaction from Cyclone Tracy. It was certainly more than the 250 kph used now - but only 11% more. The plot in fact illustrates what appears to have been a major concern of the code writers – that design wind speeds should remain more or less constant over the years.

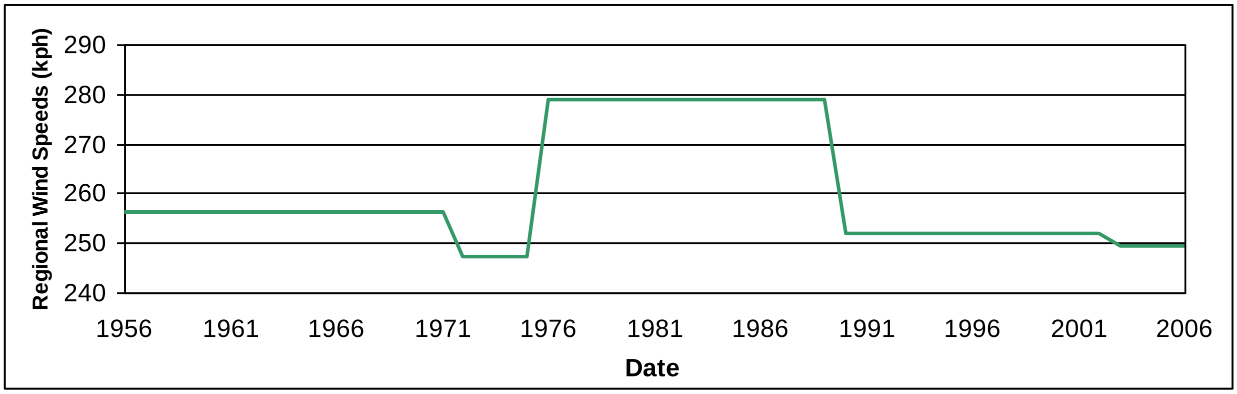


Figure 2.1.2 Plot of design wind speeds for Darwin houses adjusted to be directly comparable to the Regional Wind Speed for ARI = 500 years as given in the current wind code.

The green line in Figure 2.1.2 represents what will be called the 'comparative RWS'

3) Design loads and how they have varied over the years for typical houses in Darwin

The RWS is only one factor in determining the wind loads. In Appendix D, it is explained how a variety of other factors must come into play before arriving at the final loads. The writer has examined the rules used to determine wind loads from each of the six codes and has applied them to two types of houses in four different exposure conditions. (The topography in all cases was flat or gentle slopes and not near a cliff or a hill.)

The house types were:

- two storey with gable roof at 15° pitch – typical of an old style elevated house that has been built in underneath
- large, ground floor house with hipped roof at 30° pitch – typical of many of the new houses now being built in Palmerston

The four exposures varied from a 'worst' case of being near the beach with no shielding from surrounding buildings; to a 'best' case of being surrounded by more than 1 km of suburban development and with full shielding from surrounding buildings.

There was considerable variation between the loads obtained for the 2 x 4 = 8 different cases examined because the rules governing the calculation of the loads on different parts of a building have varied extensively, but not consistently, over the years. People are naturally interested to compare how <u>their</u> house would fare in such a comparison. The writer has deliberately prevented such comparison in Fig. 2.1.3 following by only plotting the results of the <u>average</u> of the eight cases. The plot does <u>not</u> represent any particular house type or exposure but it does allow some comparison to be made for an 'average' Darwin house. (It must be kept in mind that any particular house will probably vary significantly from this 'average'.)

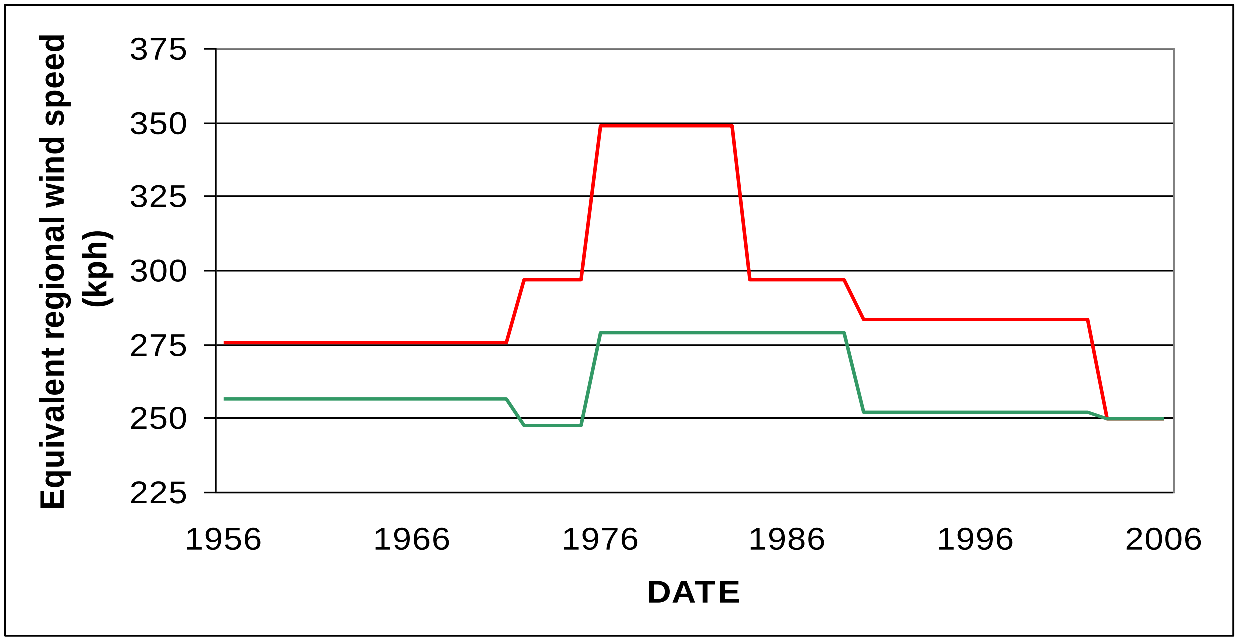


Figure 2.1.3 Showing how the 'equivalent RWS' and the 'comparative RWS' has varied between six editions of the wind code over the last 50 years for an 'average' Darwin house.
(The green line is the 'comparative RWS' as already given in Fig. 2.1.2).

The red line in Fig. 2.1.3 will be called the 'equivalent RWS' and it reflects how the <u>loads</u> derived from the 'comparative RWS' have varied. The loads calculated were the combined wind loads acting on the whole house. The loads could have been presented in terms of newtons but then probably only engineers would understand them. What was done instead was to use the current wind code rules on the loads derived from the earlier codes to derive a retrospective or 'equivalent RWS'. To put it in another way, the 'equivalent RWS' is the speed required to produce those earlier loads when using the rules in the current wind code (apart of course from the current code's RWS Table 3.1).

Figure 2.1.3 should be good news for Darwin people who live in a house built in the first eight or so years after Cyclone Tracy. As can be seen, on average, such houses should withstand winds produced by a cyclone of Monica's intensity. But the design strength of the 'average' house has declined steadily with each successive code since that time. The results above are very surprising and will be disputed by some. The analysis is described in further detail in Appendix D. The writer's calculations were carefully made and took many days to do - but they have not been independently checked. The calculations are on eleven Excel spreadsheets comprising more than 1200 cells in total. The writer will make these sheets available to structural engineers wishing to peruse or check them.

4) How the wind code allows for weakening after landfall & recent research on the subject

This subject is examined in greater detail in Appendix H.

The wind code takes a very broad brush approach to account for the reduction of wind speeds as a cyclone moves inland. For the Top End, it specifies just three regional wind speeds which for an AEP = 1/500 are 250 kph, 205 kph and 162 kph for Regions C, B and A respectively. Region C extends from the coast to a line 50 km in from a 'smoothed' coastline, Region B is a band extending a further 50 km inland and region A is everywhere else.

A map in the wind code (which takes in the whole of Australia on an A4 page) indicates the approximate location of the 50 km and 100 km demarcation lines. But there is there no definition in the code as to what constitutes a 'smoothed' coastline. Positions of the demarcation lines for the NT are indicated in Figure 2.1.4 below. **Note.** This map is only for illustration purposes for this report - actual boundaries should be obtained from the appropriate authorities.

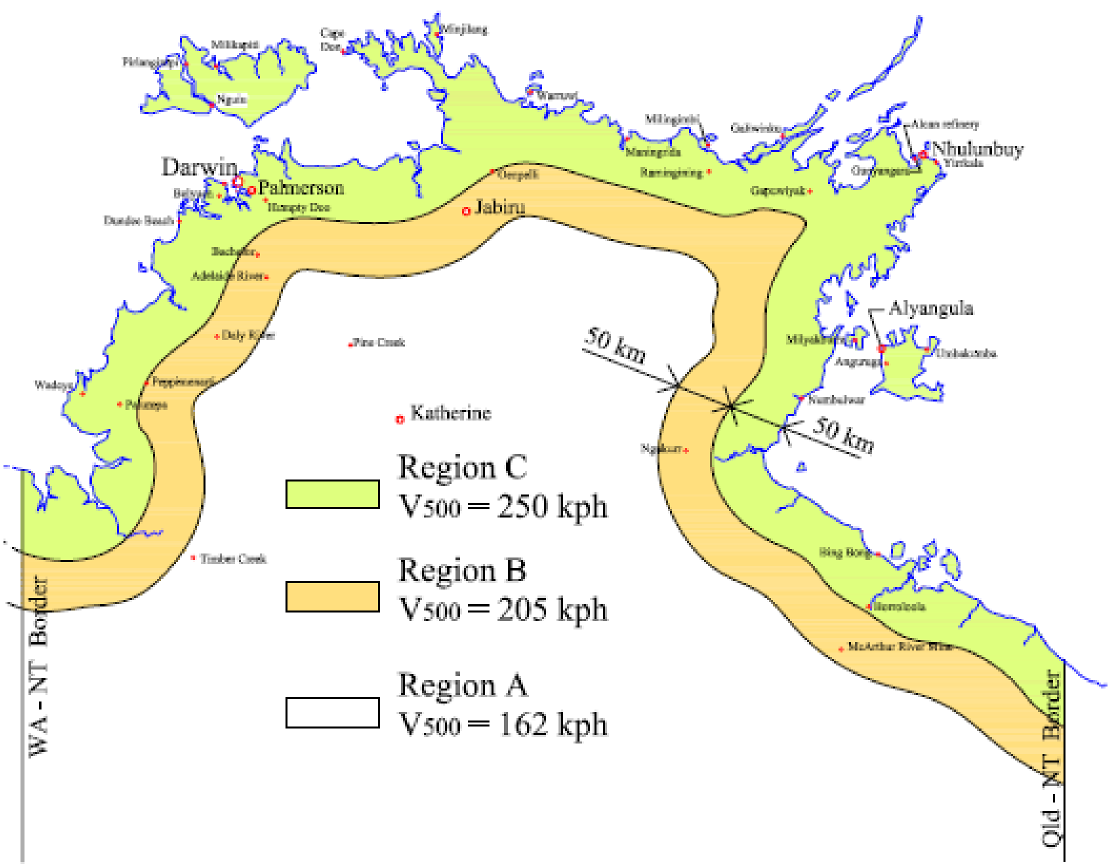


Figure 2.1.4 How the RWS varies inland from the 'smoothed' coastline in the NT.

Research in the US has provided formulae which can be used to calculate how wind speeds weaken after landfall (*Kaplan and DeMaria, 1995; DeMaria et al, 2006*). The formulae are examined in Appendix H. It was found necessary to make only slight modifications to the formulae for them to fairly accurately model the decay in Cyclone Ingrid's estimated wind speeds as it passed over the Coburg Peninsula and the Tiwi Islands.

The intensity, and hence the wind speeds, of a cyclone decay as function of time rather than of distance inland so the reduction in speed with distance inland is very much dependent on the speed of forward movement of the cyclone.

Typical values are presented in Appendix H. There is some good news for people living inland but as Cyclone George recently demonstrated, a fast moving cyclone can cause very strong winds to still prevail 50 km and even 100 km inland.

Recommendations to provide a graduated range of RWS values presented on DPI's website are made at the end of Appendix H

2.1(e) Estimates given in two recent risk studies for the NT Government

The two studies are:

- "On the Probability of Darwin being struck by a Category 5 Cyclone"; Environment and Climate Risk Assessment, 2000 by Dr Peter Georgiou for the NT Department of Transport and Works. (Georgiou, 2000)

- "Darwin Storm Tide Mapping Study 2006". Prepared by Systems Engineering Australia Pty Ltd for NT Emergency Services.(SEA, 2006)

A review of these two risk studies is given in Appendix I. Here only the wind speeds derived by the studies are presented.

AEP = 1 ⁄ ARI	Maximum gust speed in Darwin (kph)	
	Per Georgiou, 2000 (1)	Per SEA, 2006 (2)
1/250	212	209
1/500	234	223
1/2,500	295	266
1/10,000	346	-

Table 2.1.5 Comparison of maximum gust speeds against AEPs from two recent risk studies for Darwin.

Notes

1. Derived by interpolation and extrapolation from Table 3.5.1 (Georgiou, 2000)

2. SEA report is concerned with storm tide risk so gust speeds given here form one component of the model to derive that risk rather than being the endpoint of the study. Values are obtained from the line plot in Fig. 4.13 (SEA, 2006). Plot extends only to ARI = 1,000 yr. The 266 kph value was obtained by extrapolation and hence may differ slightly from the value in the SEA model.

<u>Discussion</u>

Refer to Fig. 2.1.5 next page for a graphical presentation of gust speeds vs ARI from the above table and to page 28 for some comment on the estimates.

2.1 (f) Conclusions and Recommendations

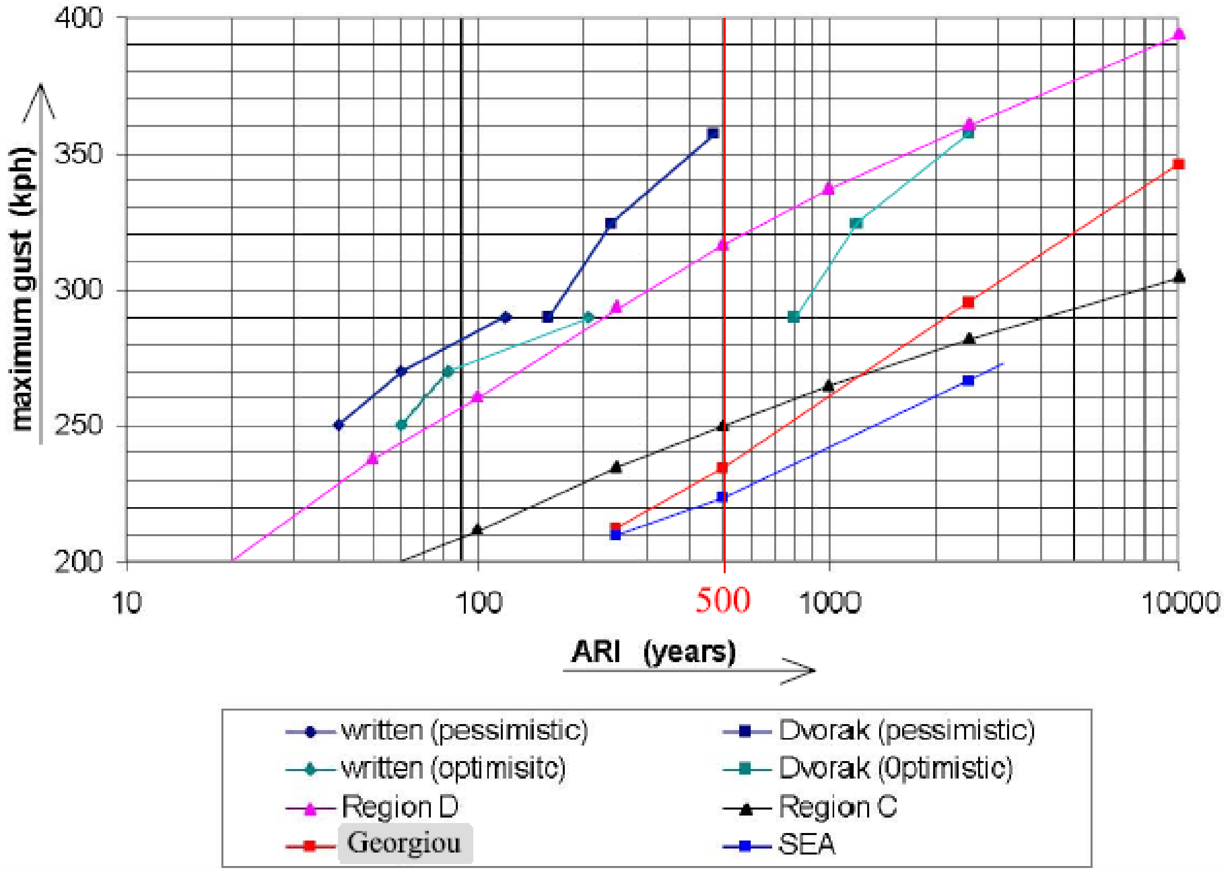


Figure 2.1.5 Plot of engineering estimates for maximum gust speeds vs. ARI. (figures relate to a single building or a very small community rather than to a city-wide area.)

The ARI = 500 year line in the above figure equates to the risk deemed appropriate by the building codes for houses, apartments and most other normal buildings. The magenta, Region D wind code line is not supposed to be appropriate for Darwin but all of the other lines were derived by examination of data from and/or for the Darwin region. The maximum wind gusts estimated for an AEP of 1/500 varies between 350 kph for the writer's pessimistic interpretation of his data down to 225 kph derived for the latest storm tide risk study for the Darwin region.

The writer's optimistic and pessimistic estimates are close to values that relate to the wind code's Region D. In the case of the estimates derived from Dvorak records, the optimistic and pessimistic lines actually straddle the Region D line. **The writer therefore concludes that Darwin should be in Region D.** (At the moment, Region D applies only to the coastline from Carnarvon to Port Hedland in Western Australia where the design wind loads are about 60% higher than for Region C.)

It was admitted at the outset of this section that the writer's estimates are 'ball park' or 'back-of-envelope' calculations. The ARI figures derived from them may well be out by a factor of two. But they are not going to be out by a factor of ten or more which would be necessary for them to fit with the Region C line or with the two engineering reports to the NT Government.

The two engineering reports to the NT Government are discussed in more detail in Appendix I. They were introduced here to demonstrate the scale of the differences in engineering estimates being made for the cyclone hazard in Darwin.

Of particular concern are the estimates derived from the latest storm tide risk study for the Darwin region (SEA, 2006). The wind speed estimates in that study are an important component in the final determination of storm tide levels but the study's predicted risk for a given wind speed is about $1/20^{th}$ of that represented by the Region D line.

Referring again to that ARI = 500 year line, houses designed for the regulated Region C value of 250 kph should be assured of survival under the 235 kph gust speeds estimated in the Georgiou study. On the other hand, they would be assured of destruction from 350 kph gust speeds as given by the writer's pessimistic estimate.

Risks from wind and the storm tide hazards for Darwin and most other coastal communities in the NT are too grave for these matters to remain in the realm of speculation. The matter demands more detailed study of the writer's data and much more refinement in the methods of calculation.

The data from long-term written records can be significantly improved by:

- careful re-analysis by a team comprising at least one meteorologist and one engineer – each having expertise in the behaviour of intense cyclones and the storm surges they produce
- further searching of archives to obtain additional information
- research by climatologists to determine if there could be multi-decadal cycles governing cyclone intensities and track directions in NT waters
- confirming the storm tide levels for the 1919 cyclone (refer Appendix G) by:
    - test holes and soil sample analysis at Nguiu and at the Narrows
    - finding the keel levels of the Warrego and calculating the storm tide required to lift the hulk to that level
- confirming the storm tide levels for the 1937 cyclone (refer Appendix F) by test holes and soil sample analysis at two low areas on the road to East Point.

The data from post-satellite era BoM records can be improved by re-analysis as discussed in Appendix G.

The analysis of the data can be improved by:

- resolving the question as to the appropriate probability distribution to use for modelling the future arrival frequencies of intense cyclones. It would seem that the distribution should be uniform rather than tailed. (This matter is mentioned in paragraph 5 on page 16 and discussed in greater detail in Appendix G.)
- using sophisticated, Monte Carlo simulation techniques rather than back-of-envelope calculations to derive the intensity – frequency relationships. (There are also some improvements that could be made to the computer models that have been used to date for Darwin. These are discussed in Appendix I.)

Interpreting the results to the public It will never be possible to come up with a "correct" answer although better indications will be obtained by adopting the above improvements and by conducting the research recommended in Sections 2.2 and 2.3 of this report. In the meantime, the hazards should be presented as a range of values rather than a single value. This can be done using optimistic and pessimistic scenarios similar to the ones used by the writer in this section and as used by the International Panel on Climate Change when presenting the predicted results from global warming.

2.2 Indications on the Probability of an Intense Cyclone Occurring from Meteorology, Climatology, Wind Damage & Storm Tide

(a) Summary
(b) Tracks and swathes
(c) Maximum Potential Intensity
(d) Other regional differences – NT, WA and Qld
(e) How accurate are BoM's wind speed estimates for the NT?
(f) How accurate are estimates of wind speed from wind damage?
(g) How accurate are estimates from storm tide levels ?
(h) Conclusions and Recommendations

2.2(a) Summary

This section deals with matters which relate either directly or indirectly to meteorology (short term weather effects) or climatology (long-term climate trends and/or weather on a regional basis) and wind speed estimates from structure damage, tree damage and storm tide.

2.2 (b) Tracks and swathes

In the following maps, a blue or mauve line is for a storm when it was a tropical low,
a green line when it was a Category 3 cyclone, orange line when Cat. 4 and red line when Cat. 5.

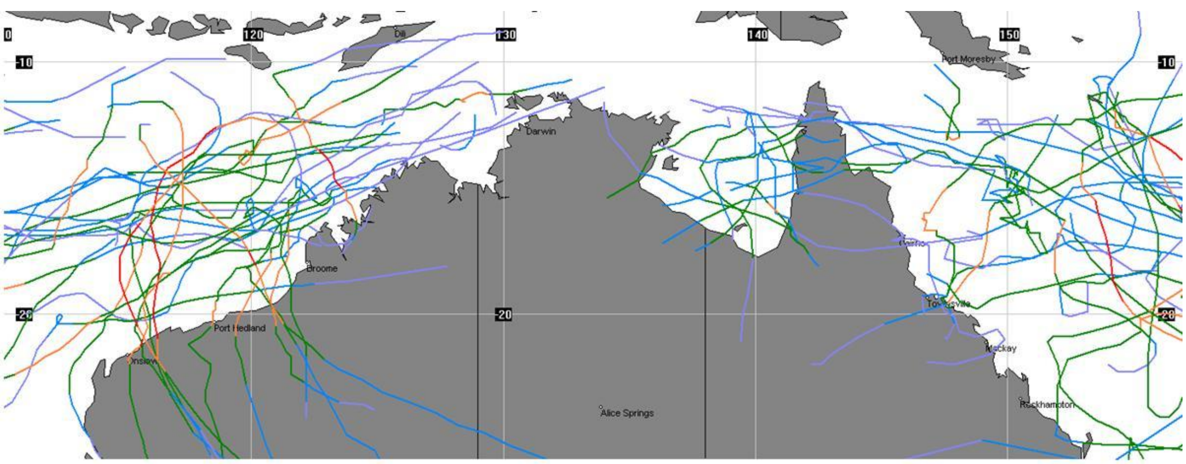


Figure 2.2.1 Tracks for all tropical lows and cyclones for decade **1987 to 1996**

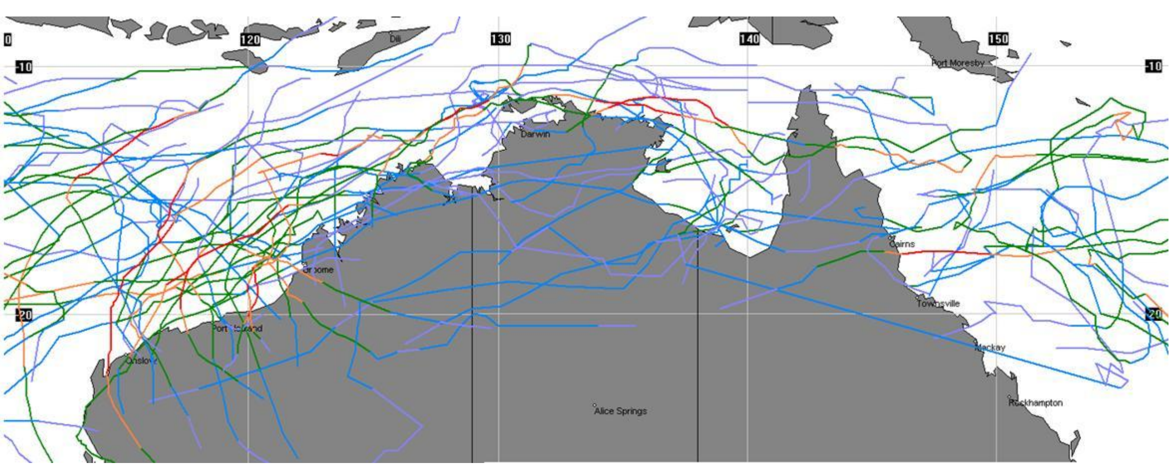


Figure 2.2.2 Tracks for all tropical lows and cyclones for decade **1997 to 2006**

Note the increase in activity around the NT in the last decade but as usual, the most activity is off the WA coast.

The following track maps are of much more interest here – they show only storms when they were at either Category 4 (orange) or Category 5 (red).

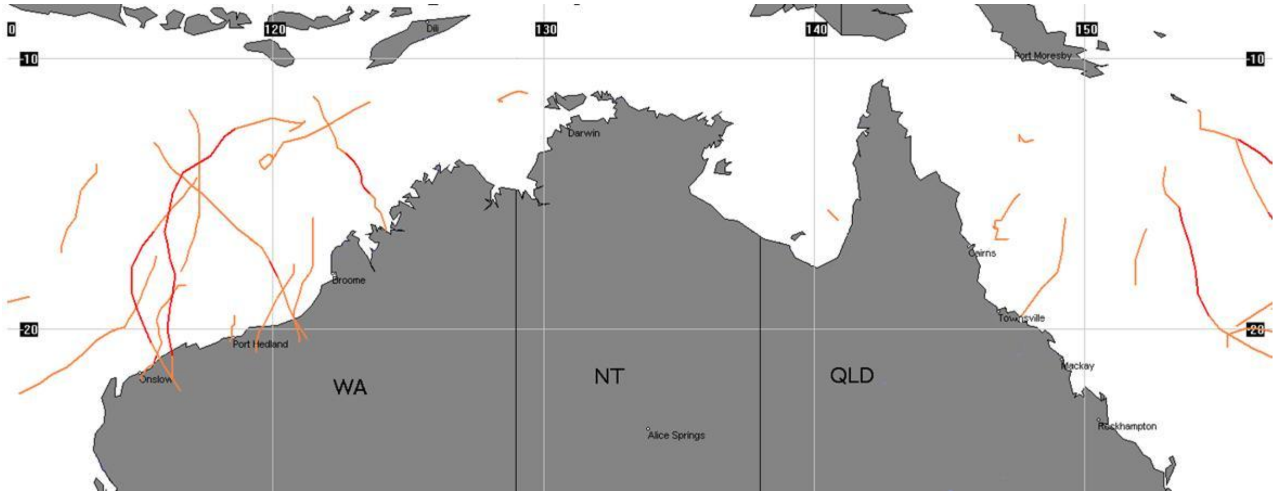


Figure 2.2.3   Tracks for all storms when at Categories 4 or 5 for decade **1987 to 1996**

The '87 – '96 decade was a quiet one for the NT as far as intense cyclones were concerned. Only Cyclone Neville shows up off Bathurst Island while it was heading away towards WA. Looking at this map, one would judge that WA faced the highest hazard, Qld the next highest and the NT the lowest.

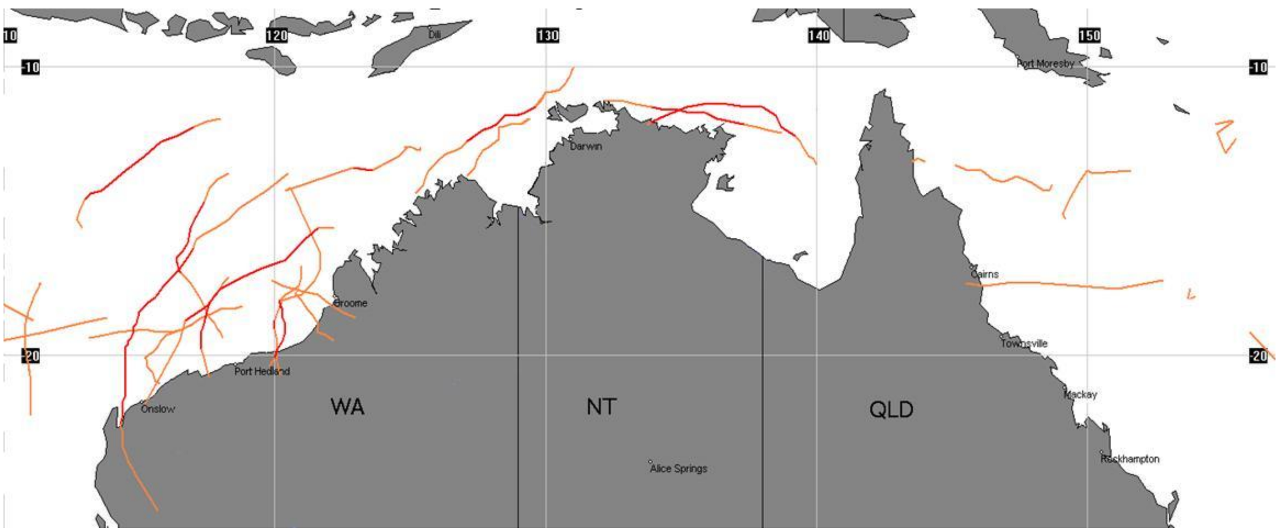


Figure 2.2.4   Tracks for all storms when at Categories 4 or 5 for decade **1997 to 2006**

The '97 – '06 decade presents quite a different picture. WA still clearly faced the highest hazard but the NT was not far behind while QLD was clearly at the low end of things. (Cyclone Larry is shown here as being Category 4 all the way to landfall. It may have attained Category 5 for a short time before landfall – the matter is still being investigated.)

The lines in the preceding maps show the track taken by the storm centre. The colours give indication of the intensity, but there is no indication given as to the diameter of the eyewall and hence of the width of the swathe carrying the intense winds. The swathe map on the next page corrects this defect in track maps.

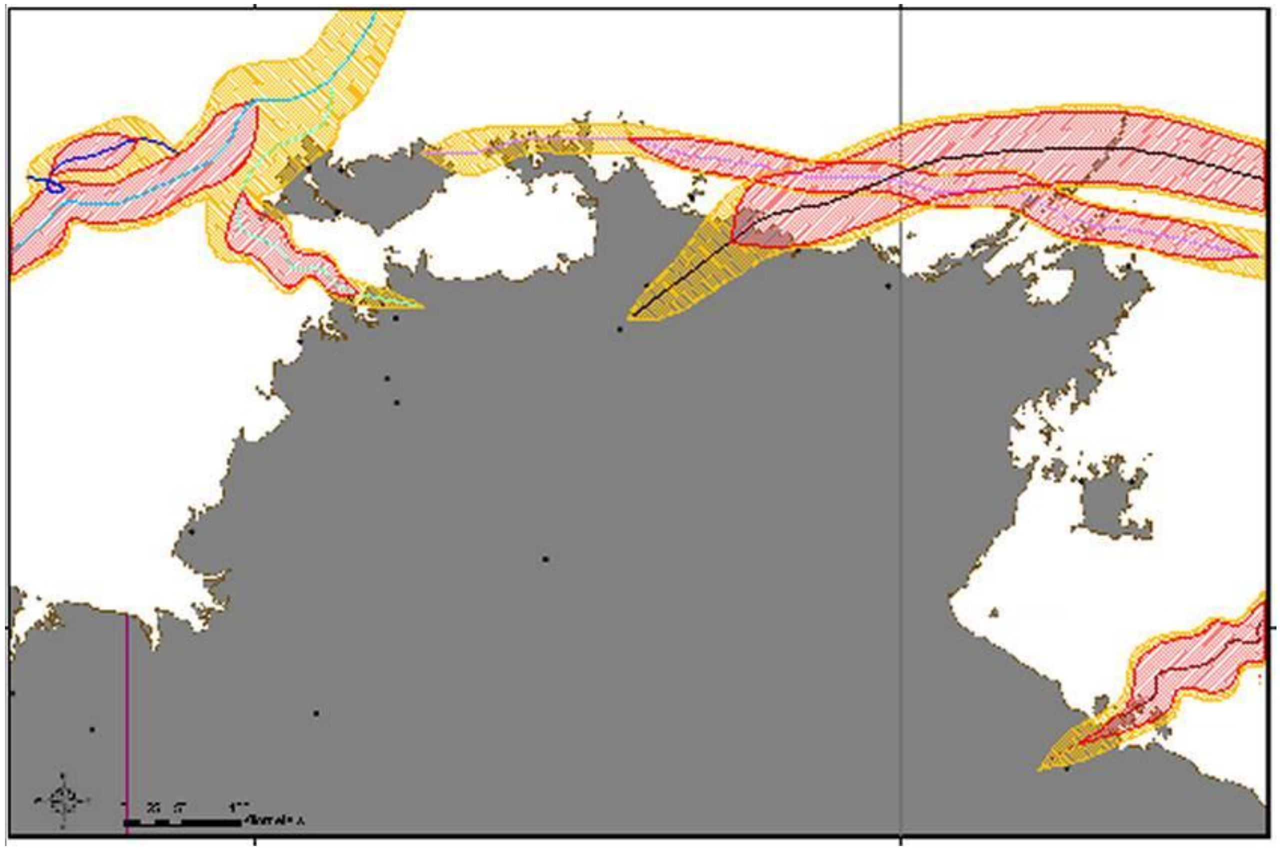


Figure 2.2.5. Swathes of Category 4 & 5 winds in NT waters over period 1974 to 2006
[The cyclones proceeding from left to right are: Thelma (Dec.1998); Neville (Apr. 1992); Tracy (Dec. 1974); Ingrid (Mar. 2005); Monica (Apr. 2006); Kathy (Mar. 1984).]

The swathes are drawn approximately to scale. The hatched:

- yellow areas are where maximum winds would have been Category 4 (224 - 279 kph gusts)
- red areas are where the maximum winds would have been Category 5 (280 – 390 kph gusts)

Name	Date	Pc minimum hPa	Maximum intensification rate hPa/hr	CI maximum Number	Vgust maximum kph	Rmw average km	Vfm average kph
Tracy	Dec. 1974	940	3.3	6.0	280	18	6.6
Kathy	Mar. 1984	920	1.7	7.0	324	22	7.5
Neville	Apr. 1992	937	2.3	6.5	290	14	5.4
Thelma	Dec. 1998	920	2.1	7.5	357	17	9.5
Ingrid	Mar. 2005	924	2.8	7.0	324	12	18.0
Monica	Apr. 2006	917	1.8	7.5	357	22	13.2
	Averages:	**926**	**2.3**	**7.0**	**324**	**17.5**	**8.0**

Table 2.2.1 Estimated* properties of the six intense cyclones shown in Fig. 2.2.5 as derived in Table G.2 in Appendix G.

Note: BoM's cyclones_ newformat database has Tracy and Neville as Category 4 cyclones only. However as discussed elsewhere in this report, re-analysis of these storms indicates that they attained Category 5 status at the locations shown in Fig 2.2.5

In the above table, Pc = central pressure, CI = the Dvorak Current Intensity number, Vgust = maximum gust speed, Rmw = radius of maximum winds, Vfm = forward speed.

Fig. 2.2.5 can be used in two ways to make rough estimates of the chance of a category 5 impact anywhere along the NT coast:

One way is to simply look at the map having in mind that the six cyclones occurred between 1974 and 2006. To be "fair" the period of record will be widened from say 1960 to 2010 or 50 years. If the interest is in an AEP of 1/500, we need to look at a swathe map for a 500 year period of record. That is of course not possible but we can at least try to imagine what the map would look like. Instead of having just six cyclone swathes distributed around the coastline – imagine if you can, what it would like if there were sixty. It would seem that there would be a large chance that at least one of those sixty category 5 swathes would cover Darwin – or any other location around the coast.

Another estimate can be made by just considering the two cyclones that actually made landfall as Category 5 cyclones – Monica in Junction Bay and Kathy on Vanderlin Island. Estimates provided by BoM suggest that at landfall:

- Monica had maximum gusts = 350 kph over 48 km width, and = 280 kph over 70 km width;
- Kathy had maximum gusts = 280 kph over 32 km width.

Assume:

- the two landfalls represent an average for a 50 year period of record
- the "smoothed" length of the NT coastline is 2,000 km
- the coastline around Darwin is more likely to be impacted by Cat. 5 winds than some other sections such as down the west coast of the NT. Therefore assume that if a cumulative length of 2,000 km of NT coastline is impacted, then over say a thousand years or more, Darwin is certain to be impacted at least once.

For landfall of minimum Category 5 winds (280 kph):
On average over 50 years there will be (70 + 32) km say 100 km of coastline impacted.
Therefore over 1,000 years, there will be 2,000 km impacted.
Therefore the ARI (= 1/AEP) for 280 kph winds on Darwin will be about 1,000 years.
(For 280 kph, Fig. 2.1.5 gives ARI = 160 yr for Region D and 2,200 yr for Region C.)

For landfall of above mid-level Category 5 winds (350 kph):
On average over 50 years there will be 48 km - say 50 km of coastline impacted.
Therefore over 2,000 years, there will be 2,000 km impacted.
Therefore the ARI for 350 kph winds on Darwin will be about 2,000 years.
(For 350 kph, Fig. 2.1.5 gives ARI = 1,700 yr for Region D. Region C is off the chart but calculation gives the ARI = about 300,000 yr.)

The above are really rough estimates but they do suggest that the hazard of Category 5 impacts along most of the NT coastline is considerably higher than indicated by the wind code's Region C values.

2.2 (c) Maximum Potential Intensity (MPI)

It is now well established that the intensity that can be attained by a cyclone in any particular location is bounded by thermodynamic principles to an upper limit. The limit value depends on regional atmospheric soundings and also on the sea surface temperature (SST) - as averaged over the area of ocean that leads to intensification of the cyclone at or near the location concerned.

A recent Australian study on **MPI** (*Tonkin et al, 2000*) examined 28 locations in the three main cyclone basins - the North Atlantic, the North-west Pacific and the Australian Region. The MPI which can prevail in cyclones at those locations for each month of the year was determined in terms of central pressures. Two thermodynamic models which give the estimated MPI (*Emanuel, 1986, 1991* and *Holland, 1997*) were compared. The model developed by Greg Holland provided the most skill in matching the extreme events that have been recorded at the various locations. (Greg Holland was working for the Bureau of Meteorology in their Darwin office during cyclone Tracy. He is now one of the world's foremost authorities on cyclones.)

The study provides bad news for Darwin:

In the month of December, the seas and the atmosphere within a 250 km radius of Darwin could theoretically combine to produce a cyclone near Darwin with a central pressure of 860 hPa. This is the most intense MPI value for any month of any location in the world.

The Tonkin paper is somewhat complex. To simplify things for this report, Table 2.2.2, next page, summarizes the results from just 12 of the 28 locations using just the Holland MPI model. Unfortunately, the Tonkin study expresses MPI in terms of central pressure (**P**C) rather than wind speed. To make things more meaningful to the average reader, the writer has converted the central pressures to an equivalent maximum gust speed (**V_{MPI}**). Table 2.2.2 gives the central pressure from the Tonkin paper for the months when the annual MPI curve is at its most intense, the **pressure drop** (**ΔP**) based on the estimated ambient pressure for the location and month and the writer's estimated V_{MPI}.

The estimate for V_{MPI} is based on Holland's formula for the wind speed-pressure relationship (*Holland, 1980*). The Holland formula calculates the **gradient wind speed** which is taken to be at 3 km height above the earth's surface (*Georgiou, 2000*). There is controversy as to appropriate values for the **Gust Conversion Factor** (**GCF**) to convert the gradient wind at 3km to a maximum gust value at 10 m. Here it is assumed that the GCF = 1.1.

The other variable of importance is the Holland B value which is a measure of the 'peakedness' of the wind field. This was set = 2.18 based on the MPI in terms of surface gusts = **400 kph.** This estimate for the absolute maximum gust speed that a cyclone can attain is based on the maximum gust speed for a Category 5 cyclone in the USA's **Saffir-Simpson Scale**.
(For GCF = 1.1, B must = 2.18 for Darwin's ΔP of 147 hPa to produce max. gusts of 400 kph.)

This is all very arbitrary, but the interest here is in obtaining accurate comparative rather than absolute values of the gusts speeds. This should be obtained in Table 2.2.2 because the values of GCF = 1.1 and B = 2.18 have been applied to all 12 locations in the table.

Authorities in each basin assume different relationships to estimate surface wind speeds from central pressures. In the Australian region, there are even different relationships used for the NT, for WA and for Qld. The NT relationship assumes higher wind speeds for a given value of **central pressure** (**Pc**) based on values obtained from cyclones Tracy, Kathy and Max and the observation that cyclones in the NT tend to be smaller in size than elsewhere (*Love and Murphy, 1985*). It is understood that the Australian relationships are currently under review.

(Hopefully the current Darwin relationship grossly over-estimates wind speeds at very low central pressures - its extrapolation for Pc = 860 HPa would give V_{MPI} for Darwin = 490 kph.)

LOCATION	BASIN	Month	Lat. Long. Dec.Deg.	P_C hPa	ΔP hPa	V_{MPI} Kph
Darwin, (Region C)	Australian	12	-12.4, 130.9	**860**	147	**400**
Broome, (Region C)	Australian	3,4	-18.0, 122.3	885	125	370
Port Hedland, (Region D)	Australian	4	-20.3, 118.4	**885**	125	**370**
Townsville, (Region C)	Australian	1	-19.3, 146.8	**935**	75	**285**
Eagle Farm [Brisbane] (B)	Australian	1-4	-27.4, 153.1	975	35	195
Guam,	N-W Pacific	7-9	13.5, 144.8	**867**	130	**376**
Guangzhou. [Hong Kong]	N-W Pacific	6-8	23.1, 113.3	945	60	255
Hachijojima, Japan	N-W Pacific	8	33.1, 139.8	935	75	285
Barbados	North Atlantic	9-10	13.1, 300.5	900	110	346
Miami, Florida	North Atlantic	8	25.8, 279.7	895	120	361
Apalachicola, Florida	North Atlantic	8	29.7, 275.0	890	125	369
Cape Hatteras, N. Carolina	North Atlantic	8	35.3, 284.5	940	75	285

Table 2.2.2 Maximum Potential Intensity cyclones at 12 selected locations

Fortunately for Darwin, the MPI values in Table 2.2.2 do not necessarily correlate with the likelihood of an MPI or "near-MPI" cyclone occurring. This is demonstrated by records from Guam which is the location with MPI nearest in value to Darwin. One of the most intense cyclones ever recorded in terms of its central pressure was Super Typhoon Tip which intensified near Guam in Oct 1979 with a P_C of 870 HPa. Tip is also the largest cyclone ever recorded with a radius of gales of 1,100 km. (Tracy is the smallest ever recorded with a radius of gales less than 50 km). The next five on the world record list in terms of central pressures also intensified near Guam. They all had Pc = 872 HPa, all occurred in the 1990s and all intensified between latitudes of 12° N and 15° N. The record indicates that Guam is at far greater risk of being impacted by an MPI cyclone than Darwin even though its MPI is somewhat less.

Although MPI may not be directly related with frequency of occurrence of very intense cyclones, it is thought to have an effect on the speed at which a cyclone will intensify. The following extract is from the **World Meteorological Organisation (WMO)** Global Guide to Tropical Cyclone Forecasting (the **WMO Guide):**

> *"Tropical Cyclones with a compact core of maximum winds and strongest convection are thought to intensify more rapidly,* ***as are those that are well below their potential intensity.****"*

If there is some correlation between the MPI at a location and the likelihood of an intense cyclone occurring at that location, then the V_{MPI} values in Table 2.2.2 become of some significance. The values for the three cities of interest are:

- **Darwin (Region C in NT) = 400 kph**
- **Port Hedland (Region D in WA) = 370 kph [slightly higher than a Monica]**
- **Townsville (Region C in Qld) = 285 kph [nothing much more than a Tracy]**

Worldwide, daily representations of MPI are given at http://wxmaps.org/pix/hurpot.html in the form of coloured charts giving central pressure and wind speeds. Almost invariably, the MPI measures for the Port Hedland to Darwin region are significantly higher than for the east coast of Queensland.

2.2 (d) Other regional differences – NT, WA and Qld

The object of this part is to examine other factors apart from MPI which might influence the cyclone intensity - frequency relationship for cyclones making landfall at a given location. These factors will relate to the climatology of the region, the orientation and latitude of the coastline and the areas, depths and temperatures of the surrounding seas.

There has been extensive research to determine how cyclones differ between the seven so-called "basins" on the globe where cyclones/typhoons/hurricanes are common. These differences are detailed in Chapter 1 of the WMO Guide, available at:
http://www.bom.gov.au/bmrc/pubs/tcguide/ch1/ch1.htm

The NT is in the Australian/southeast Indian basin which extends from longitude 100° E in the Indian Ocean (approximately 1,300 km west of the west coast of WA) to longitude 142° E (approximately the west coast of Cape York). On average, this basin has 6 cyclones per year with an average 3.4 per year being Category 3 or stronger. Unfortunately, NT cyclones hardly feature in this huge area and anything that the records might reveal that is special about NT cyclones is swamped by the data from the far more numerous cyclones further to the west.

However some conclusions and comparisons can be drawn from the data in the WMO Guide and some of them are discussed briefly in the following pages.

To simplify some of the comparisons in the following, the same three cities that have been singled out previously in this report will be considered as representing Australia's three cyclone prone coastlines – namely Port Hedland WA, Darwin NT and Townsville Qld.

1) Atmospheric conditions that enhance genesis and maintain intensity

These conditions (vorticity, low vertical wind shear, etc) have been known for a long time (Gray, 1975). They probably do not vary much from region to region for the three cities. They are all controlled to some extent by proximity to the monsoon trough. Consequently, the number of months when such conditions are favourable will also be fairly constant across the three regions. ('Vertical wind shear' is the rate at which the background, horizontal wind varies with altitude. Even low values of this shear can prevent tropical lows from intensifying into cyclones and can limit further intensification or weaken already formed cyclones.)

2) There is probably more 'peakedness' to the wind field in low latitude cyclones

Peakedness is measured by the Holland B as discussed above under MPI. The higher the peakedness the higher the maximum wind speed for a given central pressure. From qualitative observations, more intense hurricanes in lower latitudes usually have more sharply peaked wind profiles.

From the writer's analysis of the records, the Holland B for intense cyclones in the NT will be between 2.0 and 2.5. This is probably much higher than would normally prevail for intense cyclones around Port Hedland or Townsville.

3) It seems accepted that NT cyclones will tend to be smaller than those at higher latitudes
'Small' here refers to the size of the eye or to the **Radius of Maximum Winds** (**Rmw**). Obviously, the smaller the cyclone the less the risk of impact. But to counter that good news is the probability that small cyclones can intensify more quickly than large cyclones.

4) The area of sea or ocean available for intensification

It has long been thought that the limited area of the seas surrounding the NT coast inhibits the number of cyclones that can form and the intensities that they can attain. But recent experience suggests two factors which will lessen this effect:

(a) It is now recognized that given optimum conditions, cyclones can intensify much more quickly than was hitherto thought to be the case and so they require less area to reach Category 5 intensity

(b) As demonstrated by Ingrid and Monica, cyclones can easily enter NT waters from the Coral Sea by a short crossing of Cape York and then quickly re-intensify.

5) Probable track directions relative to the coastline orientation and steering conditions

The mean track directions for all cyclones (intense and non-intense) around the globe are given in Fig 1.11 of the WMO Guide and can be viewed at:
http://www.bom.gov.au/bmrc/pubs/tcguide/ch1/figures_ch1/figure1_11.htm

The graphic shows that for the three cities, the mean track directions for all cyclones within about 250 km of the coast and the city are:

(a) for **Port Hedland** they are **SW**. The adjacent coastline trends WSW which suggests that about three out of four cyclones will make landfall

(b) for **Darwin** they are **WSW to SW**. These directions approximate the two directions of the adjacent coastline as the mainland rounds the 'corner' at Point Charles and this suggests that only about two out of four cyclones will make landfall. However the Tiwi Islands and/or the Coburg Peninsula will tend to intercept such cyclones and so lift the landfalling percentage for the whole Darwin region

(c) for **Townsville** they are about **SE.** The mean direction is about parallel to the coast which suggests that about two out of four cyclones will make landfall

The tracks in Figs. 2.2.3 and 2.2.4 (page 30) for intense cyclones over the past two decades tend to confirm the above for Port Hedland but there are not enough tracks to draw any conclusions relating to Darwin and Townsville.

Table G.3 in Appendix G shows that four out of the five intense cyclones that came within 500 km of Darwin since 1974 came within 25 km of the coast or made landfall on either the mainland or the Tiwi Islands. This supports the comment in (b) above.

Time constraints precluded an analysis of BoM data to obtain comparative numbers for Port Hedland and Townsville. Some data obtained for the east coast of Queensland suggests:
- the percentage making landfall drops off markedly during El Nino conditions
- since the mid-60s, the number of intense cyclones that came within 500 km of a location on the coast and then made landfall within that range would be less than 50%

6) The translational speed (or speed of forward movement)

Figure 1.20 in the WMO Guide shows that the basin average translational speed (S) is about 14 kph at Darwin's latitude and is about 18 kph at Pt Hedland's latitude. Figure 1.21 in the WMO Guide shows the average translation speed at Townsville's latitude is 22 kph.

The differences are significant. The slower the forward speed of a cyclone the more damage that will occur due to flying debris, water ingress, and fatigue failure in steel cladding and other thin steel building components. This was dramatically demonstrated by the slow moving Tracy. It has been stated that the damage cause by Cyclone Larry would have been much worse but for the fact that it was traveling at 25 kph (*Davidson, 2006*).

7) Probable track directions relative to latitude and steering conditions

The Darwin region has latitude of about 12° S compared to Port Hedland and Townsville with latitudes of about 20° S. The higher latitudes lead to an increase in the Coriolis effect and a consequential increase in the poleward component in track directions.

Another latitude dependent difference is that between latitudes 20° S and 25° S, cyclone tracks have a tendency to re-curve to the east. This re- curvature tends to produce landfall in WA but move cyclones away from the mainland on the east coast.

Fig 1.11 in the WMO Guide shows a unique feature of track directions in the NT – the mean track direction is south-westward to the west of longitude 138° E near Nhulunbuy and south-eastward to the east of that longitude. There is no other coastline in the world with a similar divide. This obviously has significance for Nhulunbuy but the effect also carries over to Darwin where there are still occasional cyclones with an eastward track component. As already mentioned on page 14, most intense cyclones near Darwin pre-1940 had an eastward component to their tracks. This could be because whatever it is in the earth's atmosphere that now places the divide at Nhulunbuy, at one time placed it to the west of Darwin.

8) The temperature of the tropopause

The tropical cyclone heat engine is a bit like a heat engine that is powered by the difference in temperature between the heat source of the sea and the exhaust temperature at the **tropopause**. The greater that temperature difference the more intense a cyclone is likely to be. The mean tropopause temperature during February to April is 1° to 2° C colder above Darwin than it is above Port Hedland or Townsville (*Kossin and Velden, 2004*)

9) The temperature and depth of the ocean's 'mixed layer'

It is well established that cyclones will only form in seas where the surface temperature (SST) is greater than about 26°. A recent study on North Atlantic cyclones showed that the SST had to be greater than about 28° before an intense cyclone would form but after that point, there was a random spread of intensities whatever the further increase in SST (*Michaels et al, 2006*).

During the cyclone season, SSTs at all three of the subject cities tend to be greater than 28° so even though Darwin's SST temperatures tend to be about 1° warmer than the others, the Michaels study suggests that SSTs will not be a significant factor in the relative, intensity – frequency relationships.

But it is not SSTs that control a cyclone's intensity – rather it is the reservoir of heat contained in the so-called 'mixed layer'. (Deep seas and oceans normally have a variable depth layer of comparatively warm water called the 'mixed layer' over another layer called the '**thermocline**'. In the thermocline, the temperature drops rapidly with depth down to the colder water below.) It is now accepted that wind action on seas from cyclones can cause mixing and upwelling of the deep, colder water into the mixed layer and this prevents further intensification, or even weakening, of the cyclone. It may well be that the above-mentioned lack of an observed trend between cyclone intensity and SST above 28°C in the Atlantic study was in large part due to this vertical mixing and upwelling effect.

Typical reductions of intensity due to cold water mixing are in the order of 30%. (Emanuel, http://wind.mit.edu/~emanuel/anthro.html)

A study of Hurricane Opal (*Shay, 2000)* and the recent experience with Katrina have provided convincing proof that the rapid intensification and maintenance of the high intensities in these hurricanes was due to their passage over unusually deep and warm pools of water in the Gulf of Mexico.

It is noted that it is now becoming standard practice in the USA to use coupled, ocean-atmosphere computer models for operational forecasting to account for these effects.

The reason that all of this is relevant here is that although the thermocline exists in the deep waters off Port Hedland and Townsville, the seas of the NT coast tend to be only about 20 m to 80 m deep and so they are probably too shallow for the thermocline to exist. This would mean that sea temperatures off the NT coast remain fairly close to the SST all the way to the sea bed. A lack of a negative feedback effect from mixing with cold, deep waters could thus be a critical factor contributing to the intensities of NT cyclones.

As yet this factor has not been studied for NT cyclones and very little is known about sea temperatures at depth in NT waters. To get things started and to enable some comparisons to be made between Darwin, Port Hedland and Townsville, the writer examined maps which are available on line at the website of the Earth System Research Laboratory of the National Oceanic & Atmospheric Administration (NOAA). These maps derive from the NODC (Levitus) World Ocean Atlas Data (1994) which gives the mean temperatures by location and depth from recordings made between 1900 and 1992.

Studies of North Atlantic cyclones have shown that mixing to depths greater than 150 m can occur under intense cyclones. The Levitus data was used to examine the mean December to April temperatures down to 150 m over 2° squares in the seas to north of Port Hedland and to the north-east of Townsville. The results of this very preliminary analysis are tabulated below:

Depth (m)	Mean Temperature at the depth (degrees C)	Mean temperature for layer thickness (in brackets) (degrees C)
0	28.9	28.9 (1 m)
50	26.7	27.8 (50 m)
100	23.1	26.4 (100 m)
150	19.8	24.7 (150 m)

Table 2.2.3 Mean sea temperatures for Dec to April for 2° square north of Port Hedland centred at -18°S, 119° E

Depth (m)	Mean Temperature at the depth (degrees C)	Mean temperature for layer thickness (in brackets) (degrees C)
0	28.1	28.1 (1 m)
50	26.7	27.4 (50 m)
100	24.0	26.4 (100 m)
150	22.1	25.3 (150 m)

Table 2.2.4 Mean sea temperatures for Dec to April for 2° square north-east of Townsville centred at -18°S, 150° E

The above tables give indication of the cooling that an intense cyclone could cause in the waters that a cyclone would most probably pass over before impacting Port Hedland or Townsville. Some of this cooling would provide negative feedback to prevent further intensification or possible weakening of the cyclone.

Meanwhile, the Levitus data for the shallow seas off the NT coast indicates a mean SST of about 29.0°. If mixing occurred down to the sea bed in these waters, the mean layer temperature would probably still be about 28° and no negative feedback effects would occur.

This report recommends that a serious research effort be undertaken to determine:

- sea temperatures at varying depths off the NT coast
- if the temperature profiles in the shallows seas are such as to prevent negative feed-back effects from cooling of the mixed layer by using coupled, ocean-atmosphere computer models.

Conclusion

Quite apart from the MPI issue, there are at least nine other reasons why, for a given AEP, cyclones affecting Darwin may be at least as intense as those affecting Port Hedland and much more intense than those affecting Townsville.

2.2 (e) How accurate are BoM's wind speed estimates for the NT?

The writer believes that the staff at BoM, Darwin do an excellent job with the resources that they have available and that their estimates for the wind speeds associated with cyclones are likely to be reasonably accurate. But there are some problems associated with the estimates.

1) Ground truth of the maximum speeds estimated from satellites is rarely obtained

Invariably, anemometers in the NT that have been exposed to the maximum or near maximum winds from intense cyclones fail in one way or another. This of course happened in Cyclone Tracy but anemometer failures at the **Automatic Weather Stations** (**AWS**) that happened to be near the maximum wind swathes produced by Cyclones Ingrid and Monica also failed.

At one time, the standard instrument used by BoM to measure wind speeds was the Dines anemometer. This simple, pressure tube device was invented in 1892. They are usually located at airports because their main purpose is to give wind information to pilots. However for more than 50 years the gust records from these instruments have been used by engineers to derive design wind speeds for structures in Australia.

Unfortunately, they were rarely built well enough to survive intense cyclones and they routinely failed to record the maximum wind gusts. During cyclone Tracy, the Dines anemometer at Darwin airport failed before the arrival of the maximum winds and only recorded a peak gust of 217 kph – the actual peak gust at that site will never be known but it was probably at least 250 kph. If only the Dines anemometers had all been built as solidly as the one at Carnarvon, WA shown below then probably engineers would have much better records.

Figure 2.2.6 Dines anemometer at Carnarvon, WA
(photo from BoM website http://www.bom.gov.au/weather/wa/carnarvon/photos.shtml)

An important feature of the Dines anemometer for engineers is that, over a large range of speeds, its response time to a wind gust is about 3 seconds. In effect the gust it records is the average of the lesser and larger gusts that occur within that time interval. In three seconds, a 250 kph gust will travel more than 200 m so that such a gust would fully envelope a large building. For this reason, 3 second gusts are deemed the appropriate way to both measure and use wind speeds for structural design.

The gusts are recorded as thin lines sticking out above the general fuzz of the pen trace for the wind speed. There is always a second, bottom trace which records wind directions. The top trace in the chart below shows the highest wind gust ever recorded on the Australian mainland. It was obtained by a Dines anemometer at the Learmonth Airport, WA, as Cyclone Vance tracked down the Exmouth Gulf in 1999. The maximum mean winds averaged over 10 minutes were 180 kph and the maximum gust was 267 kph.

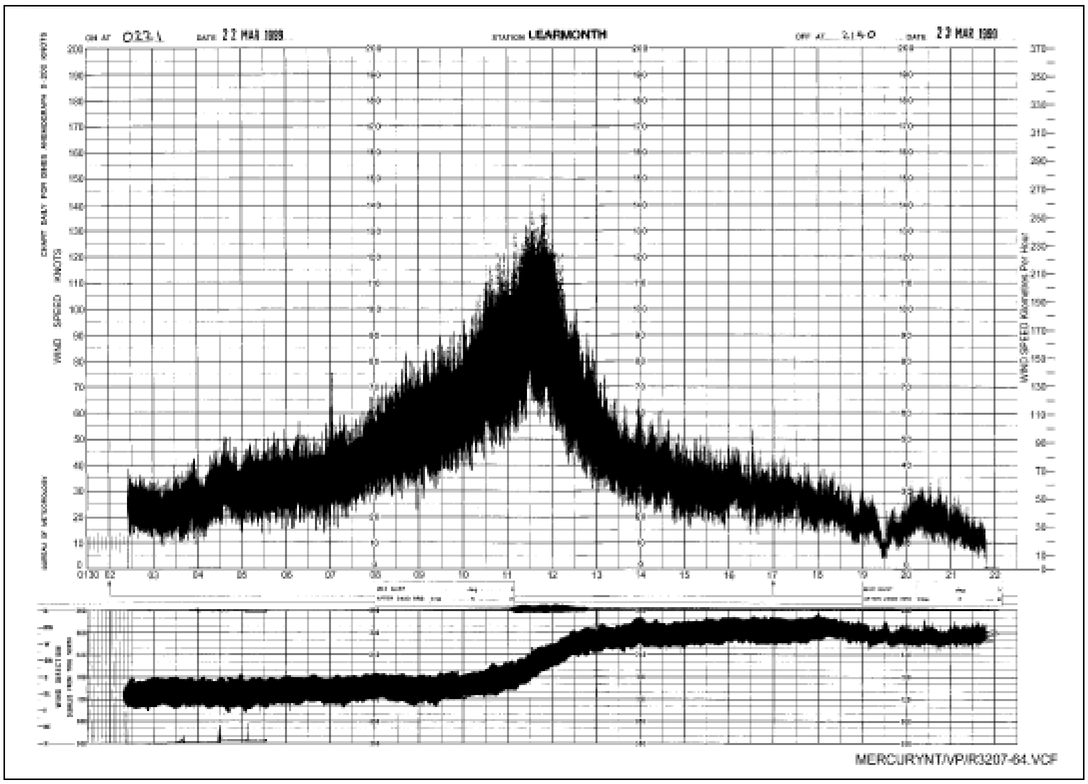


Figure 2.2.7 Anemometer Trace from Cyclone Vance (Learmonth, WA)
(from BoMs report on Vance at http://www.bom.gov.au/info/cyclone/vance/vance.pdf)

Although the instrument was probably within the eyewall, Vance's maximum winds were not recorded. Learmonth was on the west side of the cyclone which was moving south at approximately 28 kph. The maximum winds would have been on the eastern side of the cyclone where the forward speed and the rotating speeds would have been additive instead of subtractive. The peak gusts would have been more than 300 kph down the un-populated, eastern coast of the Gulf – but of course there were no anemometers to record them.

There are now fifty or more years of Dines anemometer records in Australia. The records are generally of very good quality except for the above-mentioned problem that peak winds in cyclones tend not to be recorded.

Probably one of oldest original Dines anemometer traces in Australia is held in the National Archives in Darwin. It is from the anemometer which was installed at the Parap aerodrome as part of a weather service office for the 1934 London to Melbourne air race. The instrument was still in place to record a peak gust of 160 kph from the 1937 cyclone. As usual, the maximum winds were not recorded – this time because the belt of maximum winds passed well to the south of Darwin. (At the cyclone's landfall in Bynoe Harbour, the peak gusts would have been about 250 kph – refer Appendix F.)

After Cyclone Tracy, so-called "high-speed" Dines anemometers were developed but these are now only installed at critical locations such as Darwin and Gove airports. These instruments have been designed to measure and survive 370 kph wind gusts.

Elsewhere in the NT, wind speeds are recorded at AWS from cup anemometers such as the one at Maningrida pictured below.

Figure 2.2.8 BoM's weather station at Maningrida aerodrome. The cup anemometer is atop the 10 m high mast on left and an 'Almos' type AWS is in the white box beneath the solar panels. (Photograph is copyright Australian Bureau of Meteorology and is used with permission.)

Cup anemometers were introduced for recording at AWS in the NT in the 1980s. They have several defects for recording wind speeds for engineering purposes:

- their response times vary with the wind speed (*Davenport, 1992*). The response time will also vary with the dynamics of the gusts and presumably this means that there is never certainty as to the gust duration being measured

- they may record different wind speeds to the Dines anemometers. When the Dines was recording the gust speed of 267 kph at Learmonth during Cyclone Vance, two 'Almos' electronically logged cup anemometers that were very close by each recorded maximum wind gusts of only 230 kph (Kepert, *2002*). However, subsequent investigation showed that the Almos equipment was damaged and so this comparison may not be valid.

- they are probably intrinsically less robust and more prone to debris damage than Dines anemometers. BoM have 18 AWS within 50 km of the NT coast - all of them are equipped with cup anemometers. So far, they have had a dismal performance record when it comes to measuring maximum wind gusts near the eyewall of intense cyclones. For example the maximum gust recorded for Cyclone Ingrid was 207 kph at the McCluer Island AWS which according to the BoM best track was about 9 km outside the Rmw of the inner eyewall. However, one of the cups on the anemometer was found to have been bent 90 degrees from its correct orientation so this speed recording is virtually useless

The Group's submission to a Review of the Bureau of Meteorology copied here in Appendix N has recommended:

> *"Anemometers at all AWS and manned stations within 100 km of the NT coast should be high speed Dines anemometers designed to withstand and record 360 kph gusts."*

(It should have been 370 kph gusts - the chart limit of current 'high speed Dines' anemometers.)

2) Inaccuracies in wind speed estimates derived using the Dvorak technique

The wind speeds in the Dvorak tables were derived by calibration against wind speeds recorded by aircraft flying through the eyewalls of cyclones. It was initially developed by Vern Dvorak in the early 1970s using cloud recognition patterns only and at that time was a very subjective technique. It has been refined over the years to use other data obtained from satellites, in particular the temperature difference between the top of the cyclone core and the surrounding cloud tops obtained from infra-red measurement. This refinement has made the technique more objective. Despite the limitations of it being a purely empirical system, the Dvorak technique remains the most widely applied cyclone intensity estimation method in the world.

At some time into the future the technique will probably become fully automated and objective. A research effort in the US is proceeding towards that goal.

A review of the accuracy of the Dvorak technique for Atlantic cyclones between 1997 and 2003 compared Dvorak results with results based from aircraft reconnaissance. The Dvorak line was close to the mid-range of the plotted, reconnaissance results. In terms of gust speeds, half of the errors were 12 kph or less, 75% were 28 kph or less and 90% were 40 kph or less (*Velden et al, 2006*).

Over the years local variations have crept into the application of the technique. Australia's three **Tropical Cyclone Warning Centres** (**TCWC**) , Perth, Darwin and Brisbane, each use different wind-pressure relationship tables. It is recognized that there is little scientific justification for this but the absence of aircraft reconnaissance data for Australia has made it difficult to resolve the differences (*Velden et al*, *2006*).

A recent study of 3,800 data points from a 15 year record period of cyclones in the Atlantic and North Pacific has attempted to resolve the various differences that have crept into the Dvorak technique (*Knaff and Zehr, 2007*). It is hoped that this work will provide a basis for the review of the three tables in use in Australia and that some rationalisation will occur within a couple of years. (Ian Shepherd, pers. comm.)

Some limitations with wind speed estimates using the Dvorak technique are:

- the forward speed of the cyclone when estimating the maximum winds is only partially allowed for. A mean forward speed of 10 to 20 kph, based on Dvorak's original calibration sample, is implicit in the technique. This means that nearly stationary or very fast moving storms will have small errors in the estimated maximum winds (*Garden, pers. comm.*)

- rapidly intensifying cyclones can be under-estimated

- localised effects within the eyewall are probably not allowed for in the estimated gust speeds. (These effects include small tornadoes and larger vortices circulating within the eyewall, downdrafts and boundary layer rolls.)

The Group's submission to a Review of the Bureau of Meteorology copied here in Appendix N has recommended:

> *"The Bureau should collaborate with the Engineering profession to agree (or disagree) that the* ***maximum*** *gusts speeds given in the Bureau's cyclone warnings relate directly to the Regional Wind Speed (V_R) as defined in the current wind code (AS/NZS 1170.2:2002). As part of this exercise, agreement should be reached on the meaning of the word "maximum" in the Bureau's warnings – is it instead perhaps a 95 percentile figure? Does it allow for tornadoes, boundary layer rolls, downdrafts, eye-wall vortices, etc.?"*

<u>3) BoM estimates are vague as to radial extent and inland penetration</u>

The chance of a location being impacted by the maximum gusts from an incoming cyclone increases in direct proportion to the radius of maximum winds. While the cyclone is a long way away, there is little point in BoM cluttering up their warning messages to the public by giving them values of Rmw. But if the cyclone should get close then this important information should be included in the warnings – at least by means of description if not by giving numbers.

The inland penetration of cyclones is covered by BoM in their warnings with the new Tropical Cyclone Forecast Track Map which now provides 48 hour forecasting. The decay of wind speed inland is represented by lines showing the extent of gale-force, storm-force and hurricane-force winds. At the moment those winds are described by their 10 minute mean wind speeds.

This report recommends that the new BoM maps should describe inland winds in terms of maximum gust speeds. This will enable comparison with:

- the forecast maximum gusts at landfall
- the wind code speeds

4) BoM's Dvorak estimates are not believed by some engineers

The writer has a problem with one early estimate by BoM (see Tracy below) but considers that, subject to the above caveats, modern Dvorak practitioners should be obtaining reasonably accurate estimates of wind speed.

Mostly, the engineers who are skeptical about the Dvorak technique think that it has over-estimated the speeds from recent, intense cyclones such as Ingrid, Larry, Monica, etc. These engineers should bear in mind that probably the cyclone that has been most intensively studied by both engineers and meteorologists was Hurricane Andrew. When it made landfall in Florida 1992, it had a CI = 6.5 which equates to maximum gusts of 290 kph. This is significantly less than the finally agreed figure for Andrew based on dropsonde measurements of 330 kph.

2.2 (f) How accurate are estimates of wind speed from wind damage?

Engineers can estimate damage from wind speeds by:

- building damage surveys to obtain average results over reasonably large areas
- calculation of the wind speed required to bend simple structures such as road signs (**windicators**) to obtain more localised results.

Building damage surveys provide only very approximate indications of the maximum wind speeds that impacted their area. As well as the wind speed, the damage is very much determined by the strength of the housing, the duration of the wind, the wind direction(s) relative to terrain and perhaps most importantly of all – the amount of debris that was flying through the air at the time. Such surveys require special skills and will not be discussed further here except for the one following comment

Risk studies done in the eastern states frequently refer to a step-wise increase in the strength of housing circa 1980 following the introduction of new building regulations. The writer considers that this is not the case in Darwin. The strongest houses in Darwin are probably those built under contract by the Darwin Reconstruction Commission between 1976 and 1978. Another factor which counters the case for a post-1980 increase in the strength of houses is that design loads for new house construction have progressively decreased with each introduction of a new wind code – this has already been discussed on page 24 and is covered in detail in Appendix D.

It is thought that windicators can provide more useful information. Their use in Cyclones Tracy and Larry and the various wind speed estimates that have been made for those two storms are examined in the following pages.

Wind speeds can also be estimated from tree damage. This subject is examined on page 48.

Cyclone Tracy

Many people with expert knowledge believe (or believed) that BoM's official estimates for Cyclone Tracy having maximum gusts in the range 217 kph to 240 kph **are too low.** Some examples are:

- The official report on the building damage from Cyclone Tracy (known as the Walker report) was done by a team lead by George Walker for the Department of Housing and Construction (*Walker, 1975*). After referring to the 217 kph anemometer record on page 3.3, Vol.1, Walker states:

  "From verbal reports and observation of debris it seems fairly definite that where the eye or a lull in the wind was experienced, the wind after the lull was much stronger than before the lull. On this basis, it does not seem unreasonable to postulate that the maximum gusts may have been of the order of 130 to 140 knots, ……."

  The statement continued that these speeds refer to the standard 3 second gusts at 10 m height in terrain category 2. Walker is suggesting that Tracy's maximum gusts could have been 240 to 260 kph

- An interim report on Cyclone Tracy by BoM staff members stated that "*a maximum gust of 280 kph may well have occurred.*" (*BoM, 1975*).

- The storm tide prediction system recently prepared for BoM, Darwin used the surge measured at Stokes Hill wharf during cyclone Tracy to check the accuracy of the model used in the prediction system. It was found that to successfully model the measured surge, Tracy would have had to have been a Category 5 cyclone while it was off Mandorah. Figure 7.7 in that report indicates that the winds at Nightcliff may have gusted to about 270 kph (*SEA, 2005*).

- An earlier storm surge report for Darwin also reached the conclusion that Tracy's winds had to be significantly stronger than the final BoM estimate to have produced the measured surge (*Lawson & Treloar, 1982*).

- A guide prepared in Guam (*Guard and Lander, 1999*) to relate cyclone wind speeds with structure and tree damage includes a photo of some wrecked houses in Darwin's Northern Suburbs. The caption to the photo includes the statement:

  "This devastation occurred from winds of at least medium to strong TY CAT 4. This level of devastation cannot occur from TY CAT 2 winds as were estimated at the time (BOM 1977)"

  (TY CAT 4 winds gust from 292 to 316 kph. TY CAT 2 winds gust from 196 to 224 kph.)

BoM issued their final report with the maximum gusts estimated at 217 to 240 kph in 1977. There have been many advances in knowledge about the behaviour of cyclones and in the interpretation of satellite and radar imagery since that time. As the above examples indicate, this writer is far from alone in believing that a re-evaluation using that knowledge would lead to a significant upgrade in Tracy's estimated maximum winds. Cyclone Tracy remains an important bench mark in terms of the damage and fatalities it caused. The correct value for the maximum wind speeds would have an important impact on probability calculations. It is important, particularly to people in Darwin, that this matter be settled once and for all. Funds should be provided for an in-depth review by people with demonstrated skills in such evaluations.

Tracy Windicator Study

As manager of a local, structural engineering consultant's office, the writer assisted in the investigations for the above-mentioned Walker report. The writer's contributions in Vol. 2 of the report covered:

- Investigation of the performance of major buildings
- Investigation of the behaviour of systems type buildings
- Investigation of wind velocity from the behaviour of simple structures (windicators)

The **windicator** study involved examining hundreds of road signs throughout Darwin in the weeks immediately after the cyclone. Only those signs which did not show traces of debris impact were analysed to find what force (and hence what speed) would have been necessary to bend them over. Many unbent signs were also analysed as they gave indication of the wind speed not attained at a particular location.

The results indicated that the maximum gust velocity over the northern half of Tracy's swathe while it was over Darwin was about **280 kph.** That figure is corrected for elevation and terrain. It was somewhat more than Walker's maximum estimate of 260 kph – in his report he suggested that the discrepancy was due to differences in gust averaging times and dynamic interaction between the road signs and the wind.

Over the intervening years there has been research on windicators which resolves Walker's concerns and ensures more accurate methods of calculation. (*Hazel, 1986*) The writer considers that windicators can now give a reasonably accurate ground truth estimate of wind speeds.
The writer still has the original field notes and calculations for the Tracy study. Most importantly samples could be obtained of many of the original pipes. The reason this is important is that one of the biggest uncertainties in the original calculations related to knowing the exact thickness and strength of the steel in the pipes and this uncertainty will be totally eliminated by doing bend tests on samples of those original pipes. (Most of the original pipes have been removed - but only by burning them off at the surface. More than 600 mm of the galvanized pipes remain encased in their concrete footings.)

This report recommends that the Tracy windicators be re-examined as part of a study to re-evaluate Cyclone Tracy's maximum wind speeds over Darwin.

Cyclone Larry

In the weeks after Cyclone Larry made landfall near Innisfail, Queensland in March 2006, it was widely reported as being Category 5 at landfall (gusts >=280 kph). While BoM remain fairly certain that Larry was at Category 5 as it approached the coast, investigations still in progress indicate that it was probably a high-end category 4 cyclone at landfall

Engineers making surveys immediately after the event were skeptical of the Category 5 claims. Dr Bruce Harper considered that Larry was a high Category 3 or a low Category 4 storm at landfall (200 to 240 kph). Dr John Holmes was of the opinion that peak gusts at standard exposure were likely to have been in the range 180 kph to 220 kph only (*Davidson, 2006*).

As usual, anemometers provide little assistance in resolving the issue. The highest gusts recorded were 180 kph by a cup anemometer at the South Johnstone AWS. This station is 13 km inland and the recorded winds would have been affected by shielding of forested terrain upwind and nearby hills.

Larry Windicator Study

Results from windicators along the Bruce Highway near Innisfail suggested that the gusts there were in the order of 200 kph to 240 kph. (The study area would not have been impacted by Larry's maximum winds so the results do not resolve the issue of the wind speeds at landfall.)

The windicator study was carried out by the Cyclone Testing Station at James Cook University. Samples were taken of the posts of the selected signs and the samples were load tested to verify the material and section properties (*Ginger, pers.comm.*).

Tree Damage Surveys

To date, tree damage has not been used to any great extent to estimate wind speeds in the NT. However an investigation is in progress on the tree damage caused by Cyclone Monica and comparisons will be made with the known damage swathes produced by other historic cyclones such as Cyclones Tracy and Ingrid (*Garry Cook, pers. comm*.) The results of this study should also allow estimation of the wind speeds produced by cyclones in the early written records where the area and degree of damage to the original forests were described in some detail.

Wind speeds can also be estimated from damage done to introduced species such as coconut palms and mango trees. The Guam Guide mentioned above under structural damage, also correlates tree damage with wind speed for the tropical Pacific Ocean region and has application for such trees in the Top End (*Guard and Lander*, *1999*). The guide gives descriptions of damage to various tree types for seven different speed ranges. The lowest speed range is for maximum gusts of 61 to 104 kph, the highest range is for maximum gusts of 319 to 400 kph.

2.2 (g) How accurate are estimates of wind speed from storm tide levels?

Computerised storm tide models enable estimates to be made of the intensity of a cyclone from the height of the storm tide as revealed by tide gauges, eyewitness accounts or height of the debris. But there are two provisos:

- account must be taken of the coincident astronomic tide so the time that the storm tide level peaked must be known to within an half an hour or so
- the computer model used to simulate the event must produce accurate results

Details are given in Appendices E and F of how the two most recent surge/storm tide risk studies for Darwin (*VIPAC, 1994; SEA, 2006*) appear to under-estimate recorded storm tide events for cyclones in 1919, 1937 and possibly for 1974.

The difference between recorded and model estimates for these storm tides could be the fault of the records but it is more likely to be due to the acknowledged defects in the models – namely that they do not allow for wave runup or for rainwater flooding and the model grids are too coarse to allow for small features such as creeks, rivers or estuaries in the harbour or the unusual conditions offshore from Nguiu. These matters are discussed in Appendix I

Further checks could be made on the SEA model by seeing if it will produce the storm tide height that Cyclone Thelma caused at Stokes Hill Wharf in 1998 and that Cyclone Ingrid caused in Nguiu in 2005.

(In order to check storm tide levels at Nguiu, a survey will be necessary to confirm the tidal range and tide times relative to Darwin.)

2.2 (h) Conclusions and Recommendations

Conclusions

The Fig. 2.2.5 swathe map was used to derive an indication of the likelihood of a category 5 cyclone making impact on Darwin. The results were:

- for Vg >= 280 kph, AEP = 1/1,000 which is intermediate to Region C and Region D values
- for Vg >= 350 kph, AEP = 1/2,000 which is very close to the Region D value.

These are very rough estimates are but they do confirm the writer's findings in Section 2.1.

An examination of MPI figures showed that Darwin's MPI equates to maximum possible gust speeds that are 8% higher than those for Port Hedland and 40% higher than those for Townsville.

Some other regional differences that would appear to place the NT at higher risk are:

- mean track directions and the latitudes and orientations of coastline mean that intense cyclones are more likely to make landfall in the NT than on Queensland's east coast. This is particularly true for locations in the NT such as the Tiwi Islands and the Gove Peninsula whose prominence places them in the path of cyclones moving both westward and eastward.

- the NT coastline is unique in the world in that there is a 'divide' in the vicinity of longitude 138° E near Nhulunbuy where the mean track directions of cyclones are south-west on the west of the 'divide' and south-east on its east side. If the longitude of this divide was say 10° further west pre 1940 it could explain the predominant easterly track directions for cyclones affecting Darwin before that time. (refer page 14.)

- the warm and shallow seas off the NT coast may preclude the negative feed-back effect that limits intensification in deeper seas that have a pronounced thermocline. The seas off Port Hedland and off the east coast of Queensland do have thermoclines and this potential negative feed-back effect may have a benign influence on cyclone intensities for these regions.

Part 2.2 (e) dealing with the accuracy of BoM's wind speed estimates began with: "*The writer believes that the staff at BoM, Darwin do an excellent job with the resources that they have available and that their estimates for the wind speeds associated with cyclones are likely to be reasonably accurate.*"

However some problem areas were identified:

- the poor performance of the NT's anemometers when it comes to recording maximum winds in or close to the eyewall in intense cyclones.

- improvement could be made to the new Tropical Cyclone Forecast Track Map by giving the wind speeds in terms of maximum gust values.

The model used for the latest storm tide mapping study for the Darwin region (*SEA,2006*) appears to under-estimate the storm tides produced by intense cyclones in the historic record.

Recommendations

- **For meteorologists**
  Recommendations made in the Group's submission to the Review of BoM are given in Appendix N. Some of them relate to the fundamental research into MPI and the other regional differences discussed above. Only one will be repeated here, namely:
  > *"There needs to be much more emphasis on NT related research. This would be best achieved by establishing an NT branch of the BMRC in Darwin or by increasing resources for the Darwin Regional Office."*

- **For both meterologists and engineers.** There needs to be a collaborative effort between these two professions in order to:
  - gain better appreciation and confidence in the way each discipline makes its estimates of wind speeds. It is hoped that this report will contribute to that process
  - agree (or disagree) that BoM's 'maximum gusts' relate directly to the wind codes 'Regional Wind Speeds'. A start to this process would be to have each discipline giving precise definitions of their own terms - eg are the speeds intended to be 95 percentile figures or what?
  - agree (or disagree) on the gust duration. The BoM literature refers to 2 second gusts whereas the current wind code refers to 3 second gusts. (Previous wind codes referred to 2 – 3 second gusts.) There is only about 2% or 3% difference between the theoretical values for the two durations so why not agree on using one or the other? If that is going to be too difficult, then it should at least be stated that BoM gusts are implicitly 3% (or whatever it is) faster than gusts having the same numerical value in the wind code
  - determine if the records from Almos cup anemometers as currently installed by BoM can be confidently used for engineering purposes. If not, in the NT at least, they should all be converted to Dines-type anemometers. Regardless of the type, the design and installation of BoM anemometers should have Australian engineering input to ensure that they will survive wind gusts of at least 370 kph
  - conduct a review of Cyclone Tracy's maximum wind speeds over Darwin. This could be done by means of a special edition in a suitable journal.

- **For engineers:**
  - Building damage risk studies for Darwin should <u>not</u> use the assumption made for Queensland housing that there was a step-wise increase in housing strength after 1980
  - Funding should be provided to enable a proper review of the Tracy windicator study
  - Funding should be provided to enable further development of storm tide models so that they provide more realistic estimates of maximum levels by:
    - allowing for wave runup
    - allowing for creek and river flooding from the very heavy rainfall associated with cyclones
    - using a finer grid to enable better resolution at creeks and estuaries
    - testing the models to ensure that the results obtained reasonably match the recorded storm tides in Darwin and/or Nguiu from cyclones in 1919, 1937, 1974, 1998 and 2005.

2.3 Estimating the Probability of an Intense Cyclone Occurring from Nature's Long-term Records

2.3(a) Summary

This section will make a case for the NT government to become actively involved in a research program that will study the records preserved by nature to determine the recurrence intervals of the intense cyclones which have impacted the NT coastline.

The study of past tropical cyclone activity using natural features as the 'recording' agent is termed **Paleotempestology (PT)**. These so-called proxy records may be found in a variety of naturally occurring features. The ones which will be discussed here are growth-rings in trees, layering and/or succession in beach ridges and sediment layers in the beds of coastal lagoons,

PT is a relatively new field of science and is a sub-branch of palaeoclimatology. The website of the National Oceanic & Atmospheric Administration (NOAA) of the US Department of Commerce http://www.ncdc.noaa.gov/paleo/paleo.html lists 70 references under PT. (The list mainly relates to North America and is only to 2001.)

The radiocarbon dating of beach ridges and lagoon sediments provides only coarse measurement of the dates, locations, directions and intensity of cyclones. It is also probable that they only record the most intense cyclones that affect the coastline but these proxy records have a valuable property - they can extend back more than 5,000 years.

Tree-rings in the Top End will enable cyclone occurrences to be determined for probably not more than the last 300 years but they should enable much better resolution of the location, direction and intensity of the cyclones they record. Tree-rings could therefore be a very important element in a PT study because they could enable a bridging correlation to be made between cyclones of known intensity in the brief historic record and the rare, proxy records of very intense cyclones revealed in the coastal features.

An important attribute of the Top End for PT study is that its extensive, virtually pristine coastline should not only allow hard numbers to be derived for the recurrence intervals of intense cyclones but importantly, it should be possible to derive different probabilities for different track directions. This latter refinement is a critical parameter in risk analysis for Darwin because by far the greatest risk is for an intense cyclone approaching the city from the north-west.

Whereas the historic record can show up variations in recurrence intervals on a decadal scale, PT studies can reveal variations on centennial and millennial scales. PT research will also provide information on the climate changes that have taken place in the Top End over the past 5,000 years and could provide important leads on the likely effects from global warming.

2.3(b) Tree-Rings

The use of tree-rings for dating purposes is a well established field of science known as **dendrochronology**. People interested should visit http://web.utk.edu/~grissino/ - the ULTIMATE tree-ring pages. The writer wishes to acknowledge the assistance given by Dr. Henri D. Grissino-Mayer, University of Tennessee, in getting started on researching this particular field of PT.

For the entire life of many species of tree, a year-by-year record or ring pattern is formed that reflects the climatic conditions in which the tree grew. Adequate moisture and a long growing season result in a wide growth ring. Drought, fire, disease or severe wind damage may result in a very narrow one.

Trees from the same region will tend to develop the same patterns of ring widths for a given period. These patterns can be compared and matched ring for ring. This pattern recognition used to be done by visual inspection but is nowadays done using computers and statistical analysis. Provided there is an overlap in the ages of the timber, long dead trees can be used to extend the chronology back in time.

Figure 2.3.1 A disc cut from a long dead Callitris intratropica (cypress pine) near Bulman in Arnhem Land. The sample includes 175 annual growth rings. (Photograph courtesy G. Cook, CSIRO)

The samples used for dendrochronology can be discs cut from the tree or can be mountings of 5 mm diameter cores. The latter can be harmlessly extracted from a living tree using a simple, hand powered coring device.

The use of dendrochronology as a tool for PT is relatively recent advance – so far it has been mainly confined to the US and even there it only received intensive study since the 1990s. Refer list at **http://www.ncdc.noaa.gov/paleo/hurricane/references.html**

Several studies have been carried out in Australia using tree-ring information relating to palaeoclimatology and to discern changes in the frequency and intensity of bush fires (*Bowman and Panton, 1993*).

To date, the only Australian study on tree-rings relating to PT, that is with the specific aim of determining cyclone recurrence intervals, is the one conducted for this project. Patrick Baker, a dendrochronologist at Monash University was commissioned to study samples of Callitris intratropica (cypress pine), Bombax ceiba (kapok tree) and Alstonia actinophylla (milkwood) taken from various localities around Darwin to see if known cyclone events could be identified in the tree-rings.

Baker's report is included here in Appendix J. In summary, the findings were:

- The tree-rings in Callitris intratropica are suitable for dendrochronology but those in Bombax and Alstonia are not
- There was a notable reduction in the width of the tree-rings in the Callitris samples for 1974 – the year that the trees were impacted by Cyclone Tracy
- Dendrochronological studies have the potential to identify the frequency and spatial distribution of past cyclone events in the Northern Territory

The following comments relate to some of the issues raised by Baker.
(It is suggested that Baker's report in Appendix J be read before proceeding.)

Oxygen Isotope Ratio

Scientists at the University of Tennessee have recently discovered that the oxygen isotope ratio in the cellulose of tree-rings provides high resolution, proxy records of tropical cyclone activity (*Miller et al, 2006*) The technique relies on the fact that rain produced in tropical cyclones has less of the heavy O_{18} isotope than normal rain and the water absorbed into the cellulose records this difference. This is an important finding because it should mean that a narrow growth ring can be positively identified as being caused by a tropical cyclone rather than from say, drought, fire or disease.

Oxygen isotope ratios have been used in Australia to study various climate related phenomena but as yet the technique has not been used in Australia to see if cyclone occurrences can be detected in tree-rings. There is also a possibility that the technique is not suitable for the low latitudes that prevail in the Top End. Both of these issues could be resolved very quickly and cheaply with a simple, targeted research project.

1986 Anomaly

Baker's results show a consistent low ring width for 1986 even though there was no cyclone in that year. Unless this anomaly can be explained, the overall utility of the method for detecting cyclones comes into question.
In referring to the 1986 anomaly on page 2 of his report, Baker states: *"Preliminary analyses of the rainfall record show no significant correlations between monthly or seasonal rainfall and the ring-width indices that might explain these growth anomalies."*

The writer has analysed the monthly and daily rainfall figures from the nearby Howard Springs rainfall recording station for the period 1980 to 2005 and concludes that low rainfall probably was the reason for the 1986 anomaly. The rainfall records show:

- the 1986 "growth ring" rainfall (from September of the year to May of the following year) was only 1070 mm. This was the lowest recorded over the 25 year period (the average was 1890 mm); and, more significantly
- for the 280 days between 10 April 1986 and 13 January 1987, the total rainfall was only 257 mm and there were 9 consecutive months with less than 54 mm monthly rainfall. (The only other year that came close to that record was 1982 when there were 7.5 consecutive months with < 54 mm)

Evapotranspiration rates during a normal dry season probably exceed 100 mm per month so it is likely that by December 1986 and early January 1987 there was a significant shortfall in the moisture stored in the root zone soil and within the tree cells of the Callitris and the trees underwent stress. Their recovery may then have been impeded by the very low rainfall in the following wet season. Further study is required to resolve the issue. There are moisture balance methods to estimate whether or not the trees would have undergone stress for the recorded rainfall. Comparison of the rings from trees from parts of the Howard Springs plantation having different soil type and/or topography (and hence different soil-water storage capacities) might also shed light on the matter.

Can the potential utility of the method be quantified?

Obviously not yet - but the following points are relevant:

- The Top End coastline and immediate hinterland has an abundance of trees that have managed to recover from past cyclones. These trees could not only reveal the exact year and location of a landfalling, intense cyclone but they could also reveal the lateral and inland penetration of that cyclone. It would require a lot of fieldwork but a map could be derived showing the wind swathe produced by each intense cyclone that has made landfall along the NT coast over the last three hundred years.

- The width and inland penetration of the tree damage swathe gives good indication of the size and intensity of a cyclone. Dr Garry Cook, Tropical Ecosystems Research Centre, CSIRO, Darwin is studying the effects of cyclone Monica in this regard. His work will also identify the known damage swathes produced by other historic cyclones such as cyclones Tracy and Ingrid.

- The Top End has two attributes which favour the method:
  - There has been only limited clearing of native vegetation along the coastline,
  - The normally flat topography removes the variability in wind speeds and tree damage that occurs in hilly or mountainous terrain and so should simplify interpretation.

- The utility of the method will be diminished if the only native trees that can be studied are Callitris. This species is reasonably widespread on the Tiwi Islands, Coburg Peninsula and Arnhemland but nowhere near widely enough to provide a uniform coverage of the coastline. Other, long-lived native species which can be used for dendrochronology need to be identified. Three possible species are listed on page 6 of the Baker report.

- Until quite recently, it was thought that only softwood species like Callitris could be useful for dendrochronology on the basis of their visually evident production of annual growth rings. However research led by Martin Worbes of the University of Gottingen has shown that many tropical hardwoods exhibit annual increment zones when viewed under 40x magnification. Most of this research has been done in Central and South America where it has been found that dry forest trees which endure a dry season of more than three months with less than 60 mm of rain per month are likely to exhibit increment zones – particularly if the trees are also deciduous or semi-deciduous (*Enquist and Leffler, 2001*). This research would appear to be relevant to the Top End.

- Very little is known about the maximum longevity of Top End native tree species. It is thought cypress pines can live for three hundred years. (There is a cypress pine which died in 2006 in Darwin's George Brown Botanic Gardens which is thought to be that old but two separate attempts have failed to obtain useable cores from this old, hollow tree to enable reliable dating.)

- Natural stands of Callitris were extensively logged on Indian Island in Bynoe Harbour in the 1880s and 1890s, on the Tiwi Islands in the early 1900s and around Coburg Peninsula and Murganella after that. Hopefully some trees were left for posterity but even if not, surviving stumps from those trees could provide valuable data.

- Further research is needed to ensure that late-season cyclones also leave characteristic features in tree-rings. Their effects may be quite distinct from early-season cyclones.

Refer 2.3(d) for recommendations for future research.

2.3(c) Beach Ridges and Lagoon Sediments

The writer had identified about 430 sites around the NT and nearby sections of the WA and Qld coastlines which have potentially recorded past cyclones. They comprise:

- about 230 sites having beach ridges only
- about 150 sites having lagoons only
- about 50 sites having both beach ridges and lagoons

The location of these sites is detailed in Appendix K of this report. (Appendix K in the CD format also includes an image file which contains 48 Google Earth images and 443 oblique aerial photographs covering about half of the 430 prospective sites. Anyone even remotely interested in the NT coastline should enjoy the slideshow of these fully captioned images.)

Beach Ridges

In this report the term "beach ridges" can relate to any one of five basic types:
1. cheniers comprising shells and/or sand ridges overlying and separated by mudflats having fluvial and/or mangrove origins;
2. ridges or bars – also comprising shells and/or sand but tending to be thicker and forming on and separated by steeper-sloping, marine sediments;
3. coral rubble ridges comprising broken coral washed into mangrove or onto beaches;
4. aeolian (wind formed) sand dunes; and
5. erosion terraces.

A single site will often contain more than one type and they commonly grade from one type into another.

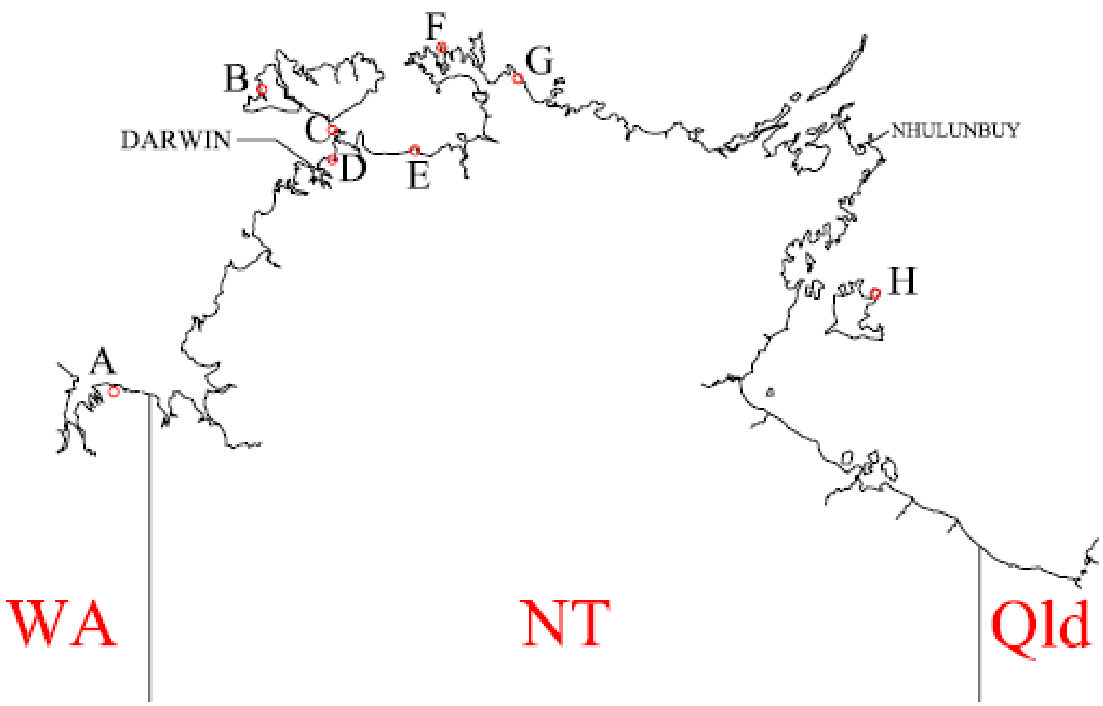


Figure 2.3.2 Map of NT and adjoining coastlines showing locations where beach ridges have already been studied. Table 2.3.1 on following two pages gives details.

Fig. 2.3 (a) alpha code and Location:	**Ridge type(s)**	**Author(s), date**	**FINDINGS.**
A Victoria Delta, WA	Cheniers & ridges	*Lees, 1992*	Five lines of cheniers formed between ~2020 yrs **B.P.*** and ~1210 yrs **B.P.*** probably during dry periods of low mud input or possibly from a delta switch of the Ord River. Beach ridges are 700 m shoreward of the cheniers. Age of ridges must be less than 1,000 yrs (sampled shells gave dates between ~4,000 yrs and ~6,000 yrs **B.P.*** but this would be the result of dredging action by storm or longshore current uncovering the old shell beds)
B Wangiti Beach, Bathurst Island, NT	Cheniers & ridges	*Fensham, 1993*	Mainly concerned with botanical study on a succession of about 30 ridges over a 2 km wide plain. Dates obtained from shells on only 2 ridges: ~3750 yrs **B.P.** 400 m inland, ~4900 yrs **B.P.** 1600 m inland. Dates may not represent age of formation of these ridges due to overwash &/or dredging.
C North West Vernon Island. NT	Coral rubble Ridges	*Wasson, (Appdx. L this report)*	A report based on preliminary sampling done in 1989 from the two most seaward of several ridges on the island. Found that in the last ~600 yrs there have been four powerful cyclones with an average frequency of ~150 years. Tracy had little effect.
D Camerons Beach, Shoal Bay, NT	Cheniers	*Hickey 1981*	Dated five discontinuous ridges using shells sampled from trenches dug through the ridges. Concluded that the **B.P.*** ages of the ridges, starting at the youngest, most seaward ridge, were ~670 yrs, ~850 yrs, ~1060 yrs, ~2350 yrs and ~2340 yrs.
D Leanyer Swamp to Camerons Beach, Shoal Bay, NT	Cheniers	*Woodroffe and Grime, 1999*	Reviewed Hickey's study. Questioned reliability of using shells for dating chenier ridges. Found that progradation of the plain probably did start ~2400 yrs **B.P.*** but also found that shells of age 900-1,000 yrs are currently being exposed by erosion on part of the modern foreshore and that these shells are being incorporated into the seawardmost cheniers which are still actively migrating landwards through the mangroves at some locations. Concluded that all of the ridges may be much younger than Hickey's shell dates. The authors also examined a sequence of aerial photos to see if cyclone Tracy had an effect on beach ridges. They found widespread impact on the mangroves but little effect on ridges. Interestingly, these photos did show erosion and accretion (unrelated to Tracy) proceeding simultaneously in different locations along the beachfront.
E Point Stuart, Chambers Bay, NT	Cheniers	*Clarke, Wasson, Williams, 1979*	Shells used to date three of the eight cheniers at this location. Most seaward ridge, named S1, was given age of ~580 yrs **B.P.*,** ridge S3 ~2745 yrs **B.P.*** and ridge S5 ~4040 yrs **B.P.*** From distance measurements, it was concluded that the most landward ridge (S8) was formed ~5650 to 6650 yrs **B.P.*.**
E Point Stuart, Chambers Bay, NT	Cheniers	*Lees, 1987*	Studied same location. Radio carbon dating of Lee's shell samples from the five seaward ridges had **B.P.*** ages of ~420 yrs, ~1020 yrs, ~1210 yrs, ~1180 yrs and ~1270 yrs. He concluded that:

			• the two oldest of the Clarke shell samples were long dead when deposited; • each of the five seaward ridges corresponds to a major storm; • the five (sic) landward ridges formed prior to about 1400 yrs B.P. in a more arid climate and/or before major delta switching of the Adelaide and/or Mary rivers.
F Coburg Peninsula, NT	Cheniers, ridges, dunes and terraces.	*Woodroffe et al, 1992*	Study was mainly directed at dating shorelines from previous interglacials at ten locations around the western end of the Coburg Peninsula. Of particular interest here is the study of the 2 km long ridge plain near Smith Point and the problems that arose with the radiocarbon dating. Two other dating techniques found that the most landward ridge is about 5,000 years old but the radiocarbon age for near surface shell fragments at this ridge was ~1870 **B.P.*** (Conclusion: the sampled material was from an overwash.) Only two other radiocarbon dates were obtained but these also gave inconsistent results with the older sample coming from a ridge nearer the shore. (sample assumed to have been long dead when deposited.)
G East of Coburg Peninsula, south east of DeCourcy Hd, NT	Dune fields	*Lees et al, 1990*	Study also included two sites on Cape York. For the NT site, TL dating on the sand in four distinct stratigraphic dune units gave ages of ~1,900 yrs, ~2,700 years, ~8,600 yrs & ~81,400 yrs. (No sample was taken from the currently mobile dune.) There were near matching ages for the three youngest dunes in the two Qld sites which suggests that there has been three, synchronous, episodic emplacements of dunes in NE Australia when there was reduced wet season rainfall. The ~1,900 yr age correlates with inferred arid climate prior to ~1400 B.P at Pt Stuart.
H Near Umbakumba, Groote Eylandt, NT	Ridges on beach spit	*Shulmeister Lees, 1993.*	Spit developed ~2500 **B.P.*** due to migration of dunes. The formation of concentric ridges is complex process. One shell type only deposited under storm conditions.

Table 2.3.1 Details of the main studies to date on beach ridge sites A to H in Fig. 2.3.2

THIS PAGE LEFT BLANK

The “findings” column in Table 2.3.1 shows that:

- the determination of recurrence intervals of cyclones from beach ridges in the NT may be possible but the research has a long way to go
- coastal processes are complex and different researchers reach different conclusions on how the various types of beach ridges form
- the age of a shell or coral sample taken from a beach ridge may not provide the date of formation of that ridge

The above-listed, ten studies have been by researchers mainly interested in geomorphology and palaeoclimatology during the late **Quaternary Period**. Most of these studies make reference to the ridges having had some connection with cyclones but only two could be considered as PT studies where there was a direct correlation made between the radiocarbon dates for ridges and the occurrence of one or more intense cyclones at that date. (*Lees, 1987; Wasson, Appendix L this report*)

Of the four types of ridges, coral rubble ridges appear to provide the most direct link to a cyclone occurrence. The only study of such ridges in the Top End was carried out at North West Vernon Island by R. J. Wasson in 1989 when he was working for the CSIRO. Professor Wasson is now Deputy Vice-Chancelor (Research) at Charles Darwin University and has provided a report for this project detailing the results of his preliminary study - see Appendix L attached.

PT studies in Queensland are much more advanced and are summarised in Appendix L.
A lot of the work has been done by Jonathon Nott of James Cook University. Nott has mainly worked on coral rubble ridges but has also studied a series of erosion terraces near Cairns. The intensity of the cyclones causing terraces (or ridges) can be calculated from their heights above highest astronomic tide level. There have been no intense cyclones in the immediate Cairns region since European settlement but the terraces indicate that there were at least two between 1815 and 1870. This has a drastic effect on the risk of inundation. For the 1 in 100 year event for instance, the inundation level increases from 2.9 m AHD as indicated by the historic record to 4.6 m AHD indicated by the PT record (*Nott, 2003*).

PT studies near Darwin will be more difficult to interpret because of the high tidal range but this is not a problem over most of the Top End coastline.

Dating ridges from coral or shells can be a trap for young players. To effectively date a ridge firstly requires its stratigraphy to be revealed. This can be achieved simply by digging a trench through it or making a line of closely spaced auger holes and using down -hole video. The stratigraphy should show if it was formed by one or more energetic cyclones or by more gradual processes. It should also enable the judicious selection of samples for dating. Surface samples need to be taken at the ridge and/or back-slope to check for overwash events and from several places within the core to ensure the ridge is aged by only the youngest of its shells, coral pieces, etc. Only one species of shell or coral should normally be chosen at a given site and only the most intact, youngest looking specimens should be sampled.

Sometimes ridges (particularly those from coral rubble) are formed during the cyclone. A large ridge was observed to have formed on Jaluit Atoll from a cyclone in1958 and another on Funafuti Atoll during a cyclone in 1971. However, it is probable that the more usual process for relatively low ridges is that the high waves generated in an intense cyclone break coral or dredge up shells from offshore beds and then sort and deposit this coarser material near-shore. Storms coinciding with high spring tides then swash this material onshore over the following years.

This gradual process is likely to occur in all regions but perhaps particularly in those having a high tidal range. It has been observed on a ridge at Channel Island in Darwin Harbour (*Michie and Presnell, 1987*) and the writer believes it is currently underway with a bar accreting coral clasts at Lee Point – probably as a result of cyclone Thelma in 1998. The fact that aerial surveys after cyclones Ingrid and Monica found no sign of ridges having been formed at or near their landfalls further supports the hypothesis that ridge formation tends to be a gradual process.

It is clear that palaeoclimatology will be an important, background component to any future research into PT using ridges. For instance:

- Studies of the dunes south of DeCourcy Head (*Lees et al 1990*) and the cheniers at Point Stuart (Lees 1987) indicate that the Top End was significantly drier in the period 2600 -1800 yr B.P.

- Something triggered widespread development of mudflats along the Shoal Bay shoreline about 2300 yr B.P. (*Woodroffe and Grime, 1999*). The writer's captions to images 2_480, 550 & 551 in Appendix K make the suggestion that this "something" may have been the Adelaide River switching from discharge into Chambers Bay on the eastern side of Cape Hotham into Adams Bay on its western side.

Refer 2.3(d) for recommendations for future research.

Lagoon Sediments

In this report the term "lagoon" is loosely applied to any depression behind the beachfront which might contain overwash deposits from an intense cyclone. Such depressions might be swales, inter-tidal or supra-tidal flats, brackish swamps or lagoons with a creek outlet to the sea or a land-locked, fresh water lake or lagoon.

The use of lagoon sediments for PT studies is recent development. It only got under way in the US in the 1990s and as yet, it has not been applied in Australia.

The theory and techniques were established in landmark studies of lagoon sediments sampled along the coastlines of the Gulf of Mexico and NW Florida (*Liu and Fearn, 1993, 2000a, 2000b*). Similar studies have been carried out along coastlines in Rhode Island, New Jersey and from an island offshore from Puerto Rico (*Donnelly et al, 2001a, 2001b, 2004a, 2004b and 2005*)

A 2004 thesis by J.T.Knowles on lagoon sediments sampled in Honduras and in two Caribbean Islands gives an excellent introduction to the subject. It is available at:
http://etd.lsu.edu/docs/available/etd-06072004-125021/unrestricted/Knowles_thesis.pdf

Nearly all of the above studies have correlated at least the top layer of sediment with an historic hurricane. The one by Knowles even correlated two layers with hurricanes in the historic record dating back to 1550 AD and 1660 AD.

The intensity of the hurricane causing the overwash can be gauged by the height of the intervening land barrier. One of the criticisms of the method is that the height of this barrier may be reduced to some unknown degree during the overwash event. This problem should not arise for cases where the barrier is well vegetated or if it is indurated (cemented). Both situations will be common for Top End lagoons.

The sediment layer forming the proxy record is usually sand but it may also contain small marine shells, foraminifera and other minute organisms as evidence of it having a marine origin. Sometimes the overwash layers are distinguished by a thin, top layer of charcoal particles resulting from the post-hurricane bushfires – an association that is now recognized in the Top End following cyclones Ingrid and Monica.

The writer made a very preliminary foray into researching lagoon sediments by retrieving a core from a tidal flat in a lagoon system near Wagait, Cox Peninsula. The site is about 20 km across the harbour from the Darwin CBD. The object was to see if the core would have marine sediment layers. It did not. This very preliminary investigation is reported in Appendix M. Although the investigation proved negative, it is reported here because it highlights some of the difficulties in obtaining good samples for analysis and the need for careful selection of sample sites.

2.3(d) Conclusions and recommendations for future research

The three possible features discussed above for PT study (tree-rings, beach ridges and lagoons) would seem at this stage to have equal claim to warrant further investigation. The following discusses general issues relating to all three types of proxy records but also includes sections with specific recommendations relating to Baker's report on tree-rings and Wasson's report on coral rubble ridges.

The research recommended here will not come cheap and so the first step is to decide if it worthwhile proceeding with PT research in the first place. To facilitate such a decision, it is recommended that:

- **The NT Government establish a formal committee of enquiry on the matter**
- Section 2.3 and Appendices J, K, L & M of this report be sent to experts in the three fields to obtain there advice
- Suitable advisors would be:

  For Tree-Rings:
  - Dr Henri Grissino-Mayer, University of Tennessee
  - Dr Martin Worbes, Universtiy of Gottingen
  - Prof. David Bowman, University of Tasmania

  For Beach Ridges:
  - Prof. Colin Woodroffe, University of Woolongong
  - Dr Jonathon Nott, James Cook University
  - Prof Brian Lees, University of New South Wales

  For Lagoon Sediments:
  - Prof. Kam-biu Liu, Louisiana State University
  - Dr Jeffrey Donnelly, Woods Hole Oceanographic Inst, MA

These eminent researchers should be asked:

- to provide criticism of the report;
- if it is worthwhile proceeding with further, PT research; and if so
- how this research would be best organized and where it would be best targeted.

The replies and the committee's final recommendations should be made available to the public.

<u>Assuming that a decision is made to proceed, the writer suggests:</u>

(1) Research on all three types of proxy records should be brought under the control of one agency

This agency could be:

- a special section in a NT government department
- an organization similar to a Cooperative Research Centre that pools talents from selected universities, industry and government
- a firm of consultants with expertise in coordinating such research

The reasons for a single agency are

- Many sites will contain all three types of proxy records

- A large proportion of the sites will be on aboriginal land and so approvals from the relevant land councils and communities will be required to conduct research on the land and to gain entry permits. Some sites will be within or near sacred sites and will also require consultation with the Aboriginal Areas Protection Authority. Hopefully aboriginal elders and rangers will become involved in the project and contribute their local knowledge and skills. The object and nature of the work should appeal to the indigenous community and the project should provide some employment. Hopefully one or more aboriginal students would be included on the staff of the agency.

- Many of the sites will be expensive and difficult to access, requiring charter of launches, fixed wing planes or helicopters. This indicates that field work should be by a single multi-skilled team able to obtain samples of all three types

- The research will probably progress from relatively small pilot studies to demonstrate the utility of the methods to (hopefully) increasingly large scale efforts. All three types will need to be in step with this progression

- Initially, only a few sites from limited lengths of coastline would be included in the pilot studies. Obviously all three types need to be represented in the same lengths of coastline to achieve correlation between the results

- If the work proceeds it would take at least a decade for a small team to complete a reasonable coverage of the entire NT coastline

- Clearly, the funding, the conduct of the research and the publication of results in a free, consistent and easily understandable format will all be enhanced by a targeted approach from a single agency

(2) Nature of the research. The work should be subject to tight budget and time constraints – for instance the pilot studies would need to be completed within say a six month time frame. Initially, extensive assistance will be required from university researchers with prior experience in the various fields. As the work progresses, this input could reduce to occasional, paid consultations for advance planning and project reviews with the bulk of the work being carried out by people engaged full time by the agency. Presumably, most university – industry partnerships are conducted in this way.

(3) If pilot studies are conducted, it will be critical that the sites are chosen because they are the most prospective rather than because they happen to be easy and cheap to access.
For that choice to be enabled, the dossier of oblique aerial photographs of prospective sites commenced in Appendix K should be completed. This could be done by a combination of fixed wing flights and helicopter flights. Later helicopter flights could be done with an expert in each type of proxy record on board to make the final selections for the pilot study sites and perhaps do some preliminary sampling.

(4) The report on tree-rings by Baker in Appendix J could be regarded as a preliminary pilot study. It warrants the following, further investigations:

- find if the oxygen isotope method can be used to distinguish cyclone occurrence in Top End tree-rings

- resolve the "1986 anomaly" in the Howard Springs plantation samples

- further prove the utility of the method by examining samples from other 1960s Callitris plantations which are relatively easy to access such as Radio Block, Gunn Point and the Tiwi Islands. It will be particularly important to observe if and how the the growth rings were affected by the late-in-the-season, cyclone Ingrid

A start could also be made on investigations to find:

- other long-lived, native trees in the Top End coastal regions (i.e. besides Callitris) which are suitable for dendrochronology

- the location of old, living trees or old stumps or timber from logged trees of Callitris and any other species found to be suitable for dendrochronology to extend the record back in time

(5) The report on coral rubble ridges by Wasson in Appendix L could also be regarded as a preliminary pilot study. It warrants the following, further investigations:

- make more detailed sampling and dating of the seaward ridges and also of the several small, landward ridges

- accurately plot the changes in the seaward ridge following cyclones Tracy and Thelma using imagery from aerial photographs and satellites

Cost Benefits

However it is organized, the research will be costly. The laboratory cost for radiocarbon dating beach ridge or lagoon sediment samples is about $400 per sample and for luminescence dating it is about $1,500 per sample. Dating of thousands of samples would be required to obtain realistic estimates of cyclone recurrence/direction intervals around the NT coast which could be incorporated into engineering, risk assessments. But the major cost would be for salaries. To put a ball park figure on the scale of investment required, a ten year programme with the goal of sampling say 20 sites per year with a staff of 6 would cost in the order of $1.5 million per year.

It would not be possible to do a rigorous cost-benefit analysis on the research recommended in this section 2.3. However, given the degree to which the NT's economy is vulnerable to cyclones and the increasing evidence that the last 40 years may not represent the risk from cyclones into the future, it would seem foolhardy not to attempt to recover the records that extend back thousands of years.

Figure 2.3.3 Looking SW down the actively accreting, coral rubble ridge on North West Vernon Island.

The fresh coral material in the seaward ridge may have been broken and sorted off-shore by Cyclone Thelma in 1998 and is being gradually moved inward by lesser storms.
An older, coral rubble ridge is inland to the left of the line of dark green mangroves.
The tree line to the right of the area containing the mangrove stumps once marked the boundary of the seaward ridge. Cyclone Tracy is believed to have swept that ridge to the southern tree line. Subsequent, lesser storms have then swept that material back so that it now underlies the fresher material on the seaward ridge.

2.4 Possible Effects of Climate Change

(a) Summary
(b) Statement by world authorities
(c) Thelma, Ingrid and Monica

2.4 (a) Summary

The NT has a cyclone problem with or without climate change. It is emphasised that the conclusions and recommendations in this report are not reliant on predictions about the future effects of climate change on the intensity or frequency of future cyclones. As discussed in part (b) following, no firm conclusions can yet be drawn on possible effects on intensity or frequency in any case.

In the writer's opinion, the aspect of climate change relating to cyclones that is of most concern is the possible rise in seal levels. It is understood that since the 1990s, engineers in Darwin have made an allowance of 0.5 m for future sea level rise when setting the safe levels for waterfront developments. This report recommends that the 0.5 m allowance be maintained for future developments and that future storm tide risk studies include decade by decade allowance for sea level rise.

The recent occurrence of cyclones Thelma, Ingrid and Monica may be related to global warming or may be indicative that some multi-decadal cycle is under way. This is discussed in part (c).

2.4 (b) Statements by World Authorities

A statement by nine prominent tropical cyclone researchers (1) on cyclones and climate change is available at http://www.bom.gov.au/info/CAS-statement.pdf (The two page statement starts at page 2 of the document.)

The highlights of the statement are:

- current knowledge is not able to provide indication of a change in cyclone **frequency**. Available evidence points to little or no change globally but regional frequencies could either increase or decrease substantially due to localised effects
- no single high impact cyclone in 2004 or 2005 can be directly attributed to global warming. However there may have been an impact overall
- whilst the existence of a large multi-decadal oscillation in Atlantic cyclones is accepted, some scientists believe that a general trend towards more **intense** cyclones is emerging. This is a hotly debated subject and no definitive conclusion can be made. However it is agreed that there is no evidence for a decreasing trend in cyclone intensities

Kerry Emanuel has a very good, plain English account of the various factors involved at: http://wind.mit.edu/~emanuel/anthro.html

(1) Dr. John McBride, Dr Jeff Kepert (Australia), Prof. Johnny Chan (Hong Kong), Julian Heming (UK), Dr Greg Holland, Prof. Kerry Emanuel, Thomas Knutson Dr. Hugh Willoughby, Dr. Chris Landsea (USA)

2.4 (c) Thelma, Ingrid and Monica

Since reliable satellite observations began in the early 1960s there have been only five cyclones thought to have attained Category 5 status whilst in NT waters. They are listed in Table 2.2.1 on page 31. From that record, one could make a reasonable assumption that the average recurrence interval for a Category 5 cyclone occurring in the NT **is about 9 years.**

However, cyclones Thelma, Ingrid and Monica (the TIM cyclones) were the most intense of the five and they all occurred within the last nine cyclone seasons. This means that they have had an average recurrence interval of 3 years.

There are three possible explanations:

(1) Any random sequence of events will occasionally have a grouping of the rare events so this is just such an instance

(2) The TIM cyclones are a response in some way to global warming

(3) Cyclones in the NT are responding to a multi-decadal cycle similar to the 50-70 year cycles known to occur in the Atlantic Ocean

There is less than 10% probability that the <u>first</u> explanation could be true.
This is demonstrated by a simple statistical analysis in Appendix O

The second and third explanations for the TIM cyclones will be related to one or more of the six environmental parameters known to influence the genesis and intensification of cyclones (Gray, 1975). The parameter that will be dealt with here relates only to ocean thermal energy.

The partial influence of SSTs on the intensity of cyclones has already been discussed under paragraph 9) on page 37. There the discussion centred on change in sea temperature between different regions. In the following, it is the change over time that is examined:

- it has been claimed that the potential destructiveness of cyclones, a measure which combines strength, duration, and frequency of hurricanes, "is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals, including multi-decadal oscillations in the North Atlantic and North Pacific, and global warming." (Emanuel, 2005)

- another study has found that the average annual number of category 4 and 5 cyclones in each of the world's tropical ocean basins has almost doubled since the 1970s and that this increase is correlated with an increase in the SSTs in these basins (Webster et al, 2005). Unfortunately, this study did not include the seas off the NT coast

- the waters of the Timor and Arafura seas and the Gulf of Carpentaria interact with currents that flow in various ways from and to the South Indian Ocean and the South Pacific Ocean. In common with most of the world's oceans, the upper layers of the South Indian Ocean and the South Pacific Ocean show a pronounced warming trend over the period 1955 to 2003 (Levitus et al. 2005). The trend in both oceans for latitudes corresponding with the NT coastline is quite strong. It therefore seems likely that the waters off the NT coast have been getting warmer.

- charts available at http://www.cdc.noaa.gov/cgi-bin/Composites/comp.pl show that SSTs off the NT coast have increased by about 0.5° C since 1948. However the increase from one decade to the next has been far from uniform. For instance the SSTs decreased during the 1967 – 1976 decade. Furthermore, mean SSTs in NT waters during the cyclone season are normally in excess of 29°C and local areas can have SSTs in excess of 31°C so an average 0.5 ° increase may not be such a big deal

Although it is logical to assume that the observed warming of the oceans is associated with global warming, the slightly warmer seas off the NT coast may **not** have been the contributing factor causing the TIM cyclones. It is equally plausible that some unknown multi-decadal cycle is coming into play. Some serious research will be required to determine which it is.

3 COMPILATION OF RECOMMENDATIONS

This section will compile the recommendations already made in various sections in the main report and in the appendices. The page number(s) in squared parenthesis after each recommendation provide the original report reference(s) to obtain background information or more detailed recommendations.

To assist people who will be evaluating these recommendations, they have been sorted into the following groupings:

A) Funding and General
B) Multi-discipline (but especially combinations involving one or more of the following disciplines: engineering, meteorology, climatology, oceanography, statistical analysis, archival searches, marine biology, soils investigation)
C) Engineering only
D) Meteorology and/or Climatology only
E) Paleotempestology and/or Dendrochronology and/or local (particularly aboriginal) knowledge.

A) FUNDING AND GENERAL

A.1 It is recommended that for the next few years, Federal, NT and local governments jointly provide funding of at least $6 million per year to fully research the likelihood of a Category 5 cyclone impacting cities and coastal communities along the NT coast.

Comments:
The prime objective of this report is to significantly increase present levels of government funding on researching cyclone risk. It is only after the likelihood of intense cyclone impact is determined with some confidence that other appropriate, mitigation measures can be brought into effect with the full knowledge that the costs involved will be justified. Many of the recommendations in this report lend themselves to be projects under the National Disaster Mitigation Program or its successor program. Hopefully, within a short space of time, the total annual expenditure by all levels of government on this first (research) phase of cyclone mitigation in the NT will increase from the current levels of about $300,000 per year to at least $6 million per year.…………………………..……………………………..…[2, 6 - 8]

(A significant proportion of the funding should be directed toward basic research on cyclones in the lower latitudes this should probably be channeled through the Bureau of Meteorology Research Centre)

A.2 It is recommended that all reports to government relating to cyclone risks in the NT should be made available for public inspection and be in a format enabling easy access and comprehension by the public..…………………………………………………[9, I9]

B) MULTI-DISCIPLINE

It is recommended that:

B.1 Multi-discipline studies be made to rigorously investigate the validity or otherwise of this report's findings - namely that the wind and storm tide hazard in the NT are much more extreme than indicated by the wind code and recent storm tide risk studies.

Comments:
By means of several different 'ball-park' estimates based on records, and by consideration of regional differences between WA, NT and Qld, the writer of the report concludes that Darwin (and by inference, the whole of the NT coastline) should be in the wind code's Region D rather than the presently regulated Region C. This would lead to design wind loads being 60% higher than at present and storm tides being much higher for a given average recurrence interval than currently predicted.

B.2 Multi-discipline studies use the 'written' records to analyse the most intense of the historic cyclones that have affected the NT coastline since European settlement began in 1824. (In particular, the intensity of the NT cyclones of 1839, 1897, 1915, 1919, 1923, 1937, 1974 and 1984 should be assessed in the light of modern knowledge and using computer modelling to hindcast the recorded winds, pressures and storm tides) **…**…………………………………..[14,15, 28 and in Appendices E & F]

Note: There are two other types of 'records' that can be used to make long term cyclone risk predictions. These are

- 'satellite era' records kept by the Bureau of Meteorology (refer D.2)
- 'proxy' records preserved in tree-rings, beach ridges and lagoon sediments (refer E.1)

B.3 Until such time as a clear picture emerges on these matters, risk assessments should present a range of values based on optimistic and pessimistic scenarios. (Presentation could be similar to the way the IPCC present their risk predictions for global warming and rise in sea-level)………………………………….…[13,18, 28 and in Appendices E & G]

B.4 The 'pessimistic scenarios' be assumed for decisions relating to emergency management and provision of cyclone shelters…………………….……….…………..…...[19, G 18]

B.5 Steps be taken to improve communication and collaboration between engineers and meteorologists to resolve differences and allow each to place confidence in the other discipline's methods and findings……………...……………………………………[51]

B.6 BoM collaborate with the Engineering profession to agree (or disagree) that the maximum gusts speeds given in cyclone warnings relate directly to the Regional Wind Speed as defined in the current wind code. (As part of this exercise, agreement should be reached on the meaning of the word "maximum" in the Bureau's warnings – is it instead perhaps a 95 percentile figure? Does it allow for tornadoes, boundary layer rolls, downdrafts, eye-wall vortices, etc.?) ......……………………………………...[44, N4]

B.7 If engineers continue (contrary to recommendation C.1 below) to use the Holland wind speed model for NT risk studies, then BMRC should make recommendations as to appropriate values for the 'Holland B' and the GCF. (There is considerable uncertainty as to the appropriate values and yet the factors are critical in engineering studies using the Monte-Carlo Simulation technique.)…………………….[I3, N4]

B.8 Funding be provided for production of a special edition in a suitable journal to allow an in-depth review of Cyclone Tracy's winds. (The articles would be peer-reviewed and by experts in various fields using modern knowledge and skills)……………...[46 – 48, 51]

C) ENGINEERING ONLY

It is recommended that funds be provided to:

C.1 derive appropriate design wind speeds for the NT for use in structural design and in storm tide risk assessments using computer models by:

(a) avoiding the use of the Holland wind speed model with its requirement to have five transformations between the basic unit of measure (CI number) and desired output (surface wind gusts) with the attendant uncertainties between each transformation [I2, I3]

(b) using the simple procedure adopted in this report which is to use the CI number as the primary variable for determining probability distributions………………….[G3-G6]

(c) obtaining wind speeds directly from the globally applicable relationship between surface wind speeds and the CI number …………………………….....[A1 & G4]

(d) using a realistic probability distribution. (For intense cyclones, such a distribution would allocate an equal probability of say 0.24 for the occurrence of a CI 6.0, 6.5 .7.0 or 7.5 cyclone and 0.04 for a cyclone with CI = 8.0) ……………[18, G6, G16-G19, I2]

(e) being based on a transparent, public model similar to the one developed in the USA for the State of Florida ……………………………………………………..............[I4]

(f) incorporating 'random walk' tracks rather than straight line tracks and make allowance for weakening or re-intensification of cyclones crossing land based on parameters appropriate to the NT………………………………………………………..[I4, H3-H6]

(g) incorporating formulae similar to those examined in Appendix H to account for the potential protection that Darwin gains from the surrounding islands and peninsulas. ……………………………………………………………[H3, H5, H6 & H8]

(h) allowing for the possibility that future cyclones may behave like pre-1940 cyclones with much higher proportion approaching Darwin with an easterly component in their tracks ....…………………………………………….[I5]

C.2 derive appropriate design wind speeds for structures between 10 km and 100 km from the NT's coastline by:

(a) locating the 'smoothed' coastline on a suitable map.......................................[H1]

(b) producing a graduated scale rather than the current step-wise changes at 50 km and 100 km inland as given in the current wind code……………………………….....[24, 25]

(c) being derived from a computer model as described for C.1 above

(d) presenting the graduated design wind speeds as lines on a map on DPI's website.[H1, H8]

C.3 enable further development of storm tide models so that they provide more realistic estimates of maximum levels by:

(a) allowing for wave runup………………………………………………………..…..[I8]

(b) allowing for creek and river flooding from the very heavy rainfall associated with cyclones………………………………………………………………………….[I9]

(c) using a finer grid to enable better resolution at creeks and estuaries…………....[I9]

(d) testing the models to ensure that the results obtained reasonably match the recorded storm tides in Darwin and/or Nguiu from cyclones in 1919, 1937, 1974, 1998 and 2005 ……………………….………..[14, 15, 49, E8 – E10, E12, F6 – F10]

(e) allowing for future climate change by including allowance for the sea level rising with each passing decade into the future………………………………………………[I9]

C.4 use the improved storm tide model to determine storm tide risk levels for all coastal communities and towns

C.5 enable improvements to NT building regulations by:

(a) Standards Australia and the Australian Building Codes Board jointly preparing a single regulatory document that deals specifically with design loads, design methods and building regulations for residential buildings in areas subject to cyclones…...[D4 & D5]

(b) DPI establishing procedures to test structural engineers who are already on the NT's approved practitioners list of structural engineers and future applicants to that list. The test would be an oral examination by a panel of experienced NT structural engineers on the practitioner's knowledge and experience in designing houses for cyclones…… [D5]

(c) DPI commissioning a consultant to check the writer's findings relating to the variable strength of houses designed under different editions of the wind codes. (The findings could be particularly important and have immediate application in cases where new buildings are to be erected in or near suburbs that were constructed in the eight or so years after Cyclone Tracy. The houses in these older suburbs probably have about twice the wind strength of houses built to the current code but they should not be subject to debris loading from their new neighbours.) ……………………………….[D13 to D16]

D) METEOROLOGY &/OR CLIMATOLOGY ONLY

Most of the recommendations in this part were made by the Group in a submission to the Review of the Bureau of Meteorology. The submission is reproduced in Appendix N. Recommendations 2 and 3(d) & 3(c) in the submission are included above as B.2, B.6 & B.7 respectively.

It is recommended that:

D.1 research be carried out to further understanding of the special characteristics of NT cyclones by:

(a) establishing an NT branch of the BMRC in Darwin or by increasing resources for the Darwin Regional Office……………………………………………………………..[N2]

(b) studying the several geographical and climatological factors that probably mean that cyclones making landfall in the NT will be more intense than anywhere else in Australia. (MPIs and the warm, shallow seas off the NT coast may be of particular importance) ……………………………………………..………[33-39, N3, N4]

(c) attempting to explain the conjunction of Cyclones Thelma, Ingrid & Monica [68,69, O1]

(d) attempting to explain the change in the track directions of intense cyclones that appears to have occurred after 1940 ………………………………………………..…[E16 - E18]

D.2 cyclones that have affected the NT coast since 1969 be re-analysed by applying modern techniques to original satellite data to provided consistent intensity estimates. (published data should include the CI numbers used in the re-analysis)..[28, G14, G15, N3]

D.3 research be undertaken to determine the appropriate probability distribution to use for risk analysis of NT cyclones. (The research team should include or consult with internationally recognised experts including K. Emanuel and M.D. Powel)..….[G16, G17]

D.4 the new BoM 'Tropical Cyclone Forecast Track Map' describes all winds in terms of maximum gust speeds. (Instead of 'gale-force', 'storm-force' and 'hurricane-force' winds in terms of 10 minute mean wind speeds.)…………………………………………..[44]

D.5 BoM be provided with more and better equipment including:

(a) anemometers that will survive to provide useful data from intense cyclones. (BoM anemometers routinely fail before recording maximum wind gusts. Even if peak gusts are recorded, it is probable that the recording device will be a cup anemometer and the results will be of little use to engineers. Anemometers at all AWS and manned stations within 100 km of the NT coast should be high speed Dines anemometers designed to withstand and record 370 kph gusts.)……………………….[40 – 43, N4]

(b) technology that will prove (or disprove) that the Dvorak technique provides reasonably accurate estimates of gust speeds in the NT. (There are numerous modern methods for measuring wind speeds more directly such as dropsondes, doppler radar, etc. BoM should research the most appropriate for use in the NT and then proceed on a suitable long term research project.)…………………………………………….[43 – 44, N4]

(c) at least two more radar installations. (One on the NW tip of Melville Island, the other on South Goulburn Island. The prime purpose of such installations would be to provide a fail-safe system with adequate coverage of cyclones coming towards Darwin from either east or west but they would also provide much needed information as to how eyewalls behave when they are making partial landfall over the islands or peninsulas.)…..….. [N5]

E) PALEOTEMPESTOLOGY &/OR DENDROCHRONOLOGY &/OR LOCAL KNOWLEDGE

(The following recommendations are given in much more detail on pages 63 to 65.)

It is recommended that:

E.1 The NT Government establish a formal committee of enquiry to determine if work should proceed on using paleotempestology (PT) to derive the recurrence intervals of intense cyclones in the NT……………………………………………………..……[63]

E.2 If the decision is made to proceed, the research program should:

(a) bring the research on tree-rings, beach ridges and lagoon sediments under the control of one agency. **(**This agency could be a special section in a NT government department, an organization similar to a Cooperative Research Centre that pools talents from selected universities, industry and government or a firm of consultants with expertise in coordinating such research……………………………………………………[63, 64]

(b) obtain the active involvement of aboriginals in the research program to obtain their assistance with permits and to utilise their local knowledge, skills and labour……..[64]

(c) regard the report on tree-rings by Baker in Appendix J as a preliminary pilot study and carry out the further investigations recommended in this report…………..……[65, J8]

(d) regard the report on coral rubble ridges by Wasson in Appendix L as a preliminary pilot study and carry out the further investigations recommended in this report…....[65, L4]

E.3 The photographic image file which is part of Appendix K should be completed to provide coverage of all PT sites around the NT coastline………………...……[57, K3]

4 REFERENCES

Bowman, D.M.J.S and W.J. Panton (1993) Decline of Callitris intratropica in the NT: Implications for pre- and post-European colonization fire regimes. *J. Biogeography*. **20,** 373-381

Bureau of Meteorology, (1975). Cyclone Tracy, An interim report by staff members of the Bureau of Meteorology, Tech Report No. 14.

Bureau of Meterology, (1977). Report on Cyclone Tracy (the 'official report')

Clark, M.F., R.J.Wasson and M.A.J. Williams (1979) Point Stewart Chenier and Holocene Sea Levels in Northern Australia. *Search,* **10 (3),** 90-92

Davenport, A.G., W.H. Melbourne, and B.J.Vickery, (1992) Wind Engineering Course Notes, Monash University. Ch 2.

Davidson, J. (2006) Cyclone Larry Forum Report, JCU Campus, 7 April 2006, organised by Bureau of Meteorology.

DeMaria, M., J.K. Knaff and J. Kaplan (2006). On the Decay of Tropical Cyclone Winds Crossing Narrow Land Masses. *J.Appl.Met.&Clim.* **45**, 491-499
http://rammb.cira.colostate.edu/resources/docs/Decay_DeMaria.pdf

Donnelly, J.P., S. S. Bryant, J. Butler, J. Dowling, L. Fan, N. Hausmann, P. Newby, B. Shuman, J. Stern, K. Westover, and T. Webb III, (2001a) A 700-Year sedimentary record of intense hurricane landfalls in southern New England: *Geological Soc. of America Bulletin*,**113**,714-727.

Donnelly, J.P., S. Roll, M. Wengren, J. Butler, R. Lederer, and T. Webb III, (2001 b), Sedimentary evidence of intense hurricane strikes from New Jersey: *Geology*, **29,** 615-618.

Donnelly, J.P**.**, J. Butler, S. Roll, M. Wengren, and T. Webb III, (2004a), A backbarrier overwash record of intense storms from Brigantine, New Jersey: *Marine Geology*, **210,** 107-121.

Donnelly, J.P., and T. Webb III, (2004b), Backbarrier sedimentary records of intense hurricane landfalls in the northeastern United States. *In*: Murnane, R. and Liu, K. (eds.), *Hurricanes and Typhoons: Past Present and Potential*, New York: Columbia Press, pp. 58-96.

Donnelly, J.P., (2005), Evidence of Past Intense Tropical Cyclones from Backbarrier Salt Pond Sediments: A Case Study from Isla de Culebrita, Puerto Rico, *.J of Coas. Res.*, **SI42**, 201-210.

Emanuel, K. (1986) An Air-Sea Interaction for Tropical Cyclones. Part 1: Steady State Maintenance. *J. Atmos. Sci.* **43**, 585-604

Emanuel, K (1991) The Theory of Hurricanes. *Annu. Rev. Fluid Mech.* **23**, 179-196

Emanuel, K. (2000). A Statistical Analysis of Tropical Cyclone Intensity. *Monthly Weather Review*, **128**, 1139-1152

Emanuel, K. (2003). Tropical Cyclones. *Annual Review of Earth and Planetary Sciences*. **31**, 75-104.

Emanuel, K. (2005) Increasing Destructiveness of Tropical Cyclones of the Past 30 Years. *Nature*, **436,** 686-688

Enquist, B.J. and A.J. Leffler (2001) Long term tree ring chronologies from sympatric tropical dry-forest trees: individualistic responses to climatic variation. *J. Tropical Ecology*, **17,** 41-60

Fensham, R.J. (1993) The Environmental Relations of Vegetation Pattern on Chenier Beach Ridges on Bathurst Island, Northern Territory. *Aust. J. Bot.*, **41,** 275-291

Gamble, A.J., M.J. Nicholls and K. Wise (1974) Is Darwin Prepared for a Cyclone? *Report by the 'Cyclone Sub-Committee' of the Institution of Engineers, Australia- Darwin Group.* 19 pp.

Georgiou, P. (2000) Darwin Region, Category 5 Cyclone Risk Assessment. A report to the NT Department of Transport and Works.

Gray, W.M., (1975) Tropical Cyclone Genesis. *Dept. of Atmos. Sci. Paper No. 232*, Colorado State University, Fort Collins, CO, USA 121 pp

Guard, C. and M.A. Lander. (1999) A Scale Relating Tropical Cyclone Wind Speed to Potential Damage for the Tropical Pacific Ocean Region: A User's Manual. University of Guam, Technical Report No. 86.

Hazel, M.T. (1986) Estimation of Wind Speeds in Cyclone Winifred using Windicators. Bachelor of Eng. Thesis. Dept. of Civil & Systems Eng. JCU

Hickey, S.H. (1981) Preliminary Investigation of Stranded Beach Ridges, Shoal Bay, Northern Territory: A Small Chenier Plain ? *NT Geological Survey* Technical Report GS 81/1

Holland, G.J. (1980) An Analytic Model of the Wind and Pressure Profiles in Hurricanes. *Monthly Weather Review.* **108**: 1212-1218.

Holland G.J. (1997) The Maximum Potential Intensity of Tropical Cyclones. *J. Atmos. Sci.* **54,** 2519-2541

Kaplan, J. and M. DeMaria. (1995) A Simple Empirical Model for Predicting the Decay of Tropical Cyclone Winds After Landfall. *J. App. Meteor.*, **34 (11),** 2499-2512.

Kepert, J.D. (2002), Topic 2.4 at Fifth WMO International Workshop on Tropical Cyclones, Cairns, Australia. http://www.aoml.noaa.gov/hrd/iwtc/Kepert2-4.html

Knaff, J.A. and R.M.Zehr. (2007) Reexamination of Tropical Cyclone Wind-Pressure Relationships. *Weather and Forecasting*, **22 (1),** 71-88.

Kossin, J.P. and C.S. Velden. (2004) A Pronounced Bias in Tropical Cyclone Minimum Sea Level Pressure Estimation Based on the Dvorak Technique. *American Met. Soc.* **Jan. 2004**, 165-173
http://www.ssec.wisc.edu/~kossin/articles/kossin_velden_MWR.pdf

Lawson & Treloar Pty Ltd. (1982). Greater Darwin Storm Surge Study for the NT Department of Lands.

Lees, B.G. (1987) Age Structure of the Point Stewart Chenier Plain: a Reassessment. *Search* **18,** 257-259

Lees, B.G., L. Lanchou and J. Head (1990) Reconnaissance Thermoluminescence Dating of Northern Australian Coastal Dune Systems. *Quaternary Research,* **34,** 169-185

Lees, B.G. (1992) The development of a chenier sequence on the Victoria River Delta, Joseph Bonaparte Gulf, northern Australia. *Marine Geology,* **103,** 215-224

Liu, K.B. and M.L. Fearn. (1993) Lake-sediment Record of Late Holocene Hurricane Activities from Coastal Alabama. *Geology* **21,** 793-796

Liu, K.B. and M.L. Fearn. (2000a) Reconstruction of Prehistoric Landfall Frequencies of Catastrophic Hurricanes in Northwestern Florida from Lake Sediment Records. *Quaternary Research* **54,** 238-245

Liu, K.B. and M.L. Fearn. (2000b) Holocene History of Catastrophic Hurricane Landfalls along the Gulf of Mexico Coast – Reconstructed from Coastal Lake and Marsh Sediments. *In* "Implications of Global Change for the Gulf Coast Region of the United States" (Z.H. Ning and K.K.Abdollahi, Eds.), pp 38-47. Franklin Press Inc.

Love G. and K. Murphy (1985) The Operational Analysis of Tropical Cyclone Wind Fields in the Australian Northern Region. *Bureau of Meterology,* Northern Territory Region Research Papers, 1984 85, Nov, 44-51

Michaels, P.J., P.C. Knappenberger, and R.E. Davis (2006), Sea-surface temperatures and tropical cyclones in the Atlantic Basin, *Geophys. Res. Lett.,* 33, LO978.

Michie, M.G. and K. Presnell (1987) Progradation of a Chenier During a Storm Event, Channel Island, Darwin Harbour, Northern Territory. *Unpublished*

Miller, D.L., C.I. Mora, H.D. Grissino-Mayer, C.J. Mock, M.E. Uhle and Z. Sharp (2006) Tree-ring isotope records of tropical cyclone activity. *Proceedings of the National Academy of Sciences (USA),* **103,** 14294-14297

Murphy, K. (1984) Big Blow Up North. (A History of Tropical Cyclones in Australia's Northern Territory), *University Planning Authority.*

Nicholls, M.J. (1990) Is Darwin Prepared for another Cyclone? *unpublished,* 51 pp.

Nott, J. F. (2003) Intensity of prehistoric tropical cyclones. *J. Geophysical Res.,* **108,** ACL 5-1 to 11

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region. SEA Pty Ltd. (2006) Darwin Storm Tide Mapping Study 2006. Prepared by Systems Engineering Australia Pty Ltd for NT Emergency Services.

Shay, L.K., G.J. Goni and P.G. Black (2000) Effects of a warm oceanic feature on Hurricane Opal *Mon. Wea. Rev.,* **128,** 1366-1384

Shulmeister, J. and B.G. Lees (1992) Morphology and chronostratigraphy of a coastal dune field; Groote Eylandt, northern Australia. *Geomorphology,* **5,** 521-534

Tonkin H., G.J. Holland, N. Holbrook and A. Henderson-Sellers. (2000) An Evaluation of Thermodynamic Estimates of Climatological Maximum Potential Tropical Cyclone Intensity. *Monthly Weather Review*, **128,** 746-762

Velden, C., B. Harper, et al. (2006) The Dvorak Tropical Cyclone Intensity Estimation Technique. *Amer. Met. Soc.* **BAMS, Sept**, 1195-1210

VIPAC (1994) Tropical Cyclone Storm Surge Risk for the Greater Darwin Region – Final Report. Vipac Report 24113-2 for the NT Department of Lands, Housing and Local Government.

Walker, G. (1975). Report on Cyclone Tracy (Vols. 1, 2 & 3) Report to the Department of Housing and Construction.

Webster, P.J., G.J. Holland, J.A. Curry and H.R. Chang, (2005) Changes in tropical cyclone number, duration and intensity in a warming environment. *Science,* **309,** 1844-1846

WMO (1993) World Meteorological Organisation, Global Guide to Tropical Cyclone Forecasting, Report TCP-31 available at:
http://www.bom.gov.au/bmrc/pubs/tcguide/globa_guide_intro.htm

Woodroffe, C.D., E.A. Bryant, D.M. Price and S.A. Short (1992) Quaternary Inheritance of Coastal Landforms, Coburg Peninsula, Northern Territory. *Australian Geographer*. **23 (2),** 101-115

Woodroffe, C.D. and D. Grime (1999) Storm impact and evolution of a mangrove-fringed chenier plain, Shoal Bay, Darwin, Australia. *Marine Geology*, **159,** 303-321

APPENDIX A

TABLES OF PROPERTIES & UNIT CONVERSIONS

TABLES

Dvorak Current Intensity (CI) Number	Australian Cyclone Severity Scale	Regional Wind Speeds (V_R) for design of buildings to the Aust. wind code AS/NZS 1170.2:2002	Max.Gust Speed [2] (kph)
2.0			66
2.5			79
	Start Category 1		90
3.0			103
	Cusp of Cat. 1 & 2		125
3.5			127
4.0			150
		Region A, V_{500}, (most buildings)	162
	Cusp of Cat. 2 & 3		170
4.5			176
5.0		Region B, V_{500}, (most buildings)	205
	Cusp of Cat. 3 & 4		225
5.5			234
		Region C, V_{500}, (most buildings)	250
6.0			262
	Cusp of Cat. 4 & 5		280
6.5			290
		Region C, $V_{10,000}$, (PCS) [1]	306
		Region D, V_{500}, (most buildings)	317
7.0			324
7.5			357
8.0			390
		Region D, $V_{10,000}$, (PCS) [1]	394

Table A1: Maximum Gust Speeds for Dvorak CI numbers, the Australian Cyclone Severity Scale and Regional Wind Speeds in the wind code.

Notes:

1. PCS = Public Cyclone Shelters. At the present time there is no specific requirement for the value of R (or ARI) to be used for the design of public cyclone shelters but it is expected that the Building Code of Australia will shortly introduce the requirement that it become 10,000 years (Mullins, pers comm.) It is unlikely that public cyclone shelters will be deemed necessary in Region B towns, but it they are, $V_{10,000}$ = 250 kph in Region B; the same speed as V_{500} for Region C.

2. Maximum Gust Speed for a 2-3 second gust at 10 m height above the sea or flat, open terrain.

TABLES (contd.)

US Saffir-Simpson Scale [1]	Max.Gust Speed [2] (kph)	Australian Cyclone Severity Scale	Max.Gust Speed [2] (kph)
Category 1	154 – 194	Category 1	90 - 124
Category 2	195 – 225	Category 2	125 – 169
Category 3	226 – 267	Category 3	170 – 224
Category 4	268 – 319	Category 4	225 – 279
Category 5	320 – 400	Category 5	> 280

Table A2: Comparison between the Saffir-Simpson Scale as used in the USA and Guam and the Australian Cyclone Severity Scale in terms of Maximum Gust Speeds in kph.

Notes:

1. The Saffir-Simpson scale is used in the USA to describe hurricanes in the Atlantic Ocean and in the northern Pacific Ocean east of the International Date Line. Naturally, the US categories are bigger and better than the Australian ones. The maximum gust speeds given here are converted from mph to kph from the table at http://www.typhoon2000.ph/tropical_SS.htm

2. Maximum Gust Speeds are for a two second gust at 10 m height above the sea or flat, open terrain. This is a global convention.

3. The US media usually report only the 'sustained wind speeds' or the 'mean surface winds' (MSW) which are the 1 minute mean wind speeds at a height of 10 m above the sea or flat, open terrain.

   1 minute mean wind speeds are:
   - ~ 15 % faster than the 10 minute mean wind speeds used in Australia
   - ~ 20 % slower than maximum gust speeds (globally)

4. When reporting on US hurricanes, the Australian media usually convert wind speeds from mph to kph but never bother to make any other conversions – neither for the different category scales nor for the different definitions of wind speed - and confusion reigns.

UNIT CONVERSIONS

Wind Speeds

1 minute mean wind speed ~ 1.15 x 10 minute mean wind speed

Maximum gust speed over water ~ 1.4 x 10 minute mean wind speed over water

Maximum gust speed over flat,
open terrain…………………… ~ 1.6 x 10 minute mean wind speed over land
(1.6 is average – it can vary from 1.5 to 1.7)

(all of the above conversions are approximate, the source is the WMO Guide)

1 mile per hour (mph) = 1.61 kph

1 knot (kn) = 1.85 kph

Meteorologists usually measure wind speed in knots or metres per second (m/s). Engineers normally use only m/s

1 m/s = 3.6 kph

Barometric Pressure

Barometric pressure in the US is measured in millibars (mbar) or (mb). The unit measure is the same as the unit of measure for barometric pressure used in Australia – the hectopascal (hPa).

1 mbar = 1 hPa

It appears that Australian meteorologists opted for an easy way out when Australia adopted the metric system – they retained the old millibars but simply renamed them as hectopascals. What they should have done is adopt the unit of pressure in the International System of Units as used by scientists, engineers and tyre pressure gauges - the kilopascal (kPa)
[refer the following web site for someone venting anger on the subject:
http://ourworld.compuserve.com/homepages/Gene_Nygaard/hectopas.htm]

1 kPa = 10 hPa

In earlier times, barometric pressure was measured in inches of mercury (inHg) or millimeters of mercury (mmHg)

1 inHg = 33.864 hPa.

1 mmHg = 1.333 hPa

APPENDIX B

GLOSSARY

TERM (& ACRONYM)	**MEANING OR DEFINITION**
Annual Probability of Exceedance (**AEP**)	The probability that a value will be exceeded in any one year. It is the inverse of the Average Recurrence Interval.
Australian Height Datum (**AHD**)	A nationally accepted height datum. 0 m AHD generally refers to mean sea level but in Darwin Harbour it is 0.1 m below mean sea level.
Automatic Weather Station (**AWS**)	Weather stations installed by BoM which automatically record and transmit weather data.
Average Recurrence Interval (**ARI**)	The average or expected number of years between exceedances of a given value.
Before Present **(B.P.*)**	Convention to indicate a radiocarbon age that has been corrected for environmental effects – 'Present' always refers to 1950.
Building Code of Australia (**BCA**)	Documentation for building regulations. Prepared by a national inter-governmental agency.
Bureau of Meteorology (**BoM**)	Australian Government agency to provide services relating to weather and climate.
Bureau of Meteorology Research Centre (**BMRC**)	BoM's research arm – based in Melbourne
Central Pressure (**Pc**)	The pressure at the centre of a cyclone.
Council of Australian Governments (**COAG**)	A national committee consisting of relevant (to the subject being considered) ministers from the Commonwealth and all states and territories.
COAG Review Report	*Natural Disasters in Australia: Reforming Mitigation, Relief and Recovery Arrangements, August 2002*
Current Intensity (**CI**)	A number (ranging from 2.0 to 8.0 in 0.5 steps) derived using the Dvorak technique from satellite images, etc. Gives a global standard measure of a cyclone's intensity (in terms of wind speed).
Dendrochronology	A method of scientific dating based on analysis of tree-ring growth patterns. The technique can date wood to exact calendar years.
Department of Planning & Infrastructure (**DPI**)	A Northern Territory Government department
Gust Conversion Factor (**GCF**)	In this report, a factor used to convert the gradient wind speed to a maximum gust speed at 10 m height.
Gradient wind speed	The wind speed just above the earth's boundary layer (above frictional turbulence) where the wind follows curved isobars. The gradient wind is in balance between outward centrifugal effects and inward pressure effects.

TERM (& ACRONYM)	MEANING OR DEFINITION
Highest Astronomic Tide (**HAT**)	Highest tide at a location. It occurs only once every 8 years or so. It is marginally higher than a 'high spring tide'. In Darwin, the HAT level is 4.0 AHD.
Maximum Potential Intensity (**MPI**)	The highest intensity that a cyclone can theoretically attain for given ambient environmental conditions.
Natural Disaster Mitigation Program (**NDMP**)	A program established in response to the COAG Review Report. Funded by all three levels of government.
Paleotempestology (**PT**)	The study of past cyclone activity using natural features as the 'recording' agent.
Pressure Drop (**ΔP**)	The pressure difference between the surrounding ambient pressure and the cyclone's central pressure.
Quaternary Period	The geologic time period covering the last 1.8 million years. The Quaternary includes two geologic subdivisions - the Pleistocene and the last post-glacial period, the Holocene.
Radius of Maximum Winds (**Rmw**)	The radius measured from the centre of a cyclone to the region of its maximum wind speeds.
Regional Wind Speeds (**RWS**)	Wind speeds applicable to a particular region in Australia as defined in AS/NZS 1170.2:2002 The speeds are for 3 second gusts at 10 m height in open, flat terrain.
Saffir-Simpson Scale	A scale used in the USA to classify hurricane intensity by allocating one of five categories based on wind speeds. It differs from the scale used in Australia (refer Appendix A).
Sea Surface Temperature (**SST**)	Temperature at the surface of a sea or ocean.
Thermocline	A layer within a body of water where the temperature drops rapidly with depth. It marks the transition between the warmer 'surface mixed layer' and cold waters at greater depths.
Tropical Cyclone Warning Centre (**TCWC**)	Offices based in Brisbane, Darwin and Perth responsible for monitoring, forecasting and issuing warnings associated with cyclones within their defined areas.
Tropopause	The top of the troposphere (the layer in which the earth's weather occurs). It is at a height which averages 6 km at the poles to 17 km at the equator. Temperatures decrease with altitude up to the tropopause, above it temperature increases with altitude.
Windicators	Simple structures which can be used to estimate wind speeds – typically bent over road signs.
World Meteorological Organisation (**WMO**)	An agency of the United Nations dealing with weather, climate and distribution of water resources.
WMO Guide	A WMO publication titled 'Global Guide to Tropical Cyclone Forecasting' – intended for operational forecasters.

APPENDIX C

RISK: THE HAZARD AND THE CONSEQUENCES

Meanings and examples

APPENDIX C RISK: THE HAZARD & THE CONSEQUENCES meanings & examples

In broad terms, risk is the chance of something having an impact on something else. But beyond that, the word means different things at different times to different people depending on their beliefs, circumstances and life experiences. The risks we are concerned with here are those resulting from the impact of cyclones of various levels of intensity (the hazards) on any particular community. This risk can be thought of as having two parts:

- the likelihood of the hazard occurring

- the consequences of the occurrence.

Engineers commonly measure the likelihood of a hazard occurring in terms of the **Average Recurrence Interval** (**ARI**). If the ARI = 100 years, then we have the 1 in 100 year flood or cyclone impact or whatever. (ARI used to be termed the "Return Period" but the new loading codes replaced the term because it gave the false impression that there was some regularity in the occurrences.)

To confuse things further, the **Building Code of Australia** (**BCA**) measures the likelihood of occurrence in terms of the **Annual Probability of Exceedance** (**AEP**).

Fortunately, AEP and ARI are really the same thing – one is just the reciprocal of the other so that AEP = 1/ARI. If for example, a hazard has an ARI of 100 years, then it will have an AEP of 1/100 per year or 1% per year or 0.01 per year – however one wants to express it.

This report uses both ARI and AEP at different times but will always express the AEP as a fraction. (Many people prefer to think in terms of the Average Recurrence Interval (or Return Period) and the relevant figure remains in view if a fraction is used.)

In general, it is better to think of the likelihood of a hazard in terms of its AEP because:

- The "exceedance" in the term makes it clear that, if for instance we are talking about the regional design wind speed for houses in Darwin being 250 kph with an AEP of 1/500 per year, the risk is referring to the occurrence of wind speeds that are <u>greater than</u> 250 kph.

- Structures whose failure would lead to large loss of life or economic loss such as large dams, large off-shore oil rigs, etc are designed for an AEP of 1/10,000 per year. It is probable that soon the BCA will require public cyclone shelters to be designed for wind speeds having that same AEP. Given the possibility that the earth will be either fried or frozen within the next 5,000 years, it makes no sense to talk of an average recurrence interval of 10,000 years – what we are really interested is just the annual risk of the event – its AEP.

To include the consequences of the hazard into the notion of risk, we use the definition given at http://www.ga.gov.au/urban/factsheets/risk_modelling.jsp by Geoscience Australia :

RISK = Hazard * Elements at Risk * Vulnerability

In using this definition here, we assume:

- "Hazard" is an abbreviation for "Probability of a particular hazard occurring"
- The * represents a multiplication symbol
- Each variable can take any value between 0 and 1. Consequently the result of the multiplication - the risk - will take a value between 0 (meaning no risk) and 1 (meaning certainty)

As the formula makes clear, the consequences of a hazard occurring can be considered as the product of the two terms, 'elements at risk' and 'vulnerability'. It should be noted that in order to reduce 'vulnerability' in a cost effective manner it is necessary to know the likelihood of the hazard occurring. Many of the recommendations in this report have that objective.

By way of example, consider the annual risk of death or injury from a cyclone impacting with wind gusts greater than say 290 kph at a particular location where the main strategy is for people to shelter within their built-to-code dwellings or to voluntarily evacuate to some distant location.

For this case:

- The "Hazard" (H) is the chance that wind gusts greater than 290 kph will impact that location in any one year. The measure of H is its AEP.
- The "Elements at Risk" (E) is a number between 0 and 1. Its value is dependent on who is evaluating the risk. If it is a person concerned about just their own or their family's safety, and they intend living within say 10 km of the coast for a full year (or cyclone season) then E = 1 for that year. Similarly, if the person is a leader of a coastal community concerned about just his community's safety, E = 1. But if the risk is being measured by someone only concerned with the safety of persons in the state or territory as a whole, then E becomes the ratio between the total population potentially exposed to the 290 kph winds and the total population of that state or territory.
- The Vulnerability (V) is a number between 0 and 1 which indicates how well the danger from death or injury has been reduced or mitigated - whether by provision of shelter which is "safe" for 290 kph wind gusts or by a "safe" evacuation plan. Obviously the objective should be to make V = 0 because in this case, no matter what the value of H or E, the result of the multiplication will make the risk zero. **The object of mitigation therefore is to make V as small as economic constraints permit.**

The maximum value of V = 1 for a person will be taken here as indicating that either their cyclone shelter has had some serious structural failure or their evacuation failed to the extent that they become trapped inside their escape vehicle which has itself become exposed to the belt of maximum winds. Such people will probably be exposed to mortal danger for several hours from death or injury from crushing, impact or laceration but, more likely than not, they will escape physically unscathed.

To demonstrate the principles behind the Geoscience Australia definition, we consider three communities which, in terms of their risk from cyclones, can be regarded as being representative of the communities that lie within 10 kilometers of the coast and along three distinctly different, 1,000 km long sections of Australia's cyclone prone coastline. The communities are:

- Port Hedland to represent communities between Carnarvon and Port Hedland in WA
- Darwin to represent communities between Wadeye and Nhulunbuy in the NT
- Townsville to represent communities between Port Douglas and Gladstone in Qld

The table below derives a comparative value for the annual personal safety risk from impact by wind gusts greater than 290 kph for each of these communities as a whole, or to an individual family within each community (in each case the value for E = 1).

Community	**H**	**E**	**V**	**Risk (= H x E x V)**
Port Hedland, WA	1/200 per yr.	1	1/40	1/200 x 1/20 = 1/8000 per yr.
Darwin, NT	1/200 per yr.	1	1/2	1/200 x 1/2 = 1/400 per yr.
Townsville, Qld	1/4000 per yr.	1	1/2	1/4000 x 1/2 = 1/8000 per yr.

Table C.1 Comparative safety risks; Port Hedland, Darwin and Townsville.

The risks are comparative only, but they illustrate how a community represented by Darwin could be facing 20 times the risks faced by communities represented by Port Hedland or Townsville.

Note:

- The AEP values of H for Pt Hedland and Townsville are approximately the values for those towns given by the current wind code for wind speeds greater than 290 kph. The value of the AEP for Darwin is the writer's estimation for that speed - as developed later in this report.
- The values for V are comparative - not absolute They are the writer's rough estimates based on the assumption that houses (and consequently private cyclone shelters) in the different towns are designed in accordance with the current wind code which means in Port Hedland they are designed for 317 kph wind gusts and in Darwin and Townsville they are designed for 250 kph wind gusts. For the evacuation option, if the strategy is to evacuate clear of the risk area and always do so at least 24 hours before the cyclone could possibly impact, then it would be appropriate to make V = 0. But if the strategy is to only evacuate after it becomes obvious to one and all that there is a good chance of a direct hit by category 5 winds, then the roads will be clogged with traffic and/or crashed vehicles, perhaps only half of the late evacuees will get clear and the other half will have a potentially wind-borne vehicle for a cyclone shelter. The writer suggests that for a community with such a strategy, the value of V would be about 1/2.

The next table derives the same risks but this time uses values of E which the ministers responsible for public safety would use if they were only worried about the state or territory as a whole and were looking at the cyclone risks faced by the populations living within 10 km of the above-mentioned, 1,000 km long stretches of coastline. Using approximate values for the various coastal and state-wide populations involved, the coastline represented by:

- Port Hedland in WA, has E = 40,000 / 2,000,000 = 1/50
- Darwin in the NT, has E = 100,000 / 200,000 = 1/2
- Townsville in Qld, has E = 400,000/ 4,000,000 = 1/10

Note that:

- South Hedland, WA and Palmerston, NT are considered to be just beyond 10 km from the "coastline" and their populations are not included in the above figures. (Their exclusion does not mean that they are "safe" from a cat 5 hit – their risks are just less and would need to be considered separately.)
- There would be a totally different set of E values if instead of the safety of persons, the concern was for infrastructure or economy related matters such as the export income to the state or territory. Then the ratios would be in dollar terms and, for example, E for the "Port Hedland" coastline in WA might equal 1/2 instead of 1/50.

1,000 km coastline represented by:	**H**	**E**	**V**	**Risk (= H x E x V)**
Port Hedland, WA	1/200 per yr.	1/50	1/40	1/200 x 1/50 x 1/40 = 1/400,000 per yr.
Darwin, NT	1/200 per yr.	1/2	1/2	1/200 x 1/2 x 1/2 = 1/800 per yr.
Townsville, Qld	1/4000 per yr.	1/10	1/2	1/4000 x 1/10 x 1/2 = 1/80,000 per yr.

Table C.2 Risks to the safety of persons on a state or territory wide basis for the 1,000 km lengths of coastline represented by Port Hedland, Darwin and Townsville.

The risks are comparative only, but they illustrate how the "minister for safety" in the NT should be very much more concerned about cyclones than the equivalent ministers in WA and Queensland.

Keeping things in perspective

It is not the intent of this report to scare people so that money will be diverted from some more needy cause. There are plenty of those in the NT - one is road safety.

When it comes to human safety it is salutary to make a comparison between the probability of Top End fatalities as a result of impact from cyclones and from road accidents. Historically, there have been 50 deaths on land from cyclones in the NT in the last 50 years. The number of fatalities from traffic accidents in Darwin and the other NT coastal communities in the same period would be more than 20 times that number.

Even if this report achieves nothing and cyclone mitigation continues more or less at present levels, road accidents present by far the greater risk to our safety. For the do- nothing strategy, a rough estimate based on the Tracy death toll, subsequent building standards and an increase in the number of intense cyclones is that the annual probability of fatality from cyclone impact in the Top End will be something like 3 per 100,000 of population exposed to the risk. Appropriate measures to mitigate the cyclone risk by provision of safe shelter, etc could reduce that figure to 1 per 100,000 or better.

To make a direct comparison, the annual probability for road accident death in NT coastal towns and communities would be about 10 per 100,000. (For the NT as a whole it averages 25 per 100,000.) Which ever way you look at it, road vehicles are many times more dangerous to us than cyclones. On the other hand, there are several reasons why the risk from cyclones cannot be compared so simply with the risk from road accidents:

- Modern vehicles have air bags, crumple zones, safety belts, safety glass, etc, to mitigate the effects of an impact at road speeds. What are the equivalent safety devices in houses to protect the occupants from impacts from debris having similar or greater speeds – a mattress maybe?

- The mitigation of road accidents is in part carried out by an impartial police force and judicial system enforcing a clear set of rules. The mitigation of cyclone risk by building appropriate shelter is carried out by a self-regulated industry primarily motivated by profit working to very complex rules and with very little oversight by impartial government agencies.

- When a cyclone is bearing down and a family seeks shelter, then the safety of that shelter becomes paramount. It may only be needed once or twice in a lifetime but every cyclone season could produce one of those times. The passenger of a vehicle has the option to tell a driver to slow down or to not get in the vehicle if the driver is drunk. But people taking shelter have no such options – their risk is involuntary and immediate. Once the cyclone starts there is little they can do to reduce their risk.

- It does not make much sense, but it seems that society will accept a steady flow of fatalities as long as they occur in small numbers. If a loaded jumbo jet were to go down in Australia, it would have far more impact on the general public that year than the combined road accidents – even though the latter may have four or five times the number of fatalities. That is one of the reasons why airline travel has been made not just safe but super-safe. Unless appropriate mitigation measures are taken beforehand, an intense category 5 impact on Darwin would also result in hundreds of fatalities.

Comparing risks to decide how to allocate money for mitigation

Governments have limited budgets to mitigate risks. When it comes to natural disasters, hopefully they examine which types of natural disasters pose the most risk and budget accordingly. This report is mainly concerned with the risks relating to human safety but it is the reality that when it comes to government spending it is the economic risk which most influences decision making. The table below indicates that if the Federal Government has a natural disaster mitigation budget then something like 32% of it should be directed at mitigating the effects of cyclones.

State	Floods	Severe Storms	**Cyclone**	Earthquake	Bushfire	Landslide	Tsunami	Total
% of total	22	19.5	**32**	7	19	0.5	0	100

Table C.3 Percentage of total building damage in Australia for period 1900 – 1999 (sourced from RiskFrontiers – Macquarie Uni.)

Obviously the different states and Territories will have differing priorities depending on which natural disasters are most prevalent. If the NT government has a natural disaster mitigation budget then the table below indicates that 134/143 or 94% of it should be directed at mitigating the effects of cyclones.

State	Floods	Severe Storms	**Cyclone**	Earthquake	Bushfire	Landslide	Tsunami	Total	% of total
NSW	128.4	195.8	0.5	141.2	16.8	1.2	0	484.1	44.5
QLD	111.7	37.3	89.8	0	0.4	0	0	239.2	22.0
NT	**8.1**	**0**	**134.2**	**0.3**	**0**	**0**	**0**	**142.6**	**13.1**
VIC	38.5	22.8	0	0	32.4	0	0	93.6	8.6
WA	2.6	11.1	41.6	3	4.5	0	0	62.7	5.8
SA	18.1	16.2	0	0	11.9	0	0	46.2	4.2
TAS	6.7	1.1	0	0	11.2	0	0	18.9	1.7
ACT	0	0.1	0	0	0	0	0	0.2	0.0
Total	314	284.4	266.2	144.5	77.2	1.2	0	1087.5	100
% of total	28.9	26.2	24.5	13.3	7.1	0.1	0	100	

Table C.4 Average annual cost in millions of dollars of Australian natural disasters by State and Territory for the period 1967 to 1999 - excluding death and injury costs. (Economic Costs of Natural Disasters in Australia, Bureau of Transport Economics, Canberra 2001)

Considering the cost per capita, Table C.4 shows that for the period 1967 - 1999:
For Australia, average natural disaster cost was $1,087 million /20 million = $54 per capita.
For the NT, average natural disaster cost was $142.6 million /0.2 million = $713 per capita.

The above statistics make it clear that the NT has particular need to mitigate the effects of intense cyclones along the Top End coastline. The statistics are used in Section 1.6 of the main report to indicate that not enough government funds are being directed to this end.

APPENDIX D

WIND CODE SPEEDS & LOADS
– DERIVATIONS & VARIATIONS

APPENDIX D WIND CODE SPEEDS – DERIVATIONS & VARIATIONS

SUMMARY

This appendix examines:

1) how engineers and building codes have evolved to allow for wind loads
2) problems with the modern building codes
3) how the Regional Wind Speed (**RWS**) for Darwin has varied over the years
4) how design loads are derived from the RWS
5) how design loads have varied over the years for typical houses in Darwin

Information on how the current wind code varies with distance inland in other parts of the NT is given in Appendix H

1) How engineers and building codes have evolved to allow for wind loads

A few snippets for a brief historical introduction:

Hammurabi who ruled Babylon circa 1750 BC was perhaps not worried about wind loads but he was certainly concerned to ensure strong buildings. Two of his 282 laws are of interest here:

- *"If a builder builds a house for a man and does not make its construction firm and the house which he has built collapses and causes the death of the owner of the house, that builder shall be put to death."*
- *"if it* (the collapse of the house) *destroys property, he* (the builder) *shall restore whatever it destroyed, and because he did not make the house which he built firm and it collapsed, he shall rebuild the house which collapsed at his own expense."*

No doubt, if structural engineers existed at that time then they would have been held jointly liable with the builder.

There had always been military engineers but it was not until the industrial revolution that the profession we now know as civil engineering fully evolved. (Structural engineering is a sub-branch of civil engineering.)

One of the most famous of the early civil engineers was Isambard Kingdom Brunel (1806 – 1859) who designed and built many of the early railways, tunnels and iron bridges and ships in England. Brunel was said to smoke up to 40 cigars a day, and get by on only four hours of sleep a night. Perhaps not unsurprisingly, he succumbed to a stroke at the age of 53.

<u>Footnote</u>: *One of Brunel's feats was to design the S.S. Great Britain. Launched in 1843, this ship was the first propeller-driven, ocean-going, iron ship in history. She was also the largest ship ever built at the time with a length of 98 m. For 25 years she carried thousands of passengers to Australia including some of the writer's ancestors. For many years the ship was a coal hulk in the Falkland Islands but has now been fully restored and can be visited in Bristol, UK.*

The 1842 edition of the US Engineering Railway Gazette included one of this writer's favourite definitions: *"Engineering is the art and science of doing for one dollar what any fool can do, more or less, for two dollars or more."*

One of Australia's early engineers who would have put this dictum to practice was Darwin's very own John George Knight. This man wore many tall hats and seems to be now remembered as an architect. But he was an engineer - he was admitted as an Associate of the Institution of Civil Engineers (London) in 1864. Later that year, was appointed Lecturer in Civil Engineering at Melbourne University - a position he held until 1868. He arrived in Darwin on 28 September 1873 as the Secretary to the Government Resident and a few months after was made Architect and Supervisor of Works. Knight is known to have designed Darwin's original town hall (which did not survive cyclone Tracy) and is believed to have been much involved in the design of Brown's Mart (1), the Fanny Bay Gaol's infirmary and the Old Court House (which all did, more or less, survive Tracy). Unlike most of Darwin's recent crop of leaders, Knight remained in Darwin. He died in 1892 and is buried in the Old Palmerston Cemetery (*Carment et al, 1993*).

The early engineers would have made some sort of allowance for wind loads but they had precious little to guide them. The writer still has his father's 1922 edition of Trautwine's *The Civil Engineer's Pocket-Book.* The first edition was printed in 1872 and J.G. Knight almost certainly would have had his own copy of this very important 1,528 page length 'pocket-book'. The section dealing with the design of buildings has only two lines dealing with loads, namely: *"Snow, 20 lbs per sq ft of horizontal projection of roof surface. Wind, 30 lbs per sq ft, horizontal in any direction. Min total, 40 lbs per sq ft."* (Trautwine, 1922)

In 1939, Australia's engineers were given additional guidance on wind loads. It was contained in an appendix to the Structural Steel in Building Code - SAA Code No. CA.1-1939 and was probably Australia's first official wind code.

SAA Interim 350

This was Australia's first loading code which was not related to any particular building material. It was introduced in 1952 and remained in use until 1971. The writer began using it for structural design of buildings in the mid 1960s. The entire loading code consisted of only twenty-three A4 pages. Part I was for dead and live loads, Part II was for wind loads and that part comprised twelve pages.

The only limitation given for Part II was that it could not be used for buildings more than 90 m high. It specified just two regions for wind – inland and coastal south of latitude 25° S and coastal north of latitude 25° S. After allowing for changes in units and calculation methods used, Interim 350 specified that buildings north of latitude 25° S and situated on an exposed sea coast were to be designed for a 'comparative' speed of 256 kph. Lesser values were specified for more inland or sheltered locations.

Anyone could understand this document and apply its rules. And importantly, anyone could afford to own a copy. It was probably free or may have cost a dollar or two.

Footnote (1): The writer did the structural design for the post-Tracy reconstruction and replacement roof for Brown's Mart in 1975.

2) Problems with the modern building codes

The equivalent, modern day set of Australian standards that are needed to design for wind, dead and live loads in Darwin comprise three books of Australian (& New Zealand) standards plus three books of associated commentaries. These six books are just part of the AS 1170 series which came out in 2002. Together with their subsequent amendments they total over 250 pages and retail for over $400. But the folly does not stop there because to know what our "societal goals" are in terms of what buildings need what wind loads, since 2002, one now has to also consult Volumes One and Two of the Building Code of Australia (BCA) plus the Guide to the Building Code. In total, the BCA volumes have more than 2,000 pages. At least they are better value on a per page basis and cost only about $350.

The 2,000 pages of the BCA volumes deal mainly with all sorts of non-structural, building related matters such as fire, energy efficiency, health & amenity, termites, etc. Because a lot of these matters cannot be "measured" or quantified and because the BCA committees want to encourage innovation, the governing committee decided that it is no longer necessary for designers to produce a "measurable" result for their designs. This may be reasonable when dealing with things like fire or termites, but it is ludicrous to suggest that structural engineers no longer need to have "measurable" loads or building strengths.

But apparently that is the situation and according to the BCA (and therefore NT government law) a certifying engineer now only needs to "judge" that a certain sized beam is adequate without going through all the tedium of calculations. Given that there is only about a 2% chance that the engineer's "judgement" on the size of the beam will be tested by a full, load testing cyclone within the 10 years that the engineer has legal liability for his design, there may well be a few busy engineers in Australia who have set aside their calculators and codes and are now just trusting to their luck and their "judgements". Hopefully that is not happening in Darwin. But who would know? The writer has been informed that the Building Advisory Services Branch no longer does any checking of engineering calculations and instead merely relies on someone who is not an engineer to peruse drawings looking for obvious defects.

AS 4055 Wind Loads for Housing

AS 4055 - Wind Loads for Housing was introduced in 1992 to respond to a need to have a very simple code for those jurisdictions where building designers other than structural engineers can certify the structural content of houses. This applies virtually everywhere in Australia except for the cyclone prone areas in WA and the NT so no doubt the document was needed.

Some engineers unkindly refer to this code as "The Wind Code for Dummies". It is a good attempt at simplifying things but suffers from the big disadvantage that by allocating only four classifications for the cyclonic regions, some houses are inevitably over-designed and there will be cases where some are under-designed. The writer considers that its use should not be permitted for NT coastal regions.

A new edition, AS 4055 – 2006 is now available and may be an improvement on the 1992 edition - but the writer has not been tempted to pay the $89 to download its 50 pages.

Conclusion and Recommendations

The lumping together of all types of 'actions' for all types of buildings for all regions in Australia into the one set of documents is all very sensible except:

- such complexity can become a breeding ground for uncertainty and errors
- it inhibits specific attention being paid to specific regional problems
- the exorbitant cost of the documents puts them out of reach of the general public

Where engineers are involved in the structural design they do not need the simplicity of an AS 4055 – type document but what is badly needed is a single regulatory document that deals specifically with design loads, design methods and building regulations for simple (not dynamically sensitive) residential buildings in areas subject to cyclones.

If it appears too difficult to get WA and Qld to agree to such an obvious move, then a good start would be to prepare a document just for use in the coastal regions of the NT. It would contain only the relevant sections of the BCA, the wind code and the 'General principles' loading code. With any luck it could all be condensed down to 23 pages and cost just a dollar or two.

Based on the writer's experience when he was practicing as a structural engineer, and on conversations with structural engineers who are still in practice, such a document should include provisions to:

1. prevent the use of plasterboard as a structural membrane unless it can be proven to retain its strength when saturated for several hours

2. discourage the use of ventilation openings that allow water penetration into the roof space

3. discourage the use of steeply pitched roofs and fancy 'parasol' arrangements on roof tops

4. give special care to ensure that things such as window awnings, air conditioners, solar panels, satellite dishes, gutters, flashings, garden sheds, etc, etc. do not become flying debris

5. give special care in design, detailing and construction to ensure that the reinforcing bars in structural block-work are correctly sized and located

6. give special care to providing corrosion resistant structural components in all buildings within 1 km of the sea

7. give special care to simplifying the 'chain of strength' and ensuring ease of inspection of all components in the 'chain'

8. give special care to ensuring that internal walls can withstand probable wind loads – especially for walls to rooms that may be relied on for shelter during cyclones. (Such walls would need to allow for full pressurisation including the suction pressure from venting to roof level in internal bathrooms.)

9. specify the design loads and rules for rooms (or smaller spaces) to be used as designated cyclone shelters within residential buildings

10. specify an on-site proof-load testing regime for all structural masonry anchors

11. make allowance for fatigue in thin, high tensile steel components subject to load reversal

12. include a degree of robustness and/or redundancy in critical structural components that could be exposed to debris impact such as steel columns and bracing in elevated houses

13. make allowance for the buoyant weight of foundations unless it can be proven that the water-table will be below the underside of the foundations during a cyclone

14. increase the value of the 'combination factors' governing overall stability in the 'General Principles' code to provide greater safety against buildings blowing over

Even before such a document is produced, structural engineers wishing to design for the cyclonic regions in the NT should be required to pass a rigorous oral examination to demonstrate their appreciation of the importance and understanding of the above matters. Such an examination should be by a panel of experienced NT structural engineers including some that were practicing in Darwin pre-Tracy. The panel should start testing engineers already on the NT's approved practitioners list of structural engineers. This list is on the NT Department of Planning and Infrastructure's website. At last viewing, there were 125 approved, structural engineering practitioners and about two thirds of them have their offices in non-cyclonic regions.

3) How the Regional Wind Speed (RWS) for coastal NT has varied over the years

There are four wind speed regions in Australia. They are described on page 20 of the report. This Appendix will only deal with the 'cyclonic region' for the NT. This is the so-called Region C and extends in a strip 50 km wide around the NT coastline.

The RWS specified in the combination of the BCA, AS/NZS 1170.0:2002 and AS/NZS 1170.2:2002 are the minimum design values to be used in structural design. As well as being dependant on the 'Region', the RWS values also depend on the type of building (or its 'importance level') and on the chosen design life of the building.

To keep things simple, this Appendix will only deal with buildings such as houses, apartments, and other conventional buildings not designed to accommodate large numbers of people. According to the BCA, such buildings all have 'importance level 2'. If it is decided that the design life for such a buildings is 50 years (and that is the normal assumption) then the corresponding RWS has a notional ARI of 500 years. For Region C that corresponds to 250 kph.

The RWS is a 3 second gust at 10 m height for winds coming directly off the sea or over a large expanse of flat, open country. It is believed to correspond fairly closely in definition to the maximum gust speeds given in BoM warnings.

The RWS should not be confused with the Design Wind Speed which is the speed that applies to some particular building and is derived from the RWS by multiplying it by factors to account for the building height, the extent to which the building is embedded within suburban or city development, the amount of shielding afforded by buildings in the immediate vicinity, topographic effects such as cliffs or hills and wind direction effects.

A brief history on the variation of Regional Wind Speeds for Darwin

Successive revisions to the wind codes have lead to changing values for the Regional Wind Speeds throughout Australia. Figure D.1 indicates the changes that have taken place for Darwin – other places such as Nhulunbuy would have a slightly different graph.

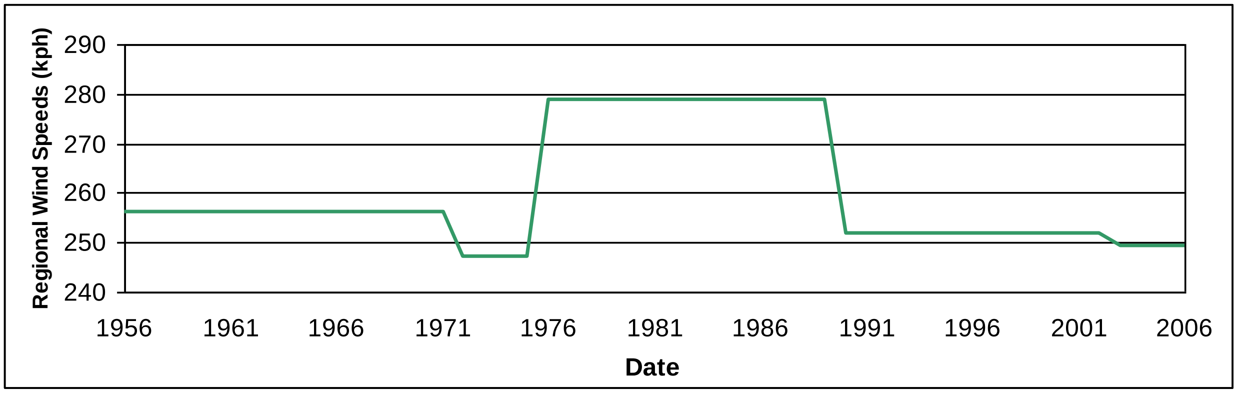


Figure D.1 Plot of design wind speeds for Darwin houses adjusted to be directly comparable to the Regional Wind Speed for ARI = 500 years as given in the current wind code.
The green line represents what the following text refers to as 'comparative RWS' values.

The step changes in the graph indicate the introduction of new wind code rules. The dates have been deliberately left vague and the "steps" are sloped to reflect the fact that although there is always a definite date given for the release of a new code and usually there is only a 12 month change over period, some engineers take longer than others to adopt the new rules.

The circumstances surrounding the various changes to the RWS were:

- From 1952 to 1989, buildings were designed using only the 'permissible stress' method which meant designing for wind speed loads that had a return period equal to the expected, 50 year lifetime of the building (the speeds had an AEP of 1/50 per year) and then multiplying those loads with a 1.5 safety factor to ensure that buildings did not blow down every 50 years or so.

  With the introduction of the 1989 edition of the wind code, buildings could be designed to the 'Ultimate Stress, Limit State' (**USLS**) method. This method entails designing for wind speeds that have only a 'small' (1) chance of occurring in the expected 50 year life of the building and using the ultimate strength of the materials in the design. Effectively this means that the USLS method provides no specific safety factor against wind overloads.

(1) The wind code that was introduced in 1989 made the "small" chance 5% or 1/20 in 50 years. This is equivalent to an AEP = 1/20 x 1/50 = 1/1000.
Risks were doubled in 2002 by the BCA making the "small" chance 10%. This is equivalent to an AEP = 1/10 x 1/50 = 1/500.

- In the following, to allow for the removal of the 1.5 safety factor, the RWS values from the earlier codes have been multiplied by √1.5 (remembering that wind loads increase with the square of the wind speed) to obtain the 'comparative RWS' to allow direct comparison with the current wind code values

- SAA Interim 350 started in 1952 (not 1956 as indicated in Fig D.1) and continued unchanged until 1971. The 'RWS' in those days for cyclone prone areas was 130 mph (209 kph). Dines anemometers began to be generally installed at airports in the early 1940s and that 130 mph was probably based on the very few records of cyclonic wind speeds obtained during that decade. Presumably it was more of a guess than anything but judging from the current codes it was a good guess. Converting to allow for the USLS method, the 'comparative RWS' becomes 209 x √1.5 = **256 kph** - very close to the current value for houses.

- The wind code introduced in 1971 was the first code to relate the RWS values to a detailed analysis of anemometer records. It also introduced the rule (maintained until 1989) that because the record period was so short and the uncertainty high, the regional wind speed values given for cyclone-prone locations were to be multiplied by 1.15 – this to maintain a certain risk parity level with non-cyclone areas.
  For Darwin, the 1971 'RWS' became 1.15 x 175.5 = 202 kph.
  Allowing for the USLS method, the 'comparative RWS' becomes 202 x √1.5 = **247 kph**.

- The 1971 code is of particular interest here because it used the local anemometer records to derive values of the RWS for the town served by that anemometer. The results for five towns of interest are shown in the table below. Note that the 1971 code produced results that, in hindsight, were obviously too low for Pt Hedland and Cairns.

Type of RWS	RWS in kph for:				
	Onslow WA	Pt Hedland WA	Darwin NT	Cairns Qld	Townsville Qld
1971 'comparative RWS'	306	**227**	247	**197**	233
Current wind code RWS	317	317	250	250	250

Table D.1. Comparison of RWS values for the 1971 and 2002 wind codes.

- Cyclone Tracy in December 1974 gave the wind code writers a jolt and in a new code released in November 1975, nearly all towns (1) in the cyclone prone areas had their 'RWS' values increased from 202 kph to 228 kph.
  Allowing for the USLS method, the 'comparative RWS' became 228 x √1.5 = **279 kph**.
  (Note that this speed is on the cusp between category 4 and category 5 cyclones. It is also the maximum speed estimated for Tracy in the interim report issued by the BoM in 1975)

(1) The one exception was Onslow, WA – an old town with a long record of being whacked by very intense cyclones. The 'RWS' there for the 1975 code was 248 kph or a 'comparative RWS' of 304 kph.

- The 1975 code writers had to make quick adjustments for cyclone Tracy. They recognized the folly in the 1971 code of allocating different RWS values for different towns on the basis of very short periods of anemometer records for that town. But they then went from the sublime to the ridiculous and assumed that the whole cyclone-prone coastline (except for Onslow) was at equal risk. Presumably there were hurried analyses of the anemometer records all grouped together but I understand that the final choice to make the ‘comparative RWS’ = 279 kph was simply the committee’s consensus of what at the time appeared reasonable.

- The ‘comparative RWS’ of **279 kph**, was maintained in the 1981 and 1983 versions of the wind code and survived until the introduction of the 1989 code. Between 1975 and 1989, there was much analysis by engineers of anemometer records throughout Australia to derive more appropriate values of the RWS for the various regions and several learned papers on the subject appeared in the Transactions of the Institution of Engineers, Australia. Subsequent discussions published in the transactions indicated that there was considerable difference of opinion between the various experts at the time. (*Gomes and Vickery, 1976; Dorman, 1984*)

- Despite disagreement over details, there was a clear consensus that the value adopted after Tracy was an over-reaction and in 1989, the RWS was dropped to **252 kph** for the whole of the cyclone-prone coast north and east of Port Hedland, WA around to Bundaberg, Qld - what then became known as Region C. (On the other hand, a new Region D was created stretching south from Pt Hedland to Carnarvon. Here the RWS values were <u>increased</u> to 306 kph – close to the value that previously had been applied only to Onslow.)

- It appears that there were several reasons for the dropping the RWS for Region C back to pre-Tracy values, they were:

    1) analyses using Monte Carlo Simulation techniques (*Gomes and Vickery, 1976*) and a modified Gumbel technique (*Dorman, 1984*) found that the RWS values adopted in the 1975 code were too conservative

    2) the introduction of the USLS method in the 1989 code had introduced a new problem. With the permissible stress method the RWS was an event that on average could be expected to occur once every 50 years but the USLS method required deriving a RWS that could be expected to occur only once every 1,000 years. Clearly it needed a very long period of record to safely predict such rare events. By assuming that the risk was the <u>same</u> at all of the 20 or so stations in Region C, it was judged that a sufficiently long period of record was obtained for a Region C ‘super station’ and that confidence could therefore be placed in an analysis of such data. It would appear that analyses were carried out using a modified Gumbel approach (*Rattan and Sharma, 2005*) and that it confirmed the Gomes & Vickery and the Dorman results (*Holmes et al, 1990*). (However, to the writer’s knowledge, the details of such ‘super station’ analyses for the cyclonic regions have never been published.)

    3) the effects from Tracy were fast being forgotten and it is probable that political and commercial pressures were being applied to reduce design wind speed values for Region C

- Whether or not political or commercial pressures were a factor, the weight of evidence indicated that Tracy was an outlier and simply represented a very early arrival of an event with a much longer ARI and so in the 1989 edition of the wind code, the RWS for Region C was dropped from 279 kph to 252 kph. The concurrent introduction of the new USLS design method in this code meant that this sudden change in the real value of the RWS probably meant that it escaped the public attention that it deserved.

- The final chapter in this saga came with the introduction of the current editions of the various loading codes and the 'importance level' provisions in the BCA – all in 2002. It is understood that engineers in WA had become alarmed at the apparent increase in intensity and frequency of cyclones impacting the Region D coastline over the previous few years and they persuaded the wind code committee that the RWS values for Region D should be increased by 10%. But the strip for the next 50 km inland from Region D in WA is Region C and obviously, that strip would also need to have increased values of RWS. The upshot was that RWS value for the whole of Region C in all of Australia was increased by 5%.

- But, as was the case with the introduction of the 1989 code, the change in wind speed was effectively masked by another factor. This time it was the summary decision by the BCA committee to <u>double</u> the acceptable risk for a normal building being impacted by its ultimate load in its 50 year lifetime from 5% to 10%. The net effect for Darwin was that instead of the RWS increasing by 1.05 x 252 kph to 265 kph, the change in AEP from 1/1000 to 1/500 meant that the new RWS reduced slightly to 250 kph.

- The lessons to be learnt from the foregoing are that a prime consideration for the code writers appears to be to maintain fairly constant values for the 'comparative RWS' and that factors other than statistical analysis may at times play a role in determining such values.

The RWS values are important but what really determines the strength of a building is the magnitude of the <u>loads</u> it can carry. This all-important matter will be examined in the following two parts of this Appendix but first a brief discussion on the real meaning of USLS loads and building strengths.

The USLS design method

The 2002 editions of the various codes were the first to <u>not</u> include allowance for 'permissible strength' design methods. Only USLS methods are now allowed. (The USLS method actually includes for other factors such as deflections etc, but here only loads and strength will be considered.)

In the following parts of this appendix:

- use will be made of the notation in the current wind code whereby $\mathbf{V_R}$ represents the RWS at an ARI = R years [Note, in the main report, this value is referred to as $V_{(ARI)}$]

- discussion will continue to be confined to 'normal' buildings such as houses, apartments, shops, factories etc. with a 50 year design life.

As already described, the change over to the USLS method meant that the value for the RWS became V_{500} instead of V_{50} as used in the 'permissible stress' method. A corollary was the disappearance of the big fat 1.5 factor of safety on the strength of the materials that was part of the 'permissible stress' method (and consequent allowance for wind over-load).

In general terms, the only "factor of safety" remaining in USLS design results from:

- the average strength of construction materials is a bit more than the minimum strength assumed in the design

- the loads that will be applied to an average building in the ARI = 500 year event will generally be a be a bit less than the values derived from the code. Note however that in the currently used USLS design method, there is no longer any implicit allowance for wind speeds exceeding the wind speed used in the design.

In simplistic terms, the new, reduced 'factor of safety' means that if a cyclone having V_{500} winds hits a large number of buildings which have all been correctly constructed and designed to the USLS method for those winds, then only a very small percentage of the buildings would start to fail structurally in some way. These would be the buildings which happen to be subject to the strongest gusts hitting at the worst possible angle and the same buildings contain within their 'chains of strength', one or two components having only the required minimum rather than average strength.

The downside to this good news is that at least a third of all of these buildings would fail structurally in one way or another from pure wind loading if winds speeds were say 28% higher than V_{500}. (Cyclone Ingrid's maximum gusts were 320 kph which is 28% higher than 250 kph which is the V_{500} for Region C.)

But the news gets worse because some of the debris from these structural failures would impact on the remaining, intact houses leading to a cascade of further failures downwind. Here, it is most important to understand that the only allowance that the wind code makes for the effect of debris is that, unless the building envelope can be shown to be capable of resisting penetration by a 4 kg piece of 100 mm x 50 mm timber traveling at about 50 kph, then allowance must be made for internal pressures effects There is no allowance for debris impact loading as such on the design of structural components. In fact the commentary to the current wind code (AS/NZS 1170.2 Supplement 1:2002) when referring to both tornadoes and debris states: *"Such wind events are not covered due to their small nature and low occurrence in populated areas of Australia and New Zealand."*

The writer has previously recommended a Darwin study to determine how allowance (in addition to pressurisation) should be made for the effects of debris (Nicholls, 1990). The recommendation was not accepted by the authorities. The writer still considers that some allowance should be made because, despite the above quote, debris 'events' will be of a very large nature and have very high occurrence for an intense cyclone impact on Darwin. The very least allowance that should be made is that design wind speeds for 'pure wind' loading err on the conservative side in a range of estimates.

The combination of wind loading plus debris impacts means that if a cyclone having the intensity of an Ingrid were to impact the whole of Darwin with its maximum winds then probably more than 80% of houses would suffer serious structural failures leading to collapse of all or parts of the houses.

Insurance companies are interested in so-called ‘vulnerability curves’ which relate repair costs to wind speeds. Such work that has been published (Walker, 1995; Holmes, 2001) supports the grim predictions made above by the writer.

Obviously, impact from a ‘Monica’ with wind speeds producing loads 25% higher than an ‘Ingrid’ would cause much greater damage. Fortunately, the following sections can provide some good news - NT houses that were designed and built between 1975 and 1989 should be able to withstand even Monica-type winds.

4) How design loads are derived from the RWS

A structural engineer should go through two basic steps to arrive at the design loads for a particular component of a particular building:

i) firstly, determine the wind speeds that will actually impact on the different sides of the particular building using four modifying factors from the wind code. This will produce the so-called Design Wind Speeds which will be given the notation here $\mathbf{V_D}$

ii) secondly, multiply the derived value of V_D by several more factors from the wind code to obtain the pressure on the building component - multiplying by the components area then gives the load.

The Design Wind Speed ($\mathbf{V_D}$)

RWS values (V_{500} or whatever) are the starting point for deriving the V_D value for a particular building or component of a building. Factors to allow for the direction of the wind, the height of the building and roughness of the terrain upwind (near the coast or open country, or in the middle of a large suburb, or some intermediate zone) the shielding that might be afforded by neighbouring buildings and the effects of topography (on or near a steep hill or cliff etc) must all be accounted for by the structural designer in order to derive V_D for a particular building and/or building component.

In mathematical terms, $\mathbf{V_D = (M_d \times M_{z,cat} \times M_s \times M_t) \times V_R}$ ………………………..(1)

Where (using the notation in the current wind code):

- M_d, takes account of the likely direction of the wind,
- $M_{z,cat}$, allows for the height of the component above ground and the type of terrain upwind of the building,
- M_s, takes account of any shielding that might be provided by neighbouring buildings,
- M_t, is an allowance for wind speed increasing if the house is on or near a steep hill or escarpment.

To simplify Eq.1, make $M = (M_d \times M_{z,cat} \times M_s \times M_t)$ and therefore, $V_D = M \times V_R$ …..(2)

The application of the above four factors could mean that the V_D used for a two storey house on a hill top somewhere out in open country in one of the southern states might be 230 kph whereas a single storey house which is shielded by closely surrounding houses and is in the middle of a large, suburban area in Darwin might have a V_D of only 170 kph.

The Design Loads

To find the loads, a fundamental physical relationship is used which gives the wind pressure (**p**) on something as a function of the imposed wind speed V_D, namely:

$$p = 0.5 \times \rho \times C \times (V_D)^2 \quad \text{..(3)}$$

Where:

- ρ is the density of air (approximately 1.2 kg/m3)
- C is the <u>product</u> of several coefficients determined from the wind code rules which take account of the component's shape and size, its orientation to the wind and possibly its roughness and porosity. (Also, for this simplified account, C would have to allow for the conversion of kph to m/s to produce a value of p measured in pascals)

Finally the load on the surface of the component is simply the product of the pressure p and the area (**A)** of the component exposed to the wind or pressure.

Substituting from Eq. 2, wind force (**F**) on the surface area (A) of a component is given by:

$$F = 0.5 \times \rho \times C \times M^2 \times (V_R)^2 \times A \quad \text{...................................(4)}$$

C and M in the above equation are dimensionless coefficients. The other variables can be expressed in different units but the equality in Eq. (4) only holds if the load is measured in newtons (1) and the density of air, the wind speed and the area are measured in terms of kilograms, meters and seconds. If we define a new term $\beta = (C \times M^2)$ and measure the regional wind speed in kph, the component's area in sq m and the wind force in kilonewtons (kN), then equation (4) becomes:

$$F = 0.5 \times 1.2 \times \beta \times (V_R/3.6)^2 \times A \times 1/1000 \quad kN$$
$$= 4.6 \times 10^{-5} \times \beta \times (V_R)^2 \times A \quad kN \quad \text{..............................(5)}$$

Comment

The difficulty in deriving a correct value for V_R is the main subject of this report. However, it should also be realised that the coefficients that make up C and M and hence β in the above formulae are measures of very complex parameters that fluctuate in value in space and time. The values given in the wind code for these parameters are really just the best estimates that can be made of <u>average</u> values. Over the years, continuing research and wind tunnel testing have led to various changes in the wind code rules relating to the values of the various coefficients and the way that they are applied. Hopefully the current wind code rules now provide realistic estimates of the actual loads that will be experienced for any given value of V_R.

<u>Footnote (1)</u> A good way to remember the magnitude of one newton is that it is the <u>weight</u> of a small apple having a <u>mass</u> of 100 gm - of the kind that possibly fell on Isaac Newton's head. Because a newton is such a small force, engineers usually measure force in kilonewtons (kN) where 1kN = 1,000 newtons. The best way to remember the magnitude of a kilonewton is that big people who have a <u>mass</u> of 102 kg have a <u>weight</u> of 1 kN.

5) How design loads have varied over the years for typical houses in Darwin

The following pages describe the meaning and derivation of the **'equivalent RWS'** as plotted in the figure below. (It is the same as Fig. 2.1.3 on page 24 of the report.)

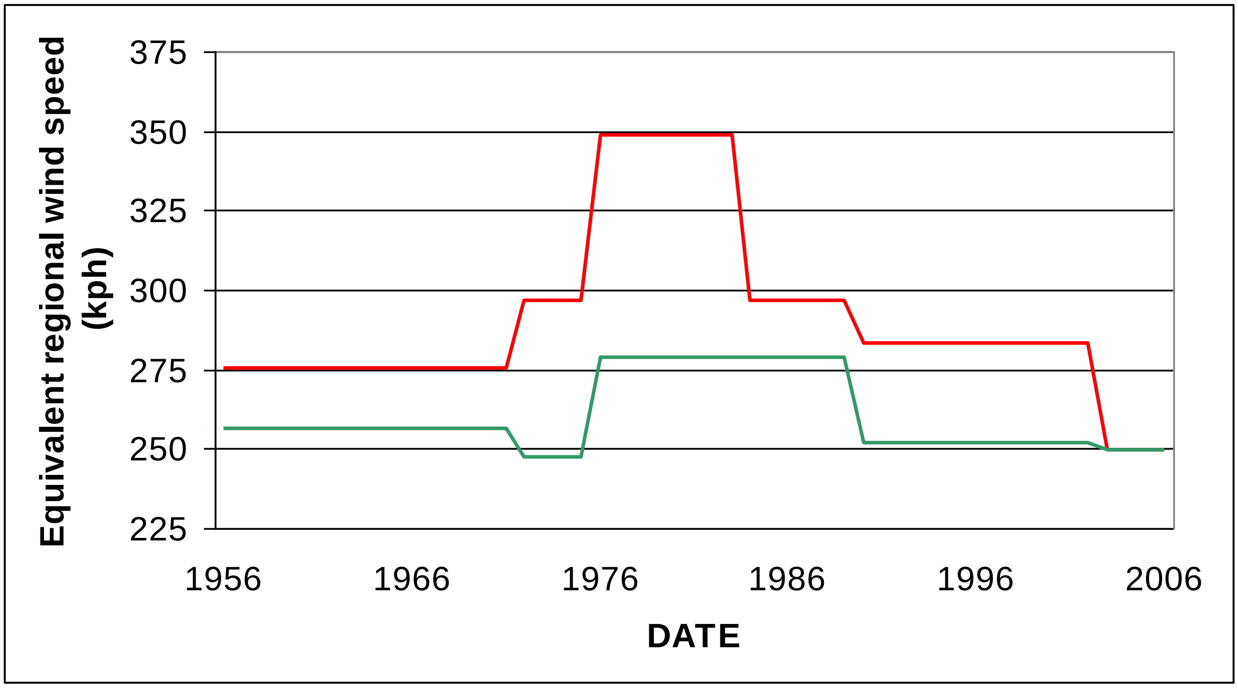


Figure D.2 Showing how the 'equivalent RWS' and the 'comparative RWS' has varied between six editions of the wind code over the last 50 years for an 'average' Darwin house.
(The green line is the 'comparative RWS' as already given in Fig.D.1).

The 'equivalent RWS' is the speed required to produce the loads derived by earlier editions of the wind code when using the rules in the current wind code (apart from its Table 3.1).

The use of an 'equivalent RWS' is really just a device to overcome the fact that most older people don't know what a kilonewton is – and if they do know that it is a unit of force, they are still unlikely to have any concept of the magnitude of one kilonewton.

This is really an indictment on the education system that followed metrication in this country. Hopefully the graduates from today's secondary schools now have the same appreciation on the magnitude of the unit of measure for a force or a load or a weight as everyone did in the days of I.K. Brunel and J.G. Knight and the writer's youth. Those were the good old days when such things were measured in tons or pounds, mass and weight were the same and nobody cared what something might weigh on the moon.

To explain Fig. D.2 in more detail will require using kilonewtons for the next page or two. If a benchmark is needed, remember that big Jonathan Brown of the Brisbane Lions exerts a force on the earth beneath him (weighs) 1 kN.

This page demonstrates how the value of β (refer Eqs. 4 & 5 above) has varied in the six codes and the dominant effect this has had on derived loads.

The table below gives the horizontal wind load (F_H) on the external surface of the windward wall of a typical building in Darwin as would have been derived using the six named editions of the wind code. The example building could be a 2 storey house, school building, block of flats or simply an industrial shed. The windward wall is 14 m long and 6 m high, the building is within one of the large suburbs more than one kilometer from any large, open space and it is fully shielded by neighbouring buildings. The values of V_R are the 'comparative RWS' values as described previously and represented by the green line in Fig. D.2.

Code Name	When used	β	V_R (kph)	F_H (kN)
SAA Int. 350	1952 - 1971	0.43	256	**110**
AS CA34 Part 2 - 1971	1972 - 1975	0.39	248	93
AS 1170 Part 2 - 1975	1976 - 1983	0.51	279	**154**
AS 1170 Part 2 - 1983	1984 - 1989	0.345	279	104
AS 1170.2 - 1989	1990 - 2002	0.36	252	89
AS/NZS 1170.2 - 2002	2003 - ??	0.25	249	**61**

Table D.2 Design loads (F_H) on front wall of a typical building in suburban terrain with full shielding using the successive wind codes.

The values of β in Table D.2 are appropriate only for the windward wall of the described building. The table below shows how these values of β were derived.

year code was introduced	(Cp,e x Ka x Kc) x (Md x Mz,cat x Ms)^2 = β
1952	(0.8 x 1 x 1) x (1 x 0.846 x 0.866)^2 = 0.43
1971	(0.8 x 1.0 x 1) x (1 x 0.700 x 1)^2 = 0.39
1975	(0.8 x 0.986 x 1) x (1 x 0.804 x 1)^2 = 0.51`
1983	(0.6 x 0.986 x 1) x (0.95 x 0.804 x 1)^2 = 0.345
1989	(0.7 x 1.0 x 1) x (0.95 x 0.889 x 0.85)^2 = 0.36
2002	(0.7 x 1.0 x 0.8) x (0.95 x 0.828 x 0.85)^2 = 0.25

Table D.3 Derivation of the values of β used in Table D.2. [Md, Mz,cat, & Ms are defined under Eq.1 above, Cp,e is the external pressure coefficient, Ka is the area reduction factor and Kc is the combination factor.]

The significant thing to note in Table D.2, is that despite the fact that the RWS, V_R has remained fairly constant over the years, the resulting loads have varied significantly due to large variations in the value for β. The jump in the load in 1975 was a consequence of the re-evaluation of things after cyclone Tracy. But as can be seen, that was just a temporary "blip" in what tends to be a downward trend in design loads with time.

The next table shows the values that engineers would have used in their designs when following the different codes for the total horizontal load (not just on the front wall) for the building described for Table D.2. (To keep things simple, the building has a gable roof with 15º pitch, no eaves and is 14.0 m x 8.5 m in plan.) Most of the load comes from the load on the windward wall as calculated previously but suction on the leeward wall and on the roof also contribute horizontal loads. The main point of Table D.4 is that it also shows 'equivalent RWS' for each code. As already indicated, this is derived by working backwards from the design load derived from that particular code but using the rules and parameters from the 2002 wind code.

Code Name	When used	Total horizontal load on building (kN)	'equivalent RWS' (kph)
SAA Int. 350	1952 - 1971	173	**363**
AS CA34 Part 2 - 1971	1972 - 1975	149	337
AS 1170 Part 2 - 1975	1976 - 1983	243	**431**
AS 1170 Part 2 - 1983	1984 - 1989	150	339
AS 1170.2 - 1989	1990 - 2002	134	320
AS/NZS 1170.2 - 2002	2003 - ??	81	**249**

Table D.4 Total horizontal load and the 'equivalent RWS' for a typical, old style, two storey Darwin building in suburban terrain with full shielding from neighbouring buildings.

The results for the 'equivalent RWS' in Table D.4 are quite astonishing but they are for the rather extreme case of a fully shielded building embedded more than one kilometer within a suburb and the load reductions allowed now for such situations were not allowed in earlier codes. It should also be noted that the values for the 'equivalent RWS' in the above table only apply to the horizontal loads. There are a different set of figures for the vertical loads.

A better way to compare wind loads between codes for a given building is to find the total wind loads acting on the building. This was done to derive the red line in Fig. D.2 where the horizontal loads (F_H) were combined with the vertical, uplift loads on the roof (F_V) to give the resultant wind load (F_R) $= \sqrt{[(FH)^2 + (F_V)^2]}$. (In obtaining the vertical loads, it was assumed that debris has penetrated the windward surfaces somehow and caused maximum internal pressurisation.)

In order to obtain a result that would more accurately depict the situation for an 'average' Darwin house, the writer laboriously went through the calculations for each of the six codes for two 'typical' Darwin house types in four different exposure environments. All cases were for flat topography.

The house types were:

- a two storey house with gable roof at 15° pitch – typical of an old style elevated house that has been built in underneath
- a large, ground floor house with hipped roof at 30° pitch – typical of many of the new houses now being built in Palmerston

The four exposures were:

- sea coast exposure (TC 1), no shielding
- open, inland terrain (TC 2), no shielding
- embedded 500 m within suburban terrain (TC 2.5), partial shielding
- embedded at least one km within suburban terrain (TC 3), full shielding.

There was considerable variation between the loads obtained for the 2 x 4 = 8 different cases because the rules governing the calculation of the loads on different parts of a building have varied extensively, but not consistently, over the years. People are naturally interested to compare how their house would fare in such a comparison. The writer has deliberately prevented such comparison in Fig. D.2 by only plotting the average values for the eight cases.

The purpose of Fig. D.2 is to allow comparison to be made for an 'average' Darwin house. It must be kept in mind that a particular house will probably vary significantly from the 'average'.

Similar calculations were made to examine the variation between codes for the peak wind pressures operative at the 'local pressure areas' on the roofs of the two house types. A similar downward trend from the post-Tracy code also prevailed although it was not as pronounced as for the total load case.

Comment

If all of the research and deliberation that has gone into the selection of the various parameters in the modern wind code has meant that the loads determined for a given RWS are now reasonable approximations to the loads that would in fact occur for such a wind speed, then provided the designer and builder do their jobs properly, the strength of a modern house should be adequate to safely withstand the RWS used in the design.

But the bottom line is that a house being built today using the minimum RWS value of V_{500} = 250 kph is designed to withstand only about half the load that the same house would have been designed for immediately after Tracy. Perhaps even more surprising is that most buildings built before cyclone Tracy (including all of the ones that blew away) should have been designed for loads substantially more than those that would be used in the design for similar buildings today.

These results are very surprising and will be disputed by some. The writer's calculations were carefully made and took many days to do - but they have not been independently checked. The calculations are on eleven Excel spreadsheets comprising more than 1200 cells in total. The writer will make these sheets available to structural engineers wishing to peruse or check them.

The wind codes have always allowed users some latitude in how a particular rule can be interpreted so other engineers may well derive different loads to the writer's loads. Hopefully the differences will not be as much as 100% as was found would be the case for some buildings near the Casuarina complex (Nicholls, 1990).

RECOMMENDATIONS

1) That the Australian Building Codes Board and Standards Australia prepare a single regulatory document that deals specifically with design loads, design methods and building regulations for simple (not dynamically sensitive) residential buildings in areas subject to cyclones. If WA and/or Qld do not agree to such a proposal, then a document should be prepared for use in the coastal regions of the NT. It would contain the relevant sections of the BCA, the wind code and the 'General principles' loading code and deal with specific provisions relating to cyclone resistant design including the 14 examples given in pp G4 & G5

2) That the NT Department of Planning and Infrastructure establish procedures to test structural engineers who are already on the NT's approved practitioners list of structural engineers and future applicants. The test would be an oral examination by a panel of experienced NT structural engineers on the practitioner's knowledge and experience in designing houses for intense cyclones.

3) That the NT Department of Planning and Infrastructure commission a consultant to check the writer's finding relating to the variation in the 'equivalent RWS' for different editions of the wind codes. (The findings could be particularly important, and have immediate application, in cases where new buildings are to be erected in or near suburbs that were constructed in the eight or so years after Cyclone Tracy. The houses in these older suburbs probably have about twice the wind strength of houses built to the current code but they should not be subject to debris loading from their much weaker, new neighbours.)

REFERENCES

Carment, D., H.J.Wilson and B.James (1993). The Life and Work of John George Knight, *Historical Society of the Northern Territory.* 65 pp.

Dorman, C.M.L. (1984) Tropical Cyclone Wind Speeds in Australia, *Civil Engineering Transactions, The Institution of Engineers, Australia,* pp 132-143 and 245,246.

Gomes, L. and B.J. Vickery, (1976) Tropical Cyclone Gust Speeds along the Northern Australian Coast, *Civil Eng. Trans., The Institution of Engineers, Australia,* pp 40-49.

Holmes, J.D., W.H. Melbourne and G.R. Walker (1990) A Commentary on the Australian Standard for Wind Loads, AS 1170 Part 2, 1989. *Australian Wind Engineering Society*, 72 pp.

Holmes, J.D. (2001) Wind Loading of Structures, *Spon Press,*

Nicholls, M.J. (1990) Is Darwin Prepared for Another Cyclone? *self- published,* 51 pp.

Rattan, S.P. and R.N. Sharma (2005) Extreme value analysis of Fiji's wind records. *The South Pacific Journal of Natural Science,* Vol. 23.

Trautwine, J.C. (1922) The Civil Engineer's Pocket-Book, *Chapman & Hall Ltd,* 1528 pp.

Walker, G.R. (1995) Wind Vulnerability Curves for Queensland Houses, *Alexander Howden Insurance Brokers (Australia) Ltd.*

Appendix E

CYCLONES WITHIN 50 Km OF A SETTLEMENT, (1824 – 2007)

Using the written records of intense cyclones to derive

- **intensity – frequency estimates,**
- **probable track directions.**

APPENDIX E CYLONES THAT HAVE COME WITHIN 50 KM OF A SETTLEMENT - DARWIN REGION RECORDS (1824 – 2006)

SUMMARY

This Appendix analyses the record of cyclones which have come within 50 km of Darwin (or a proxy settlement) between 1824 and the present day. These records are then used to derive:

- 'ball-park'*(1)* estimates of the Annual Probabilities of Exceedance (AEPs) for maximum gust speeds of 250 kph, 270 kph and 290 kph for intense cyclones impacting any location along the coastline in the Darwin Region.
- an indication of the likely track directions for cyclones impacting Darwin.

The derived probabilities and directions are significantly different to those used in engineering studies to derive design wind speeds and surge levels for Darwin.

INTRODUCTION

Generally, the written records before the satellite era are considered too incomplete and unreliable to be used for a rigorous, statistical analysis of wind speeds or central pressures. They will certainly be incomplete for the whole region. In the nineteenth century, the coastline was sparsely settled. Ships used barometers to know where to sail or steam to get away from the eye of a cyclone – not to sail into it to record the central pressure. Many ships and crew that did end up in, or close to, the eye did not survive to tell the tale.

On the other hand, events such as cyclones had a vital impact on the viability of the early white settlements and wind damage, wind directions, surge heights and sometimes barometric readings were faithfully recorded for dispatch to senior officers in the south. So if just a single location is considered, diligent research should reveal a fairly reliable record of all of the cyclones that came close enough to a settlement for it to have made some sort of impact. Fortunately, that diligent research has already been undertaken by Kevin Murphy who was a Senior Technical Officer with BoM, Darwin. His book 'Big Blow Up North' (*Murphy, 1984*) and the archived copies of the original records for the book are the source of most of the information in this chapter. (Other sources are as noted.)

Palmerston (later called Darwin) was not settled until February 1869 which means that Darwin has records for 138 cyclone seasons to the present day. If the four, earlier, settlements of Fort Dundas on Melville Island, Fort Wellington in Raffles Bay, Victoria in Port Essington and Escape Cliffs on Cape Hotham are included as proxies for Darwin, a further 20 cyclones seasons can be added to the records giving a total of 158 seasons.

(1) Ball-park estimates (also known as back-of the-envelope calculations) should be routinely used by scientists and engineers to provide a reality check on results derived by complicated, computerized calculations.

Except for 18 months when both Fort Dundas and Fort Wellington were in existence, the four early settlements were unique in that in their day, each was the only place along the NT coastline where written records of a cyclone would have been kept. It is almost certain that if the centre of an intense cyclone came within 50 km of any one of those settlements then its effects would have been recorded. Two such cyclones are included in this analysis, one impacted Fort Dundas and another Victoria (Settlement). After 1869, only cyclones that have been detected in Darwin are included in the analysis. By doing this we have been able to create 158 years of records for a "single settlement" in the Darwin region.

Some people who have reviewed this Appendix have been troubled with the writer using records from five different locations to derive AEPs for a single location. It is submitted that the intensity- frequency relationship for cyclones in all five locations will be reasonably uniform and that therefore this artifact to extend the period of record is valid.

To make a consistent data set, cyclones that were detected by plane or satellite as having come within 50 km of Darwin but which nevertheless did not produce gale force winds (gusts exceeding 90 kph) in Darwin have not been included in the analysis. The cyclones that are included in this analysis theefore are those that would have been detected using 19th century technology.

Settlement	Lat/Long. (degrees)	Period	No. of seasons	Date cyclone recorded	Intense Y/N
Fort Dundas	-11.4, 130.4	Sep 1824 – Feb 1829	4.5	**03/04/1827**	**Y**
Fort Wellington	-11.3, 132.4	Jun 1827 – Aug 1829	2	**-----**	**----**
Victoria	-11.3, 132.2	Nov 1838 – Nov 1849	11	**25/11/1839**	**Y**
Escape Cliffs	-12.1, 131.3	Jun 1864 – Jan 1867	2.5	----	----
Darwin	-12.4, 130.9	Feb 1869 – Jun 2006	138	16/01/1882 **07/01/1897** **22/12/1915** 01/04/1917 **06/03/1919** **11/03/1937** 01/12/1948 11/04/1954 05/12/1971 **25/12/1974** 12/03/1981 13/04/1985	N **Y** **Y** N **Y** **Y** N N N **Y** N N

Table E.1 Details of the five "single settlements" and a listing of the fourteen cyclones which came within 50 km of them.

In the above table and in the following text, an "intense" cyclone is one estimated to have had maximum gust speeds greater than 250 kph in the eyewall when its centre was within 50 km of the 'single settlement'.

There have been 14 cyclones coming within 50 km of a single settlement in 158 years of record – on average, about one such cyclone every 11 years. However, if we consider only the intense cyclones, there were six in the first 90 years or say 1 in 15 years but only one (Tracy) in the last 70 years. Further, six of the eight cyclones in the first 90 years were intense compared with only one of the six cyclones in the following 70 years. These statistics suggest that a significant shift took place circa 1940 in climatic conditions relating to the frequency of intense cyclones. However, the numbers need to be treated with caution because:

- it is probable that in the first 20 or 30 years of record, only cyclones that produced significant damage were recorded. This would mean that cyclones like 1981's Max and 1985's Gretel which produced maximum gusts in Darwin of only 107 kph and 117 kph respectively would not have been recorded in those early years
- the intensity of the early cyclones is only approximately estimated in this analysis. Further investigation may lead to a downgrading of some of these estimates

To overcome the problem of trying to fix on a single frequency estimate to derive the AEP figures later in this Appendix, two scenarios will be assumed:

- **Optimistic Scenario:** The clumping of the six cyclones in the early part of the record is a statistical aberration and it is reasonable to assume that the frequency of similar arrivals into the future will be represented by the averages in 158 years of record

- **Pessimistic Scenario:** The advent of six intense cyclones in the first 90 years of record and only one intense cyclone in the next 70 years was a result of a multi-decadal cycle. The recent passage of three Category 5 cyclones near Darwin over the last 9 years indicates that this multi-decadal cycle may be re-appearing. Therefore the prudent thing to assume is that for the immediate future, the frequency of intense cyclones coming within 50 km of Darwin will be as represented by the first 90 years of record

DETAILS OF THE SEVEN INTENSE CYCLONES

The following pages give details of the cyclones of 1827, 1839, 1897, 1915, 1919, 1937 and 1974. The tracks of the cyclones are plotted and reasons given for denoting them as being either mid-level Category 4 with gusts greater than or equal to (>=) 250 kph, high- level Category 4 with gusts >= 270 kph or low-level Category 5 with gusts >=290 kph.

03/04/1827

Two and a half years after Fort Dundas was established (at the site of present day Pirlangimpi) on Melville Island, it was devastated by what is believed to have been an intense cyclone. A report by Major J. Campbell to the Colonial Secretary stated *"… a very severe gale or tempest on the 2nd of April, accompanied with torrents of rain. It commenced a little after midnight on the first, and lasted without any abatement of its violence until after sunset on the 3rd. It threw down all our fences, either broke or rooted up mostly every fruit tree,……and unroofed all our huts and sheds. ….*" The fruit trees could only have been 2 ½ years old and although the fences and buildings had to be strong enough to resist the attentions of the less than friendly Tiwi, it could be argued that they were not well constructed to resist strong winds.

However, the report continues "*The sea rolled in with such violence that it swept away the wharf, foundered and deprived us of a new boat, and stove in the bottom of our only remaining one. I am happy to say that neither the Anne nor the Isabella sustained any injury, although the latter drove within a few yards of the rocks.*" Based on the coastline of Port Cockburn and the location of its rocky shoreline, this passage indicates that the maximum winds (and the seas) were coming down The Narrows from NNW – consistent with a cyclone centred off the north-west coast of Bathurst Island.

If we assume that "*a little after midnight on the first"* means very early morning on the 2nd, then the gales lasted about 40 hours. Weak cyclones can cause gale force winds but it is well established that they tend to move faster and have a smaller radius of gales than intense cyclones. The averages for the 8 cyclones that did not reach category 4 but came within 500 km of Darwin in the last 20 years are 18 kph for the forward speed and 110 km for the radius of gales. On the other hand, intense cyclones move slower and tend to have a larger radius of gales. If we exclude Tracy and Ingrid which were extremely small cyclones then the averages for Thelma, Neville and Monica are **10 kph** for the forward speed and 200 km radius of gales.

A cyclone moving in a SW or NE direction off-shore of the Tiwi Islands could travel about 400 km and remain within a 200 km radius of Fort Dundas. If it took about 40 hours to travel that distance it would need to move at an average of about **10 kph**.

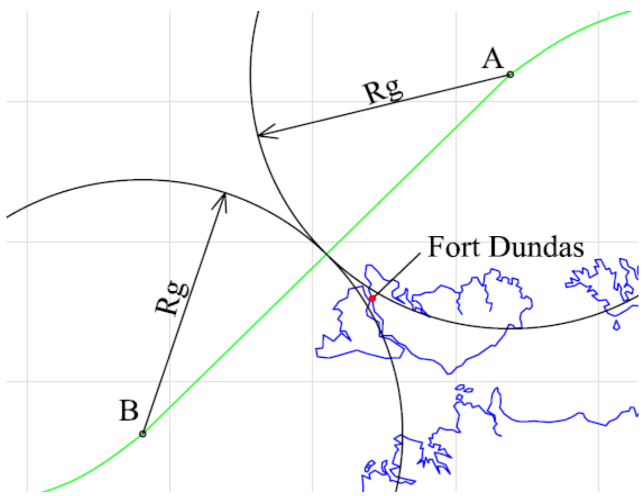


Figure E.1 Possible track for 1827 Cyclone - shown green.
Distance A to B is 400 km. Radius of Gales, Rg = 200 km,

The above argument might be regarded as tenuous. Meteorologists have suggested that it could have been an unusually large and unusually slow moving, weak cyclone or that possibly it was not even a cyclone but simply some rare system associated with the monsoon trough. However, the writer considers that the most likely explanation for the recorded effects is that it was an intense cyclone.

For the purpose of this analysis, the writer assumes that the 1824 cyclone was mid-level Category 4 when its centre was within 50 km of the 'single settlement' (Fort Dundas) (A mid-level Category 4 cyclone producing maximum gusts of 250 kph at its radius of maximum winds of say 15 km would produce maximum gusts of less than 100 kph at 50 km radius.)

25/11/1839

This cyclone devastated the settlement of Victoria on the Coburg Peninsula. The port for the settlement was well within the Port Essington harbour – 25 km south of its opening to the Arafura Sea. Barometric readings, wind directions, etc. are described in 'Big Blow Up North' and given in more detail in the archived copies of the original records. The writer's preliminary analysis of this information indicates that the central pressure of this cyclone was about 940 hPa and that it was on a SW heading when its centre passed about 15 to 20 km west of the settlement in the early hours of the 26th

The cyclone produced a storm tide 3.2 m above the high water spring tide level.
The actual tide level that night should be able to be computed but at the time of writing, the National Tide Centre has been unable to provide the information. With the astronomic tide known, a check could be made as to the probable track, size and intensity of the cyclone. This should be done as part of a future research project.

It is probable that this cyclone remained very intense, or perhaps even intensified further, and that it passed over or very close to Darwin the next day. The reasons for these assumptions are:

- On 4/12/1839, Commander Wickham and Lieutenant John Lort Stokes returned to the Gulf from an exploring expedition 80 km up the Victoria River in HMS Beagle they were surprised to see a great number of dead turtles on what they duly named 'Turtle Point'. Stokes thought that the turtles must have been *"thrown up by some earthquake wave*" – in fact they would have been there as a result of this cyclone.
- The weather report in Stokes' log, (while he was far upstream in the Victoria River) indicates that the cyclone was in the Joseph Bonaparte Gulf on the 27th . (refer http://www.gutenberg.org/files/12146/12146-h/12146-h.htm#chapter203)

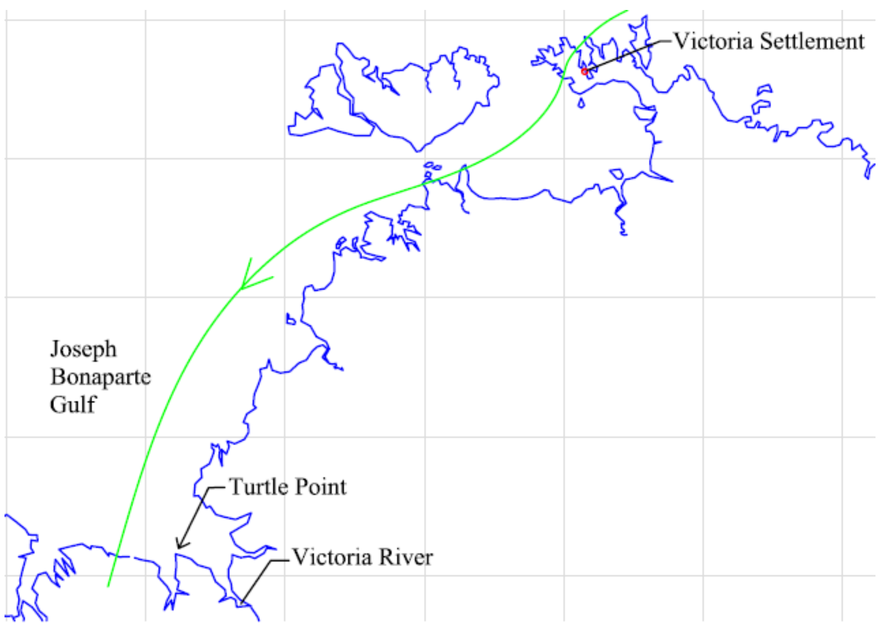


Figure E.2 Probable track for 1839 cyclone

For the purpose of this analysis, the writer assumes that the 1839 cyclone was low-level Category 5 when its centre was 15 km west of the 'single settlement' (Victoria)

07/01/1897

The wind directions and barometric pressure during 'The Great Hurricane' of 1897 were carefully recorded by the Lighthouse Keeper, Hugh Christie at the Charles Point Lighthouse which is 25 km NNW of Darwin and by Post Master, J.A.G. Little in the telegraph office in Darwin (now the site of NT Parliament House). Using their data, the writer's preliminary analysis indicates that this cyclone had a central pressure of between 940 and 950 hPa between 4:00PM and midnight on 6/1/1897. It weakened slightly as it passed about 12 km west of the Charles Point lighthouse. The closest it came to Darwin was about 23 km but at this stage it had been more than one hour overland (tracking towards the site of the present Darwin River Dam) and its central pressure would have risen to 965 hPa or more.

Using the barometric data, the writer estimates the radius of maximum winds (Rmw) was 25 km which is larger than the Rmw for any of the intense cyclones recorded in the Darwin Region during the post-satellite era. Trees along the coast were reported as being either uprooted or defoliated and stripped of bark for some unknown distance east of Rapid Creek (which is 35 km NE of the cyclone track) and as far as Point Blaze to the SW. (This information was given to Christie by aboriginals who had traveled up the coast – it may have been an exaggeration because Point Blaze is 65 km to the SW of the cyclone track.) Postmaster Little reported that "*the timber inland along the railway line has been leveled for a distance of about 50 miles*". This should have been an accurate estimate because there were mile posts every mile down the railway track. The 50 mile post on the railway line was 54 km SSE of the Darwin CBD, 14 km north of Batchelor and was 70 km inland from the cyclone's point of landfall.)

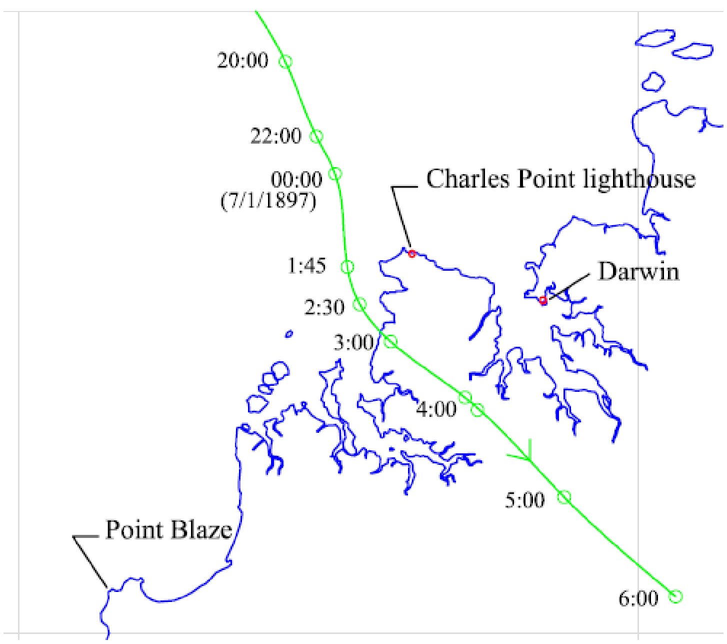


Fig E.3 Track of 1897 Cyclone as indicated by barometric data.

For the purpose of this analysis, the writer assumes that the 1897 cyclone was high- level Category 4 when its centre was 45 km to the north-west of the 'single settlement' (Darwin CBD).

23/12/1915

This cyclone started in the Joseph Bonaparte Gulf, passed to the north of Darwin and then headed back inland.

The centre would have passed less than 20 km to the north of the Charles Point lighthouse. Lighthouse keeper Hugh Christie recorded a pressure reading of 977 hPa. He reported that the lighthouse station buildings had little damage but the trees at Charles Point were either uprooted or left as bare poles. Aboriginals told Christie that the islands shown on Fig. E.4 suffered similar devastation.

The lowest reading in Darwin was 991 hPa. Darwin escaped major damage although several boats were sunk or damaged and part of the jetty was washed away. The decaying cyclone caused heavy rain and flooding inland. The next day, Brocks Creek recorded 364 mm and Bonbrook Station near Pine Creek reported 265 mm. The rain produced the biggest flood ever seen on the Fergusson River and the railway line was washed away in several places between Darwin and Pine Creek.

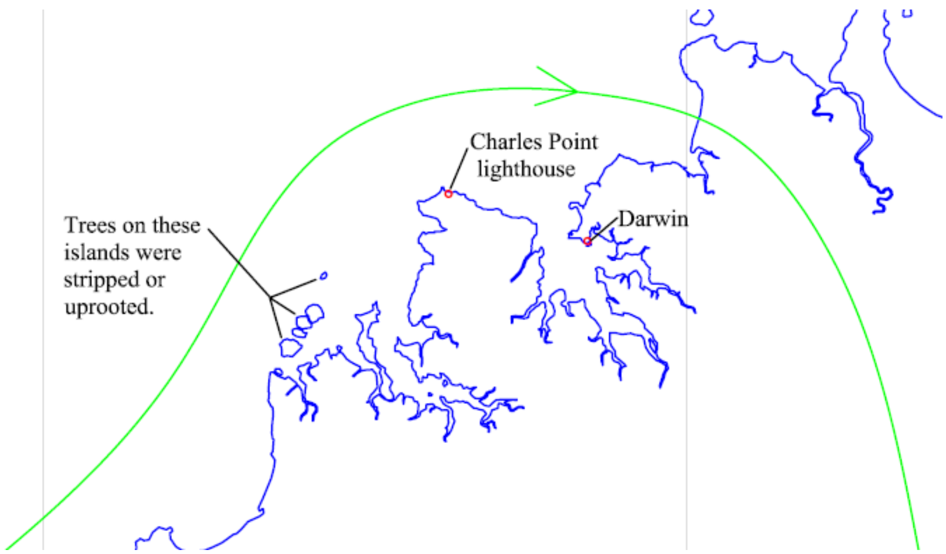


Figure E.4. Estimated track of 1915 cyclone

For the purpose of this analysis, the writer assumes that the 1915 cyclone was high- level Category 4 when its centre was 25 km to the north of the 'single settlement' (Darwin CBD).

06/03/1919

This was probably a Category 5 cyclone while it was passing 45 km to the north of Darwin. The cyclone started near Wyndham in the Joseph Bonaparte Gulf on 3rd March, looped around the Top End coastline and finished heading towards Queensland along the bottom of the Gulf of Carpentaria on about 14th March.

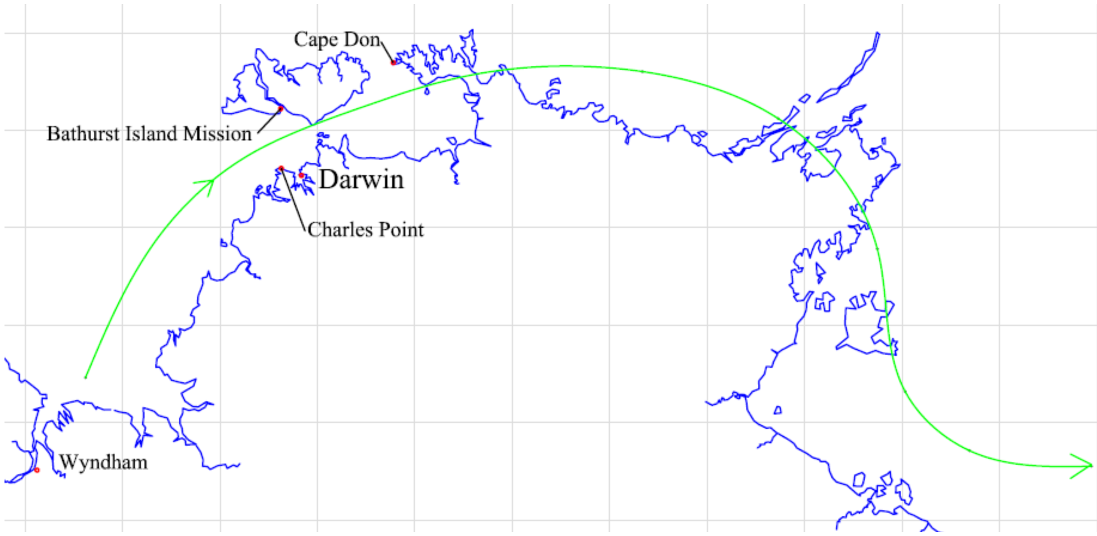


Figure E.5 Track of 1919 cyclone.

During the night of the 5th, the cyclone centre passed about 30 km north of the Point Charles lighthouse. Apparently the new lighthouse keeper did not record the barometric pressure but he did report that the wind tore the roof off the blacksmiths shop and the ridge capping from the oil store and that heavy seas eroded the cliff. It is significant that the 1915 cyclone which probably tracked a lot closer to the lighthouse did not cause this level of damage to the buildings.

The cyclone centre passed about 30 km south of the Bathurst Island Mission (now Nguiu). Father Gsell described the damage as "*a clean sweep*". The peak winds occurred at 5 AM when "*the elements seemed even more frenzied as more trees and huts fell. Finally a tidal wave came rushing in and carried away the lot."* (Gsell, 1956).

Br. Pye heard reports that indicated to him "*that the tidal wave came inland about a quarter of a mile and was about five feet in depth*." The topography does not allow a height estimate from that description but he also said that one of the sisters who was there said that the water was "*Altar high and came through the church near the beach*." (Pye, 1977). From photographs, the writer infers that the original church was on or very near the site of the existing Catholic Church of present-day Nguiu. The ground level at the church is about 5.9 m **Australian Height Datum** (**AHD**) and so 'altar high' would have been about 7.2 m AHD.

A senior aboriginal who was there said that when morning came there was water all over and nothing standing (Pye, 1977). This indicates that the surge came in before first light so the latest time for the storm tide peak would have been about 6 AM.

The latest government report on surge risk in the Darwin region (SEA, 2006) lists the **Highest Astronomic Tide** (**HAT**) as 3.7 m AHD at Nguiu compared to 4.0 m AHD at Darwin. From anecdotal evidence, the tide changes occur three quarters to one hour before Darwin. According to a table supplied by the National Tide Centre (**NTC**), the tide at 7:00 AM on the 6th March 1919 in Darwin was 6.27 m. A 6.27 m tide is equal to 2.27 m AHD in Darwin.
This should produce a tide level = 2.27 x 3.7 ⁄ 4.0 = 2.1 m AHD in Nguiu, indicating that the surge + setup + runup was 7.2 – 2.1 = 5.1 m. (It is noted that the above-mentioned report gives the ARI = 10,000 yr storm tide level at Nguiu as 5.7 m AHD. This is 1.5 m less than the 7.2 m AHD inundation level observed in 1919)

Hugh Christie was now the lighthouse keeper at the new, 35 m high, reinforced concrete lighthouse at Cape Don. He recorded that the structure swayed alarmingly, thousands of trees were uprooted or denuded of leaves and the minimum pressure was 986 hPa at 3 PM on the 6th.

Winds in Darwin were gale force or stronger for about 30 hours and the minimum pressure recorded was 992 hPa.. Only superficial damage was done to the Darwin township but there was extensive damage to ships in the harbour. Two pearling luggers were sunk, the mission lugger St Francis was washed onto rocks and several smaller boats were lost. A good deal of erosion occurred around the foreshore and about 15 m of the stone approaches to the government jetty were washed away.

Of particular interest is the report that "*The old coal hulk 'Warrego' though beached with 600 tons of coal inside her was shifted 30 or 40 feet by the force of the gale"* (NT News & Gazette, 8th March 1919).

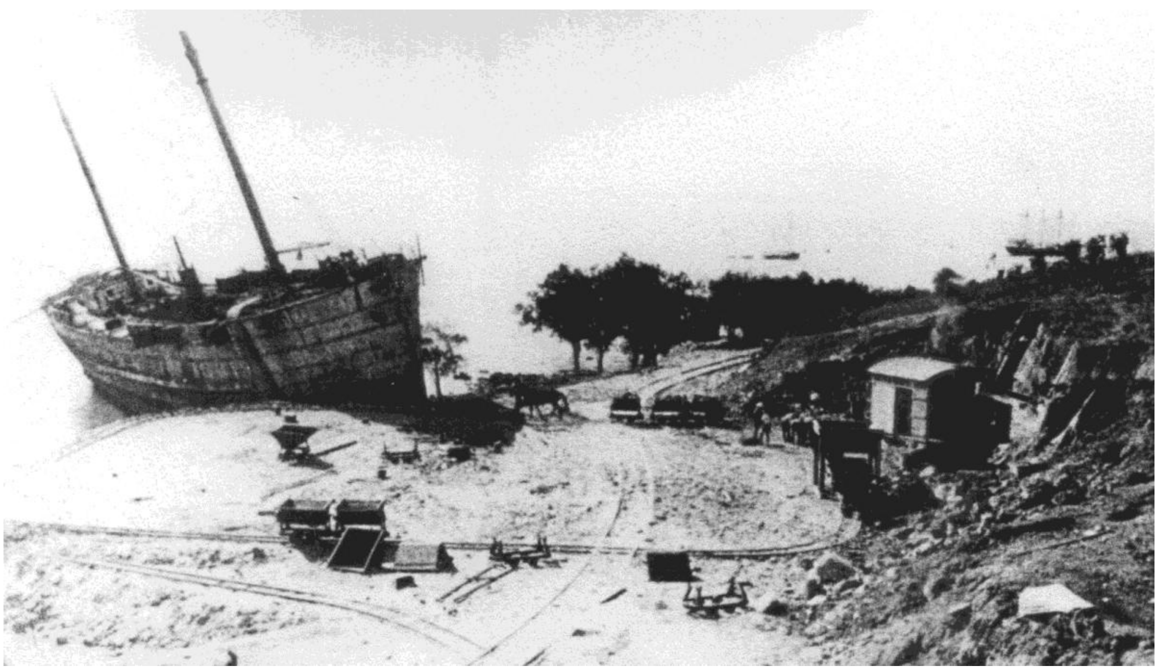


Figure E.6 The Warrego in her position in Frances Bay after the 1919 cyclone.
Photograph date c. 1926. Construction just starting on Navy Fuel Installation tank No.3.
(Photo 238/1525 from the MAGNT collection.)

From the above photograph and several others taken from different angles, it would appear that the mean water level would have had to have reached about 1.5 m above HAT to have lifted the loaded Warrego into its position. From the newspaper description, it seems that the vessel was already beached – presumably at a level where she could be re-floated at a high spring tide. According to NTC data, the normal high tide that morning was 7.4 m which is about 0.5 m less than a high spring tide. These figures indicate that surge + setup in Frances Bay would have been at least (1.5 + 0.5) = 2 m and the storm tide level was about (4.0 + 1.5) = **5.5 m AHD**.

The Warrego is still there - buried beneath fill in front of the Navy's No.3 Oil Tank This 76 m long, steel hulled steamer was built in Sunderland in 1883. Her hull was a landmark in Darwin for nearly five decades before being completely buried under earth fill in 1960. The stern of the hull is intact and hopefully it will one day be uncovered to form part of a display detailing the history of the ship and its location. In the meantime, digging a test hole at the bow would allow accurate measurement of its uplift in1919 which would then enable calculation of the 1919 storm tide.

A more disturbing account of the height of the surge was handed down to Jack Haritos and his brothers by their father, Eustratios (George) Haritos who came to Darwin in 1915. Jack recalls his father saying that during the cyclone that washed up the Warrego, the jetty went under several meters of water and "*Darwin became an island*" for an hour or so when Ludmilla Ck and Sadgroves Ck joined up at the Narrows (Jack Haritos, pers. comm.).

The writer has checked the newspapers of the day and there is no mention of the two creeks meeting - but the Narrows was so far out of town in those days, very few people would have noticed or cared about the event. George Haritos was a well read, intelligent and serious man who would not have made up the story. At the time he operated a salt works on the tidal flats beside Ludmilla Creek and presumably he saw the debris lines or the event itself or was told of it by someone who did.

The natural surface level along the toe of the embankment at the old railway bridge at the Narrows is at **8.5 m AHD**. For Darwin to have 'become an island', sea water at that point would have had to reach about that level. It is noted that 8.5 m AHD is 3 m higher than the level given above for the Warrego but the following paragraph provides an explanation for this.

According to the latest government report on surge risk in Darwin harbour (SEA, 2006), for an ARI = 10,000 years, surge + setup at Frances Bay is at 5.5 m AHD whereas the inundation at the narrows for the same ARI is 6.6 m AHD. But further to this, the levels in the SEA report do not allow for the effects of wave runup, rainfall creek flooding or local bathymetry scaled less than the 560 m grid of the model. These effects could possibly increase the SEA report's 6.6 m AHD level to 8.5 m AHD, thus making the Haritos account feasible.

The storm tide levels produced by the 1919 cyclone at Nguiu and Darwin should be investigated further to enable greater confidence to be placed in the risk predictions for storm tide inundation levels at those places. A few test holes, a scientist able to identify a layer having high salinity or containing small marine shells, foraminifera, etc and some carbon dating may well validate the Haritos account.

For the purpose of this analysis, the writer assumes that the 1919 cyclone was low-level Category 5 when its centre passed 45 km to the north of Darwin.

11/03/1937

This cyclone's track, intensity and associated storm surge are examined in detail in Appendix F of this report.

The cyclone caused extensive damage to Darwin after it made landfall in Bynoe Harbour in the early hours of the 11th March. The maximum gust speed recorded on a Dines anemometer at the Parap Aerodrome was only 160 kph but the writer estimates that maximum gusts in the belt of maximum winds were 250 kph.

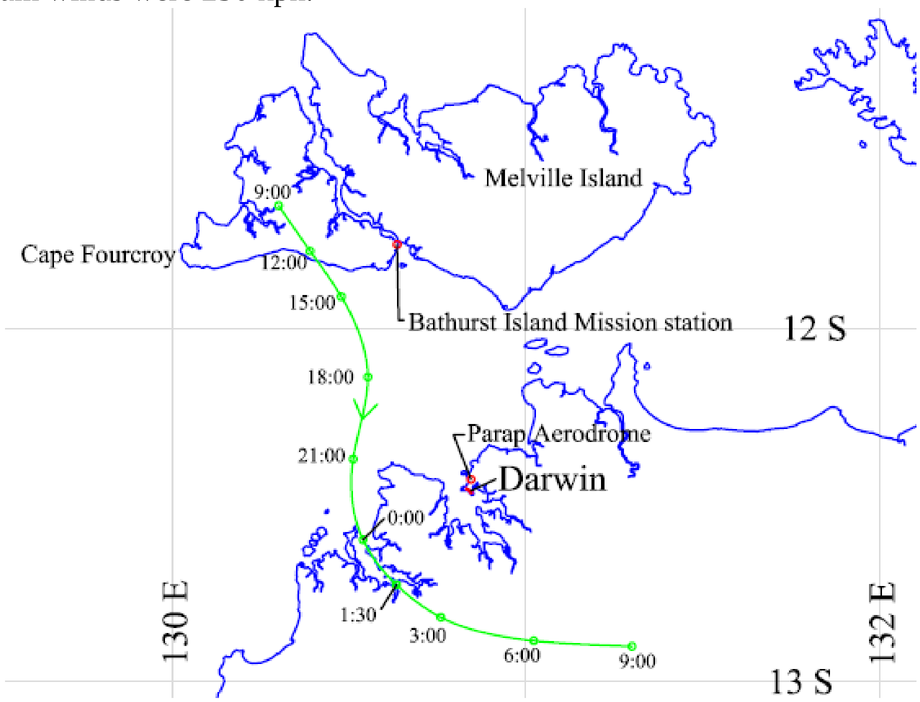


Figure E.7 Track of 1937 cyclone between 9AM on the 10th and 9AM on the 11th March as indicated by anecdotal records and wind-pressure data.

For the purpose of this analysis, the writer assumes that the 1937 cyclone was a mid-level Category 4 cyclone when its centre passed 38 km to the west of Darwin.

25/12/1974

Cyclone Tracy's track as shown below is the first modern track in this series. The meanders are as determined from radar observations. The tracks for the earlier cyclones probably had similar minor deviations or wobbles rather than the smoothed curves drawn.

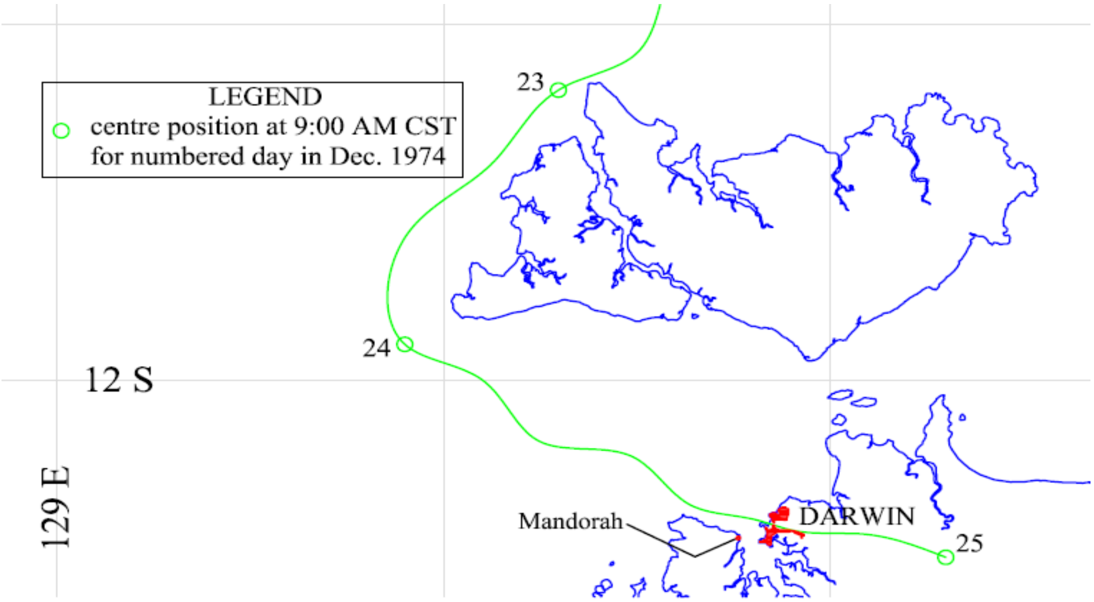


Figure E.8 Track of Cyclone Tracy per the official report (BoM, 1977)

The writer considers that Cyclone Tracy almost certainly produced maximum gusts in the northern suburbs higher than BoM's official estimates of 217 kph to 240 kph. (217 kph was the maximum recorded by the anemometer before its recording system failed.)

Studies by different consultants examining the storm surge produced by the cyclone have found that the winds must have been significantly higher than BoM's values to have produced the 1.55 m surge measured on the automatic tide gauge at Stokes Hill Wharf.

A recent report to BoM to enable better forecasting of storm tides in the NT (SEA, 2005) used the Tracy records to test the accuracy of the computer model. The test proved positive but relied on Tracy being a Category 5 cyclone while it was moving offshore along the Cox Peninsula so that maximum gusts at Mandorah would have been close to 300 kph. Although this appears quite reasonable, the study also found that the 'Holland B' (1) would have had to momentarily risen above its normal maximum value of 2.5 to an extraordinary value of 5.0. The author of the study speculated that this very high value could be explained by the proximity to land causing a rapid collapse of Tracy's 'outer eye' into the 'inner eye' and that *"the storm approached the characteristics of a 'large tornado' shortly before it made landfall at Darwin and then underwent rapid weakening."* (This important matter deserves further study by meteorologists experienced in analyzing cyclones with double eyewalls as they approach land.)

For the purpose of this analysis, the writer assumes that Tracy was a high-level Category 4 cyclone when its centre was 10 km NW of the Darwin CBD.

(1) The 'Holland B' is a measure of the 'peakedness' of the wind field in the Holland pressure wind model. Refer Appendix I for a further discussion on this variable.

Date	Category	Estimated maximum gusts at the Rmw (kph)	Distance of cyclone centre from 'single settlement' (km)
03/04/1827	Mid - Cat. 4	250	50
25/11/1839	Low - Cat. 5	290	15
07/01/1897	High - Cat. 4	270	45
23/12/1915	High - Cat. 4	270	25
06/03/1919	Low - Cat. 5	290	45
11/03/1937	Mid - Cat. 4	250	38
25/12/1974	High -Cat. 4	270	10
	Averages:	**270**	**33**

TABLE E.2 Estimated maximum gust speeds and proximities of the seven intense cyclones that have come within 50 km of Darwin or its proxy 'single settlement'.

It should be noted that the estimated maximum gusts are at the radius of maximum winds – usually the 'settlement' was impacted by lesser winds.

The data is sparse and approximate but nevertheless ball-park figures for wind speed – frequency relationships can be obtained. The analysis will be grossly simplified by considering just average values rather than a range of possible values as is done in computer simulations. Here we assume that all cyclones have:

(i) a radius of maximum winds (Rmw) = 15 km. (The average Rmw for Tracy, Neville, Thelma, Ingrid and Monica when they were most intense was 15.6 km.)

(ii) relatively 'peaked' wind fields (as they tend to be in the NT) so that beyond 19 km from the centre, the maximum gusts drop below the value under consideration

For this exercise, the AEP for maximum gusts greater than 250 kph, 270 kph or 290 kph impacting any one particular building in the 'settlement' will be estimated by assuming:

a) the centre of a cyclone entering the 50 km radius circle can pass that building at any distance between zero and 50 km – there is no preferred distance, all distances having equal probability
b) because of (ii) above, only cyclones with centres coming within 19 km of a building will produce maximum gusts on that building
c) From a) and b), for any one cyclone, the probability of its maximum gusts impacting the building is 19/50
d) Table E.2 provides only rough guidance as to the frequency of intense cyclones coming within a 50 km radius circle drawn around Darwin. Here we will consider the two scenarios given on page E-3, namely:

> **Optimistic Scenario**: The Table E.2 arrivals can be averaged over 158 years;
> **Pessimistic Scenario**: Only the arrival frequency of the first six cyclones in Table E.2 will represent arrivals in the immediate future.

Optimistic Scenario:
The AEPs for gusts of a given speed impacting a single building are approximately**:**

- for gusts > 250 kph, AEP = 7/158 x 19/50 = 1/60
- for gusts > 270 kph, AEP = 5/158 x 19/50 = 1/80
- for gusts > 290 kph, AEP = 2/158 x 19/50 = 1/210

Pessimistic Scenario
The AEPs for gusts of a given speed impacting a single building are approximately**:**

- for gusts > 250 kph, AEP = 6/90 x 19/50 = 1/40.
- for gusts > 270 kph, AEP = 4/90 x 19/50 = 1/60.
- for gusts > 290 kph, AEP = 2/90 x 19/50 = 1/120

The probabilities derived above will be much the same for a small community or suburb but the probabilities of the respective gusts impacting **all** buildings in progressively larger areas become progressively **less** - in effect, the bigger the target, the smaller the chance that the **whole** target area will be impacted by the particular maximum gust speed.

To some this may appear counter-intuitive. The natural assumption is to assume that the bigger the target, the easier it will be to hit and therefore the higher the probability of the hit. But instead of a bullet at a target, imagine shot gun pellets aimed at a flock of birds. For a cyclone to hit **all** of the buildings in a target area is like the shot gun blast hitting **all** of the birds in the flock. The bigger the flock of birds, the more accurate must be the aim and hence the **lower** the probability that all of the birds will be hit.

The effect is illustrated in the figure below. A seven km radius circle will encompass the whole of Darwin including the northern suburbs and extending out to Berrimah (but excluding Palmerston). In Fig E.9, a 7 km radius circle is coloured red and a cyclone's 19 km radius to a given gust speed is coloured green. With a bit of thought, the diagram will show that the probability of a green cyclone tracking within the 50 km radius circle and impacting the **whole** 'target' with its maximum gusts is 12/50 (compared to 19/50 for a single building anywhere within the red circle).

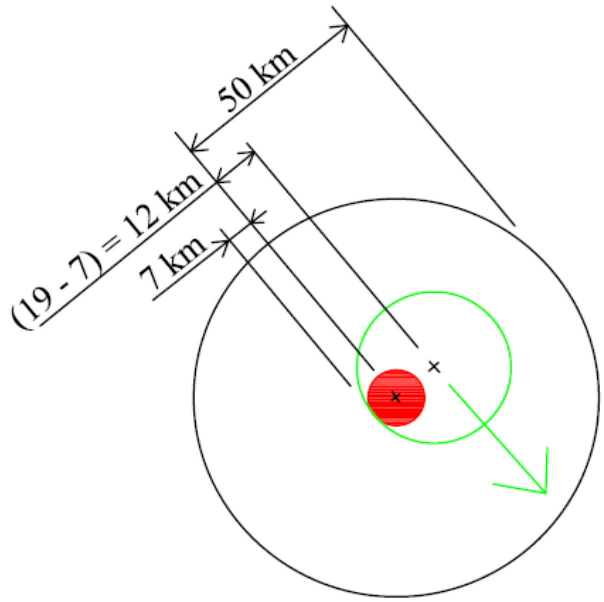


Figure E.9 Diagram showing chance of impact on a target.

Using similar assumptions to those on the previous page for a single building, the AEP for gusts of a given speed impacting the whole of Darwin that can be enclosed within a 7 km radius circle are approximately:

Optimistic Scenario:

The AEPs for gusts of a given speed impacting all buildings in Darwin are approximately**:**

- for gusts > 250 kph, AEP = 7/158 x 12/50 = 1/90.
- for gusts > 270 kph, AEP = 5/158 x 12/50 = 1/130
- for gusts > 290 kph, AEP = 2/158 x 12/50 = 1/330

Pessimistic Scenario

The AEPs for gusts of a given speed impacting all buildings in Darwin are approximately**:**

- for gusts > 250 kph, AEP = 6/90 x 12/50 = 1/60
- for gusts > 270 kph, AEP = 4/90 x 12/50 = 1/90
- for gusts > 290 kph, AEP = 2/90 x 12/50 = 1/190

Emergency managers and re-insurers will concentrate on the above figures but most people will be more interested in the single (their own) building figures on the previous page.

TRACK DIRECTIONS

The direction of a cyclone's track has a critical influence on the height of the generated storm tide. In engineering studies to determine storm surge heights for Darwin harbour, the track direction probabilities have been determined by analyzing the directions taken by all cyclones that have come within a certain radius from Darwin since the late 1950s. (It is only since the satellite era that the records are considered to be sufficiently accurate.) The radius used to select the cyclones of interest has varied between 300 km and 500 km depending on the investigator. It would seem that regardless of the radius chosen, the very much larger datasets indicate that about 75% of cyclones will have tracks bearing between 210° and 270° when closest to Darwin. This is a good thing because for a given cyclone intensity and proximity, these directions will lead to the lowest surge heights in Darwin harbour.

In the following analysis, only cyclones coming within 50 km of Darwin are considered. The reasons for not including the intense cyclones at Fort Dundas and Victoria are:

- It is probable that the Fort Dundas cyclone was heading SW, but as far as the records reveal, it could also have been heading NE

- Track directions when closest to a location may be influenced by the shape of the surrounding coastline. (The writer considers that such a localized effect is less likely to govern intensities within a 50 km radius of a location.)

Date of Cyclone	Track Direction when closest to Darwin
Intense cyclones:	
07/01/1897	135°
22/12/1915	100°
06/03/1919	70°
11/03/1937	150°
25/12/1974	110°
Average:	**113°**
Non-intense cyclones	
16/01/1882	80°
01/04/1917	240°
01/12/1948	225°
11/04/1954	170°
05/12/1971	225°
12/03/1981	250°
13/04/1985	240°
Average:	**204°**

Table E.3 Track directions of intense and non-intense cyclones that have come within 50 km of Darwin.

Table E.3 raises questions about the engineering surge studies because it indicates that historically, the tracks for intense cyclones near Darwin:

- track differently to non-intense ones; and
- tend to approach Darwin in directions that cause the highest surges in the harbour.

It should also be noted that the 1882 cyclone, which is the only non-intense cyclone with a distinctly easterly track, was almost certainly an intense cyclone when it made landfall near the Peron Islands. (The westward tracking cyclones may have also been intense at some stage but would have been weakened by tracking over the Tiwi Islands or the Coburg Peninsula.)

Date of Cyclone	Track Direction when closest to Darwin
pre - 1940 cyclones:	
16/01/1882	80°
07/01/1897	135°
22/12/1915	100°
01/04/1917	240°
06/03/1919	70°
11/03/1937	150°
Average:	**129°**
post - 1940 cyclones	
01/12/1948	225°
11/04/1954	170°
05/12/1971	225°
25/12/1974	110°
12/03/1981	250°
13/04/1985	240°
Average:	**203°**

Table E.4 Track directions of pre-1940 and post-1940 cyclones that have come within 50 km of Darwin.

Taken together, Tables E.3 and E.4 suggest that their may have been something tending to influence both increased intensity and easterly track directions between about 1870 and 1940.

DISCUSSION

The use of a few old records will not of themselves provide clear indications of intensity-frequency relationships nor of the probable track directions but if used in conjunction with the more numerous records from the post- satellite era they can provide vital clues as to variations that may take place on multi-decadal scales.

The utility of using old records has been recognized by the National Oceanic & Atmospheric Administration (NOAA) of the US Dept. of Commerce with their work in updating and extending back in time their HURDAT database. HURDAT is the official record of tropical storms and hurricanes for the Atlantic Ocean, Gulf of Mexico and Caribbean Sea. It is utilized for a wide variety of purposes such as: setting of appropriate building codes for coastal zones, risk assessment for emergency managers, analysis of potential losses for insurance and business interests, intensity forecasting techniques, verification of official and model predictions of track and intensity, seasonal forecasting, and climatic change studies.

The webpage http://www.aoml.noaa.gov/hrd/hurdat/index.html includes the following:

> ***Cycles of hurricane activity****: These records* (HURDAT) *reflect the existence of cycles of hurricane activity, rather than trends toward more frequent or stronger hurricanes. In general, the period of the 1850s to the mid-1860s was quiet, the late 1860s through the 1890s were busy and the first decade of the 1900s were quiet. (There were five hurricane seasons with at least 10 hurricanes per year in the active period of the late 1860s to the 1890s and none in the quiet periods.) Earlier work had linked these cycles of busy and quiet hurricane period in the 20th Century to natural changes in Atlantic Ocean temperatures.*

The above suggests that the observed variation in the frequency of intense cyclones noted on the top of page 3 and allowed for in the pessimistic scenario may have indeed occurred.

Table E.5 gives the pessimistic and optimistic AEPs and compares them with AEP values from the wind code. The current wind code has Darwin in Region C, the table below indicates that it should be in Region D.

Maximum Gust Speed (kph)	Frequency estimates in terms of AEP		
	For a single building, as derived page E12	Using formulae in the Wind Code	
		For Region C	For Region D
> 250	1/40 to 1/60	1/500	1/70
> 270	1/60 to 1/80	1/1,350	1/120
> 290	1/120 to 1/210	1/4,000	1/220

Table E.5 Annual probabilities of various gust speeds impacting a building – as derived in this appendix and from the wind code.

Region D encompasses the coastline from Carnarvon to Port Hedland in Western Australia where design wind loads are about 60% higher than for Region C. Given the magnitude of the difference, the derivation of the ‘single building’ AEPs in the above table clearly requires careful re-examination. Each of the seven historic cyclones deserves re-analysis by a team which should comprise at least one meteorologist and one engineer – each having expertise in the behaviour of intense cyclones and the storm surges they produce.

Track Directions

Even though the dataset is very small, the difference in the track directions between the two sets of cyclones given in Tables E.3 and E.4 would appear to have statistical significance. It would seem that the frequency of intense cyclones and track directions underwent a shift circa.1940.

It is quite possible that the intensity and track direction trends in the early part of the record relate to some inter-decadal variation, similar to those noted in the North Atlantic. Further study is needed to investigate whether any such cycles affect the number of easterly moving and/or eastward re-curving cyclones. Any increase in this number could, by implication from Table E4 lead to a higher frequency of intense cyclones approaching Darwin.

Given that it has such significant impact on the risk predictions for surge levels in Darwin harbour, the track direction issue deserves a serious research commitment from BoM.

REFERENCES

Gsell, F.X. (1956) The Bishop with 150 Wives. *Angus and Robertson.*

Murphy, K. (1984) Big Blow Up North. (A History of Tropical Cyclones in Australia's Northern Territory), *University Planning Authority.*

Pye, J. (1977) The Tiwi Islands. *Kensington, NSW: Brother J.Pye.*

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region.

SEA Pty Ltd. (2006) Darwin Storm Tide Mapping Study 2006. Prepared by Systems Engineering Australia Pty Ltd for the NT Emergency Services.

VIPAC (1994) Tropical Cyclone Storm Surge Risk for the Greater Darwin Region – Final Report. Vipac Report 24113-2 for the NT Department of Lands, Housing and Local Government.

Appendix F

REVIEW OF DARWIN'S 1937 CYCLONE

APPENDIX F REVIEW OF DARWIN'S 1937 CYCLONE

SUMMARY

This appendix investigates the cyclone that passed near Darwin on the 10th and 11th of March 1937.

Anecdotal reports, meteorological records, and a mathematical, wind-pressure model used by engineers have been combined to produce a plausible best track which differs somewhat from the track proposed by the Bureau of Meteorology (BoM).

Estimates made from anecdotal evidence of the storm tide at Fannie Bay produce levels that are significantly higher than the inundation levels indicated by a surge risk report commissioned by the NT government.

This does not purport to be a definitive study but hopefully it will:

- demonstrate how fresh information can be obtained on pre-1960s cyclones; and
- encourage funding for a more extensive investigation of these cyclones and their storm tides.

THE BoM CYCLONE TRACK

The track given in BoM's "new_format" database is plotted below.

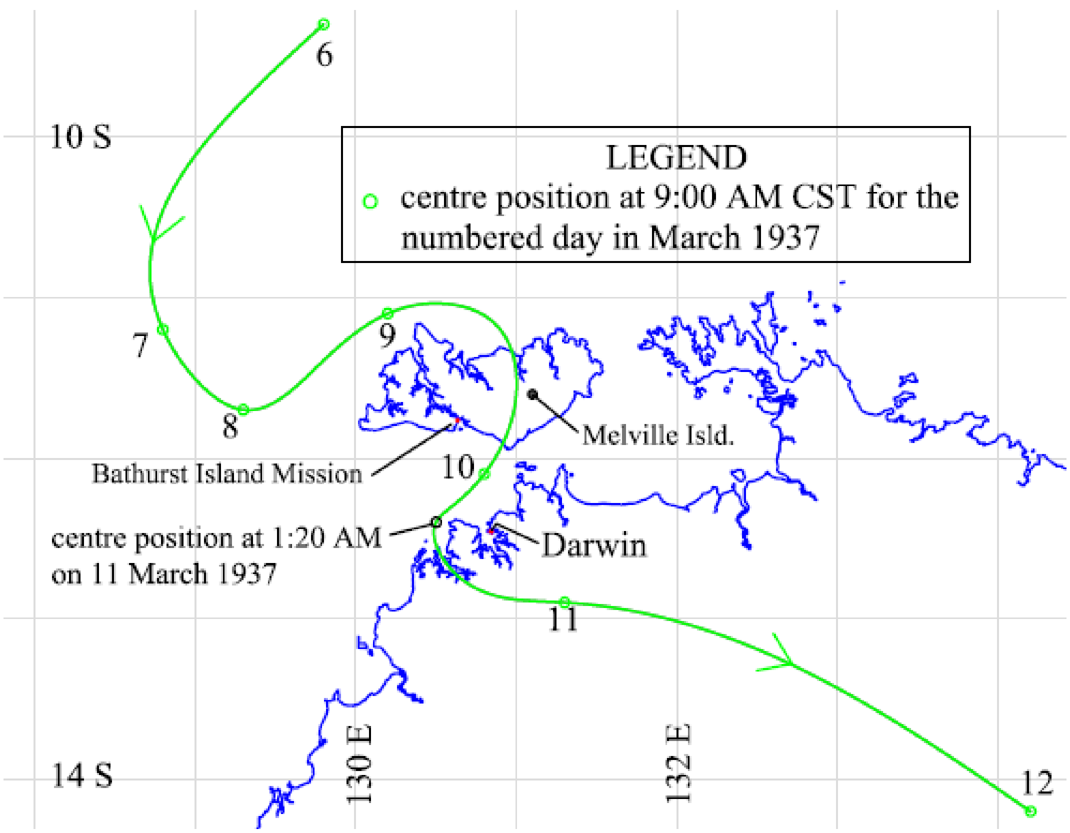


Figure F.1 Track of 1937 Cyclone per the Bureau of Meteorology database

A significant feature of the BoM track is that it has the cyclone passing over the full depth of Melville Island but it was nevertheless able to re- intensify with sufficient speed and to a strength to cause considerable damage in Darwin 18 hours later.

The track may have been the result of a study by Neal and Dexter circa 1976. The track appears in a BoM compendium of tropical cyclone tracks (Lourensz, 1981). BoM are unable to locate the unpublished, Neal and Dexter report (R. Evans, 1999, pers. comm.) but the report's findings are given in a published report on cyclone Tracy (Wilkie and Neal, 1976). These findings were that the 1937 cyclone had a minimum central pressure of 955 hPa, a "maximum wind ring" radius of about 14 km and an approach speed to the coast of about 12 kph.

This appendix proposes that the location and timing of the track in Fig. F.1 is in error. A simple demonstration of this is given by the fact that at 1:20 AM on the 11th, the winds in Darwin were recorded as being from the NW. A cyclone with BoM's 1:20 AM position in Figure F.1 would have produced winds from between NE and NNE.

As shown in the following pages, Darwin obtained good meteorological records of the cyclone's wind and pressures but not so for other locations. By 1937, the Charles Point lighthouse was an un-manned, automatic lighthouse and so, unlike in 1897 and 1915, there were no pressure readings or wind direction data obtained there.

A search of the archived weather reports at the Bathurst Island Mission revealed no data on the wind strength or wind directions for the cyclone. However, Sister Eucharia who was there in 1937 gave an account which is very significant, namely: "*although the cyclone was not in the same class as Tracy, it was quite formidable, uprooting trees and blowing buildings over. One thing she remembered well was that the mission's lugger, the St Francis, broke its moorings and was being blown out to sea and the local Tiwi chased it in canoes and brought it back by sail."* (Pye, 1977). A glance at the map will indicate that the lugger could only be blown out to sea by a cyclone passing to the west of the Bathurst Island Mission.

Other indications that the cyclone tracked to west of the mission station are:

- When interviewed in 1984, residents who could remember the 1937 cyclone said there was little change in the wind direction and that the strongest winds were from the north. (Kevin Murphy, pers. comm.)

- On page 90 of "Big Blow Up North", the cyclone has been plotted tracking west of Cape Fourcroy. (Murphy, 1984) [Note: The writer considers this to be too far west because it would not have produced even gale force winds at Bathurst Island Mission and the inflow angle at Parap (refer Table F.1) would become an improbable 75°]

- The Northern Standard of Friday, 12th March 1937 reported:
"*the barometer commenced to fall early on Wednesday afternoon and it was reported that a cyclonic disturbance with its centre north of Bathurst Island was traveling in a south-westerly direction.*" (At that time, the BoM track has the cyclone only 35 km north of Darwin.)

- The Northern Standard of 19th March 1937 reported: *" Brother Smith states that very little damage was done to the* (Bathurst Island Mission) *station buildings but numerous trees, including many of the large shady mango trees, have been destroyed. Messrs. Frank Kurger and W. Harney, who have been at Point Fourcroy............... report that the blow made a clean sweep at the point.* (The W. Harney is probably the famous bush poet, buffalo hunter, patrol officer and story teller.)

A REVISED ESTIMATE OF TRACK AND INTENSITY

A fully equipped weather service office had been set up at the Parap aerodrome to service the 1934 London to Melbourne air race. When the 1937 cyclone came along, this office was able to obtain a barograph of the pressures from an aneroid barometer and an anemogram of wind speeds and directions from a Dines anemometer. These records, coupled with the mercury barometer readings taken at both the post office and the aerodrome, mean that there are very good quality records of the effects of this cyclone at Darwin. The records are in the National Archives, Darwin, Series E490/2. An attachment on pages F-11 & F-12 details how the records have been interpreted.

A wind-pressure model (Holland, 1980) was used to produce a good fit with the recorded properties of the 1937 cyclone when it was close to Darwin. The data used and obtained is given in Tables F.1 and F.2 on the following page. The writer's "best track" from that data is plotted below:

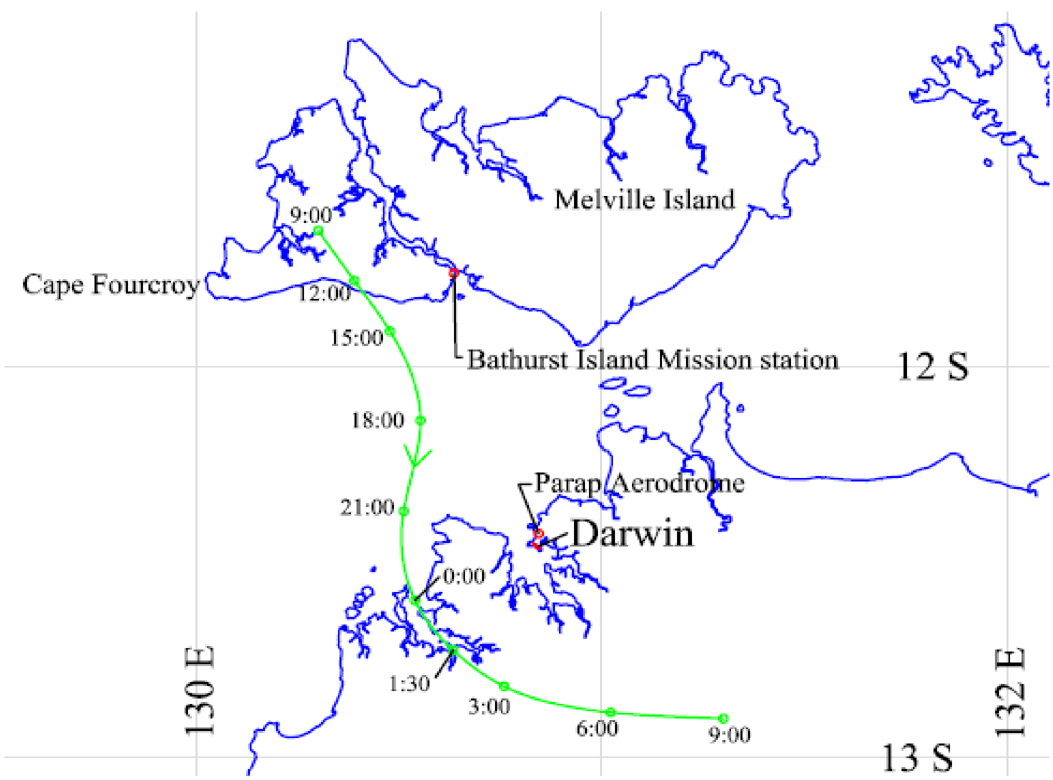


Figure F.2 Revised track, 1937 cyclone from 9AM on 10th to 9AM on 11th of March. Derived from the recorded, pressure-wind data as detailed in Tables F.1 and F.2 following.

date and time		Station records			estimated centre location, resulting Vfm and β				
Date (1937)	time CST	p(s) (hPa)	V(s) (kph)	Wind directn (deg.)	latitude (dec deg)	longitude (dec deg)	Vfm (kph)	Inflow, off Land off Sea	β (deg)
		(1)	(2)				(3)		(4)
10 Mar.	9:00	**997**	**72**	110	-11.65	130.30	N/A	L	55
	12:00	**996**	**72**	110	-11.78	130.39	5.8	L	55
	15:00	**994**	**58**	110	-11.91	130.48	5.8	L	55
	18:00	**991**	**94**	90	-12.14	130.55	8.8	L	45
	21:00	**991**	**122**	45	-12.37	130.51	8.5	L	35
11 Mar.	0:00	**988**	**166**	338	-12.60	130.54	8.4	S	7
	1:30	**981**	**180**	330	-12.73	130.63	11.7	S	25
	3:00	**983**	**148**	300	-12.82	130.76	11.4	S	18
	6:00	**986**	**108**	270	-12.88	131.02	9.9	S	21
	9:00	**992**	**90**	250	-12.90	131.30	10.2	L & S	24

Table F.1 Station records and estimated values for location of track centre, forward speed (Vfm) and inflow angle (β)

date and time		Holland model							Converting station gradient speed to surface gusts		
		Inputs (5)					Outputs				
Date (1937)	time CST	pn (hPa)	pc (hPa)	B	Rmw (km)	r (km)	p(r) (hPa)	Vg(r) (kph)	r/R	GCF	V(r) (kph)
		(6)	(7)	(8)	(9)	(10)	(11)	(12)		(13)	(14)
10 Mar.	9:00	1004	970	1.20	30	104	**997**	85	3.5	0.8	**68**
	12:00	1003	967	1.20	24	87	**996**	87	3.6	0.8	**70**
	15:00	1000	961	1.30	18	70	**994**	87	3.9	0.7	**61**
	18:00	1000	955	1.50	16	45	**991**	112	2.8	0.8	**90**
	21:00	1002	949	1.75	16	37	**991**	136	2.3	0.9	**122**
11 Mar.	0:00	1002	**944**	***2.05***	20	38	**988**	164	1.9	1.0	**164**
	1:30	1002	954	1.70	29	40	**981**	170	1.4	1.06	**180**
	3:00	1002	956	1.70	30	44	**984**	164	1.5	0.88	**144**
	6:00	1002	961	1.70	35	54	**986**	150	1.5	0.72	**108**
	9:00	1004	966	1.60	40	72	**992**	131	1.8	0.7	**92**

Table F.2 Data for modelled values of station pressure, p(r) and gust speeds V(r)

Notes for the bracketed numbers in Tables F.1 and F.2

(1) p(s) = pressures are from the barograph and mercury barometer at the Parap aerodrome and from the Darwin Post Office mercury barometer, all appropriately corrected to MSL. The data requires interpretation – refer attachment, pages F-11,12

(2) V(s) = gust speeds using values from the anemogram are divided by appropriate terrain category factors to bring to standard terrain category 2 conditions – refer F-11

(3) Vfm = forward track speed, measured as the average speed from the previous point

(4) β= the inflow angle at station = [wind direction - (bearing to centre + 90°)]

Notes for the bracketed numbers in Tables F.1 and F.2 (contd.)

(5) Inputs are obtained by trial and error balancing of reasonable trends in values to produce outputs that are in closest possible agreement with the recorded values

(6) p_n = ambient pressure (most distant closed isobar at 9AM, 10th and 11th =1004 hPa. Other times reflect Darwin's mean diurnal QNH variation. (Todd Smith, pers. comm.)

(7) p_c = assumed central pressure

(8) B = assumed Holland constant

(9) R_{mw} = assumed radius of maximum winds

(10) r = distance between the estimated track centre and the Parap aerodrome

(11) $p_{(r)}$ = modelled station pressure values (they are within 1 hPa of Table F.1 values)

(12) $V_g(r)$ = modelled gradient wind speed. (= mean wind speed at about 3 km height.)

(13) GCF = Gust Conversion Factor. This factor converts gradient wind speeds to gust speeds at 10 m height. The values are approximately those in Table 3.2.1 of a report to the NT government concerning extreme wind speeds in Darwin (Georgiou, 2000)

(14) V(r) = modelled station maximum gusts (they are within 4 kph of Table F.1 values)

Comments on the analysis for the revised track

1) The revised track presented in Fig. F.2 simulates the recorded pressures and gusts speeds at Parap using the Holland wind-pressure model (Holland, 1980). Different assumptions for the values of p_c and/or Rmw and/or B and/or the GCF would lead to different tracks. The only merit in the track presented here is that the values chosen for the above variables would seem to be within reasonable limits.
2) For the track presented here, the maximum pressure drop occurs at 0:00 on the 11th and equals 1002 – 944 = 58 hPa. This pressure drop is intermediate to the values given for Dvorak CI = 5.5 and 6.0 in the Northern Region pressure – wind relationship. For CI intermediate to 5.5 and 6.0, maximum gust speed is 248 kph.
3) The value for the Holland B of 2.05 at 0:00 was chosen so that the maximum gust speed at the Rmw would be close to the Dvorak value and at the same time have the model reproduce the 988 hPa pressure and 166 kph gust speed at Parap.
4) The final figures are critically dependant on the value chosen for the GCF. For the system at 0:00, the GCF at Parap was assumed to be 1.0. (Note; for GCF = 1.13 at the Rmw, the **maximum gust speed** at the Rmw becomes 1.13 x 221 = **250 kph.)**
5) The values of p_c, B and Rmw were carefully chosen to simulate the cyclone intensifying after crossing Bathurst Island. The 23 hPa deepening over the 12 hours between midday and midnight on the 10^{th} as the cyclone crossed the Beagle Gulf may be regarded as too high by some but it is nowhere near the world record value of 83 hPa in 12 hour produced by Hurricane Wilma over the Caribbean in October 2005 -refer http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf
   The values for Rmw when the cyclone was intensifying are close to the observed mean value of 15 km for intense cyclones in the Darwin region.
6) Normally the inflow angle, β, varies between about 20° for wind coming off the sea to about 45° for wind traveling overland. The large β values at 9:00, 12:00 and 15:00 hours on the 10^{th} may have been due to the presence of a monsoon convergence line lying between Darwin and the cyclone centre. The very low β value at 0:00 on the 11^{th} could be due to land friction effects causing asymmetries in the rotation at landfall. A study by meteorologists using the synoptic charts and new understanding of cyclone behaviour during landfall would throw light on these speculations.

WAVE HEIGHTS

On page 37 of "Big Blow Up North" it is stated:

> *"During the height of the cyclone huge seas were running in the harbour. Waves were crashing over the cliffs at Myilly Point and Fannie Bay."*

Cliff heights at Myilly Point are fairly uniformly at 16 m AHD so it should be made clear that it would not have been the wave tops breaking over the cliffs but rather that copious amounts of water were being blown inland from the cliffs from the spray thrown up by impact at the base of the cliffs. (Murphy, pers. comm.)

In Douglas Lockwood's "The Front Door" there is a quote from Walter Dwyer who was in charge of the BoM Weather Office at the time. He is quoted as saying that in his house at Fannie Bay, *"The floors were awash with sea spray, the seas below the cliffs were roaring….."* If the wave tops were going over the cliffs, Dwyer would have said more about the waves than just that they were roaring.

However it is clear that there were very large waves in the harbour. The seas in the BoM weather report were described as "phenomenal". The newspaper reported that the sea spray swept right across the Darwin peninsula to Francis Bay and that the salt water blackened all of the vegetation in Darwin.

OBSERVED STORM TIDE

On page 37 of "Big Blow Up North" it is stated:

> *"Eyewitnesses claimed that the sea inundated the road to East Point and also the golf-course."*

The notes to this sentence state:

> *"This information was passed on by the late Capt. Tom Milner, for many years chairman of N.T. Port Authority who spoke to several survivors of the cyclone."*

The inundation of the golf course is not really significant. The golf course referred to has since been converted to Lake Alexander. The course was on what was originally a back-beach swamp and had some areas below Highest Astronomic Tide (HAT). Sea levels higher than 4.1 m AHD can enter this low area from the Ludmilla Creek side of the peninsula across a low section on Colivas Road and it was probably here that most of the water entered to flood the golf course.

However the inundation of the "road to East Point" is significant because the road levels are somewhat higher than Colivas Road. Determining these levels should allow an estimate to be made of the height of the 1937 storm tide.

Unfortunately we do not know exactly where the inundation took place. If we use existing road levels as a guide, then the two obvious locations are as indicated on the Google Earth image next page.

Figure F.3 Google Earth image showing location of two low areas in the "road to East Point".

Low area #1 is a short section of Alec Fong Lim drive just inside the park entrance. The original road would have been built to a reasonable standard in 1933 when the gun emplacements at East Point were constructed. A 1945 aerial photograph shows a kink in the alignment of the road which matches the kink in the existing road at this point. Judging from the natural surface levels on the beach side of the road, the existing road follows the contours of that original road but would be slightly higher due to addition of a base-course and asphalt. At its lowest point, the existing road is at 5.2 m AHD. There is a length of about 60 meters where the road level is less than 5.5 AHD.

Fig F.4 Looking north showing how the road at low area #1 is only 1.2 m above the HAT level of 4.0 m AHD.

Low area #2 is in East Point Road at its junction with Lampe Street. The area would be more accurately described as being on the "road to Fannie Bay" but it needs to be considered because the existing road level is lower here than at area #1. A 1987 orthophoto indicates that the road level was about 4.9 m AHD opposite Lampe Street rising to about 5.5m AHD at the junction with Gregory Street. The road is probably still at that these same levels.

The road at low area #2 is about 200 m from the beach. In 1937 the dune top along this section of beach would have been at least to 6.0 m AHD. (The dunes that were once on the sites of the Sailing Club and the Trailer Boat Club were presumably leveled out to provide pads for those facilities.) Consequently, it is clear that the sea water that inundated low area #2 would have come via the tidal creek and swamp to the south.

The time that the maximum storm tide occurred is unknown (the tide gauge at Stokes Hill wharf was not installed until 1957) but judging from the timing of the cyclone, it probably occurred at night and what the eyewitness saw were debris lines the next morning. Furthermore, the depth of flow across the road is unknown but it would have to have been at least 0.1 m to have left any appreciable lines of debris.

For the following calculations, it will be assumed that the 1937 inundation level on the "road to East Point" was 5.0 m AHD.

The most recent report to the NT Government on storm tide inundation levels in the Darwin region (SEA, 2006) includes three maps giving inundation levels for AEPs of 1/500, 1/1,000 and 1/10,000. The SEA map for AEP = 1/500 has the inundation level at:

- low area #1 = 5.1 m
- low area #2 = 4.9 m.

CALCULATION OF THE THEORETICAL STORM TIDE

The SEA report does not enable direct calculation of a storm surge from best track data. Therefore, the following calculations will be derived from:

- An earlier report to the NT government to estimate the storm surge (VIPAC, 1994);
- charts from the National Tide Centre to determine the concurrent, astronomic tide.

The charts in Appendix B of the VIPAC report are for cyclones having central pressure, Pc = 890 hPa and ambient pressure, Pn = 1010 hPa, on five different storm directions (θ), at five different minimum approach distances to Darwin (Dmin) and having three different translation speeds (V_T). All cyclones in the study had Rmw = 15 km. Although the charts refer only to "storm surge" they include an allowance for wave set-up but not for the more localized effect of wave run-up.

The "storm directions" in the VIPAC report are similar to the wind directions in Table F.1 in that they refer to the direction from which the storm or wind came. (The term "track direction" used elsewhere in this report equates to the heading of the moving cyclone. A VIPAC "storm direction" of 320° is equivalent to a "track direction" of 140°.)

Calculations:

- The chart from the VIPAC report used to derive a figure for the 1937 storm surge (S) is one of Chart 13 series for Fannie Bay.
- The modelled track in Fig. F.2 above is assumed equivalent to the straight line track in Chart 13 having wind coming from bearing (θ) = 320° and the distance left of target (Dmin) = 30 km.
- Between 18:00 on the 10th and 03:00 on the 11th, Table F.2 gives the average value for Vfm = 10 Kph. This is equivalent to VIPAC's V_T = 2.8 m/s
- For V_T = 2 m/s, the chart gives S = 4.0 m. For V_T = 5 m/s, the chart gives S = 5.8 m. Interpolating for V_T = 2.8 m/s gives S = 4.0 + 0.8 ⁄ 3.0 x (5.8 – 4.0) = 4.5 m.
- The preceding value is for Δp = 1010 – 890 = 120 hPa
- Between 18:00 on the 10th and 03:00 on the 11th, Table F.2 gives the average Δp for the 1937 cyclone as 50 hPa.
- Assuming S varies linearly with Δp, then for Δp = 50 hPa:

  S = 50/120 x 4.5 = 1.9 m
- Using NTC figures, the high astronomic tides during the period of interest were:

  17:24 on the 10th: = (6.245 – 4.024) = 2.22 m AHD at Darwin
  = 0.95 x 2.22 = 2.1 m AHD at Fannie Bay.
  05:06 on the 11th = (5.871 – 4.024) = 1.85 m AHD at Darwin
  = 0.95 x 1.85 = 1.75 m AHD at Fannie Bay.

The modelled track in Fig. F.2 indicates that the surge could not have peaked as early as 17:24 on the 10th and nor could it have peaked as late as 05:06 on the 11th. For this calculation it will be assumed that the surge was sustained by the eastward curve of the track until about 4:15 AM on the 11th when the astronomic tide at Fannie Bay was approximately 1.6 m AHD.

Therefore: Theoretical Storm Tide = storm surge + astronomic tide
= 1.9 + 1.6 = 3.5 m AHD.

This is (5.0 – 3.5) = 1.5 m less than the assumed minimum inundation level.

Comments on the analysis of the storm tide

The significant difference between the storm tide inferred from the eyewitness account and the value calculated using the VIPAC report could be due to one or more of the following:

1. The cyclone was more intense or was on a significantly different track
2. The straight line, θ = 320°, and Dmin = 30 km track produces a smaller value of the storm surge than would the curved, modelled track
3. The VIPAC report under-estimates surge + wave set-up at Fannie Bay
4. The shortfall is made up by wave run-up which was 1.5 m or more at the low areas.
5. The road levels in 1937 were much less than assumed so the inundation level was much less than 5.0 m AHD

The scale of the discrepancy demands further investigation. Initial steps should be:

- Use BoM's Storm Tide Prediction System to check on reasons 2) and 3)
- Investigate if Capt. Tom Milner left papers that better describe the location of the inundation. (The 1937 cyclone is not listed in Milner's archived, Port Authority papers.)
- Make a request to members of the public who may have information or memories regarding the inundation of the "road to East Point"
- Dig three or four test holes to establish the 1937 road levels at the two low areas

REFERENCES

Georgiou, P. (2000) Darwin Region, Category 5 Cyclone Risk Assessment. A report to the NT Department of Transport and Works.

Holland, G.J. (1980) An Analytic Model of the Wind and Pressure Profiles in Hurricanes. *Monthly Weather Review*. **108,** 1212-1218.

Lourenz, R.S. (1981) Tropical Cyclones in the Australian Region July 1909 to June 1980. *Australian Government Publishing Service.*

Murphy, K. (1984) Big Blow Up North. (A History of Tropical Cyclones in Australia's Northern Territory), *University Planning Authority*.

Pye, J. (1977) The Tiwi Islands. *Kensington, NSW: Brother J.Pye.*

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region.

SEA Pty Ltd. (2006) Darwin Storm Tide Mapping Study 2006. Prepared by Systems Engineering Australia Pty Ltd for the NT Emergency Services.

VIPAC (1994) Tropical Cyclone Storm Surge Risk for the Greater Darwin Region – Final Report. Vipac Report 24113-2 for the NT Department of Lands, Housing and Local Government.

Wilkie, W.R. and A.B. Neal. (1976) Meteorological Features of Cyclone Tracy. Natural Hazards in Australia Conference. *Australian Academy of Science.*

ATTACHMENT Interpretation of the wind and pressure records (in National Archives, Darwin, Series E490/2).

The Dines anemometer was probably located near the Weather Office at the Parap Aerodrome. This office is believed to have been housed in a long narrow building (shown in a 1945 aerial photograph) which was on the eastern side of what is now the Old Qantas Hangar in MacDonald Street, Parap. (Bob Alford, pers. comm.)

Judging from a 1945 aerial photograph, clearing surrounding the airstrip was fairly minimal. Consequently, the winds recorded by the anemometer need to be corrected for the upwind terrain by dividing them by a "terrain category factor". This converts the speeds to standardized (terrain category 2) values as would be obtained at a large airfield in open terrain. It is assumed the anemometer was mounted at the standard 10 m height.

Until about 2:00 AM on the 11th the upwind terrain would have been category 3 and the terrain category factor is 0.89 - refer Table 4.1 (B) of wind code (AS/NZS 1170.2:2002).
After 2:00 AM on the 11th, the upwind terrain was about 700 m of sparse urban development to the coast. The wind code gives the terrain category factor for this intermediate situation as (0.7 x 0.89 + 0.3) = 0.92. The gust speeds $V_{(s)}$ in Table F.1 were derived accordingly.

Barometers:
Aneroid barograph:
A note on the barograph says "put on at 9:30" but the start point plots at about 10:30. Consequently, 1 hour was deducted from the barograph times.
The minimum barograph record was 29.04 inches at 1:25 AM on 11/3/1937. = 983.4 hPa.
The instrument would have been at about 15 m AHD. Applying a height correction of 1 hPa per 10 m means adding 1.5 hPa to the barograph value which would give a MSL pressure of 984.9 hPa. But the aneroid was obviously out of adjustment – see below.

Mercury Barometer readings at 12°26', 130°50' (Parap aerodrome)
At 3:00 PM on 10/3/37, temp was 77.1 °F (25.06°C) and pressure corrected to MSL, 32°F and specific gravity was 29.344 inches = 993.7 hPa. At this time, the barograph shows 29.43 inches (996.6 hPa) which indicates that the barograph pressures should be reduced by 2.9 hPa rather than increased by 1.5 hPa.

At 9:00 AM on 11/3/37, corrected pressure was 29.297 inch = 992.1 hPa. At this time, the barograph shows 29.33 inch (993.23 hPa) which indicates that the barograph pressures should be reduced by 1.1 hPa. rather than increased by 1.5 hPa. (There are little steps in the barograph trace indicating that the instrument tended to over-record the pressure when it was dropping and under-record when it was rising.)

The BoM log for the 11th is clearly written from the aerodrome records - it gives the above, corrected mercury barometer measurements for 3:00 PM on the 10th and 9:00 AM on the 11th. It also states "Min Bar = 28.98" at 1:25 AM. (981.4 hPa) This is 2 hPa less than the aneroid barometer reading of 29.04 inch (983.4 hPa).

It is noted that 2 hPa is also the average of the above, 2.9 hPa and 1.1 hPa corrections and indicates that the BoM intentionally corrected the barograph to best fit the mercury readings taken before and after the minimum.

Mercury barometer records from "Darwin Division No.2, SA" – presumed to be from the Darwin Post Office – taken at 9 am, noon, 3 pm, 6 pm and 9 pm each day. Elevation of the Post Office instrument would have been about 30 m AHD.

Time on 10/11/1937	9:00 AM	NOON	3:00 PM	6:00 PM	9:00 PM	9:00 AM 11/11/37
Temp °F	78.8	78.0	78.0	78.0	78.0	77.5
Bar as read inches	29.538	29.500	29.428	29.362	29.350	29.402
Temperature correction	-0.132	-0.132	-0.131	-0.131	-0.131	-0.130
Corrected to 32°F	29.406	29.368	29.297	29.231	29.219	
Gravity correction	-0.073	-0.073	-0.073	-0.073	-0.073	-0.073
Station Press	29.323	29.295	29.224	29.158	29.146	29.289
MSL correction	+0.106	+0.106	+0.106	+0.106	+0.106	+0.106
MSL press inches	29.429	29.401	29.330	29.264	29.250(1)	29.305
MSL press inches at aerodrome	29.454		29.344			29.297
Adopt for analysis	29.44	29.41	29.34	29.26	29.25	29.30
Adopt for analysis hPa	997	996	994	991	991	992

Table F.3 Corrections to the mercury barometer readings.
(1) Record sheet has "29.248" noted opposite the 29.350 reading.

The pressures at 0:00, 1:30. 3:00 and 6:00 AM on the 11th can only be derived from the barograph. This was done by allowing for the barograph times as being 1 hour fast and deducting 2 hPa from the resulting pressure. Values for the average of the two mercury barometer readings and for the corrected barograph readings are tabulated below:

Time	9:00	12:00	15:00	18:00	21:00	0:00	1:30	3:00	6:00	9:00
Merc. Baro	**997**	**996**	**994**	**991**	**991**					**992**
Barograph (B)	29.54	29.52	29.45	29.35	29.29	29.23	20.04	29.08	29.19	29.33
Corrected B	998	998	995	992	990	**988**	**981**	**983**	**986**	991

Table F.4 Corrected pressures from mercury barometers and from barograph.

The values used in Table F.1 for the station pressure $p_{(s)}$ are in bold font in Table F.4.

Appendix G

CYCLONES WITHIN 500 KM OF DARWIN (1974 – 2006)

Using the Bureau of Meteorology's database records to derive intensity frequency estimates.

APPENDIX G CYCLONES WITHIN 500 Km OF DARWIN, 1974 – 2006

SUMMARY

This Appendix examines data on tropical lows and/or cyclones (**storms**) that have come within 500 km of Darwin as recorded in a database maintained by the Australian Bureau of Meteorology (BoM). (In Australian terminology a system is a cyclone only if it produces gale force winds having gusts exceeding 90 kph in its eyewall.)

The records of 112 storms over the past 100 years are first examined and the variations in month of occurrence and number of storms per decade are tabulated. However, for most of the Appendix, the only records which will be used are those compiled since BoM, Darwin began using the Dvorak technique circa 1974. These records are analysed in various ways to see if they can reveal intensity-frequency relationships for intense cyclones in the Darwin Region.

THE DATA

The 500 km radius is chosen as being large enough to enable statistical analysis of a reasonably large number of cyclones but small enough to ensure uniformity in the regional variables which control the formation and intensity of cyclones.

The data is extracted from a publicly available database (cyclones_newformat) provided by BoM at http://www.bom.gov.au/climate/how/ (This database commences in 1906 and covers the whole of Australia. It is in a barely comprehensible format with more than 22,000 lines of data having 40 columns of parameters. Each line is for one position on a storm track, at either 24 hour, 12 hr or 6 hr intervals depending on the era of the record. Only the most recent storms have the 40 different parameters recorded - the early records contain little more than the position, date and time and occasionally a recorded central pressure.)

Table G.1 (next page) is derived from the database and gives the number of storms recorded as having come within 500 km of Darwin for each decade over the last century. On average, for the first three decades only two storms were recorded per decade. This jumped to an average of seven storms per decade for the period 1936 to 1956. This increase would almost certainly have been due to the better detection provided by the increased number of aircraft flights and the fact that a meteorological office was established in Darwin in 1934. Similarly, the sudden jump in numbers starting with the decade 1956 – 1966 is almost certainly due to the increased detection afforded by weather satellites which first came into use in 1959 rather than any real increase in the frequency of tropical lows or cyclones.

The last 50 years of records give an average of nearly two storms per year coming within 500 km of Darwin. But there was considerable variability. For instance, in the1965/66 season there were five storms but there were also four seasons when there were no storms at all.

All 112 storms recorded in the last 100 years occurred within the regular cyclone season of November through to May. The occurrences within each month on a percentage basis are:

November	December	January	February	March	April	May
2%	25%	0%	16%	14%	27%	16%

The following table reflects improvements in the detection of storms.

DECADE (For cyclone seasons)	Number in decade
July 1906 - June 1916	2
July 1916 - June 1926	4
July1926 - June 1936	0
July1936 - June1946	5
July1946 - June 1956	9
July 1956 - June 1966	22
July 1966 - June 1976	17
July 1976 - June 1986	17
July 1986 - June 1996	15
July 1996 - June 2006	21

TABLE G.1 Number of tropical lows and/or cyclones per decade that have come within 500 km of Darwin as recorded in the BoM 'cyclones_newformat' database.

The above statistics of tropical lows and cyclones will be of interest to people concerned with extreme rainfall events. For instance the record floods in Katherine in 1998 were produced by Cyclone Les which was a cyclone when it was over the Gulf of Carpentaria but had weakened into a tropical low when it dumped rain into the catchment of the Katherine River. (The flooding was exacerbated because the rain producing low traveled roughly at the speed of discharge along the catchment.)

But this report is concerned with extreme wind and storm surge events rather than with extreme rainfall. To proceed further, the data needs to be sorted into intensity related groups.

Cyclones producing maximum gusts less than 250 kph will be a problem for caravans, etc but should not cause structural damage to buildings properly designed and constructed in accordance with the current NT building regulations. (Exceptions to this rule will be some older buildings where rot or corrosion have taken their toll or for buildings under large, wind weak trees such as African mahoganies.)

For this analysis, three intensity groups will be considered; tropical lows, non-intense cyclones (gusts < 250 kph) and intense cyclones (gusts >250 kph).

Table G.2 on the following pages is derived from the BoM database. It gives details of 49 named storms sorted into the above three intensity groups. The records are for each storm at its most intense stage of development when within 500 km of Darwin for the 32 year period July 1974 to June 2006. (Tropical lows that are inland for the whole time when within 500 km of Darwin have been omitted as not representing any sort of wind risk to Darwin.) The start date is 1974 because that is when BoM began using the Dvorak technique and some intensity estimates in the database before that time may not be reliable.

*FOOTNOTE : The Dvorak technique allows experienced practitioners to estimate the maximum wind speed of a cyclone by analyzing distinctive cloud patterns and other data obtained from satellites. The endpoint of the satellite analysis is to obtain a so-called Current Intensity (**CI**) number. A good explanation of the technique should be found at http://en.wikipedia.org/wiki/Dvorak_technique*

Database No. [1]	NAME	Date/Time UTC [2}	[3]	Lat. S [4]	Long. E [4]	dist [5]	central press.	ΔP [6]	CI [7]	*V2 [8]*	*Vtr [9]*	*land fall [10]*
				deg.	deg.	km	hPa	hPa		*kph*	kph	
TROPICAL LOWS:												
1975	**Linda**	**197603150530**	WW	**12.0**	**131.0**	***46***	**994**	***11***	***2.5***	***79***	***18***	***1***
1979.6	BRIAN	198001190000	WW	13.2	126.6	*475*	1000	*9*	*2.0*	*66*	*18*	*0*
1979.1	GLORIA	198003200000	LW	13.7	129.4	*218*	1003	*6*	*1.5*	*56*	*38*	*1*
1977.3	TRUDY	197801100000	WW	10.6	129.0	*288*	1004	*5*	*1.5*	*56*	*37*	*0*
1980.6	FELIX	198012220000	WW	10.6	127.0	470	1002	*7*	2.0	*66*	*19*	*0*
1981.3	AMELIA	198112032000	WW	11.6	129.5	*176*	999	*8*	*2.0*	*66*	*28*	*1*
1981.4	UNNAMED	198112220500	WW	11.4	126.4	500	1000	*5*	*1.5*	*56*	*30*	*1*
1984.7	HUBERT	198502101200	LL	14.3	127.9	388	998	*12*	2.5	*79*	*11*	*1*
1984.9	JACOB	198502151200	WW	11.0	127.1	*443*	1000	*10*	*2.5*	*79*	*15*	*0*
1985.9	TIFFANY	198602251200	WW	10.6	128.7	*313*	1004	*6*	*2.0*	*66*	*38*	*0*
1988.1	ILONA	198812120600	WW	13.2	126.8	*454*	998	*12*	2.5	*79*	*33*	*0*
1988.10	ORSON	198904170000	WW	10.0	129.0	*338*	1000	*10*	*2.5*	*79*	*22*	*0*
1989.2	FELICITY	198912130600	WL	12.1	134.0	*339*	997	*13*	2.5	*79*	*12*	*1*
1989.4	SAM	199001121800	WW	13.2	126.7	*465*	1001	*9*	2.0	*66*	*20*	*0*
1990.1	LAURENCE	199012101800	WW	12.6	128.9	*218*	994	*13*	*2.5*	*79*	*8*	*0*
1990.8	MARIAN	199104090000	WW	8.8	130.0	413	1004	*6*	*2.0*	*66*	*11*	*0*
1993.3	OSCAR	199312301200	WW	11.1	127.2	428	998	*12*	2.5	*79*	*8*	*0*
1994.2	BOBBY	199502191200	WW	12.0	131.3	*62*	1005	*5*	*1.5*	*56*	*26*	*1*
1997.2	SID	199712261200	WW	11.3	133.8	*339*	992	*15*	*2.5*	*79*	*18*	*1*
1998.13	GWENDA	199904030000	WW	11.0	129.2	*242*	1006	*4*	*1.5*	*56*	*13*	*1*
1999.6	STEVE	200003021800	LL	14.7	130.5	*260*	992	*15*	2.5	*79*	*12*	*1*
1999.11	PAUL	200004102200	WW	13.0	127.5	*375*	1000	*10*	*2.5*	*79*	*20*	*0*
2003.6	EVAN	200403030300	LL	14.3	129.5	*260*	999	*9*	*2.0*	*66*	*18*	*1*
Averages tropical lows				12.0	129.0	327	999.6	*9.2*	*2.1*	*70.0*	*20.6*	*0.5*
NON-INTENSE CYCLONES:												
1974.4	SELMA	197412030000	WW	12.1	130.2	*83*	980	*29*	*4.0*	*150*	*7*	*1*
1974.1	WILMA	197503140600	WL	14.6	128.1	*390*	980	*25*	*3.5*	*127*	*15*	*1*
1974.2	AMELIA	197504081200	LL	12.0	133.4	*276*	990	*17*	*3.0*	*103*	*31*	*1*
1975.2	JOAN	197512030700	WW	13.5	126.6	482	973	*35*	*4.5*	*176*	*8*	*1*
1976.1	VERNA	197705010000	WW	10.3	128.0	*393*	973	*36*	*4.5*	*176*	*13*	*0*
1979.8	DEAN	198001281200	WW	11.5	126.2	*522*	990	*20*	*3.5*	*127*	*26*	*0*
1980.1	MAX	198103130600	WW	12.8	127.0	426	975	*34*	*4.5*	*176*	*19*	*1*
1981.6	BRUNO	198201152300	LW	14.0	129.5	*234*	991	*18*	*3.0*	*103*	*17*	*1*
1983.2	FERDINAND	198403040800	WW	11.9	134.3	*374*	980	*25*	*4.0*	*150*	*6*	*1*
1984.2	GRETEL	198504130000	WW	12.5	130.5	*45*	984	*25*	*4.0*	*150*	*16*	*1*
1985.4	HECTOR	**198601190000**	**WW**	**14.0**	**128.5**	***315***	**982**	*27*	*3.5*	*127*	*7*	*1*
1986.6	KAY	**198704090000**	WW	**10.3**	**134.9**	**495**	*990*	*17*	*3.0*	*103*	*21*	*1*
1995.14	OLIVIA	199604060100	WW	12.8	125.9	*545*	990	*20*	*3.5*	*127*	*19*	*0*
1996.6	PHIL	199612271200	WW	14.5	128.2	*374*	990	*17*	*3.0*	*103*	*33*	*1*
1996.7	RACHEL	199701031800	WL	13.9	127.1	*444*	982	*25*	*3.5*	*127*	*15*	*1*
1998.10	VANCE	199903180600	WW	12.6	126.7	457	994	*16*	3.0	*103*	*20*	*1*
2000.1	SAM	200012040600	LL	14.3	126.9	*482*	996	*14*	*3.0*	*103*	*15*	*1*
2000.8	ALISTAIR	200104172200	WW	12.5	127.2	*402*	985	*25*	*4.0*	*150*	*32*	*0*
2002.7	CRAIG	200303102100	LW	11.5	131.8	*140*	976	*31*	*4.0*	*150*	*15*	*1*
2003.2	DEBBIE	200312200600	WW	11.4	133.8	*335*	970	*35*	*4.5*	*176*	*8*	*1*
2003.8	FAY	200403181200	WW	13.2	126.6	*475*	968	*39*	*4.5*	*176*	*4*	*1*
Averages non-intense cyclones				*12.7*	*129.1*	366	982.8	*25.2*	*3.7*	*137*	*16.5*	*0.8*
INTENSE CYCLONES:												
1974.5	TRACY	197412241730	WW	12.3	130.5	*45*	940	*64*	*6.0*	*262*	*8*	*1*
1991.9	NEVILLE	199204081800	WW	11.3	128.9	*250*	937	67	*6.5*	*290*	*7*	*1*
1998.3	THELMA	199812081130	WW	11.6	129.2	*205*	920	*87*	*7.5*	*357*	*10*	*0*
2004.7	INGRID	200503121200	WW	11.4	133.9	*345*	924	*83*	*7.0*	*324*	*19*	*1*
2005	**MONICA**	**200604241030**	**WL**	**11.9**	**133.9**	*331*	**917**	*89*	*7.5*	*357*	*13*	*1*
Averages intense cyclones				11.7	131.3	235	927.6	*78*	*6.9*	*318*	*11.4*	*0.8*

TABLE G.2 Tropical Lows and Cyclones when most intense within 500 km of Darwin
For Period July 1974 to June 2006. Refer next page for notes

General Notes to Table G.2

(a) Most data comes from the BoM text file '*cyclones_new format'*. Figures in **bold** font come from BoM, Darwin. Figures in *italics* derive from calculation by writer
(b) Records are for the minimum pressure when within 500 km radius of Darwin, (record closest to Darwin is used if there was more than one record with the same minimum)
(c) Systems which formed in the Gulf of Carpentaria and subsequently came inland within 500 km of Darwin but did not re-cross to open seas within that distance from Darwin are not included (they have significantly different characteristics to systems over water and do not pose a wind threat to Darwin).
(d) Intensity figures for Tracy are the writer's estimate that V_2 > 262 kph and CI = 6.0. (Official BoM report has CI = 5.5.)
(e) Intensity figures for Neville based on work for Woodside Energy Ltd. (SEA, 2005)

Numbered Notes to Table G.2

1. For instance, 1974.4 means SELMA was the 4th named tropical low or cyclone in Australia for the 1974/75 season,
2. UTC = coordinated Universal Time which is 9 hrs 30 min less than CST. The format for the date/time is yyyymmddhhmm
3. WW=over water, LL=over land, WL=water to land crossing, LW=land to water crossing.
4. Position in decimal degrees of latitude and longitude.
5. Distance from Darwin
6. ΔP for assumed ambient pressure, Pn = 1009 hPa at 00 UTC & allowing for diurnal variations.
7. Dvorak CI number derived from BoM's pressure value by assuming:

   1974 - 1984, Perth & Darwin used the Dvorak (1974) wind-pressure relationship with an estimated or measured ΔP

   1985 onwards, Darwin used the Love & Murphy (1985) wind-pressure relationship with estimated or measured ΔP

   1985 to 2000, Perth used the Dvorak (1985) - Atlantic wind-pressure relationship adjusted for Pn = 1010

   2001 onwards, Perth used the Dvorak (1985) - Atlantic wind-pressure relationship with estimated or measured ΔP.
8. V_2 = maximum 2 second gust speed at 10 m height. Derived from global, Dvorak relationship between CI & wind speeds.
9. Vtr = track speed. Calculated from differences in the positions/times before and after record position/time.
10. Did system make landfall or pass within 25 km of an island or the mainland coast when within the 500 km arc from Darwin? 1= Yes, 0 = No. (Note that the system was not necessarily at its most intense at landfall)

ANALYSIS OF THE DATA

Table G.2 has been examined to see if there is any difference between the intensity groups in relation to their month of occurrence. The only trend that may be significant was that for the 23 tropical lows; 17% occurred in February and 35% in March - April, whereas for the 26 cyclones, none occurred in February and 60% occurred in March – April.

There are definitely significant differences relating to track speeds and landfall.

Intensity Group	Number in group	Average track speed (kph)	Made landfall or came within 25 km of coast %	Average central pressure (hPa)	Average estimated max. gusts* (kph)
Tropical lows	23	21	50	1,000	70
Non-intense cyclones	21	17	80	983	137
Intense cyclones	5	11	80	928	318

TABLE G.3: Summary of some of the Data from Table G.2
*No allowance has been made for the track speed.

<u>Table G.3 presents four interesting facts about the Table G.2 cyclones</u>

(a) **Intense cyclones are comparative rare events – only 5 out of a total 49 systems over 32 years**.
This introduces the dominant problem in deriving wind speed – AEP relationships for cyclone prone areas; even when a 'catchment' area as large as 500 km radius is used, intense cyclones are so rare that there are not enough reliable records to confidently derive such a relationship. This problem is discussed further on page G-15.

(b) **The track speeds are consistent with a trend that applies generally in the Australian region (***Wang and Wu, 2004***) - the higher the intensity, the lower the average track speed**.

(c) **80% of the cyclones made landfall or came within 25 km of a coastline compared with only 50% of the tropical lows. (**A higher proportion of the tropical lows formed north or west of Darwin and proceeded westward.)

(d) **There is a pronounced difference between the average maximum gust speeds of the non-intense and the intense cyclones.**
In Australian terms, the average maximum gust speed of:
- 137 kph for the non-intense cyclones corresponds to about mid-level Category 2;
- 318 kph for the intense cyclones corresponds to about mid-level Category 5.

PRESENTATION OF THE INTENSITY DATA

The intensity of a cyclone can be measured in terms of:

- the pressure drop (ΔP) between the ambient pressure and its central pressure,
- the wind speeds generated in the eye wall;
- its Severity Category number; or
- its Dvorak Current Intensity (CI) number.

For the reasons given below, the following analysis will use CI numbers.

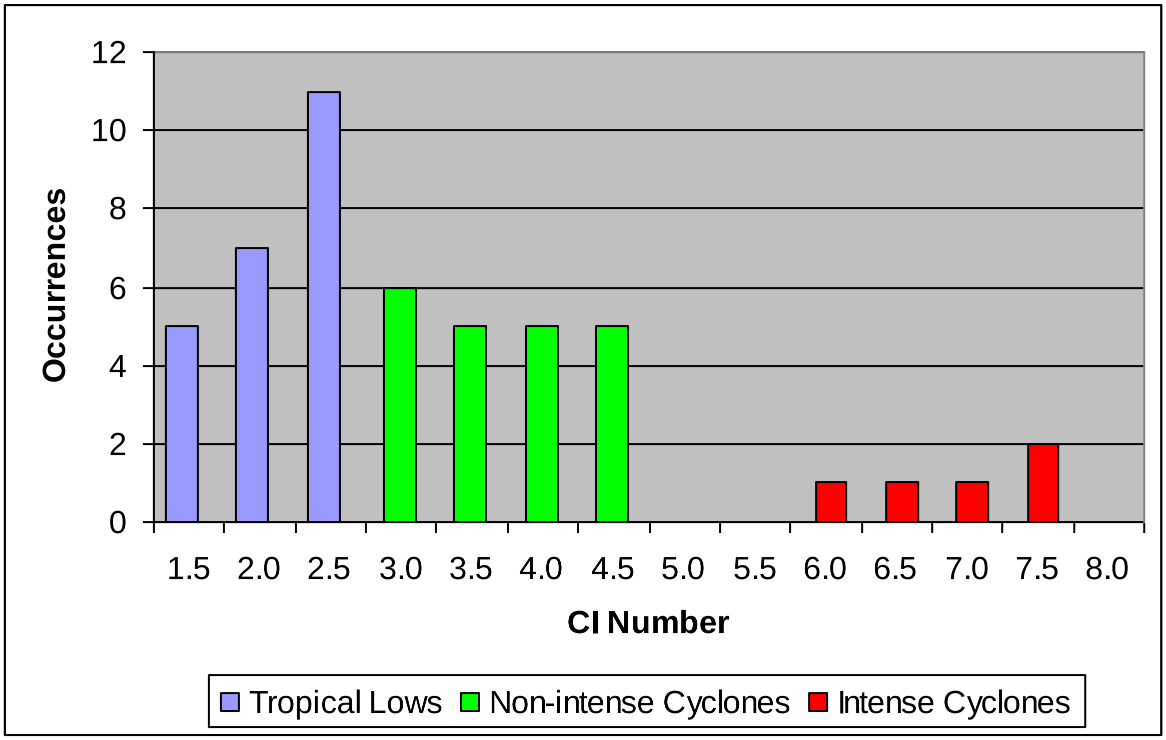


Figure G.1 Histogram of Occurrences vs. CI Number for the 49 tropical lows and cyclones that have come within 500 km of Darwin over the 32 years between July 1974 and June 2006. Refer Table G.2 for data.

The reasons that the CI number is used to 'measure' intensity rather than more familiar parameters such as central pressure, wind speed or Severity Category number are:

- in the NT, surface observations of central pressure or maximum wind speeds are rarely obtained. They are nearly always estimated from the more basic parameter - the satellite derived, CI number;
- The NT uses a globally recognized CI – wind speed relationship (per the WMO's Global Guide to TC Forecasting) whereas the pressure – wind speed relationship used in the NT is peculiar to the region and there is some controversy as to its accuracy.
- CI numbers are recognized globally by meteorologists but for instance, a meteorologist in the US might find gust speeds measured in kph very annoying.
- The 14 possible CI numbers allow finer resolution than using just 'Tropical Low' or one of five possible Severity Category numbers.

However, there is also a good reason for not using CI numbers – they are not included in the 'cyclones_newformat' database. The CI data in table G.2 had to be derived by a tedious process of working backwards from the pressure data - refer Note No. 7 of Table G.2.

Appendix A includes tables relating CI numbers with Severity Category numbers and wind speeds. In summary, the relationship is:
CI 1.5 to 2.5 = tropical lows with maximum gusts between 56 kph and 79 kph;
CI 3.0 to 5.5 = non-intense cyclones with maximum gusts between 103 kph and 234 kph;
CI 6.0 to 8.0 = intense cyclones with maximum gusts between 262 kph and 390 kph.
(It should be noted that the mid-value between CI = 5.5 and 6.0 is 248 kph, so the above grouping is close to the previous definition of intense cyclones as having maximum gusts > 250 kph.)

Figure G.1, previous page, is significant because it does not accord with the theories normally used by engineers to relate intensity with frequency of occurrence. These theories assume that, given enough data, the line connecting the top of the bars in a histogram such as Fig. G.1 will reach a peak and then taper off in a nice curve down to zero (or near zero) occurrences at some maximum value as indicated by the blue line in Fig. G.2 next page. The fact that the number of occurrences for the non – intense cyclones is nearly constant at 5 and the number for the intense cyclones is nearly constant at 1 suggests that the probability distributions used by engineers may not reflect the distributions in nature.

ANALYSIS FOR INTENSITY – FREQUENCY RELATIONSHIPS

PROBABILITY DISTRIBUTIONS

Statisticians have derived several different probability distributions with mathematical formulae to describe the shape of the line that should connect the top of the bars in a histogram. (Actually the formulae produce curved lines and strictly only apply to continuous variables but the curves can still be 'fitted' to cases where the variables are discrete values such as the CI numbers above.)

Following the passage of Cyclone Thelma in 1998, the NT government commissioned a study to determine the probability of Darwin being struck by a Category 5 cyclone (Georgiou, 2000). The data comprised 41 tropical lows and cyclones that had come within 250 km of Darwin over the period 1964 to 1999.

The results were reassuring. For instance the study found:

- that a building in Darwin being impacted by a Category 5 cyclone with wind gusts of 320 kph would have an AEP of 1/4,600
- that the design wind speed of 252 kph proposed for the new (now current) wind code had an AEP of 1/850 in Darwin and was therefore a reasonable value for residential buildings in Darwin.

Georgiou used ΔP to measure intensity and considered several alternative probability distributions to relate values of ΔP with frequency of occurrence for use in the computerized simulation model. He decided that the **lognormal distribution** was best for the purpose.

THE LOGNORMAL DISTRIBUTION

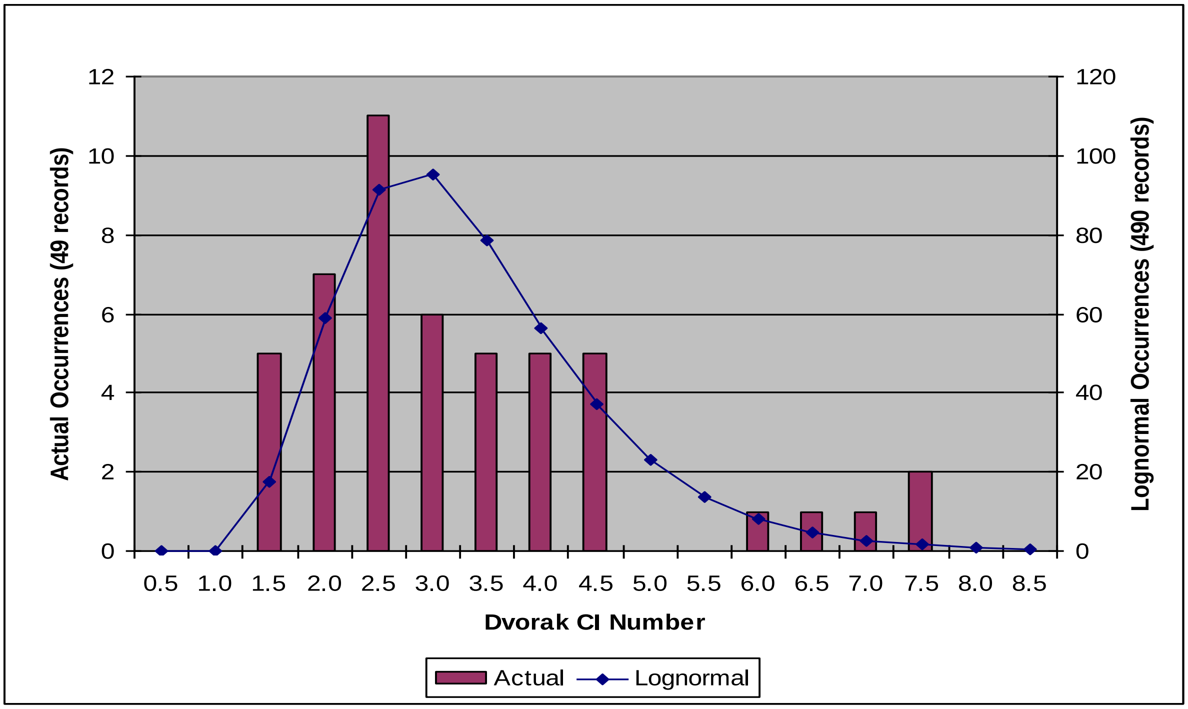


Figure G.2 Histogram of Occurrences vs. CI Numbers. The red bars are for the 49 records as previously plotted in Fig. G.1, the blue line is for an idealized, 490 records having a lognormal distribution.

Fig.G.2 demonstrates how the lognormal distribution does not fit the Table G.2 data. The 490 'records' represented by the blue line can be imagined as being obtained over a record period of 320 years instead of 32 years. Instead of showing a bar plot, the lognormal 'histogram' for the 490 records is shown as a line joining what would be the tops of the bars. The x10 difference in the ordinates on the two vertical axes means that a direct comparison can be made between the shape of the lognormal line for the 490 records and the envelope of the bars for the 49 records.

For intense cyclones, the most important attribute for the chosen probability distribution is that the occurrence rates obtained for cyclones with CI greater than or equal to 6.0 will reflect the rates in the records. In effect, only the 'tail' of the distribution is important – the storms with CI less than 6.0 are really just there to provide input data to 'shape' the 'tail'.
The lognormal distribution family of curves has three parameters which determine its actual shape. The parameters used for the blue line above were 0.34 for the shape parameter, 4.6 for the scale parameter and 2.81 for the location parameter. Because it is the tail of the curve that is important, the three parameters were chosen to produce a distribution giving the maximum number of occurrences in the high CI range (consistent with CI = 8.0 as the upper limit).
As can be seen, the 'fat tail' was achieved by deliberately sacrificing the fit to the lower CI values in the histogram for the 49 records. Despite this deliberate bias the distribution fails.

For readers who would rather look at figures than a graph, Table G.4 next page gives the CI occurrences for the 49 actual records and the 490 'lognormal' records. To enable a direct comparison, the occurrence numbers for the 49 records have been multiplied by 10.

What the table shows is that for CI = 6, the lognormal distribution gives a reasonable match with the actual record, but for CI = 6.5, 7.0 and 7.5 it gives only 1/2, 3/10 and1/10 respectively of the number of occurrences suggested by that 32 year long record.

CI =	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**
‘49’x 10	0	50	70	110	60	50	50	50	0	0	**10**	**10**	**10**	**20**	**0**
‘490’	0	18	59	91	95	79	57	37	23	14	**8**	**5**	**3**	**2**	**1**

Table G.4 CI number vs. the actual occurrences x10 and the ‘lognormal’ occurrences

THE GUMBEL DISTRIBUTION

Engineers frequently use an alternative family of distributions to extrapolate their data known as Generalised Extreme Value Distributions **(GEV).** One group in the family comprises the Gumbel distribution (Type I), the Frechet distribution (Type II) and the Weibull distribution (Type III)**.** These distributions deal only with the series of maxima recorded for a set time interval - usually the annual maxima. Another group known as the Pareto distribution deals with maxima above a certain threshold level rather than with annual maxima. All of these distributions would assume that as the intensity limit is approached (CI = 6.0 to CI = 8.0), the occurrences diminish in a similar way to the ‘490’ records in the above table.

The Gumbel distribution will be considered in some detail here because it has been traditionally used by engineers for extrapolating records of flood levels and wind speeds to produce estimates such as the 1 in 100 year or 1 in 1,000 year event. It was used in a modified form to derive the Regional Wind Speeds used in the 1989 edition of the Australian wind code (Georgiou, 2000) and it was also used to derive the cyclone central pressure – frequency relationship in the most recent report to the NT government on storm tide risk in the Darwin region (SEA, 2006).

An attempt will be made here to derive the intensity – frequency relationship for Darwin using a Gumbel analysis and the CI data from Table G.2. Because only annual maxima are used, the cyclones with the lowest CIs are discarded from the data when there is more than one cyclone per season. Also, because there were five seasons when there were no cyclones, dummy records have been implanted for these five seasons with values equal to the largest of the discards. The 32 records for the 32 cyclone seasons are processed using a standardized, simple procedure and the results are plotted in Figure G.3.

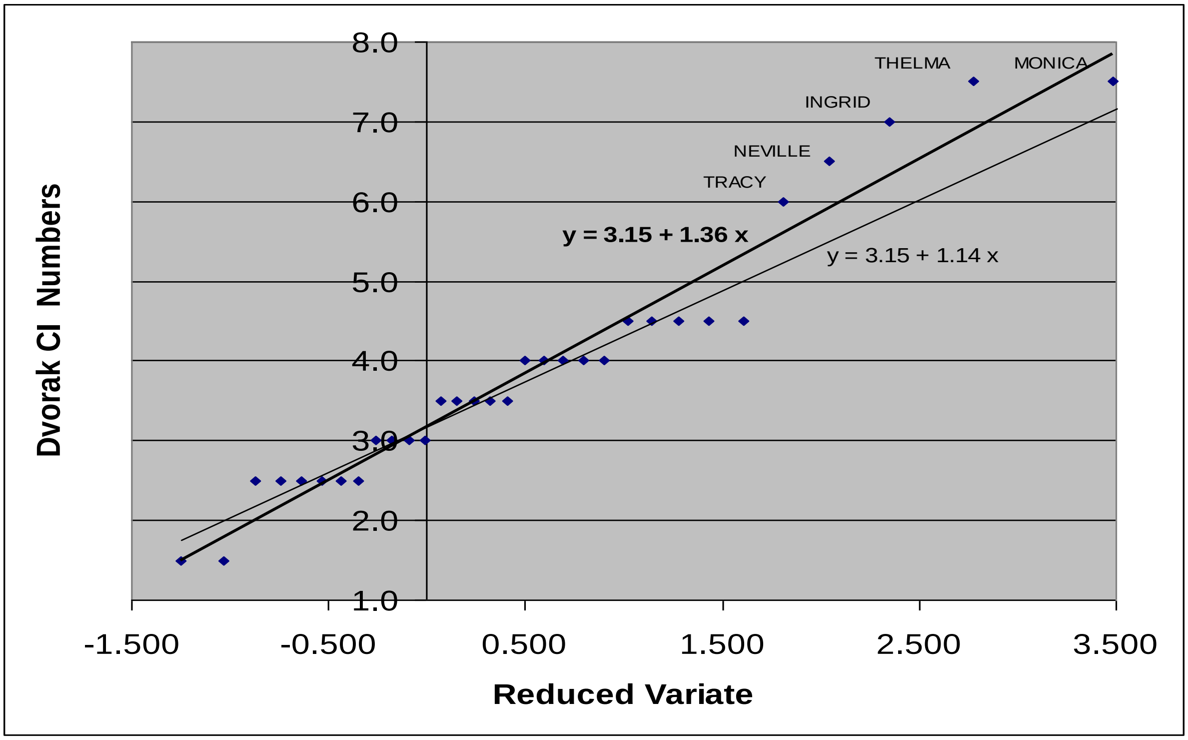


Figure G.3 Analysis of annual maximum CI numbers using the Gumbel method.

Each diamond in the graph is one year's maxima. The step-wise shape for the lower numbers is a result of the 'coarse' 0.5 steps in the CI numbers. If the data did in fact fit a Gumbel distribution, there would be a straight line which would pass through or near the middle of each of the lower CI 'steps' and would also pass near most of the points for the five intense cyclones. As can be seen, no such straight line can be drawn.

The thin line fits the lower CI numbers reasonably well but all of the intense cyclones become outliers. The thick line is the least squares best fit line for all of the points. It 'fits' the CI = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 & 7.5 'steps' reasonably well but Cyclones Tracy, Neville and Ingrid remain outliers and the 'step' for CI = 4.5 also becomes an outlier.

The Gumbel distribution proves to have another problem when we attempt to use one or other of the best fit lines to derive the relationship between CI and the Average Recurrence Interval (ARI). Consider the following:

For reasonably large values of ARI, the Gumbel relationship can be written as:
CI = a + b · ln (ARI) ; where a is the intercept (3.15) and b is the slope (1.14 or 1.36) of the lines in Fig G.3. The table below shows sample results.

ARI	CI [= 3.15 + 1.14 ln (ARI)]	**CI [= 3.15 + 1.36 ln (ARI)]**
50 years	7.6	**8.5**
100 years	8.4	**9.4**
500 years	10.2	**11.6**

Table G.5 CI vs ARI relationship indicated by a Gumbel analysis.

Table G.5 illustrates a fundamental flaw with the Gumbel distribution – it does not allow for maximum (or minimum) possible values. The maximum possible value for CI is 8.0 but clearly, the Gumbel distribution does not model that restriction.

A Gumbel analysis was used to derive the central pressure – ARI relationship in the most recent report to the NT government on storm tide risk in the Darwin region (SEA, 2006). The report assumes that Maximum Potential Intensity (MPI) of cyclones in the Darwin region corresponds to central pressure of 880 hPa. The pressure – ARI relationship derived from the Gumbel analysis is assumed to only hold for pressures down to that minimum 880 hPa which according to the report is first attained for an ARI of 500 years. The pressure is then held constant at 880 hPa regardless of subsequent increase in the ARI.

The writer has no problem with the device used in the SEA report to force the Gumbel distribution to fit the assumed reality of a minimum pressure value.

However the ARI for that minimum pressure and the number and extent of the outliers for the plotted distribution in the SEA report is problematic. The SEA report claims that the wind speed – frequency relationship (which is also derived from a Gumbel analysis and forms a critically important component of the computer model) was successfully verified by comparing it with the maximum gusts recorded at Darwin Airport for each of the 46 tropical cyclones that have come within 300 km of the airport since 1947.

The writer finds the verification unconvincing. Out of the 46 records, the only intense cyclone that came anywhere near Darwin was cyclone Tracy with its <u>recorded</u> maximum gust speed of 217 kph. (The next highest gust was 115 kph from cyclone Gretel which caused hardly any damage in Darwin apart from blowing over a few African mahoganies.) The SEA report's wind speed – ARI relationship gives the ARI for 217 kph wind gusts in Darwin as 400 years. The report indicates that is a reasonable result and therefore verified the relationship used in the model. To the writer, an ARI of 400 years seems far too high for Tracy-type winds in Darwin.

But the SEA report's verification check becomes even more dubious if instead of using 217 kph (which was the anemometer's recording when the instrument failed), the writer's estimate of the probable maximum value of 250 kph is considered. Extrapolating the graph in the SEA report then indicates that the ARI for Tracy-type winds in Darwin is 1,500 years.

Unless the reduced variate plot (Fig. G.3) used to derive the Gumbel parameters a and b is a reasonably straight line without outliers, then the Gumbel analysis can give a range of equally possible answers and is therefore not a suitable probability distribution to use in risk analysis relating to cyclones. To further demonstrate this, consider the SEA report's finding that out of all of the cyclones that come within 500 km of Darwin, on average, there will be only one cyclone every 500 years that will attain MPI. (ie. the ARI for MPI is 500 yr.)

The Gumbel parameters derived in this report produce very different estimates to the above: The formula CI = a + b · ln (ARI) [page G-10] can be re-written as ARI = exp [(CI – a) ⁄ b] Using the latter formula and assuming that a cyclone at MPI has CI = 8.0, then the plot lines in Fig. G.3 indicate that the ARI for a cyclone at MPI within 500 km of Darwin is either:

- = exp [(8 - 3.15) ⁄ 1.14] = 70 years for the thin line; or
- = exp [(8 – 3.15) ⁄ 1.36] = 35 years for the thick line.

There have been two cyclones having CI = 7.5 within 500 km of Darwin in the last 9 years so a figure of between 35 and 70 years for a CI = 8.0 appears far more reasonable than the SEA report's figure of 500 years.

Problems with the Gumbel analysis are well known. A paper written by an authority on wind loads (Holmes, 1998) includes the following:

> *"In the 1970s, the enthusiasm for the by-now standard 'Gumbel analysis' was tempered by events such as Cyclone 'Tracy' in Darwin, Australia, in 1974. when the previous design wind speed determined by a Gumbel fitting procedure, was exceeded considerably. This highlighted the importance of:*
>
> - *Sampling errors inherent in the recorded database, usually less than 50 years, and*
> - *The importance of separating out data originating from different storm types."*

THE WEIBULL DISTRIBUTION

Because the Weibull distribution can have parameters that do simulate an upper (or lower) limit, it should give better results than the unbounded, Gumbel distribution. An analysis similar to the one done previously for the Lognormal distribution was done with the Weibull distribution. The parameters were massaged to produce a tail that was slightly 'fatter' than the 'blue line' in Fig. G.2. Nevertheless, the 'fit' for CI >=6.0 was only slightly better than for the Lognormal distribution – the Weibull distribution does not fit the Table G.2 data for cyclones coming within 500 km of Darwin since July 1974.

According to the commentary to the current wind code, (AS/NZS 1170.2 Supplement 1:2002) the Weibull distribution was used to derive the Regional Wind Speeds for the current wind code. The parameters used and the goodness of fit to the data have not been published.

THE PARETO DISTRIBUTION

A review of the recent literature indicates that the method of choice to derive wind speed – AEP relationships in the USA is now the generalized Pareto distribution (**GPD**) using the so-called 'Peaks Over Threshold' method for the analysis. The main advantage of the method is that the data input comprises individual maxima above a certain threshold rather than just the annual maxima. (So if there were two intense cyclones in a given year, they would be both included, if there were none - that is no problem either.)

The Peaks Over Threshold (**POT**) method has been successfully applied to derive wind speeds – AEP relationships for thunderstorm downdrafts and for synoptic gales in Melbourne (Holmes, 2001). The data came from a total of 128 years of records from four aerodromes.

An attempt was made by the writer to apply the POT method to the Table G.2 data but the method could not be made to work due to the limited number of records. However, the Pareto Distribution will be similar to all of the other distributions in that it will assume that occurrences from CI = 6 to CI = 8 should dramatically tail off in some way – as such it will not fit the Table G.2 data for intense cyclones.

The GPD distribution has been used recently to derive wind speed – AEP relationships for Atlantic hurricanes that have affected the coastline of the United States (Jagger and Elsner, 2006). The data set comprised 383 hurricanes over the period 1899 to 2004 separated into three regions - the Gulf coast, Florida and the East Coast. Each region produced markedly different relationships. This US study was partly funded by the Risk Prediction Initiative (a Bermuda based research organization sponsored by reinsurance companies).

Four of the findings from the study are of interest here:

1) the histogram of occurrences vs wind speed for Florida was almost zero for the wind speed range equivalent to CI = 5.0 to 5.5 – ie. similar to Fig. G.1 above. (However, for higher CI numbers, the occurrence numbers tapered off markedly rather than remaining constant as in Fig. G.1 above.)

2) the most intense cyclone in the data was for Hurricane Camille when it made landfall on the coast of Mississippi in 1969 with wind speeds equivalent to 385 kph maximum gusts. (This is the most intense in the world for a landfalling cyclone. Presumably its CI was 8.0)

3) there were strong correlations between wind speeds and climate conditions such as the El Nino – Southern Oscillation (ENSO), the Atlantic Multi-decadal Oscillation, the North Atlantic Oscillation and Global Temperatures.

   Comments:

   a) It is now well established that the ENSO has a marked influence on the frequency of cyclones affecting Australia's east coast. However, as far as can be determined from the sparse data, the ENSO has little effect on the frequency or intensity of cyclones in the NT.

   b) As discussed under Section 2.1 (b) and Appendix E, the long term historic records indicate that there may be, as yet undiscovered, multi-decadal cycles which affect sea temperatures, the characteristics of the monsoon trough or other atmospheric variables that have a direct influence on the intensity and/or frequency and/or track directions of cyclones in this region.

   c) Engineering estimates that extrapolate 30 or 40 years of post-satellite era data to estimate wind speeds or surge levels corresponding to a one in 500 year or one in 10,000 year event need to somehow allow for the possibility that their short period of data is not representative of what may happen in the future. This is discussed further in Appendix I.

4) A **Bayesian** statistical procedure was used to bolster the data by incorporating less reliable, historic records that extended from 1851 to 1898. This procedure uses subjective judgement to qualify the data but at least it provides a rigorous means to incorporate such data into an analysis. The authors noted that the procedure *"is important in light of the ongoing efforts to detect hurricane events from geological records … and collate historical information."*

   Comment: Section 2.1 (b) and Appendix E in this report examines cyclones in the written record extending back to 1824. Section 2.3 and Appendices J, K, L and M in this report examine tree rings and coastal landforms as probable recorders of cyclone activity extending back thousands of years. Bayesian principles may be the appropriate tool to utilize such records.

Why won't the conventionally used distributions fit the data in Table G.2 ?

There are several possible explanations:

1) the BoM 'cyclones_newformat' database is defective; and/or
2) the writer's derivation of CI values from the BoM pressure data is defective; and/or
3) the period of record is too short to draw any conclusions, a longer period of data collection will rectify the matter; and/or
4) the intense cyclones belong to a different statistical population to the non-intense cyclones; and/or
5) there are other statistical distributions which will fit the data.

Resolving this issue is obviously very important for confidence to be placed in the results of engineering risk studies.

Each of the above five explanations is further examined below:

1) the BoM 'cyclones_newformat' database is defective

There is no question that this is the case.

Even in the limited work done by the writer in deriving Table G.2 from the data, two cases were found where a single cyclone had been entered as two separate cyclones. (Audrey 1968.12 = Bonnie 1968.13 and Bertha 1967.7 = Bettie 1967.9) BoM have been advised but at the time of writing, both of these double entries are still in the database.

But there are much more important defects in the data. The increased knowledge and skill of Dvorak practitioners means that re-analysis of the original satellite imagery will commonly lead to revised estimates of the intensities of cyclones. (Unfortunately the revisions tend to increase the intensities.) In 2002, Woodside Energy Limited (WEL) engaged experienced BoM practitioners to re-analyse the post 1969 cyclones that have occurred west of Darwin in the Timor Sea region so as to provide better estimation of design wind speeds and wave heights for their oil platforms.

It would seem that if it was worth while for WEL to pay for this work to be done for their offshore facilities, then surely it should also be done for the coastal cities and towns along Australia's cyclone prone coast. . It is understood that the BoM have plans (which are as yet unfunded) to do a full-scale re-analysis, applying modern techniques to original satellite data to allow a consistent analysis of intensity from about 1970 onwards (Trewin. pers. comm..)

This report recommends that BoM's re-analysis commence with cyclones that have affected the Top End coast. The writer has been informed (Kepert. pers. comm.) that valuable lessons have been learnt from the WEL exercise, which would enable a better job of re-analyzing the storms east of Darwin, given appropriate funding. There may also be scope to build on the WEL results and experience, and further improve the results to the west of Darwin.

The published data should include the CI (and TI) numbers used in the re-analysis.

2) the writer's derivation of CI values from the BoM pressure data is defective

BoM, Darwin were consulted on the different methods used by the Perth and Darwin offices over the years to obtain the recorded pressure from the Dvorak CI number that would have been obtained at the time (refer numbered note 7 to Table G.2). These different methods have been carefully applied to recreate CI values from the pressure data.

The process, although tedious is relatively simple but to date, the writer has not found anyone willing to check the derivations. However the results should be reasonably accurate – this will certainly be the case for the five intense cyclones.

3) The period of record is too short to draw any conclusions.

When it comes to cyclones affecting a particular locality, there can be no question that a record period of 32 years as used in Table G.2 is too short to enable any firm predictions to be made about the future.

To demonstrate the problem, two plausible scenarios will be drawn from Table G.2:

- **Optimistic Scenario:** There have been five intense cyclones within 500 km of Darwin since 1974. The first one occurred in 1974 and the last one only last year so the period of record should be more than just 2007 – 1974 = 33 years. To be rational, the period of record should start about mid-way between the 1974 cyclone and the previous intense cyclone (1937) and it is reasonable to assume that there will not be another intense cyclone until at least say 2010. This gives the period of record = 2010 – 1955 = 55 years and indicates that the future ARI for an intense cyclone coming within 500 km of Darwin is 55 ⁄ 5 = 11 yr.

- **Pessimistic Scenario:** There have been three intense cyclones within 500 km of Darwin in the last nine years and all of them have been mid to high level Category 5 cyclones. Some people believe that global warming is a factor in this increase in intensity and frequency. Therefore the prudent thing to assume is that the future ARI for a Category 5 cyclone coming within 500 km of Darwin is 9 ⁄ 3 = 3 yr.

(Possible reasons for the recent passage of three Category 5 cyclones in the Darwin region are a statistical aberration, global warming, or a multi-decadal cycle. These are discussed in Section 2.4 (c) of the report and in Appendix O)

4) Intense cyclones belong to a different statistical population to less intense systems.

Fig. G.2 gives graphic illustration of this possibility. The lognormal line plot which assumes that all of the cyclones belong to one **statistical population** bears little relationship to the histogram of the actual records. The lack of records having CI = 5.0 and 5.5 and then the lack of a tapering off in the occurrence rate for the higher CIs suggests that in the Darwin region at least, once cyclones exceed CI = 4.5, something 'lets them loose', they quickly pass through the CI = 5.0 and 5.5 levels and enter a class which is subject to quite different controls - they effectively enter a different statistical population.

A possible physical explanation for this behaviour has been provided. A study of GPS dropsonde records obtained from 15 hurricanes between 1997 and 1998 found that there was a large decrease in the drag coefficient and surface roughness of the sea when the wind speed went from speeds equivalent to maximum 200 kph to 260 kph surface gusts (Powell et al, 2003). A possible physical explanation for the phenomena made by the authors was that within the speed range, the sea surface turns to foam to create a 'slip surface' which suddenly reduces the frictional restraint provided by rough seas at the lesser wind speeds.

The speed range mentioned in the above paper is equivalent to CI = 5.0 to 6.0. The writer has been advised (Kepert pers. comm..) that there are several other physical or thermodynamic reasons that could explain how and why cyclones might quickly pass from one class to another.

The writer considers that there is also a plausible explanation why there is no apparent tapering off in the frequency with increase in intensity after passing the CI = 6.0 threshold – namely that the factors which let the system suddenly intensify are subsequently opposed by a new set of factors which restrain further intensification (increasing asymmetry for example) and it is the net effect of these counteracting factors which leads to the constant rather than diminishing frequency. This would mean that for this region, there will be more or less equal numbers of cyclones having CIs between say CI = 6.0 and 7.5 rather than the numbers tapering off from a high number at CI = 6.0 to a very low value at CI = 7.5.

5) Other statistical methods should be used which make a better fit to the data.

Given all of the above, it would seem entirely logical that to project future trends from the Darwin region records, the probability distribution to use is simply the one directly indicated by the data. That is, the number of CI occurrences in the range 6.0 to 7.5 will be constant.

After coming to this rather obvious conclusion, the writer was heartened to stumble across a passage in a paper by an eminent authority on cyclones supporting the idea (Emanuel, 2003). That passage is so important to this discussion that it will be quoted in full:

"There are now enough measurements of tropical cyclone wind speeds, since such estimates became accurate, to make some elementary statistical analyses of intensity. The author (Emanuel 2000) calculated cumulative frequency distributions of the wind speeds in North Atlantic and western North Pacific tropical cyclones. The peak winds reached during the storms, normalized by their theoretical maximum values, [refer Section 2.2 (c)] *tend to fall into one of two linear cumulative distributions depending on whether the storm does or does not reach hurricane intensity, as shown in Figure 2.* ***This means that a randomly chosen tropical cyclone has the same probability of reaching any given intensity up to marginal hurricane intensity, and another (but constant) probability of reaching any intensity between marginal hurricane intensity and the maximum theoretical intensity at that time and place.****"*

The figure 2 referred to in the above will not be reproduced here but basically it explains the general form taken by the green and red histogram bars in Fig. G.1.

The referenced paper (Emanuel, 2000) describes the study in detail. The data came from 56 North Atlantic hurricanes post 1958 and 73 western North Pacific hurricanes post 1970. Storms whose peak winds would have been limited by landfall or passage over cold water were not included.

It should be noted that the constant probabilities for intensity only prevails if the data has been first 'normalized' by dividing the recorded intensity with the prevailing MPI.

Recommendation

Research the appropriate probability distribution to use for risk analysis of NT cyclones. The research team should include or consult with internationally recognised experts including K. Emanuel and M.D. Powel.

WIND SPEED – FREQUENCY RELATIONSHIPS FOR THE DARWIN REGION USING TABLE G.2 DATA

These will be an engineer's ball park estimates similar to the ones made in Appendix E from the long-term written records.

The analysis will be grossly simplified by considering just average values rather than a range of possible values as is done in computer simulations. We assume that all intense cyclones have:

(i) a radius of maximum winds (Rmw) = 15 km. (The average Rmw for Tracy, Neville, Thelma, Ingrid and Monica when they were most intense was 15.6 km.);
(ii) relatively 'peaked' wind fields (as they tend to be in the NT) so that beyond 19 km from the centre, the maximum gusts drop below the value under consideration;
(iii) the same MPI regardless of the month of occurrence (but that MPI is so rarely attained that its probability can be ignored);
(iv) equal probability of having CI = 6.0, 6.5, 7.0 or 7.5 when they are at their most intense.

At this point it will be better to convert back to measuring intensity in terms of maximum gusts speeds rather than CIs. The conversions again are:

CI	6.0	6.5	7.0	7.5
Maximum gusts (kph)	262	290	324	357

The AEP for maximum gusts greater than (>) any one of the above speeds impacting any one particular building in Darwin will be estimated by assuming:

a) the centre of a cyclone entering the 500 km radius circle can pass that building at any distance between zero and 500 km – there is no preferred distance, all distances having equal probability.
b) because of (ii) above, only cyclones with centres coming within 19 km of a building will produce maximum gusts on that building.
c) From a) and b), for any one cyclone, the chance of its maximum gusts impacting the building is 19/500.
d) The intensities in Table G.2 are for the cyclones when they are at their most intense. A large proportion of cyclones will weaken considerably from that value before impacting Darwin. For this rough estimate we assume 50% of cyclones maintain that peak intensity through to impact and 50% weaken to be non-intense at impact.
e) Table G.2 provides only rough guidance as to the frequency of intense cyclones coming within a 500 km radius circle drawn around Darwin. Here we will consider the two scenarios given on page G-15, namely:
   Optimistic Scenario: an intense cyclone will enter on average once every 11 years; or
   Pessimistic Scenario: a category 5 cyclone will enter on average once every 3 years.

Optimistic Scenario:

The AEPs for intense cyclone gusts of a given speed impacting a single building are approximately**:**

- for gusts > 262 kph, AEP = 19/500 x 50/100 x 4/44 = 1/600
- for gusts > 290 kph, AEP = 19/500 x 50/100 x 3/44 = 1/800
- for gusts > 324 kph, AEP = 19/500 x 50/100 x 2/44 = 1/1,200
- for gusts > 357 kph, AEP = 19/500 x 50/100 x 1/44 = 1/2,300

Pessimisitic Scenario

The AEPs for Category 5 gusts of a given speed impacting a single building are approximately**:**

- for gusts > 290 kph, AEP = 19/500 x 50/100 x 3/9 = 1/160
- for gusts > 324 kph, AEP = 19/500 x 50/100 x 2/9 = 1/240
- for gusts > 357 kph, AEP = 19/500 x 50/100 x 1/9 = 1/470

DISCUSSION

Without further research, there is really no way of knowing whether the writer's optimistic or pessimistic estimates will prove to be more accurate in the long term. But two observations are made:

- The optimistic scenario above predicts wind speeds for a given AEP which are well in excess of the values predicted in the most recent studies for government relating to design wind speeds and storm surge inundation heights for the Darwin region;
- Until further research throws light on the matter, the pessimistic scenario should be assumed for decisions relating to emergency management and provision of cyclone shelters.

REFERENCES

Emanuel, K. (2000). A Statistical Analysis of Tropical Cyclone Intensity. *Monthly Weather Review*, **128,** 1139-1152

Emanuel, K. (2003). Tropical Cyclones. *Annual Review of Earth and Planetary Sciences*. **31,** 75-104.

Georgiou, P. (2000) Darwin Region, Category 5 Cyclone Risk Assessment. A report to the NT Department of Transport and Works.

Holmes, J.D. (1998) Wind loading of structures. *Progress in Structural Engineering and Materials. .* ***1 (2),*** *193-199.*

Holmes, J.D. (2001) Wind Loading of Structures. *Spon Press.*

Jagger, T.H. and J.B. Elsner. (2006) Climatology Models for Extreme Hurricane Winds near the United States. *Journal of Climate.* **19**, 3220-3236.

Love G. and K. Murphy (1985) The Operational Analysis of Tropical Cyclone Wind Fields in the Australian Northern Region. *Bureau of Meterology*, Northern Territory Region Research Papers, 1984 85, Nov, 44-51

Powell, M.D., P.J. Vickery and T.A. Reinhold. (2003) Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279-283.

Wang, Y. and C-C. Wu (2004) Current Understanding of tropical cyclone structure and intensity changes – a review. *Met. Atmos. Phys,* **87,** 257 - 278

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region.

SEA Pty Ltd. (2006) Darwin Storm Tide Mapping Study 2006. Prepared by Systems Engineering Australia Pty Ltd for NT Emergency Services.

Appendix H

GUST SPEED WEAKENING AFTER LANDFALL

APPENDIX H   GUST SPEED WEAKENING AFTER LANDFALL

SUMMARY

This appendix examines how cyclones weaken after they make landfall. The weakening is caused by the cyclone being deprived of some or all of its energy as the eyewall fully or partially moves away from the warm seas which are the source of its energy. The effect has two important practical applications; it determines to what extent:

- design wind speeds can be reduced with distance inland,
- intervening islands (such as the Tiwi islands or Croker island) or mainland projections (such as the Coburg or Cox peninsulas or Cape Hotham and Gunn Point) can reduce wind speeds on down-track locations such as Darwin.

The following looks at three aspects of the subject:

- the provisions made in the current wind code to allow for weakening
- recent research which has provided formulae to calculate the maximum wind speed in a cyclone's eyewall in terms of the number of hours after landfall
- application of the formulae to NT conditions

THE WIND CODE

The Australian/New Zealand wind code, AS/NZS 1170.2:2002 takes a very broad brush approach to account for the reduction of wind speeds as a cyclone moves inland. For the Top End, it specifies just three regional wind speeds which for an AEP = 1/500 are 250 kph, 205 kph and 162 kph for Regions C, B and A respectively. Region C extends from the coast to a line 50 km in from a 'smoothed' coastline, Region B is a band extending a further 50 km inland and region A is everywhere else.

The wind code includes a map which takes in the whole of Australia on an A4 page and indicates the approximate location of the 50 km and 100 km demarcation lines. There is no definition in the code as to what constitutes the 'smoothed' coastline. Positions of the demarcation lines for the NT are indicated in Figure H.1 next page. **Note.** This map is only for illustration purposes for this report - actual boundaries should be obtained from the appropriate authorities.

It is generally accepted that a cyclone's maximum gusts have become a lot weaker by the time it has gone 50 km inland - so why is that reality not reflected in building regulations? The answer presumably is that the use of just two cyclonic zones in the NT (WA has three cyclonic zones) may simplify descriptions in codes and regulations - but it is an absurd simplification of the reality.

It is suggested that in these days of computerised Graphical Information Systems, a much more graduated zonation could be easily displayed for the public on DPI's website. This would allow everyone to know exactly how their own property fares in relation to the maximum wind speeds predicted for or recorded at the coast.

It would also enable the 'smoothed' coastline to be graphically represented – it is an important but not trivial problem for indented coastlines such as those that prevail in the NT.

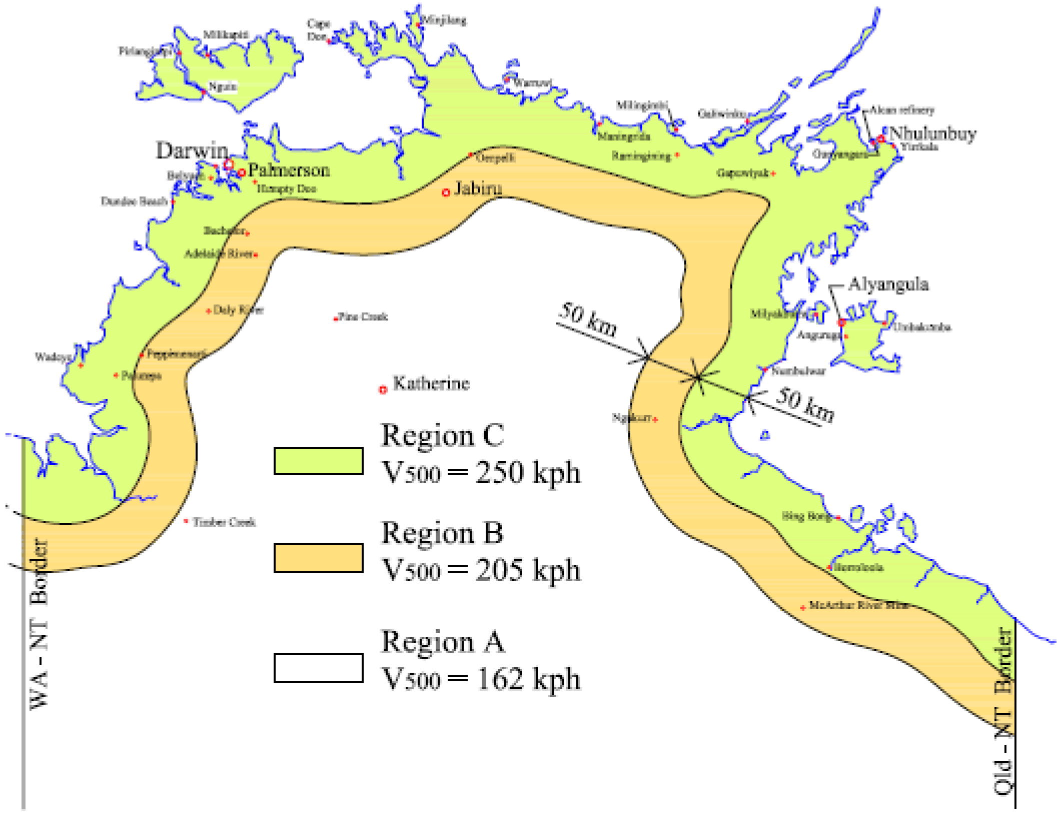


Figure H.1 How the wind code's Regional Wind Speed varies inland from a 'smoothed' coastline

RECENT RESEARCH

Actually the first phase of this research is not so recent. Data from more than 400 hurricanes that made landfall on the US mainland in the period 1967-93 was examined to determine how they had decayed inland (Kaplan and DeMaria, 1995). An empirical formula was derived based on the assumption that cyclones/hurricanes decay at a rate which is proportional to their landfall intensity reduced by what is termed 'background' intensity. The formula, given below, is used for operational forecasting in the US and is partly the basis for the wind speed isopleths used for structural design in the hurricane prone states.

$$V(t) = Vb + (R \times Vo - Vb) \exp(-\alpha \times t) \qquad \text{.............................(1)}$$

Where V(t) is the maximum wind speed after the centre has had time t over land,
Vb is the background wind speed that the storm decays toward over land,
Vo is the maximum wind speed just before landfall,
R is a reduction factor to allow for the observed rapid decrease in wind speeds within a few kilometers of the coast as a landfalling cyclone adjusts to the increased roughness over land,
α is a decay constant,
t is the time that the cyclone centre has been over land since landfall.

Formula (1) can be applied to cyclones such as Tracy or Monica which move more or less from being entirely over water shortly before landfall to being entirely over land shortly after landfall. However, it can not be used for cyclones such as Ingrid which move over islands and peninsulas or move close to, and parallel to, the coast

The recent research was carried out when the same group examined hurricanes moving across Caribbean Islands (DeMaria et al, 2006). This paper allows for the more general case of cyclones such as Ingrid which make only a partial landfall. DeMaria derived the following formula:

$$Va = \{Vb + (R \times V_0 - Vb) \exp[-(\alpha \times F \times t)]\}/R \quad \ldots\ldots\ldots\ldots(2)$$

Where Vb, Vo, α, t and R (as the multiplier) are as defined above,

Va is the maximum mean winds after the centre moves back over water,

R (as the divisor) is to allow for the immediate increase in mean wind speed as the cyclone moves back over water.

F is the proportion of the cyclone's 'circulation area' which is over land. (There is no specific or correct radius for the circulation area but values of about 2 x Rmw proved to give the most accurate results.)

Although not stated by DeMaria, it is apparent that before the cyclone fully makes 'land departure', the wind speed $V(T_1)$ at some intermediate time T_1 after landfall can be obtained from formula (2) by deleting the divisor R so that:

$$V(T_1) = Vb + (R \times V_0 - Vb) \exp[-(\alpha \times F \times T_1)] \ldots\ldots\ldots\ldots\ldots(3)$$

Further, the wind speed $V(T_2)$ at some intermediate time T_2 after landfall can be obtained by using appropriate values in formula (3) or, if after time T_1, F changes value to F_2, by using:

$$V(T_2) = Vb + (V(T_1) - Vb) \exp[-(\alpha \times F_2 \times (T_2 - T_1))] \ldots\ldots\ldots (4)$$

The following values for the three constants in the formulae were derived for hurricanes south of latitude 36°N: R = 0.9, $\alpha = 0.095\ hr^{-1}$ and Vb = 26.7 knots (Kaplan and DeMaria, 1995). DeMaria, in his 2006 paper adopted the same values for his Caribbean results but comments:

"it might be possible to further improve the model by first determining a new set of the basic model parameters (R, Vb and α) for the very low latitude storms."

The only modification to the constants made here to account for the NT's low latitudes is to use a value of R = 1.0 instead of 0.9. The change was made simply because it made a better fit with the best-track data for Ingrid rather than for any theoretical reason. This is explained on page H-7.

The formulae in the referenced papers have been modified here to account for different units of wind speed. Here V(t) and V(a) are in terms of 2 second gust speeds in kph instead of 1 minute mean wind speeds in knots. (To do this, the 26.7 figure for Vb in the referenced papers becomes: 26.7 x 1.85 x 1.35 = 67 kph. (1.85 to convert from knots to kph and 1.35 is the gust factor to convert 1 minute mean wind speeds to 2 second gust speeds over Terrain Category 2 land surfaces. (WMO, 1993)

CHECKING THE KAPLAN-DEMARIA FORMULAE FOR THE NT

Testing Formula (1) against the actual decay estimated for cyclones Tracy and Monica:

Cyclone	Time after landfall (t) hours	Gust speeds V(t) in kph from Formula (1)	Gust speeds in kph from 'records' (a)
Tracy Vo = 260 kph	0	234	-
	3	193	155
	8	145	110
Monica Vo = 360 kph	0	324	-
	3	260	234
	9	176	127
	15	129	66

Table H.1 Maximum gust speeds for Cyclones Tracy and Monica as derived from Formula (1) and from 'records'

Notes:
(a) The speed 'records' for Tracy are estimates based on tree damage and recorded lull times at Howard Springs and the CSIRO village. For Monica they are based on BoM's Dvorak estimates.
(b) The value for R in Formula (1) was made = 0.9 as recommended by Kaplan-DeMaria for Atlantic hurricanes. As shown in the next section dealing with Ingrid, R should probably be 1.0 in the NT. (Using the latter value for Monica would change V(t) at 9 hours from the 176 kph tabulated to 192 kph.)

As the above table shows, both cyclones decayed more rapidly than predicted by Formula (1). However both cyclones probably decayed much faster than normal for reasons unrelated to landfall: The rapid decay near landfall for:

- Tracy was probably related to an eyewall replacement cycle (SEA, 2005)
- Monica was probably related to environmental conditions which caused the eyewall to shear and dry, continental air to be entrained (Todd Smith, pers.comm.)

So the good news from the above is that NT cyclones may sometimes weaken more rapidly than predicted by the Kaplan-DeMaria formulae.

There are at least two other regional factors which might to lead to NT cyclones decaying more rapidly than those in the US. They are:

- Kaplan refers to the mean radius of maximum winds of hurricanes in the US being 35 km. This means that US hurricanes will have greater momentum and therefore presumably greater persistence than a cyclone of Monica's size (Rmw = 22 km) and much greater for one of Tracy's size (Rmw = 12 km).

- Top End cyclones are powered by sea temperatures that are considerably higher than those for US hurricanes. Therefore removal from the heat source after landfall could be expected to lead to more rapid decay in intensity.

Testing formulae (1) and (3) against the actual decay of Cyclone Ingrid:

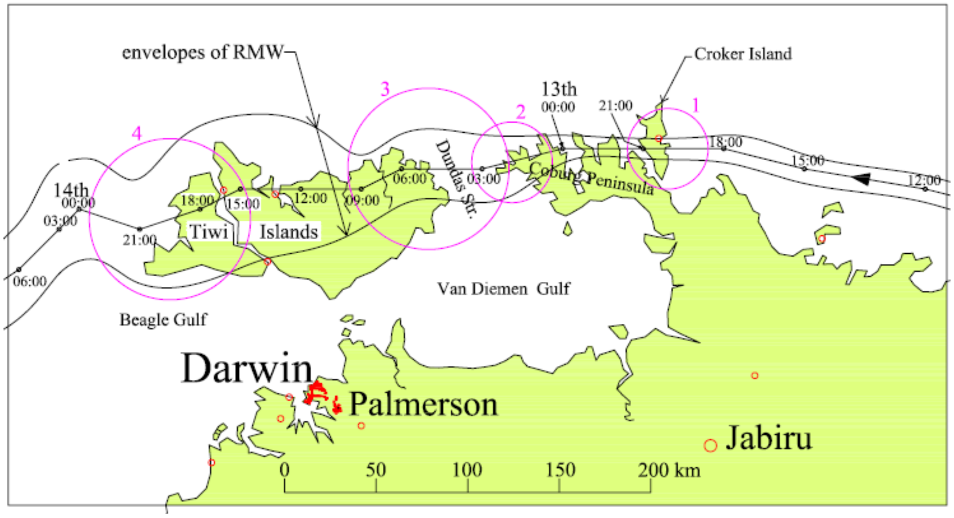


Figure H.2 Track of Cyclone Ingrid showing the swathe for the radius of maximum winds. The magenta circles are the assumed ‘circulation areas’ used to derive the ‘F’ value.

The first test was to simply use Kaplan’s original formula on Cyclone Ingrid’s best track data. Contrary to Tracy and Monica, Ingrid decayed less rapidly than predicted by Formula (1).

Kaplan Formula (1) for Ingrid after its landfall on Croker Island

Formula (1): Vt =Vb +(R x Vo - Vb) exp-0.095 x t

where Vt = 2 second gust in kph after time t inland.

Vo = 2 second gusts at landfall in kph.

t = time in hours after landfall.

R = 0.90, Vb = 67 kph

landfall' when both sides of eyewall over the east shore of Croker at 20:00 UTC.

maximum Vo = 243 kph (based on interpolation of BoM's estimates)

Vfm = speed of forward movement of cyclone [Kaplan allows for it Formula (1)]

Estimated Actual Vt per BoM [Dvorak allows for Vfm = 10 -20 kph in value of Vt]

	Kaplan formula:		Vo =	Estimated Actual (Dvorak)	
Time UTC	t	Vt	243	Vt	Vfm
20:00	0	219			
21:00	1	205		234	13
0:00	4	171		234	15
3:00	7	145		205	15
6:00	10	126		205	15
9:00	13	111		176	8
12:00	16	100		176	11
15:00	19	92		176	11
18:00	22	86		150	8

CONCLUSION: Ingrid decayed much slower than the Kaplan formula predicts.
(At least 50% of the eyewall was over water or mangrove over the 22 hours.)

Table H.2 Cyclone Ingrid decayed much more slowly than predicted by Formula (1).

The second test was to use DeMaria's formula modified to calculate maximum gusts whilst crossing a narrow landmass – ie by using Formula (3) (refer page H-4).

By trial and error, it was found that a better fit could be made by using R = 1.0 in the formula rather than the Kaplan – DeMaria value of R = 0.9. However the factor does not make a great deal of difference in final results. For instance, using R = 0.9 instead of R = 0.1 in Table H.3 below would give Vt = 138 kph instead of 150 kph at 18:00 hrs on the 13th.

Similarly, it was found that results were not particularly sensitive to the value chosen for F. A mean value of F = 0.4 was chosen in the table below:

DeMaria Formula (3) for Ingrid after its landfall on Croker Island

Formula (3) Vt = Vb + (R x Vo – Vb) exp-0.095 x F x t
Use F = 0.4 between 20:00 and 2:00 on 13th (as far as Cape Don)
Use Vb = 67 kph, R = 1.0

	DeMaria Formula		Vo =	Estimated Actual	
Time UTC	t	Vt	243	Vt	Vfm
20:00	0	243			
21:00	1	236		**234**	13
0:00	4	218		**234**	15
2:00	7	202		**205**	15

Vfm = speed of forward movement of cyclone [Kaplan allows for it Formula (1)]
Estimated Actual Vt per BoM [Dvorak allows for Vfm = 10 -20 kph in value of Vt]

Assume while crossing Dundas Straight, Ingrid re-intensified to over water state: but no further intensification - ie. Between 2:00 and 5:00, Vt remained at 202 kph

Time UTC	t	Vt	202	Vt	Vfm
2:00	0	202			
3:00	1	202		205	15
5:00	3	202			

Now consider decay as Ingrid crosses the Tiwi Islands:

Formula (3) Vt = Vb + (R x Vo – Vb) exp-0.095 x F x t
Use F = 0.4 between 5:00 and 19:30 on 13th (over the Tiwi Islands)
Use Vb = 67 kph, R = 1.0

	DeMaria Formula		Vo =	Estimated Actual	
Time UTC	t	Vt	202	Vt	Vfm
5:00	0	203			
6:00	1	198		**205**	15
9:00	4	184		**176**	8
12:00	7	171		**176**	11
15:00	10	160		**176**	11
18:00	13	150		**150**	8
19:30	14.5	145		**150**	
21:00				150	12

Table H.3 Cyclone Ingrid's decay is reasonably well predicted by Formula (3).

As can be seen, the modified DeMaria formula produced a good fit with the observed weakening of Cyclone Ingrid from its landfall on Croker Island to its re-entry into the Timor Sea west of Bathurst Island.

USING THE KAPLAN - DEMARIA FORMULAE TO PREDICT THE INLAND WEAKENING OF NT CYLONES

As already mentioned, the wind speeds inland are very much dependent on the speed of forward movement (Vfm) of the cyclone. An inspection of Vfm values after landfall of the 1937 cyclone and Cyclones Tracy, Kathy, Thelma (in WA), Ingrid (in NT), Ingrid (in WA) and Monica revealed that minimum values for Vfm varied from 7 to 13 kph and the maximum values varied from 11 to 19 kph. The two most intense cyclones, Thelma and Monica had maximum Vfm values of 19 kph and 18 kph respectively. In the following analysis, the Vfm values adopted were 10 kph for a 'slow moving' cyclone and 20 kph for a 'fast moving' cyclone. The 'fast' values have been deliberately chosen to err on the high side to produce conservative estimates.

The following table gives results for slow moving and fast moving cyclones having maximum gusts at landfall of 250 kph and 360 kph respectively. The table uses Formula (1) with R = 1.0. This means that the results would be for a cyclone moving inland perpendicular to the coast and that the coastline in question is neither indented nor fringed with mangrove. To enable comparisons, the wind code values given in Fig. H.1 are repeated in the second column of the table.

Distance Inland (km)	Wind Code for NT RWS (kph)	Maximum Gust Speeds (Vt) in kph					
		'Slow Moving' Vfm = 10 kph			'Fast Moving' Vfm = 20 kph		
		t (hr)	Vo = 250	Vo = 360	t (hr)	Vo = 250	Vo = 360
0	250	0	250	360	0	250	360
25	250	2.5	211	298	1.25	230	327
50	250/205	5.0	181	250	2.50	211	298
75	205	7.5	157	211	3.75	195	272
100	205/162	10.0	138	180	5.00	181	250

Table H.4 Wind code values for RWS for distances inland in the NT and maximum inland gust speeds for slow and fast moving cyclones having maximum gust speeds at landfall of 250 kph and 360 kph

The above table is included here mainly to demonstrate that a cyclone's speed of forward movement is a very important factor in determining its inland gust speeds. Clearly the correct choice of inland RWS values involves much more complicated analysis than has been done here.

Table H.4 is based on Formula (1). For Darwin, Formula (3) is more important because it enables prediction of the potential weakening effects that the various islands and peninsulas could have on a cyclone passing over them on its way to Darwin. Unfortunately, Formula (3) shows that the weakening effects are not as great as some hope. However, there are so many combinations of possible tracks, forward speeds, intensities etc, that it is pointless trying to draw up a table to demonstrate the effects.

RECOMMENDATIONS

This report recommends:

- that funds be provided for a study to derive appropriate RWS values for the Top End's inland towns and communities. The study should:
    - allow for decay inland using the Kaplan-DeMaria formulae suitably modified for NT conditions using constants similar to those derived above for Cyclone Ingrid
    - be derived from one of the modern computer models based on the Monte Carlo Simulation technique. (The probability distribution function for maximum gust speeds at landfall should reflect a uniform rather than a tailed distribution.)
    - produce a more finely graduated range of RWS values rather than the large step-wise increases at 50 km and 100 km inland given in the current wind code.
    - present the graduated RWS as lines on a map on DPI's website. (As well as providing the necessary information to structural engineers, the website would allow everyone to know exactly how their own properties fare in relation to forecast maximum gust speeds in cyclone warnings. It would also enable the 'smoothed' coastline to be graphically, and unambiguously presented)

- that future studies using computerised models to determine storm tide and wind speed-frequency relationships for Darwin should incorporate formulae similar to those discussed above to account for the potential protection that Darwin gains from the surrounding islands and peninsulas.

REFERENCES

DeMaria, M., J.K. Knaff and J. Kaplan (2006). On the Decay of Tropical Cyclone Winds Crossing Narrow Land Masses. *American Met. Soc.* March 2006, 491-499. http://rammb.cira.colostate.edu/resources/docs/Decay_DeMaria.pdf

Kaplan, J. and M. DeMaria. (1995) A Simple Empirical Model for Predicting the Decay of Tropical Cyclone Winds After Landfall. *J. App. Meteor.*, **34 (11),** 2499-2512.

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region.

WMO (1993) World Meteorological Organisation, Global Guide to Tropical Cyclone Forecasting, Report TCP-31 available at: http://www.bom.gov.au/bmrc/pubs/tcguide/globa_guide_intro.htm

APPENDIX I

REVIEW OF TWO RECENT RISK STUDIES

APPENDIX I REVIEW OF TWO RECENT RISK STUDIES

SUMMARY

The two studies to be examined have been released to the public and should be found in the NT Public Library. They are:

- "On the Probability of Darwin being struck by a Category 5 Cyclone"; Environment and Climate Risk Assessment, 2000 by Dr Peter Georgiou for the NT Department of Transport and Works (*Georgiou, 2000*).
  In the following it will be referred to simply as the Georgiou study.
- "Darwin Storm Tide Mapping Study 2006". Prepared by Systems Engineering Australia Pty Ltd for the NT Emergency Service (*SEA, 2006*).
  In the following it will be referred to simply as the SEA study.

Both studies are by engineers who have used computer simulation techniques to model thousands of storms to derive wind speeds or storm tide levels as a function of ARI for the Darwin region. The authors of these reports are internationally recognised as being highly skilled and experienced practitioners in the use of their computer models in risk analysis. Some of the criticisms made here may possibly be due to the limited funds that were made available for the studies in the first place. In their conclusions, both authors comment on ways in which their studies could be improved. (These comments have been included along with this writer's own criticisms of some of the data, assumptions, methodology and report presentation in the following sections.)

The two studies are singled out because they are probably being used to guide the NT government in decisions relating to risks from intense winds or from storm tide for the Darwin region. Both studies are reassuring in that they predict risk levels that are equal to or less than previously accepted values. The studies are referred to several times in the main report of this review and in some of the other appendices. This appendix will consolidate those references and present an overview and a critique of these two very important studies.

PROBLEMS THAT ARE COMMON TO BOTH STUDIES

1) Limited period of record and doubtful quality of the data used for the models

The Georgiou study used BoM data from 1963 to 1999 for storms coming within 250 km of Darwin. Georgiou notes that the Northern Region wind-pressure relationship introduced by BoM, Darwin in 1985 (*Love and Murphy, 1985*) would have biased the data either side of that date but was unsure which side would be closer to the truth.

The SEA study used BoM data from 1959 to June 2006 for storms coming within 500 km of Darwin to produce a much larger dataset. The SEA study comments that the 1960s data possibly under-estimates intensity.

The limitations of such short periods of record are discussed on page 18 of the report and in Appendices G & O. The writer has concluded that at the present time it is not possible to define a definite risk level to any particular wind speed in Darwin and that until further research provides such definition, risk levels should be given in terms of an optimistic and a pessimistic scenario.

The research necessary to extend the length of the record are discussed in Sections 2.1 (b) and 2.3 of the report and in Appendices E, F, J, K, L & M

Improvements that can be made to the BoM database are discussed on pp 16 and 28 in the report and Appendices G & N.

2) Assumed probability distribution for pressures

Both studies used the central pressures in the BoM database as the starting point for their analyses. The probability distribution assumed for the pressures in the database was the input to determine the wind speed – frequency relationship used in the models. Although wind speed is not the endpoint of the SEA study, on its page 19 is the statement: *"The most significant parameter affecting regional storm tide is the intensity of tropical cyclone winds."*

The writer believes that both studies seriously under-estimate the wind risk level by assuming probability distributions for pressures that do not match the reality for intense NT cyclones. Problems with the lognormal distribution used for the Georgiou study and with the Gumbel distribution used for the SEA study are discussed in Appendix G.

These problems can be easily corrected if further research validates the recent findings on the distribution of intense cyclones relative to their MPI (*Emanuel, 2000*). [This is discussed in Appendix G.] Unfortunately, the corrections will lead to the models producing much higher risk levels for Darwin.

3) Use of the Holland wind speed model

Both studies rely on this model (*Holland, 1980*) to convert central pressures to the surface wind speeds. The problem with using pressures and the Holland model to derive wind speeds is that the variables involved must pass through several transformations and each transformation critically relies on parameters that as yet have no commonly accepted values. The transformations are:

- Apart from the rare cases where the minimum central pressure for a cyclone is measured directly with a barometer, the central pressures in the BoM database derive from the CI numbers (which are <u>not</u> entered in the database). As yet there is no accepted, uniform relationship in Australia between CI number and pressure and each TCWC uses a different table to make the conversion

- The required input to the Holland formula is the pressure drop, ΔP, between the ambient pressure and the minimum central pressure. The ambient pressure is not included in the database and some value must be assumed. Its value in the NT can vary between about 1000 hPa and 1010 hPa. The Georgiou study assumed an ambient pressure of 1010 hPa. The SEA study assumed an ambient pressure of 1007 hPa.

- The Holland formula produces a wind speed from the ΔP input but that speed is the **gradient wind speed** which is the mean wind speed at 3 km height. The speed produced by the formula is very much dependent on the so-called 'Holland B' which determines the 'peakedness' of the wind field. The value of B can lie between 1.0 and 2.5 (*Holland, 1980*). The table below demonstrates how the value chosen for B will effect the maximum gradient wind speed (ie the value at the peak) for a cyclone similar to Cyclone Ingrid with maximum ΔP = 80 hPa:

Holland B	Maximum Gradient Wind Speed (kph)
1.5	222
2.0	257
2.5	287

Table I.1 Comparison of maximum gradient winds produced by the Holland wind speed model with different values of the Holland B for a cyclone having ΔP = 80 hPa.

The significance of Table I.1 is that there is very little guidance to appropriate values for B and yet, as the table demonstrates, the probable range for B produces wind speeds that can vary between speeds equivalent to a high Category 3 cyclone to a low Category 5 cyclone.

The Georgiou study used values for B for intense cyclones which varied between about 1.2 and 1.8 depending on the intensity. (The report states that "*more recently the possibility of the higher end range of B values has been discounted"* – but no reference is given for this very important qualification.)
The SEA study used values for B of either1.5, 1.8 or 2.4 regardless of intensity.

- To convert from the gradient wind speeds to surface gust speeds requires application of a so-called Gust Conversion Factor (GCF). Once again, there is no generally accepted value for this critical factor. It is known that the factor varies between over water and overland conditions, between distance from the Rmw and, according to Georgiou, with distance inland.

- The Georgiou study used GCF values which vary between 1.0 and 1.2 for the first 10 km inland to 0.7 to 0.9 for locations more than 20 km inland.
The SEA study is of course concerned with wind speeds over the water and used different, lesser values for the GCF.

It seems that there is no consensus on appropriate values for B and GCF. This is demonstrated if the values used by BoM, Darwin for their regional wind-pressure relationship are considered. BoM, Darwin does <u>not</u> rely on the Holland wind speed model for their regional CI – wind – pressure relationship but if they did the values used would vary as indicated in the table below:

CI Number	ΔP (hPa)	Maximum surface gust speed (kph)	Required value of Holland B for:	
			GCF = 1.0	GCF = 1.2
6.0	62	262	2.6	1.9
6.5	70	290	2.9	2.0
7.0	80	324	3.2	2.2
7.5	90	357	3.4	2.4

Table I.2 Values of Holland B required to match BoM, Darwin's regional CI – wind – pressure relationship for two possible values of GCF.

Comment: The above problems are overcome in this report by simply using wind speeds that derive directly from the basic unit of measure for cyclone intensity that is most commonly used in the NT – the Dvorak CI number. This same approach should be used in future risk studies.

4) MPI

The Georgiou study refers to the importance of MPI but makes no direct mention of an appropriate value. However, from the results, it would seem that the MPI value assumed in the study was about 880 hPa.
The SEA study specifically allowed for an MPI corresponding to a central pressure of 880 hPa.

However, on the basis of the wind-pressure relationship used for the NT, BoM, Darwin assumes that the MPI pressure is about 907 hPa. (This is assuming that BoM, Darwin regard a CI number of 8.0 and a maximum gust speed of 390 kph as also representing a MPI event.)

The writer has no opinion as to which MPI central pressure is more likely to represent the reality. The concern should be with wind speeds – not pressures.

5) Proprietary Information

Both studies use computer models which are understood to be proprietary so that members of the public have no direct way of assessing the reasonableness of the results obtained from them. It is considered that a public model should be developed with goals similar to the cyclone risk model developed by the State of Florida - refer:
www.cis.fiu.edu/hurricaneloss/documents/Meteorology/Final_Report_Atmos.pdf

Such a model should:

- cover the weather related aspects and effects on landfall in the current proprietary models
- be open and transparent so that members of the public could make their own judgements on the validity of the assumptions made and could make comparisons with past or future, proprietary models

6) Track shapes

The models in both studies only consider cyclones with straight line tracks. This simplification could have an adverse effect on the results. The three cyclones that have caused most damage to Darwin (1897, 1937 and 1974) all recurved dramatically before making their closest approach and that same possibility should be accounted for in the future.

The State of Florida public model referred to above was developed by Risk Management Solutions Inc. and they incorporated what is known as a *random walk* into the model to properly simulate track and pressure distributions. The parameters of the *random walk* model were obtained from analyses of historical hurricanes for the time period 1900 to 1999. It is believed that the model also allows for the weakening or re-intensification of cyclones as they pass or leave the mainland or islands.

Future risk studies for Darwin should incorporate similar features. The 'sheltering' effect afforded by the Tiwi Islands, the Coburg Peninsula, the Cox Peninsula, Gunn Point, Cape Hotham, etc. needs to be accurately modeled within the random walk module. The writer's findings in Appendix H demonstrate how these effects can be calculated.

7) Track directions

Both studies relied on the analysis of their short period records to derive the most likely track directions for cyclone nearing Darwin for use in the model. The analyses correctly indicated that the dominant track direction for cyclones approaching Darwin in the last fifty years is toward the south-west. The use of this track direction has an effect on the results – particularly for the storm tide levels in the SEA study. (For all other variables held constant, cyclones with an easterly component in their tracks produce the highest storm tides).

The SEA study assumed that only **4%** of future cyclones will have an **easterly** component in their tracks. However, as discussed on page 14 of the report and detailed in Appendix E, between 1859 and circa 1940, five of the six cyclones (and all four of the intense cyclones) that came within 50 km of Darwin had an easterly component to their tracks.

There is a possibility that the pre-1940 track direction preference might return sometime into the future – that possibility needs to be researched.

THE GEORGIOU 2000 STUDY

This study was commissioned by the NT Department of Transport and Works and followed the occurrence of Cyclone Thelma in 1998. There were fears that the unprecedented passage of a Category 5 cyclone so close to Darwin indicated that the wind code seriously under-estimated the real risk to Darwin and to other coastal communities.

[Dr. Peter Georgiou was also the prime author of a 1994 report to the NT government on storm tide risk for Darwin (*VIPAC, 1994*)]

The findings of the Georgiou study are simplistically summarised by the red line in Fig. 2.1.5, page 27 of this report. In general the study derived similar risk levels to those given in the wind codes – particularly for houses, apartments, shops etc. As shown in Fig 2.1.5, risk levels for buildings such as hospitals, etc with a higher ARI requirement were found to be higher than given in the wind code. The study also found that the risk levels for dynamically sensitive structures such as high, slender masts and towers were higher than given in the wind code. However, on the whole, the findings were reassuring and gave no cause to make changes to the regulations covering the design of buildings in Darwin.

Some additional faults with the Georgiou study are:

1) It is a very difficult document to understand

This fault is probably a consequence of the funding and time constraints involved. Many aspects of the report are complex and the report merely reflects this complexity instead of trying to present the information in a way that could be readily understood by the layperson. The report was withheld from public release for about a year - this may have been simply because very few people could comprehend the report’s findings.

2) Some aspects of the parameters and methodology used were not detailed

These aspects could have been given in appendices in the study's report. The missing details relate to things such as:

- wind behaviour during and after landfall
- sources and details for the all important Gust Conversion Factor (Table 3.2.1 in the study)
- choice of the lognormal probability distribution for ΔP and the shape parameters used

It may be that the above were omitted because they are proprietary information. Documents that deal with public risk issues should be fully disclosed for detailed examination by members of the public. A solution to this problem is discussed in paragraph 5 on page H-4.

3) Confusion caused relating to criticisms of Dvorak speed estimates

Section 6 of the study report comprises nine pages which are mostly devoted to raising doubts as to the validity of wind speed estimates derived by the Dvorak technique. There is not a single reference to support any of the author's statements so it is hard to know which are opinions and which are supported by peer reviewed literature.

Some of the criticism revolves around wind-pressure relationships and appropriate values for the Holland B. As discussed above, these problems can be overcome by avoiding use of the Holland wind speed model.

4) Confusion caused relating to provisions in the wind codes

Georgiou examines various provisions in the wind codes but appears to have not fully appreciated their complexities. The wind codes should have been accepted as is and the study merely concentrate on providing risk levels for what are now called the Regional Wind Speeds. Examples of unnecessary complications being introduced are:

a) There are several comments about city-wide risk being less than the risks for a single building. This point needs to be made but it need only be made once. Engineers understand that the wind code risks refer to a 'point' or a single building. 'City- wide' risks should have been presented in a single section rather than repeatedly qualifying the single building risk.

b) The findings in the report were complicated by them being compared to the then current (1989) version of the wind code and DR 99419 which was the draft version of the now current (2002) version of the wind code. The author was probably compelled to consider both because of the timing of the report, but once again, for clarity of presentation, it would have been much better to have made the code comparisons in separate sections in the report rather than switch from one to the other.

c) The report was further complicated by presenting the risks for normal buildings in the same tables as those for slender towers – once again the two types of building should have been examined in separate sections.

d) The author has given his results relative to terrain categories but appears to think that these are somehow related to distance inland. The findings should have been given only in terms of what are now called Regional Wind Speeds and left discussion about appropriate terrain categories to another forum.

Conclusion

The Georgiou study was very important because it was the first (publicly available) study that used the Monte Carlo Simulation technique to derive wind speed risk levels that were specific for the Darwin Region. However it could now be considerably improved with more modern information. Perhaps this is best exemplified by the study's finding that: *"cyclones of Thelma's intensity are generated on a 350-year return period basis somewhere within a 250 km radius circle around Darwin."* The subsequent arrivals of Ingrid and Monica have demonstrated that was an overly optimistic projection.

THE SEA 2006 STUDY

The SEA study was commissioned by the NT Emergency Service and followed work done by the same company in 2005 to prepare a storm tide prediction system for the whole of the NT (*SEA*, *2005*). [This system is being used by BoM for operational forecasting.]

The study area centres on Darwin Harbour but extends to Cape Grose in the west, to Gunn Point in the east and to the southern coastline of the Tiwi Islands.

Before deriving storm tide risk levels, it is necessary to derive wind speed risk levels. The SEA study's wind speed – ARI relationship is simplistically summarised by the blue line in Fig. 2.1.5, page 27 of this report. Comparative maximum gust speeds for ARI = 1,000 years are:

- SEA study: 242 kph
- Georgiou study: 260 kph
- Region C wind code: 265 kph.

The storm tide levels derived in the SEA study are appreciably lower than those derived in the 1994 VIPAC report [and in earlier storm tide risk reports (1)]. For instance, for Fannie Bay, the storm tide level for ARI = 1,000 years is 5.5 m AHD according to the SEA study and 6.4 m AHD according to the VIPAC study.

Additional Faults with the SEA study

The faults discussed here are those that are additional to the faults already discussed as being common to both the SEA study and the Georgiou study:

1) No allowance for wave run up

Wave setup (2) is allowed for in the SEA study but wave runup (3) is not. This is recognised by the author of the report as a limitation of the study. The additional storm tide levels from wave runup could vary over lengths as short as 100 m and would require detailed modelling to predict.

The writer considers that until such time as results are available from detailed modelling, wave runup effects should be allowed for in some way. Probably the locations most likely to be affected could be quickly identified and an approximate value calculated. The increase in storm tide level from wave runup effects could be 1.0 m or more in some places.

Footnotes:
(1) In 1974, the writer made ball-park estimates for storm tide in Darwin for a report which was submitted by the Institution of Engineers to government one month before Cyclone Tracy. The estimate allowed for wave setup and included an allowance of 0.2 m to allow for heavy rainfall effects. The estimated storm tide level was 7.1 AHD for ARI = 1,000 years (Gamble et al, 1974).

(2) Wave setup adds to the storm surge to increase the mean water level at the shore line. It is due to cumulative effect of breaking waves coming onshore.

(3)Wave runup also adds to the storm surge and results from the familiar up-rush of breaking waves on a steep surface or inclined beach.

2) No allowance for sea level rise

This is recognised by the author of the SEA report as a problem and he recommends that sea level rise be included in future studies.

The writer understands that current engineering practice in Darwin is to continue the decade long practice of allowing 0.5 m for future sea level rise for any substantial developments on the foreshore. This would seem to be an appropriate figure to add immediately to the SEA study results.

3) No allowance for heavy rainfall

It would be quite possible to get 200 mm of rain from a cyclone before its peak surge arrived. This would tend to raise sea level everywhere by that amount but by much higher amounts up rivers, creeks and estuaries.

It will require detailed studies to determine the effects locally. The rise in water level could easily be more than 1.0 m in streams such as the Rapid Creek, Ludmilla Creek, Sadgroves Creek, Elizabeth River, etc. In the meantime, it would seem appropriate to add an allowance of at least 0.2 m for rainfall effects to the SEA study results.

4) Coarse grid resolution

This is recognised by the author of the study as a problem. The grid resolution used is 560 m which is too coarse to adequately model localised wave effects or properly allow for the shape of estuaries or channels.

Presumably, a finer grid could be easily incorporated into the model provided the necessary funds are made available.

It is noted that when the VIPAC surge model was tested against Cyclone Tracy, it was initially unable to reproduce the measured 1.6 m surge. It was only after incorporation of a finer grid into the model that a reasonable match was obtained. It would therefore seem probable that a finer grid will tend to increase storm tide levels – particularly up estuaries such as Sadgroves Creek – but the writer can offer no suggestions how to quantify the effect.

5) Presentation of the Results of the Study

The SEA study has adopted a very simple way of presenting the storm tide levels for ARI values of 500, 1,000 and 10,000 years. Each ARI has a separate map of Darwin and storm tide levels are given by over-printing the AHD levels on the maps. The only problem is that the scale of the maps is such that the storm tide level for a particular lot or street cannot be determined with any accuracy. However given that this is presumably only a preliminary study that is probably no bad thing.

Hopefully future studies will present the results in this way on a public website but to a much finer resolution so that levels for individual lots can be easily ascertained.

RECOMMENDATIONS

<u>Relevant to both studies:</u>
Future studies should:

- present a range of values based on optimistic and pessimistic scenarios (similar to the way the IPCC present their risk predictions for global warming and rise in sea-level)

- avoid the use of the Holland wind speed model with its requirement to have the five transformations and their attendant uncertainties

- use the simple procedure adopted in this report which is to use the basic measurement made by BoM (the CI number) as the primary variable for determining probability distributions.

- obtain wind speeds directly from the globally applicable relationship between surface wind speeds and the Dvorak CI number - refer Appendix A. (The only innovation that would be required to utilise such a procedure would be to derive a set of wind field shapes that would be typical for NT cyclones in terms of their Rmw and peakedness.)

- use a realistic probability distribution. For intense cyclones, such a distribution would perhaps allocate an equal probability of say 0.24 for the occurrence of a CI 6.0, 6.5 .7.0 or 7.5 cyclone and 0.04 for a (MPI) cyclone with CI = 8.0

- be based on a transparent, public model similar to the one developed for the State of Florida

- incorporate 'random walk' tracks rather than straight line tracks and make allowance for weakening or re-intensification of cyclones crossing land based on parameters appropriate to the NT

- allow for the possibility that future cyclones may behave like pre-1940 cyclones with a much higher proportion approaching Darwin with an easterly component in their tracks

<u>Relevant to the Georgiou study only:</u>

Future studies to derive appropriate design wind speeds for Darwin (or any other specific NT community) should concentrate only on values for the Regional Wind Speeds and leave the complexities (and failings) of the wind code to separate reports.

<u>Relevant to the SEA study only:</u>

Future studies should:

- allow for future climate change by including allowance for the sea level rising with each passing decade into the future.

- allow for wave run up and rainfall runoff

- improve resolution by using a much finer grid

REFERENCES

Emanuel, K. (2000). A Statistical Analysis of Tropical Cyclone Intensity. *Monthly Weather Review*, **128,** 1139-1152

Gamble, A.J., M.J. Nicholls and K. Wise (1974) Is Darwin Prepared for a Cyclone? *Report by the 'Cyclone Sub-Committee' of the Institution of Engineers, Australia- Darwin Group.* 19 pp.

Georgiou, P. (2000) Darwin Region, Category 5 Cyclone Risk Assessment. A report to the NT Department of Transport and Works.

Holland, G.J.(1980), An Analytic Model of the Wind and Pressure Profiles in Hurricanes. *Monthly Weather Review*, **108,** 1212-1218

Love G. and K. Murphy (1985) The Operational Analysis of Tropical Cyclone Wind Fields in the Australian Northern Region. *Bureau of Meterology*, Northern Territory Region Research Papers, 1984 85, Nov, 44-51

SEA Pty Ltd. (2005) Storm Tide Prediction System – System Development Technical Report. Prepared by Systems Engineering Australia Pty Ltd for the Bureau of Meteorology, NT Region.

SEA Pty Ltd. (2006) Darwin Storm Tide Mapping Study 2006. Prepared by Systems Engineering Australia Pty Ltd for NT Emergency Services.

VIPAC (1994) Tropical Cyclone Storm Surge Risk for the Greater Darwin Region – Final Report. Vipac Report 24113-2 for the NT Department of Lands, Housing and Local Government.

Appendix J

RESEARCH ON TREE RINGS

A report on the potential to reconstruct historical cyclone frequency and paths in the Northern Territory from tree-ring analyses

Dr Patrick J. Baker

Monash Tree-Ring Lab

School of Biological Sciences

Monash University

3800 VIC

Australia

January 2007

APPENDIX J RESEARCH ON TREE RINGS

A report on the potential to reconstruct historical cyclone frequency and paths in the Northern Territory from tree-ring analyses

SUMMARY

Dendrochronological methods were used to assess the potential for reconstructing historical cyclone frequency and spatial distributions across the Northern Territory using *Callitris intratropica*. *Callitris* samples taken from plantations near Darwin showed consistent patterns of ring-width variation over four decades. There was a notable reduction in growth in the Howard Springs chronology in 1974—the year that Tropical Cyclone Tracy hit Darwin. Immediately after TC Tracy some trees showed substantial growth increases, while other trees experienced intense suppression. The Howard Springs *Callitris* chronology also showed a significant reduction in growth in 1986—a year that was not associated with a cyclone. Further studies examining the isotopic composition (particularly δ18O) of crossdated tree-ring series may provide clarification of which tree-ring anomalies are associated with cyclones. It was not possible to extend the tree-ring record earlier than 1966 due to the lack of older *Callitris* samples. However, cross-sections of *Callitris* obtained from overland telegraph poles that were erected in 1870 suggest that there may be opportunities to extend *Callitris* tree-ring chronologies, and potentially the tropical cyclone record, back by 150-200 years. Identifying other tree species with annual growth rings that provide complementary records of cyclone impacts would widen the potential geographic range for reconstructing the past occurrence of intense cyclones in the Northern Territory.

PROCEDURES

<u>Sample collection</u>

The analyses are based on wood samples from several NT tree species, but primarily depend on samples of *Callitris intratropica* (Cupressaceae). Wood samples include cross-sections of trees and tree cores. Most samples were collected recently; however, several cross-sections were taken from overland telegraph poles that had been placed in the ground *c*. 1870. Non-destructive sampling using tree corers that remove a cylindrical length of wood 5 mm in diameter was used on living trees. Samples were obtained from several locations in the NT, but most were from within 20 km of Darwin. Samples were collected by Mike Nicholls (21 trees), David Bowman (2 trees), and Patrick Baker (26 trees). Of the 49 trees, 41 were *Callitris intratropica* of which 25 were collected from the *Callitris* plantation at Howard Springs.

<u>Sample preparation</u>

All of the samples were sent to the Monash Tree-Ring Lab where they were prepared using standard dendrochronological procedures (Stokes and Smiley 1968). Briefly, each sample was sanded to a mirror finish using sandpaper (grits 125-800) and then scanned at 1800-2400 dpi using a high-resolution digital scanner. The annual growth ring in *Callitris intratropica* consists of a broad band of relatively light wood, which is formed during the main growing season and constitutes the bulk of the growth ring, and a narrow band of dark wood, often only a few cells wide, which forms at the end of the growing season.

Thus, a full annual growth ring extends from the first cell of the light coloured wood to the last cell of the dark wood (Figure J.1). The tree-rings from each wood sample were then analyzed from the scanned images using an image analysis system. Tree-ring series were visually crossdated within trees if multiple radii were available. The quality of the crossdating was then assessed statistically using the program COFECHA (Grissino-Mayer 2001). A master chronology was then developed from the crossdated ring-width measurements using the program ARSTAN (Cook and Holmes 1985).

Figure 1: Example of annual growth rings in *Callitris intratropica*.

Growth analyses

We used two approaches to determine the potential impacts of past cyclones on the tree-ring series. First, we compared ring-width anomalies in the standardized chronology to known cyclone events. Second, we used Nowacki and Abram's (1997) Percent Growth Change metric to assess whether there were significant and sustained increases or decreases in radial growth in the cross-dated raw ring-width measurements. The %GC metric compares the mean growth of a predefined period preceding a given year with the mean growth of the period of identical length following that year (*e.g.*, 1970-79 vs. 1980-89). The metric is then calculated for every year in the time-series to identify periods of sudden increases or decreases in growth. A %GC threshold of 100% increase or 50% decrease is commonly used to identify severe disturbances (Nowacki and Abrams 1997).

RESULTS AND DISCUSSSION

<u>Contemporary *Callitris* chronology</u>

Of the 41 *Callitris* trees that were sampled, 39 were analyzed. We were not able to evaluate the Darwin Botanic Garden specimens due to twisting and damage to the cores. The tree cores taken by Baker from the 1964 planting at the Howard Springs plantation provided the best cross-dating among the samples and allowed the development of a master dating chronology to guide crossdating of other samples (Figure 2). Cross-dating quality was high both within trees and among trees. The mean inter-series correlation (MIC) (*i.e.*, the mean of all correlations between individual ring-width series and the master dating chronology) based on 36 of the 40 cores was 0.702, which is extremely high (and is one of the highest MIC reported for a tropical tree species). The mean sensitivity (MS), which provides an indication of year-to-year variability in ring-width was also high (0.252), indicating a good potential for reconstructing historical climate variation.

Subsequent wood samples collected by Mike Nicholls from the Howard Springs plantation were easily crossdated using the master chronology from the 1964 planting. The 40 tree cores from the 1965 planting did not cross-date as well due to severe growth suppression that led to numerous missing rings. In some cases, individual trees were missing nearly 25% of the expected number of rings. As such, we did not use the tree cores from the 1965 planting for further analyses.

<u>Evidence for cyclone occurrence from *Callitris* growth rings</u>

Standardized chronologies

The standardized ring-width indices in the Howard Springs chronology show two years (1974 and 1986) of extreme below-average growth (Figure J.2). Preliminary analyses of the rainfall record show no significant correlations between monthly or seasonal rainfall and the ring-width indices that might explain these growth anomalies. The smallest index value occurs in 1974 and appears associated with Tropical Cyclone Tracy, which impacted Darwin on 24 December 1974. The low index value of 1986 in the Howard Springs chronology is not associated with a cyclone. Tropical

Cyclone Gretel passed to the north of Darwin on 13 April 1985. However, because of the standard convention for dating tree-rings in the Southern Hemisphere, the 1986 ring represents growth from September 1986 to May 1987. It is therefore unlikely that the small ring-width index value of 1986 is a consequence of TC Gretel. The growth anomaly in 1974 (TC Tracy) and the lack of growth anomalies in 1981 (TC Max) and 1985 (TC Gretel) suggest that the tree-ring record may only be sensitive to relatively intense cyclones; however, more detailed analyses of the climate data and and a longer tree-ring chronology are required to confirm this.

Sustained growth changes

The impact of TC Tracy can also be seen in sustained growth changes in several of the *Callitris* cross-sections that we examined (Figure J.3). However, the pattern was not consistent. In some cases the cyclone was followed by a sudden reduction in growth, which is likely associated with leaf loss and crown stripping from the high winds. For example, in sample 11 from Howard Springs, a *Callitris* that was leaning significantly, there is a 95% reduction in mean growth in 1975 (*i.e.*, mean growth from 1971-5 was 95% less than mean growth from 1976-80).

In other cases there was a sudden increase in growth, which often results when neighboring trees that are competing for resources are injured or killed by a disturbance (Oliver and Larson 1996, Nowacki and Abrams 1997). For example, sample 41 from the Radio Block plantation showed a 275% growth increase in 1974; however, in the case of this tree, which was leaning, the sudden increase in ring-width is due to compression wood formation following the tree being partially blown over by the strong winds associated with the cyclone.

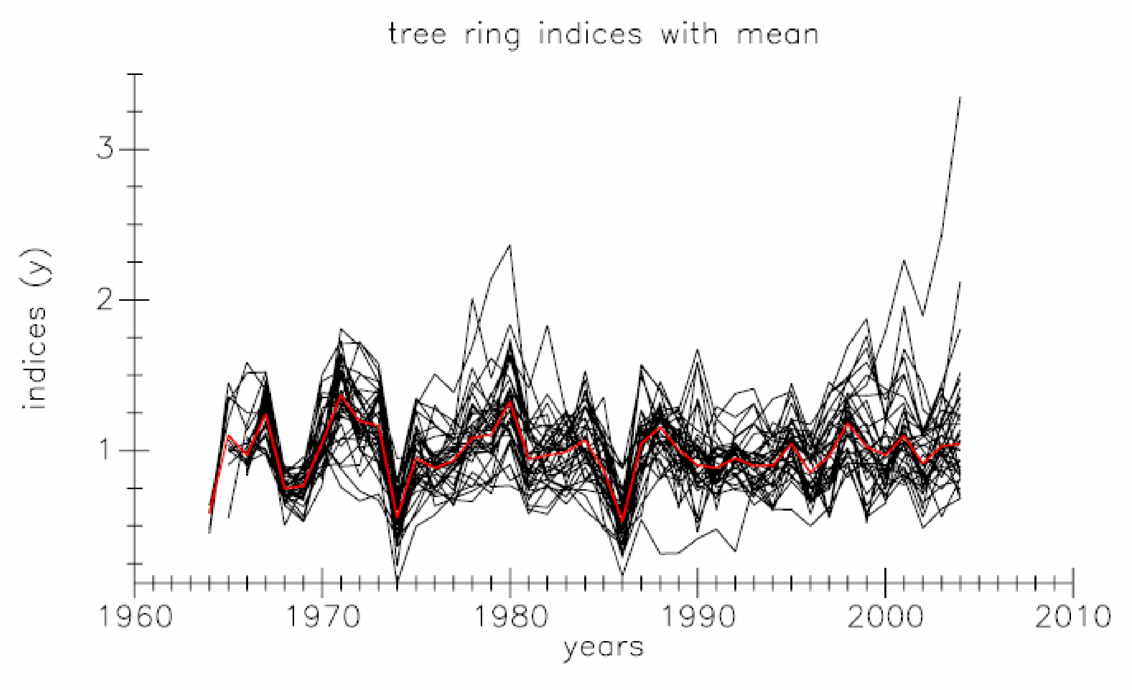


Figure J.2: Standardized ring-widths and mean index values for 36 tree cores from *Callitris intratropica* in the 1964 planting at Howard Springs, NT.

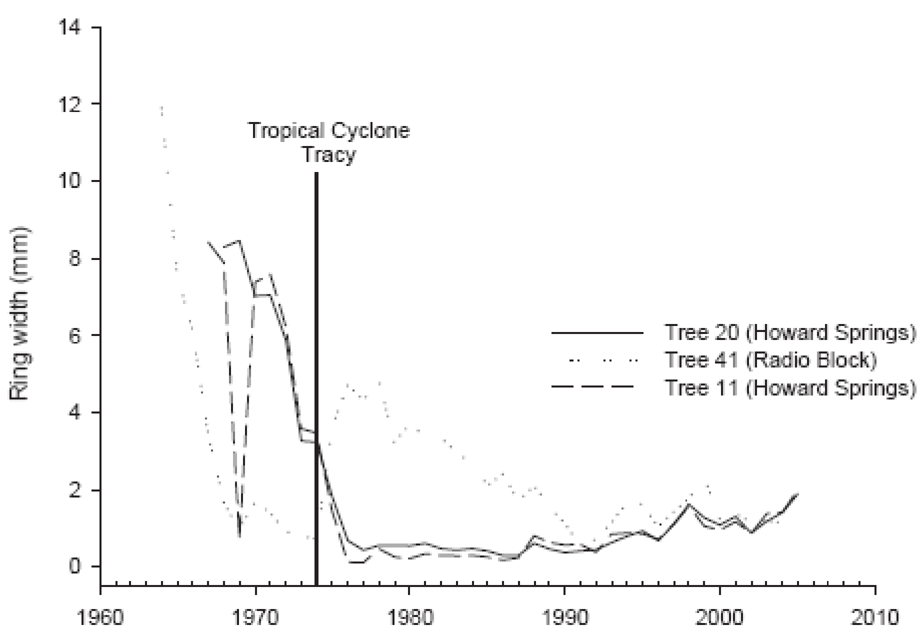


Figure J.3: Ring-width series of two *Callitris* trees showing sudden growth changes associated with Tropical Cyclone Tracy

Many of the *Callitris* at Howard Springs showed substantially reduced growth after 1974 (Figure J.4) . While this may be attributable to TC Tracy, it is also possible that the slow growth was a consequence of over-stocking in the plantation. Because wood samples of *Callitris* grown under different stocking densities were not available for comparison it was not possible to distinguish between cyclone impacts and silvicultural history in the plantations. However, it is unlikely that the lack of significant growth releases after the 1986 negative growth anomaly is a consequence of the extreme suppression of *Callitris* at Howard Springs as a thinning operation of one block in 1994 led to an immediate and substantial (~400%) growth increase in ring widths in a sample taken from that block.

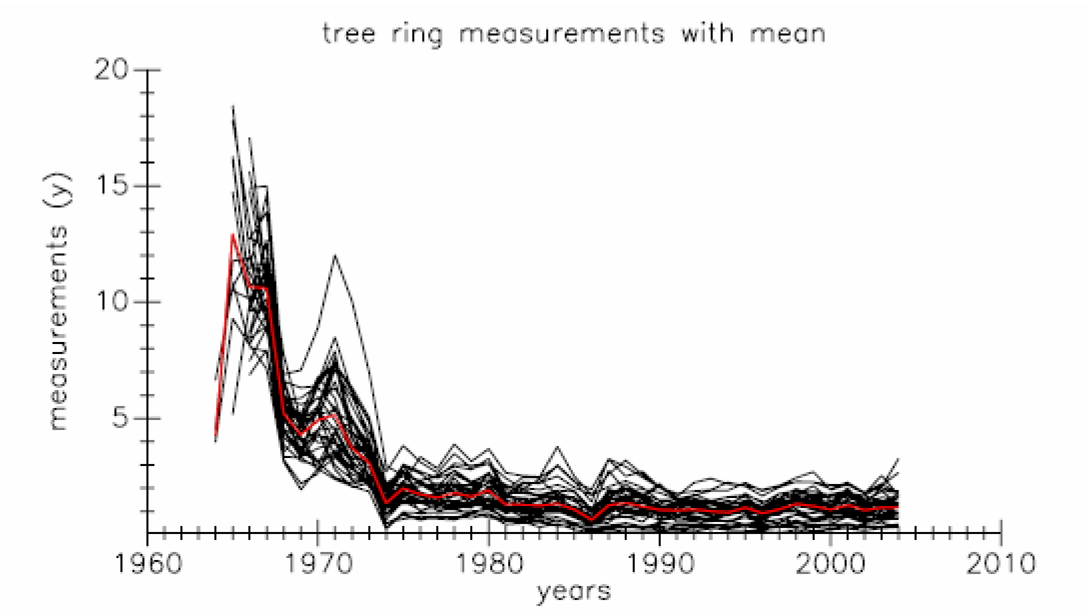


Figure J.4: Raw ring widths for *Callitris* trees at Howard Springs showing severe growth suppression after 1974.

<u>Historical *Callitris* chronology development from Overland Telegraph Line poles</u>

Samples of *Callitris* wood taken from telegraph poles used for the Overland Telegraph Line (OTL) in the first 15 km of the line south of Tumbling Waters are a potentially valuable source of historical information on cyclones. We had three *Callitris* samples from sections of OTL poles that were once located within this section near Darwin. These trees would have been cut in late September or early October 1870, although the outermost wood on the poles has been lost to rot and weathering. Consequently, because the date of the outer ring cannot be determined, the chronologies of the samples cannot be tied to a specific year. However, the known cutting date and remarkable durability of the *Callitris* wood mean that the outermost annual growth rings will be associated with a relatively narrow window of time, most likely 1850-1865. It is hoped that further investigation will rectify this. From the known occurrences of *Callitris* in the locality, the poles for the first 15 km south of Tumbling Waters would have almost certainly have been cut from trees growing near Tumbling Waters. If so, these trees may well have recorded the effects of intense cyclones tracking inland from the north or northwest.

It is worth noting, however, that the ring-width series from the OTL poles appear to cross-date well internally (*i.e.*, multiple radii from the same tree show the same pattern of annual ring-width variation) and moderately well between trees. Sample 71, which was taken from near the Darwin River, showed considerable variation in ring-widths with several years of anomalously low growth (Figure J.5). To incorporate the OTL poles into the tree-ring record will require the acquisition of 1) a greater number of OTL samples for crossdating and 2) *Callitris* tree-ring records that span the period 1840-50 to the present.

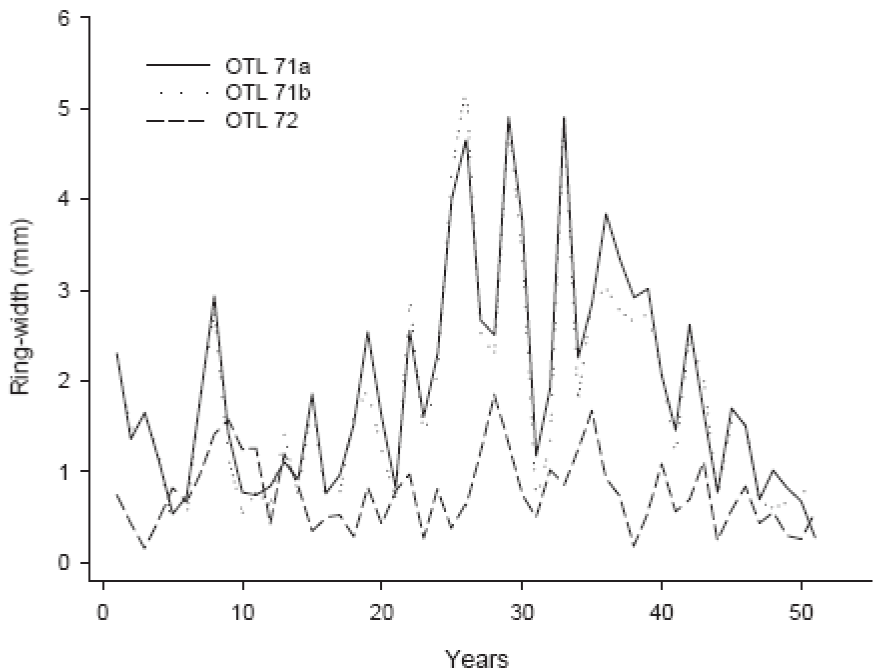


Figure J.5: Undated raw ring-widths for *Callitris* cross-sections taken from Overland Telegraph Line poles near Darwin.

<u>Extending the spatial and temporal range of *Callitris* chronologies</u>

A key element to developing a long-term record of tropical cyclone activity from *Callitris* tree-rings is widening the spatial coverage of the chronologies and extending the chronologies further back in time. Widening the spatial coverage of chronologies will require broad-scale sampling of *Callitris* populations across those parts of the Northern Territory that are subject to cyclones. Sites of particular interest include the Tiwi Islands and near-coastal Arnhem Land. Several avenues for obtaining such material are available. In some cases *Callitris* samples have been collected for other studies (*e.g.*, Bowman and Panton 1993). Elsewhere opportunistic collections may be made; for example, branches of large *Callitris* at the Darwin Botanical Gardens that are pruned for safety reasons may be of use. Where these opportunities do not exist, a focused sampling campaign will be required. To extend the temporal record back in time, sampling must target large, relict trees or historical wood samples such as the OTL poles or stumps that remain from trees cut in the past. Figure J.6 shows an example of a >160 yr tree-ring series from a large *Callitris* section from the Northern Territory. The multiple radii from the wood section crossdate well and show potential for extending the tree-ring record into the early 1800s.

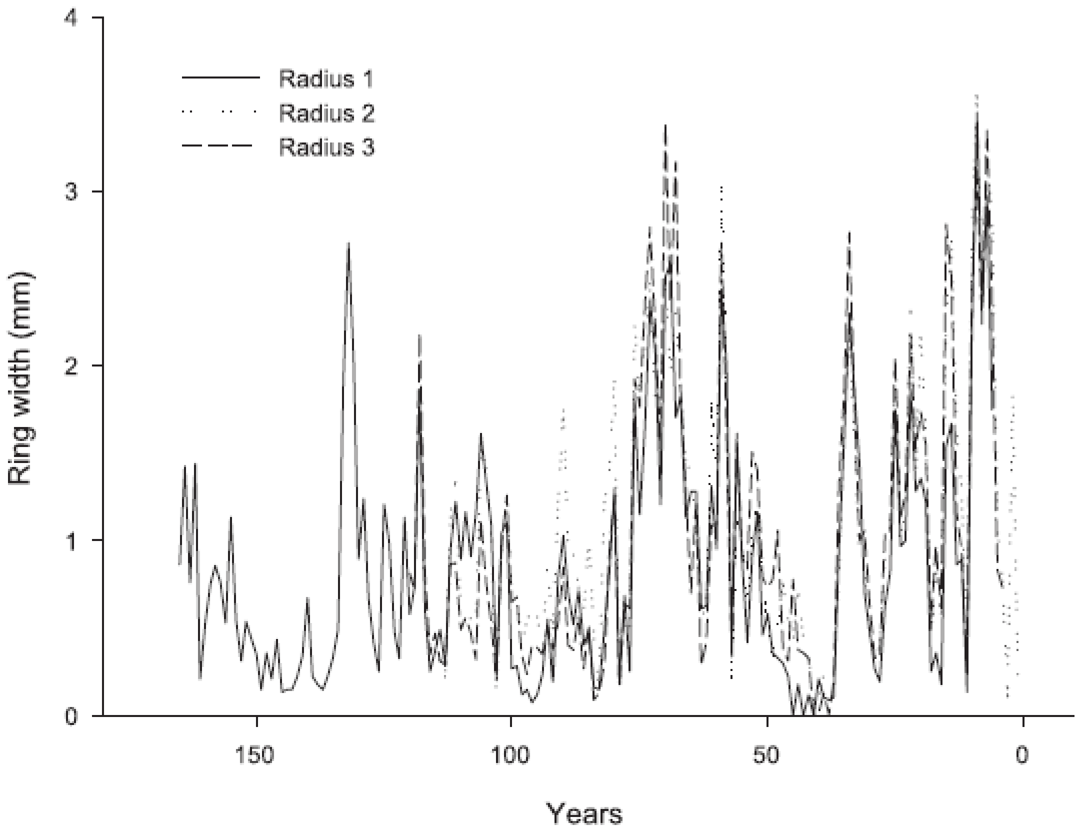


Figure J.6 Tree-ring time series for a wood section of *Callitris* that is 164 yr old. Actual years are not given because the date of the outer ring was unknown. The x-axis represents the number of years from the outermost ring; so, the most recent growth rings are on the right.

<u>Dendrochronological potential of other tree species in the Northern Territory</u>

Two other species, *Bombax ceiba* and *Alstonia scholaris*, were examined as part of this study. However, neither species showed evidence of annual growth rings that were suitable for dendrochronological analyses. *Alstonia* had highly variable parenchymatous growth rings with indistinct ring boundaries and is of no use for dendrochronological analyses. *Bombax* had growth rings that were more distinct morphologically; however, they too had indistinct boundaries and we were unable to cross-date any of the *Bombax* samples successfully. A review of tree species that occur in the coastal and near-coastal regions of the Northern Territory suggests several tree species that may have greater potential for dendrochronological studies. These include *Cordia subcordata*, *Gmelina schlecteri*, and *Vitex* spp. Because of the limited geographical range of *Callitris intratropica*, finding other species that may show dendrochronological evidence of past cyclones would broaden the geographic range for reconstructing such past events.

CONCLUSIONS

Dendrochronological studies have the potential to identify the frequency and spatial distribution of past cyclone events in the Northern Territory. Based on the relatively small number of wood samples collected for this project, we were able to identify the timing and location of Tropical Cyclone Tracy, the most intense cyclone that Darwin has experienced in recorded history. However, less intense tropical cyclones such as Gretel and Max did not register in the tree-ring record. While these preliminary results are encouraging it must be stressed that identifying unique historical events such as cyclones from the tropical records requires rigorous cross-dating of tree-ring series. If the quality of the rings is inadequate, as it was for *Bombax* and *Alstonia* examined in this study, or if the samples cannot be confidently anchored to a specific year, as in the OTL pole samples, dendrochronology will be of little use. However, where annual growth-rings are of high quality, as in *Callitris intratropica*, and can be confidently cross-dated, as across the study area, dendrochronology may be the best means of reconstructing the historical passage of intense tropical cyclones over the Northern Territory. Complementary studies examining the isotope ratios within individual tree-rings may provide further support for dendrochronological reconstructions of cyclone occurrence (see Miller *et al*. 2006 for a recent example). Focused efforts to extend the *Callitris intratropica* chronology spatially and temporally are needed to achieve this.

REFERENCES

Bowman, D.M.J.S, and Panton, W.J. 1993. Decline of *Callitris intratropica* in the Northern Territory: Implications for pre- and post-European colonization fire regimes. *Journal of Biogeography*, 20: 373-381.

Cook, E.R., and Holmes, R.L. 1985. Program ARSTAN and users manual. Tucson, Laboratory of Tree Ring Research, University of Arizona.

Grissino-Mayer, H. 2001. Evaluating cross-dating accuracy: A manual and tutorial for the computer program COFECHA. *Tree-Ring Research*, 57: 205-221.

Miller, D.L., Mora, C.I., Grissino-Mayer, H.D., Mock, C.J., Uhle, M.E., and Sharp, Z. 2006. Tree-ring isotope records of tropical cyclone activity. *Proceedings of the National Academy of Sciences (USA)*, 103: 14294-14297.

Nowacki, G., and Abrams, M. 1997. Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. *Ecological Monographs*, 67: 225-249.

Oliver, C.D., and Larson, B.C. 1996. Forest stand dynamics. John Wiley and Sons, New York, USA. 520 p.

Stokes, M.A., and Smiley, T.L. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicag

Appendix K

BEACH RIDGES & LAGOONS

Locations and images

In the CD format, Appendix K should to be read in conjunction with viewing the images in the folder named: 'Beach Ridges & Lagoons – jpg images'

APPENDIX K BEACH RIDGES & LAGOONS (Locations and Images)

This appendix locates 418 sites around and near the NT coastline that have the potential to reveal cyclone recurrence intervals using **palaeotempestology** (**PT**).

The object of this appendix is:

- to quantify the potential of PT around the Top End coastline by providing maps which locate and number the PT sites

- to provide good quality images of many of the sites

There are more than 500 images in the CD format of this report in the folder 'Beach Ridges & Lagoons – jpg images' Most of the images are oblique aerial photographs that were taken as part of the project. The photographs should:

- assist providers of future research funds to fully appreciate the scope and nature of PT study sites around the Top End
- assist future researchers in the selection of specific PT study sites and in planning appropriately for field work
- display to people who do not already know, that the Top End has an incredibly beautiful and diverse coastline

Cyclones do not observe state boundaries so the coastline of interest to the NT will extend somewhat into Western Australia and into Queensland. The limits have been arbitrarily chosen as longitude 128°E on the WA coast and -17°N and Mornington Island on the Qld coast.

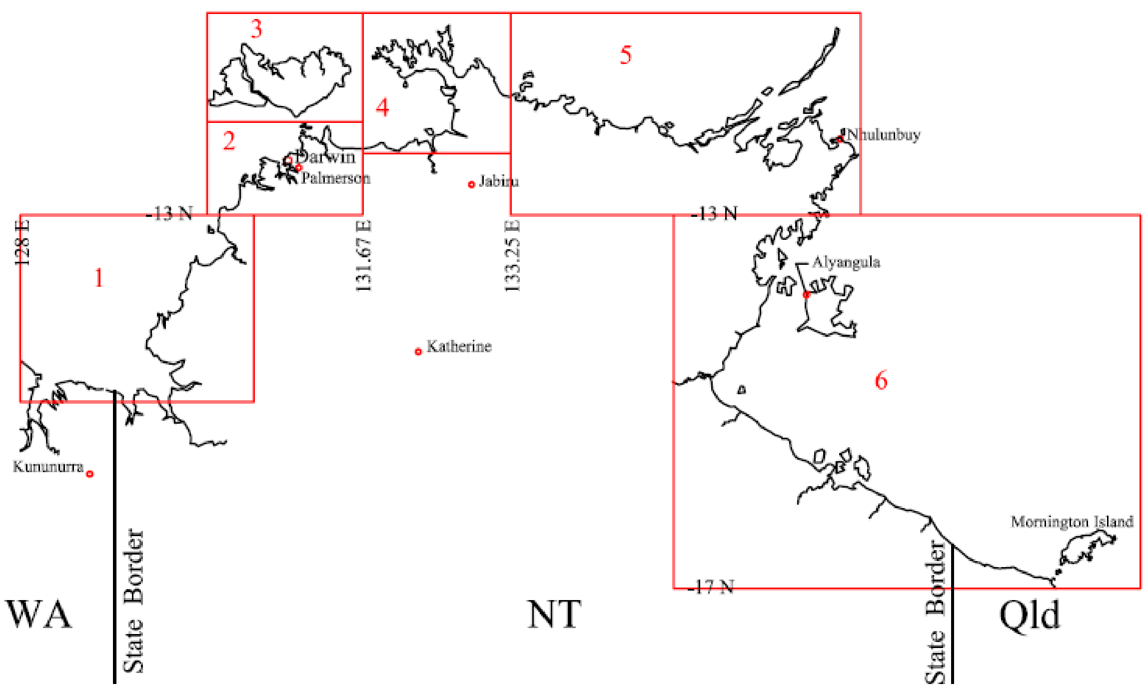


Figure K.0 Extent of the coastline examined and its subdivision into six sectors.

To simplify and manage the viewing of the large number of PT study sites in the accompanying images, the coastline has been subdivided into six sectors as shown in Fig. K.0. (There are reasonably detailed maps of each sector on pages K-5 to K-8 following.)

A PT study site ("a site") is an area containing beach ridges and/or cheniers and/or lagoons and/or tidal flats and which has an identifiable geographic location such as a bay, headland or small island. Usually a site will be confined to a single bay or headland but at other times a site may extend over a fairly long length of coastline. It is a fairly arbitrary system designed simply to enable the correct ordering of images along a coastline. Closer investigation in the future will no doubt reveal that some of the numbered sites have little or no potential for PT – on the other hand, sites will be found that do have potential but are not located or numbered here.

About 430 sites have been identified. If we include bars, cheniers, coral rubble ridges and dunes into "beach ridges" and include supra-tidal flats, inter-tidal flats and swamps in with lagoons then the sites comprise:

- about 230 sites with beach ridges only;
- about 150 sites with lagoons only;
- about 50 sites with both beach ridges and lagoons.

Most of the potential study sites were identified using Google Earth. It is strongly recommended that anyone who does not have this amazing, free program should download it from http://earth.google.com/ (It is not necessary to have the software installed to view the images herein but cross-referencing to Google Earth imagery will in many cases be instructive.) To date, Google has covered about 70% of the NT coastline with high resolution imagery – almost all of it free of cloud cover. The resolution is such that individual, small trees can be identified. The remainder is of a lesser resolution providing detail not much better than a 1:100,000 topographic map. Presumably, Google will cover the entire coastline to the higher resolution in due course.

Unless noted otherwise, the photographs in Sectors 2, 3 and 4 were taken by the writer using digital cameras from a high-wing, Cessna 210 flying at 1000 feet with the passenger door off. A timed, GPS log was used to assist with the accurate location of the photographs. The photographs were taken in August and September 2006.

Unless noted otherwise, the photographs in Sector 5 were taken by staff of the Northern Territory Regional Office of the Bureau of Meteorology using digital cameras from a Robinson R44 helicopter at varying elevations. The photographs were taken in the weeks after cyclone Monica made landfall near Maningrida in April 2006. Photographs taken on land showing the effects of the wind, waves and storm tide from the cyclone are also included. Only the coastlines between Junction Bay and Maningrida and the northernmost part of the Wessel Islands are covered. The photographs for Sector 5 are copyright Australian Bureau of Meteorology and are used with permission.

Most of the original photograph image files are 1.5 to 3.0 MB but have been reduced to 200 to 400 KB in the folder with the CD.

Google Earth images have been included with the photos to assist in accurately identifying some site locations or to highlight sites of particular interest. (Sectors 1 and 6 contain only Google Earth images.) So as not to be too boring, the odd photograph of a feature of scenic or common interest has been included in its appropriate sequence.

The 'Beach Ridges & Lagoons - jpg images' folder starts with the Fig.K.0 sector map. Each sector then follows in numerical order - starting with a more detailed map for the sector followed by the images for that sector. The detailed maps allocate a two digit Location number for each site with the numbering proceeding from left to right along the coast and in a clockwise direction around islands. Each image file is numbered so that it relates to its Sector and Location numbers so that for instance an image with file number 4_932 is the 2nd photo image for Location 93 in Sector 4. Image numbers ending in zero are reserved for maps or Google Earth images.

The images are in jpg format and can be viewed directly from the CD with any one of the various photo viewer programs such as Windows Picture and Fax Viewer. However, in order to see the IPTC standard, descriptive captions attached to each image, special software will be required on the user's computer. For Microsoft Windows 2000/XP, suitable software is the free, Google product known as Picasa - see instructions on page K4 for using this software with the CD.

The captions follow a standard format:

- They begin with the image file number,
- Followed by the approximate viewing direction to the nearest 1/16th compass point abbreviated so that for instance, "> NNE" means "looking North-North-East".
- Followed by a brief description of the subject,
- Followed (where necessary) by a reference to the nearest, named, geographical feature such as a bay, headland, settlement, etc.
- They end with the latitude and longitude in decimal degrees of the area in centre frame.

The viewing direction and lat/longs in the photo captions enable the subject in each oblique photo to be easily and precisely located on Google Earth or on the NATMAP Raster Viewer sold by Geoscience Australia.

Due to limited funds, only the eastern half of Sector 2 and most of Sectors 3 and 4 were flown under this project. It is hoped that the images file in this Appendix will provide a basis for future work so that eventually oblique aerial and on-land photographs of all sites in all sectors can be compiled. Anyone willing to share (with attribution) locatable, good quality photographs of sites is asked to contact the writer.

For readers using the CD, printing the instructions next page will assist the novice Picasa user in obtaining captioned images. Also, printing the detailed sector maps on pages K5 to K8 and having them to hand would assist in keeping track of locations whilst viewing the images.

INSTRUCTIONS FOR VIEWING CAPTIONS TO IMAGES USING PICASA
(Requires Microsoft Windows 2000/XP and Microsoft Windows Internet Explorer 5.0+)

1. If not already installed, download Picasa from http://picasa.google.com/
2. Unlike other image viewing programs, Picasa requires the image files to be on the C: drive. They can be copied using the import option in Picasa but it is much easier to simply copy the image folder from the CD to the C: drive using copy and paste under Windows Explorer. (It does not matter where the folder goes on the C: drive – under My Pictures or wherever.)
3. Start Picasa, wait for the image files to load then select the “Appendix K Beach Ridges & Lagoons – jpg images” folder from the file list and thumbnail view appears. (Picasa does not bother with file/folder trees – it simply lists all image folders on the C: drive sorted alphabetically by folder name and by the year the folder was created.)
4. In the thumbnail view, select **View** (top tool bar), **Thumbnail caption, filename.** This brings up the image file numbers under the thumbnails.
5. Still in the thumbnail view, select **Folder** (top tool bar), **Sort by ►, name.** This sorts the thumbnail images into the correct sequence.
6. Picasa has three basic viewing modes:
   (i) Thumbnails which allow quick scrolling to select particular images,
   (ii) Half-size views (obtained by clicking on a thumbnail) which give file, photographic and caption details,
   (iii) Full screen views – obtained by selecting any particular thumbnail or half-sized view and then clicking the **Slideshow** button.
7. In the full screen mode, dragging the cursor to the bottom of the screen brings up the caption for that image and a menu bar which allows subsequent viewing control. Clicking anywhere in the top of part of the screen starts or re-starts the automatic slideshow (to a user- selected time interval). To bring up a caption and/or to stop at a particular image, simply drag the cursor back to the bottom of the screen.

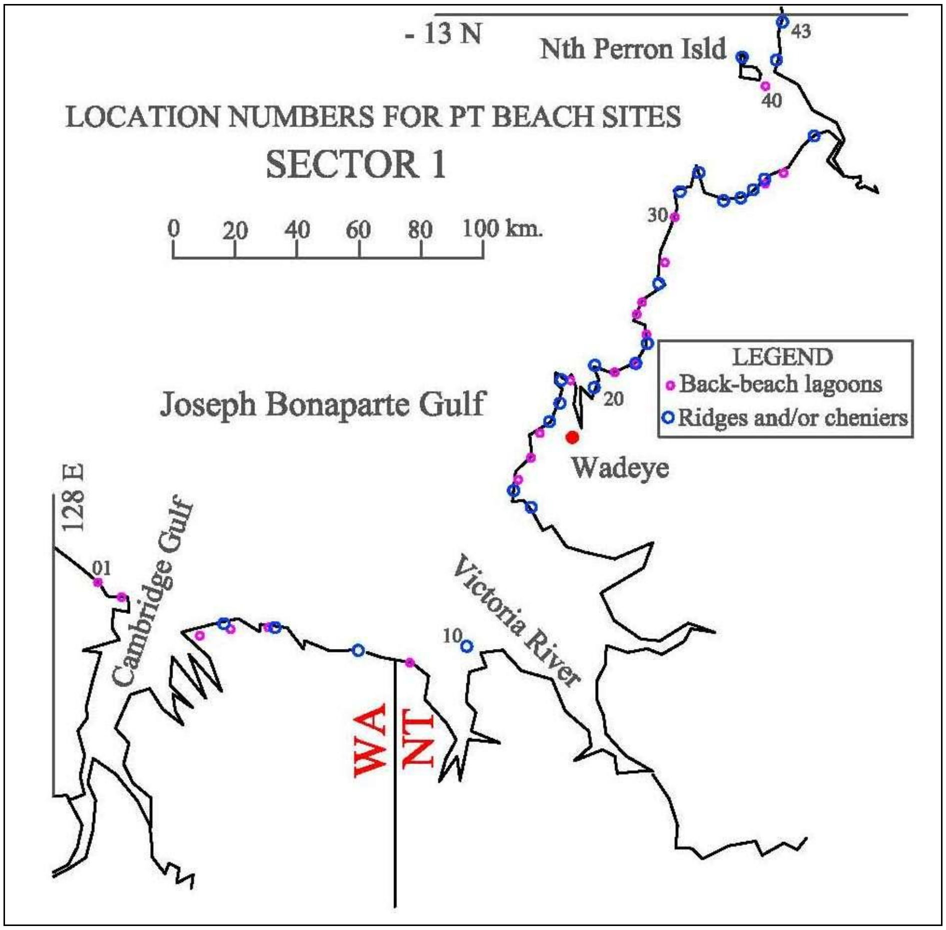


Figure K.1

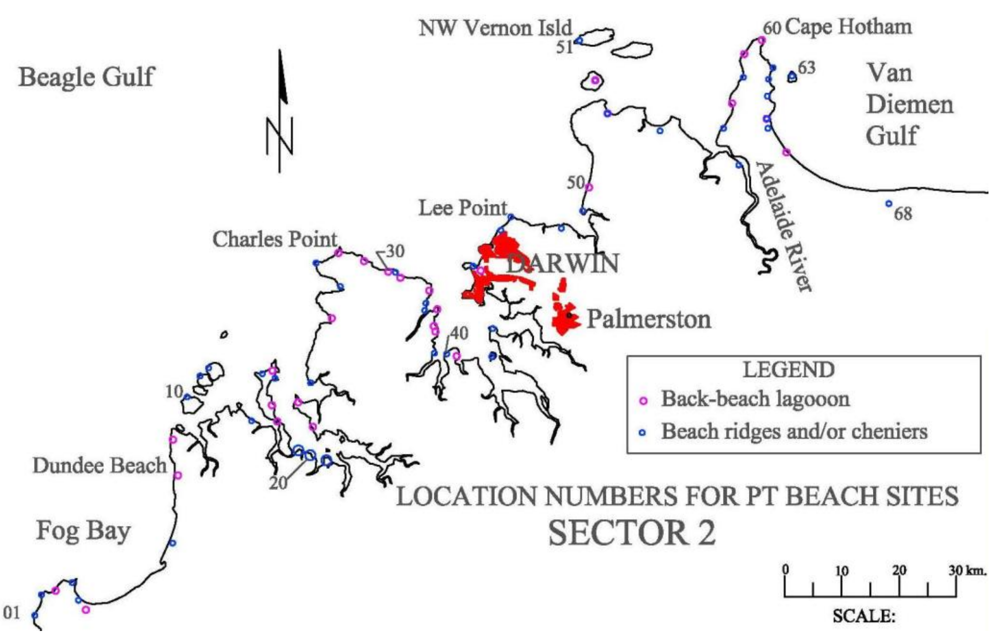


Figure K.2

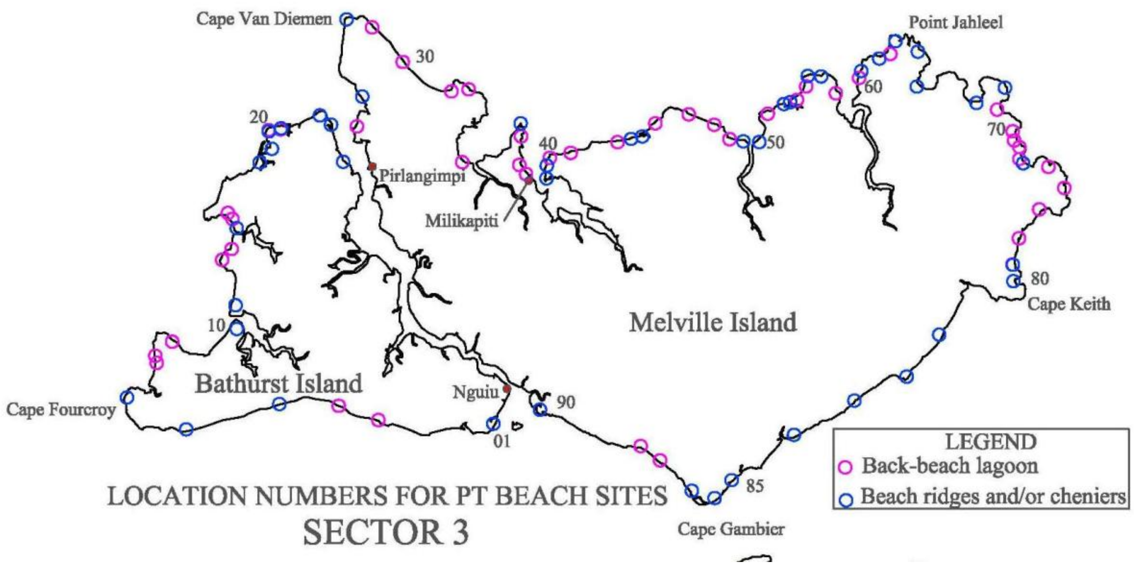

Cape Van Diemen
30
Point Jahleel
60
20
70
40
50
Pirlangimpi
Milikapiti
80
Cape Keith
Melville Island
10
Bathurst Island
Nguiu
90
Cape Fourcroy
01
LEGEND
Back-beach lagoon
Beach ridges and/or cheniers
85
LOCATION NUMBERS FOR PT BEACH SITES
SECTOR 3
Cape Gambier

Figure K.3

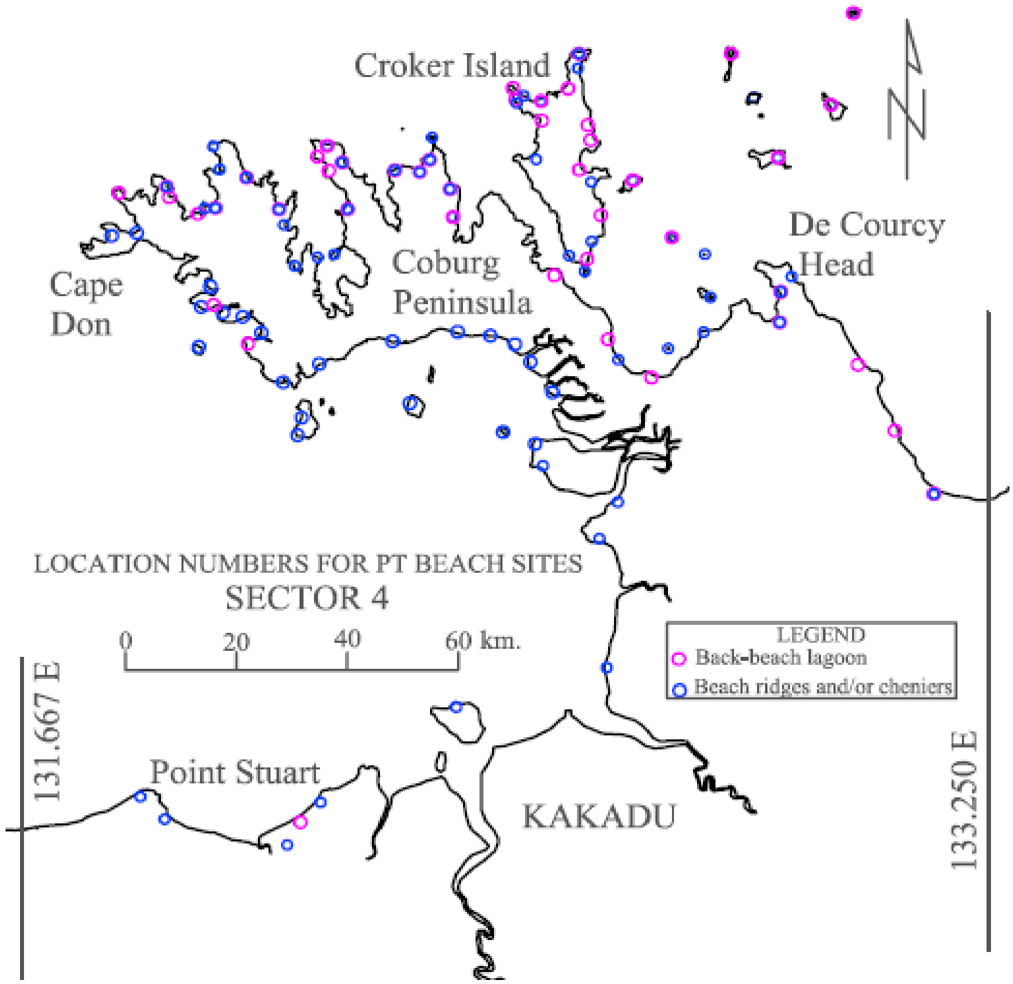


Figure K.4

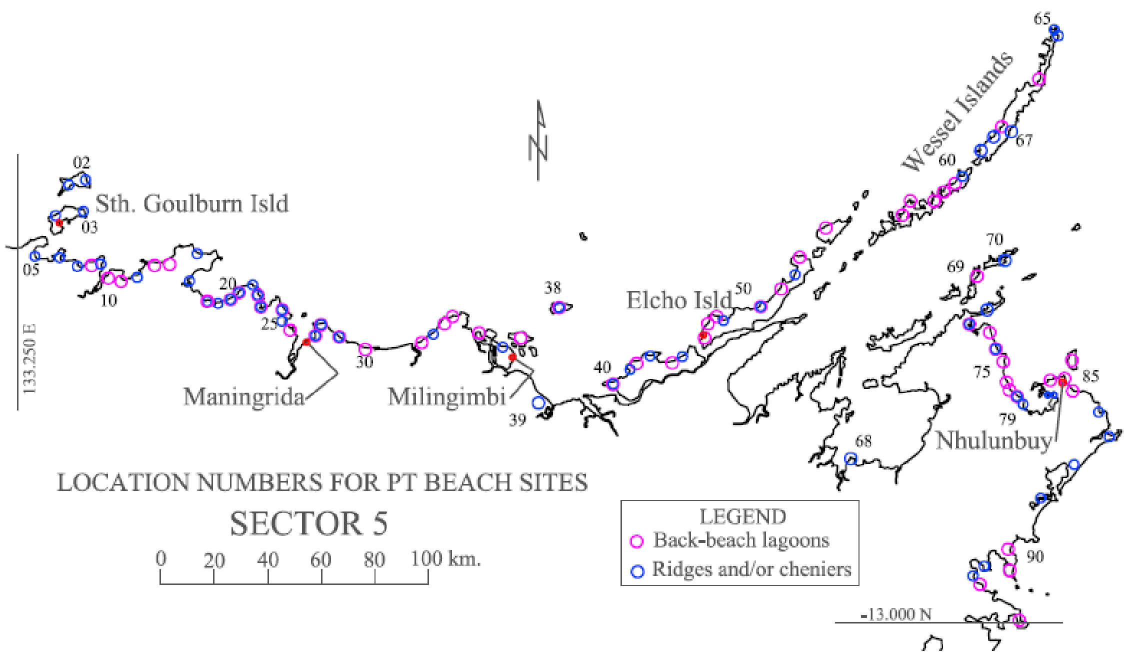


Figure K.5

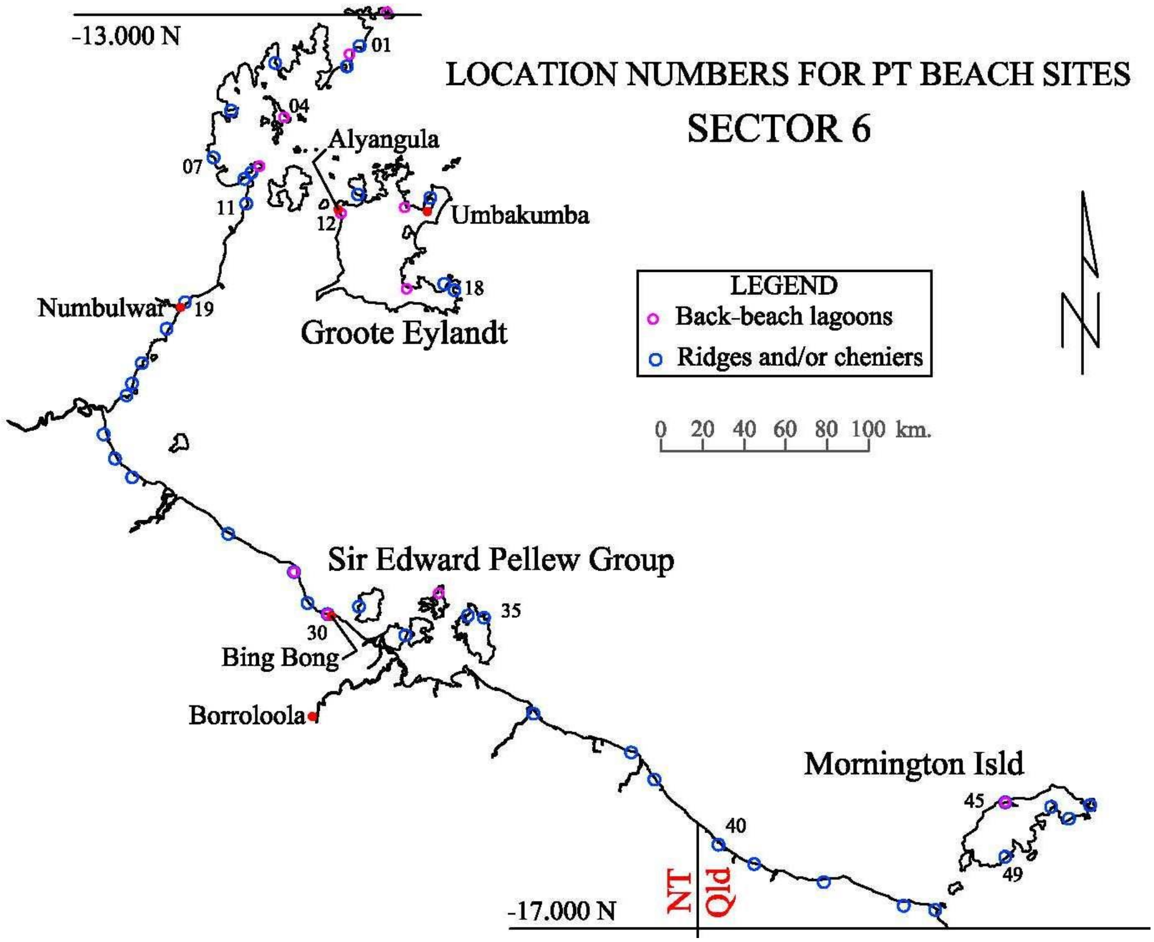

-13.000 N
LOCATION NUMBERS FOR PT BEACH SITES
SECTOR 6
01
04
Alyangula
07
11
12
Umbakumba
18
Numbulwar
19
Groote Eylandt
LEGEND
Back-beach lagoons
Ridges and/or cheniers
0 20 40 60 80 100 km.
Sir Edward Pellew Group
35
30
Bing Bong
Borroloola
Mornington Isld
45
40
49
NT
Qld
-17.000 N

Figure K.6

Appendix L

RESEARCH ON CORAL RUBBLE RIDGES NW VERNON ISLAND

Severe cyclone history in the vicinity of Darwin

R.J. Wasson
Charles Darwin University
Darwin, NT
Australia

December 2006

SEVERE CYCLONE HISTORY IN THE VICINITY OF DARWIN

INTRODUCTION

Estimates of the hazards presented by tropical cyclones in the vicinity of Darwin are based upon the instrumental record. This record is best during the era of satellites, and so is about 40 years long, but there is a good data set from 1945 (Qi et al, ms). If longer records could be produced, the frequency of rare high magnitude cyclones could be determined with greater accuracy. In addition, the stationarity of the occurrence of cyclones could be determined, and therefore whether or not the probability of destructive cyclones changes through time.

The only record of tropical cyclones that exists for periods longer than the instrumental record is that left as sedimentary deposits or in tree rings. In the Darwin area, the sedimentary deposits consist of ridges constructed of shell and coral debris on offshore islands, cheniers constructed of shell and sand debris on coastal mudflats, beach ridges built of sand and shell debris on the mainland coast, and wash-over deposits in coastal lagoons.

This brief report is only concerned with the shells and coral debris built by cyclone-induced waves on offshore islands. And data only comes from NW Vernon Island 50km north east of Darwin.

This is a preliminary report only, based on sampling in 1989. The opportunity for establishing reliable long-term records of cyclone magnitude and frequency has been demonstrated. But much more work needs to be done.

THE NW VERNON ISLAND RIDGES

On the western end of this island is a set of compound ridges (Figure 1). This island is flanked by a coral reef platform with abundant soft corals. Hard corals occur on the reef front. The ridge complex closest to the shore is separated from the coral platform by mangroves. This first ridge complex consists of several individual ridges that adjoin. One of these sets of ridges is separated from the shoreward ridge set by a narrow belt of mangroves. The second ridge complex is further inland, and over most of its length is separated from the first complex by mangroves and saline mudflats. The second complex joins the first complex, continuing for some distance to the east until a small tidal creek is reached. The third ridge complex is further inland, and is completely separated from the second complex by mangrove and saline mudflats.

It is clear that the first complex is younger than the second which is younger than the third. There is no physically plausible way in which the third or second could have been constructed by waves after the first, for example, without destroying the first complex.

The youngest ridge is fronted by a bench which at the highest tides is just reached by waves. The coral and shell debris of this ridge is white, and is overrunning shell and coral debris which has a dark patina. All of the older ridges have the dark patina in the uppermost layer, but below that layer the creamy to white colour of the youngest ridge is evident. This implies that the ridges immediately behind the youngest ridge, and landward, are beyond modern wave action. The older ridges also contain more fine debris than the youngest ridge.

Modern tides flood through the porous ridges leading to collapse of the inland edges of the ridges where they abut the mangrove-covered flats.

The ridges therefore are not completely unaltered from their original state. But the bulk of ridge forms are intact, providing a record of previous extreme events. But it is not clear if single cyclones are responsible for a single ridge or multiple ridges. Also, the youngest ridge has clearly prograded shoreward, partially burying mangrove trees and moving onto the muddy substrate to the mangroves and also the landward edge of the coral platform.

The assumed origin of these ridges as the result of cyclonic surge and wave run-up is based on two considerations. First, they are very like ridges on Great Barrier Reef (GBR) islands that are known to be the result of cyclones (Nott and Hayne, 2001). Second, most of the ridges are higher than the highest astronomical tides, and waves produced under non-cyclonic conditions are small and have a limited surge component.

THE AGE OF THE RIDGES

Two approaches have been adopted to estimate the age.

The first approach uses six series of historical vertical aerial photographs from 1941 to 1977. The ridge complexes have been compared in each set of photos. While the details of the complexes are not resolvable on all of the photos, it is clear that there has been no major change over this time period. That is, all of the complexes pre-date 1941. But subsequent waves have reworked the ridges to a small extent, as described earlier. Also, Cyclone Tracy in 1974 did not build a ridge or ridge complex.

A satellite image from 2006 shows that the most seaward ridge has grown and moved inland (M. Nicholls, pers. comm.). This is probably the result of Cyclone Thelma in December 1998, one of the most severe cyclones observed off the Australia coast.

The second approach relies upon radiocarbon dates. The radiocarbon dates are set out in Table 1, and they are all determined on shell debris not coral debris. The waters in which the shells live has a finite age, and therefore the raw radiocarbon dates must be calibrated to give a real age before present (BP) where present is 1950AD. Calibration has been performed using the software OxCal 3.10 with a ΔR value of 70 ± 70 (Ulm, in press).

The dated samples are located on Figure 1. The landward edge of the youngest ridge complex is dated to 540 $^{+55}_{-78}$ cal BP (V4) the oldest date available. The most probably age is ~ 1410AD, but the errors do not allow certainty about the actual year of the event. Samples from shelly debris on the more seaward (and therefore younger) parts of the ridge complex are all within the last 150 years (V1, V2, V5, V6, V8), with the exception of V7. This sample is from a patinated ridge that stands about 50cm higher than the rest of the complex and has an age of 150 $^{+120}_{-90}$ cal BP (or ~1800AD). It appears that this ridge was built before the debris around it (possibly by a process described by Scoffin, 1993) but of course could be a mixture of old and young shelly debris. However, the morphology of the ridge suggests that it pre-dates the young material, and that the radiocarbon date reflects the age of ridge construction.

From these data, cyclones powerful enough to build ridges by ripping up coral and shells from the reef platform occurred ~1410AD, ~1800AD and sometime between 1800AD and 1941AD. There has also been a powerful cyclone since 1941, probably Thelma. Within the last ~600 years there have been four powerful cyclones, with an average frequency of ~150 years.

DISCUSSION AND CONCLUSIONS

The ridges described above are very similar to those ascribed to tropical cyclones on islands in the Great Barrier Reef (GBR) by both wave run-up and storm surge (Nott, 2004) as already noted. Nott (2003) calculated the central pressures of cyclones that have built ridges on GBR islands and the mainland coast, using numerical models that simulate both surge levels and wave characteristics. He found that severe cyclones occurred during the nineteenth century, with central pressures lower than those recorded historically and close to the theoretical thermodynamic limit. The low frequency of category 5 cyclones since is noteworthy.

Nott and Hayne (2001) showed also that the extreme cyclones (central pressures <920hPa) occur every 200 to 300 years on the GBR coast, a lower frequency than the much more limited data from NW Vernon Island. Previous estimates of frequency on the GBR coast, based on the instrumental record, are of the order of one every millennium (Nott and Hayne, 2001).

Worthy of note is the conclusion by Nott and Hayne (2001) that the frequency of severe cyclones on the GBR coast has not shown systematic variation over the last 5000 years. That is, their occurrence is random in time and the series is stationary, even though the interval between events has varied between 50 and >500 years. The last 5000 years has been a time of decreasing temperature and rainfall in tropical Queensland, but, despite this change in the 'average' climate, the average frequency of severe cyclones on a millennial scale has not changed. Therefore, it would appear that this frequency is independent of average climate.

However, in the two most complete records of ridges (Curacao Island and Princess Charlotte Bay), there were 4 severe cyclones between 35 and 120 cal BP (average frequency of 21 years), and another 4 cyclones occurred with a frequency of 66 years between 200 and 565 cal BP in the period between 565 and 1060 cal BP, there was only one cyclone. From the perspective of risk assessment, these differences would appear to be important, but require further analysis.

It is clear from NW Vernon Island that a valuable record of cyclone frequency is available, and the dating so far has not exploited the full potential of the site. Further research would need to include modelling of the surge and wave run-up values that could produce the ridges, and thereby back-calculate the central pressures of the causal tropical cyclones.

There are also many other islands offshore from Darwin where ridges occur. The prehistoric archives of severe tropical cyclones are large.

Table L.1 – Radiocarbon Dates

Sample No.	Cs No	SC-13 (‰ rel PDB)	Radiocarbon age ± lsd (years BP)	Calibrated BP (years)
V1	805	+2.3	410±80	42±76
V2	806	+1.6	460±80	50±88
V4	807	+4.1	870±60	$540\ ^{+55}_{-78}$
V5	808	+2.0	490±80	50±100
V6	809	+1.2	430±110	43±107
V7	810	+2.6	610±60	$150\ ^{+120}_{-90}$
V8	811	+2.2	560±60	100±50

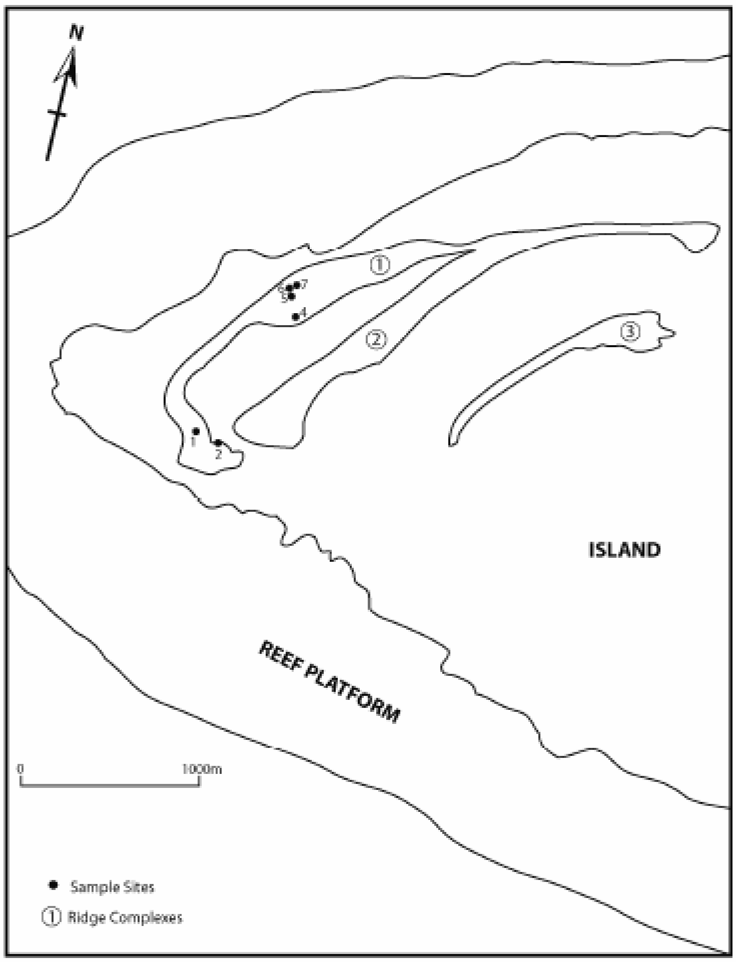


Figure L.1 Sketch map of the western end of NW Vernon Island

REFERENCES

Nott, J. (2004) Palaeotempestology: the study of prehistoric tropical cyclones – a review and implications for hazard assessment. Environment International, 30, 433-447

Nott, J. (2003). Intensity of prehistoric tropical cyclones. Journal of Geophysical Research, 108, 5-1 to 5-11.

Nott, J. and Hayne, M. (2001). High frequency of ‘super-cyclones’ along the Great Barrier Reef over the past 5000 years. Nature, 413, 508-512.

Qi, L., England, M.H. and Sen Gupta A. Tropical cyclones over Western Australia, the Leeuwin Current and South Annular Mode. MF

Scoffin, T. (1993). The geological effects of hurricanes on coral reefs and the interpretation of storm deposits. Coral Reefs, 12, 203-221.

Ulm, S. (in press). Australian Marine Reservoir Effect: A Guide to ΔR Values. Australian Archaeology

Appendix M

RESEARCH ON LAGOONS

A preliminary investigation on a tidal flat near Darwin.

APPENDIX M RESEARCH ON LAGOONS (A preliminary investigation on a tidal flat near Darwin.)

SUMMARY

To the writer's knowledge, there has been no work done to date in Australia to see if cores taken from coastal lagoons, swamps or tidal flats will reveal overwash deposits from cyclone induced storm tides for palaeotempestological (PT) studies. As part of this project, the writer obtained a core from a tidal flat on the Cox Peninsula. The object was to see if the core contained layers of marine sediments. The core obtained was not good enough to proceed with a detailed chemical or grain size analysis but from visual inspection it was obvious that it did not contain marine sediments in defined layers.

LOCATION

Figure M.1. Google Earth image showing location of core sample on Cox Peninsula.

The core was taken on 16 November 2006 in a saline flat that is only inundated by high spring tides. The flat is fringed by mangroves, mainly Ceriops tagal var. australis.

The general location was chosen initially because it was thought likely to have been overwashed when cyclone Tracy passed parallel to the shoreline in 1974. A study to calibrate and verify a storm tide prediction system has calculated that the storm tide at the adjacent Imaluk Beach was the highest that Tracy produced anywhere along the coast with the surge + tide + wave set-up calculated to be about 4.6 m AHD (SEA P/L, 2005).

The tidal flat was chosen to save messing around in a muddy swamp or on a boat in a water-filled lagoon.

The first thing that became evident on arrival at the site was that it was unlikely that Tracy would have produced any overwash. The photograph below shows the lowest point in the beach dune at the site.

Figure M.2 Dunes at the back of Imaluk Beach

The low point on the top of the dune (shown by the dip in the track) was measured at 2.5 m above highest astronomic tide (HAT) which at this location is estimated to be 3.6 to Australian height datum (AHD). This means that the dune top is at about 6.1 m AHD and there would have had to have been a further 1.5 m of wave run-up at the site during Tracy's surge to start overwash. This is possible but there was no sign of overwash behind the dune.

Behind the dune is a swale with its invert at 3.0 m AHD followed by secondary, sandy ridge with crest level at about 5.0 m AHD. Most of the remaining terrain over the 350 m to the saline flat would be slightly less than 4 m AHD and consists of a seasonal swamp with Melaleuca and slightly higher ground with Pandanus. There was also a low, isolated rise covered with loose, small boulders of ferruginous, sandstone/siltstone, with no soil visible.

The saline flat itself would be slightly below HAT or at about 3.5 m AHD. This means that the surge from Tracy could have inundated the flat by a metre or more but with the core site almost a kilometer upstream from the break in the dunes at the creek outlet, and with most of that distance covered by very thick mangrove, the surge water reaching the flat would have been loaded with wind snapped leaves and branches and may have held little if any coarse, marine sediments by the time it reached the sample site.

The next bad news was that, as feared, the saline flats are home to crabs of some sort so that even if there had been thin sediment layers at some time, bioturbation would probably have destroyed them.

Figure M.3 Typical crab holes in tidal flat (some areas were more densely populated)**.**

It is possible that most saline flats in the Top End will contain similar fauna. If this is the case it could rule them out as potential PT study sites and only swamps or lagoons then become prospective.

SAMPLING

The coring device used was a piston sampler kindly donated for the purpose by Ullman & Nolan (NT) Pty Ltd. Ideally the device would produce a 1.0 m length of 60 mm dia. core.
The saline flat was quite firm underfoot but surprisingly soft (and compressible) under the surface crust and the sampler was very easy to push down.

Recovery of a sample was not so easy. The piston was very stiff to pull upwards inside the tube as the sampler was pushed down into the mud. Extracting the assemblage was easy enough but it was then very difficult to push the core out of the sampler tube into a half round, container tube. After several attempts, the best core recovery that could be obtained was only 500 mm from the 1,000 mm of penetration. Using a better lubricant inside the sampler tube would have aided the process and may have lead to better, less compressed, core recovery. Some sort of indicator so that the operator knew where the piston head was in relation to the ground surface level would also have been of assistance.

Lack of time and money has prevented an intended return to the site to try an alternative method of sampling. This alternative method simply involves pushing down and extracting thin-walled PVC pipes, leaving the cores within the pipes and accessing them later by sawing the pipes plus cores into halves.

Figure M.4 Coring with piston sampler.

RESULTS

The core, as compressed, consisted of:

- a top 140 mm thick layer of yellow-brown silty mud
- a mid 60 mm thick layer of transitional material
- a bottom 300 mm thick layer of dark grey, organic mud with some woody particles

Figure M.5 Recovered core.

The darker zone within the top layer on the bottom side of the split sample is a pocket (presumably a filled crab hole) of material which is about 40% fine, light brown, quartz sand. Largest particle size is 2mm, most less than 1 mm. The particles were rounded. This sand probably derives from the modern beach, perhaps wind blown, perhaps migrated from the back of the secondary dune during wet season run-off or perhaps the result of cyclone overwash. However it could be that the sand derives from weathering of the sandstone bedrock that surrounds the site. It would seem that the crabs, or whatever they are, concentrate these particles.

The dark grey, bottom layer is obviously from the pre-existing mangrove that still surrounds the saline flat. Probably that pre-existing mangrove was killed off by hyper salinity following the normal process that leads to the formation of these flats.

The yellow-brown top layer is probably sediment from the wet-season surface run-off from the surrounding terrain which is the weathered surface of a ferruginous sandstone (Bathurst Island Formation of the Darwin Member).

CONCLUSIONS

1. The investigation showed that there may be problems in using tidal flats for PT studies but more cores need to be obtained using better techniques to clarify this. Cores from within the fringing mangrove to the saline flat should also have been obtained
2. Study sites need to be carefully chosen so that only overwash events could produce marine sediments in cores
3. The saline flat sampled is only a small part of the PT study site shown on the left side of Fig. M.1. The whole site contains a variety of back-beach features that could reveal past cyclone occurrences and they warrant further study

REFERENCES:

Systems Engineering Australia Pty Ltd, (2005). System Development Technical Report, Storm Tide Prediction System, for the Bureau of Meteorology (Darwin Region).

Appendix N

SUBMISSION for a REVIEW OF THE BUREAU OF METEOROLOGY

(Copy of a submission submitted to BoM by the Group in Feb, 2007)

APPENDIX N

Submission for a Review of the Bureau of Meteorology
by
Community Group for the Review of NT Cyclone Risks Inc.

(This is a copy of the Group's submission to BoM. Invitations to the public to make submissions to this review by the Federal Government appeared on the BoM website early in 2007. Submissions closed on 23rd February 2007.)

1. Introduction

The Community Group for the Review of NT Cyclone Risks Inc. (the "Group"):

- comprises twelve long-term Darwin residents, most of whom had their houses collapse around them during cyclone Tracy. Most members of the Group have expertise in various fields related to cyclone risk.
- has concern that cyclone risk in the Top End is under-estimated by the authorities and that consequently, public safety is being compromised.
- was formed in July 2005. In April 2006, the Group obtained a grant of $50,000 from Emergency Management Australia to prepare and publish a report "Review of NT Cyclone Risks". (This report is near completion and will be issued to territory and federal politicians and relevant departmental ministers by 22nd March 2007.)

The writer of the report sub-contracts to the Group as its Project Manager. He has prepared this submission to reflect the findings in the report. The writer has an engineering background - two Group members who are past members of the Bureau's staff have provided minor corrections but have not otherwise contributed to the content of this submission.

2. Topics covered:

All topics in this submission relate to NT cyclone risks and ways in which the Bureau could improve the assessment and mitigation of those risks.

To assist with the processing of this submission it will address, in order, the dot points in the Call for Submissions.

2.1 <u>How important are the Bureau's services to you?</u>
They are absolutely critical for the provision of :

- data to improve the engineering assessment of cyclone risks ;
- investigation and research to improve the scientific understanding of cyclone behaviour;
- public education about cyclones and their risks; and
- adequate alerts and warnings when cyclones threaten.

2.2 <u>Do the Bureau's services currently meet your needs?</u>

The short answer is no. A summary of the reasons is given in the attached Appendix A.
The long answer is given in the Group's report – a copy of which will be sent to Bruce Stewart by 22 March 2007.

2.3 Are there additional needs that the Bureau should fulfill?
No

2.4 What would be the impact of the significant changes proposed in Appendix A ?
The impact would be significant for the 90% of the NT's population and economy which is subject to cyclone risk.
If the Group's findings are correct, then NT cyclone risk is much higher than is currently allowed for by the wind code, the building regulations and the provision of cyclone shelters. To correct the situation will take decades and cost hundreds of millions of dollars. Hopefully the corrections will be completed in time. If a cyclone having Monica's intensity was to strike Darwin now it would kill hundreds of people, injure many thousands and cause tens of billions of dollars worth of damage to infrastructure. The NT economy would collapse and NT government would become totally reliant on Commonwealth Government money to recover from the disaster. If corrections are made, the statistics in that grim account could be reduced by at least an order of magnitude.
The range of items in Appendix A indicates the Bureau has not devoted sufficient resources in the past for investigations into factors that critically relate to the evaluation of risk from tropical cyclones – particularly those in the low latitudes.

2.5 Does the Bureau's current structure with national and state-based services meet your needs?
There needs to be much more emphasis on NT related research. This would be best achieved by:

- establishing an NT branch of the BMRC in Darwin; or
- increasing resources for the Darwin Regional Office.

2.6 Re. Climate Change
The Group is not making a big issue about climate change because it seems that the expert jury is still out as to how it will affect the frequency and intensity of cyclones. However we note that the passage of the Category 5 "TIM" cyclones (Thelma in 1998, Ingrid in 2005 and Monica in 2006) suggests that an adverse effect may already be under way in the NT.

Mike Nicholls,
Project Manager,
Community Group for the Review of NT Cyclone Risks Inc.

APPENDIX A …………. (To APPENDIX N)

Ways in which the Bureau's services could be improved to meet the Group's needs

1. Re-analyse post 1969 cyclones that have affected the NT coast.

   It is obvious that engineering analyses to determine intensity – frequency relationships for cyclones in a region require accurate historic data.

   It is understood that the Bureau has plans (which may be as yet unfunded) to do a full-scale re-analysis of cyclones affecting the whole Australian coastline by applying modern techniques to original satellite data to allow a consistent analysis of intensity from about 1970 onwards (Trewin, pers. comm.)

   The Group considers that this work is long overdue. The risk is such that the cyclones which have affected NT should receive priority with this re-analysis.

   In 2002, Woodside Exploration Limited (WEL) re-analysed the post 1969 cyclones that have occurred west of Darwin in the Timor Sea. A number of Bureau staff were involved in some aspects of this re-analysis. In some critical cases, intensities were revised significantly upwards. The writer has been informed (Kepert, pers. comm.) that valuable lessons have been learnt from the WEL exercise which will assist with the re-analysis of storms east of Darwin. There may also be scope to build on the WEL results and experience, and further improve the results to the west of Darwin.

   (The Group estimates the cost to re-analyse these cyclones would be $100,000)

2. **R**e-analyse the most intense of the historic cyclones that have affected the NT coastline since European settlement began in 1824.

   Detailed study of the records of intense cyclones in the historic record can provide important information that will assist with frequency analysis. The Bureau should provide additional resources for the Darwin Regional Office to enable such research. In particular, the intensity of the NT cyclones of 1839, 1897, 1915, 1919, 1923, 1937, 1974 and 1984 should be assessed in the light of modern knowledge and using computer modeling to hindcast the recorded winds, pressures and storm tides.

3. Target Research to further understand cyclones in the NT's low latitudes.

   (a) A paper by Tonkin, Holland, Holbrook and Henderson-Sellers in the March 2000 edition of the Monthly Weather Review contains a series of small graphics that show the monthly variation in Maximum Potential Intensity (MPI) of cyclones in 28 locations around the world. Darwin's MPI in the month of December is the most intense of any month in any location. According to the wind code, houses in both Darwin and Townsville should be designed for wind gusts of 69.3 m/s. But according to the above-mentioned paper, the Holland MPI model indicates that it is theoretically possible for Darwin to have a cyclone with a central pressure of 860 hPa whereas the best Townsville could produce is 925 hPa. Clearly the assessment of the MPI of cyclones in the NT and other Australian regions requires further, detailed research.

(b) It is now well established that cyclones are weakened when the sea surface temperatures are reduced by winds from the cyclone causing mixing and upwelling of colder water from below the thermocline. This negative feedback effect may not apply in the very warm and shallow NT seas.

This could be a critical factor contributing to the intensities of NT cyclones. The temperature profiles for the seas surrounding NT coastline should be determined and this matter resolved using coupled ocean-atmosphere computer models such as are now commonly used for operational forecasting in the US.

(c) The Bureau should make recommendations as to appropriate gust factors to relate gradient wind speeds with surface gust speeds for landfalling cyclones. These factors are known to vary with the distance that winds have traveled overland and with the distance from the cyclone's radius of maximum winds but there is considerable uncertainty as to the appropriate values. The factors are critical in engineering studies using Monte-Carlo Simulation technique.

(d) The Bureau should collaborate with the Engineering profession to agree (or disagree) that the **maximum** gusts speeds given in the Bureau's cyclone warnings relate directly to the Regional Wind Speed (V_R) as defined in the current wind code (AS/NZS 1170.2:2002). As part of this exercise, agreement should be reached on the meaning of the word "maximum" in the Bureau's warnings – is it instead perhaps a 95 percentile figure? Does it allow for tornadoes, boundary layer rolls, downdrafts, eye-wall vortices, etc.?

4. <u>Provide more and/or better equipment</u>

(a) The Bureau's anemometers routinely fail before recording maximum wind gusts. Even if peak gusts are recorded, it is probable that the recording device will be a cup anemometer and the results will be of little use to engineers. Anemometers at all AWS and manned stations within 100 km of the NT coast should be high speed Dines anemometers designed to withstand and record 360 kph gusts.

(b) The Bureau should deploy technology that will prove (or disprove) that the Dvorak technique provides reasonably accurate estimates of gust speeds in the NT. Many engineers are skeptical on the matter. There are numerous modern methods for measuring wind speeds more directly such as dropsondes, doppler radar, etc. The Bureau should have an enquiry as to how to best do this measuring and then proceed on a suitable long term research project.

(c) The NT should have at least two more radar installations to provide a fail-safe system with adequate coverage of cyclones coming towards Darwin from either east or west.

Figure A1 shows the extra coverage that would be provided for a radar station on the northern tip of Melville Island and one on South Goulburn Island.

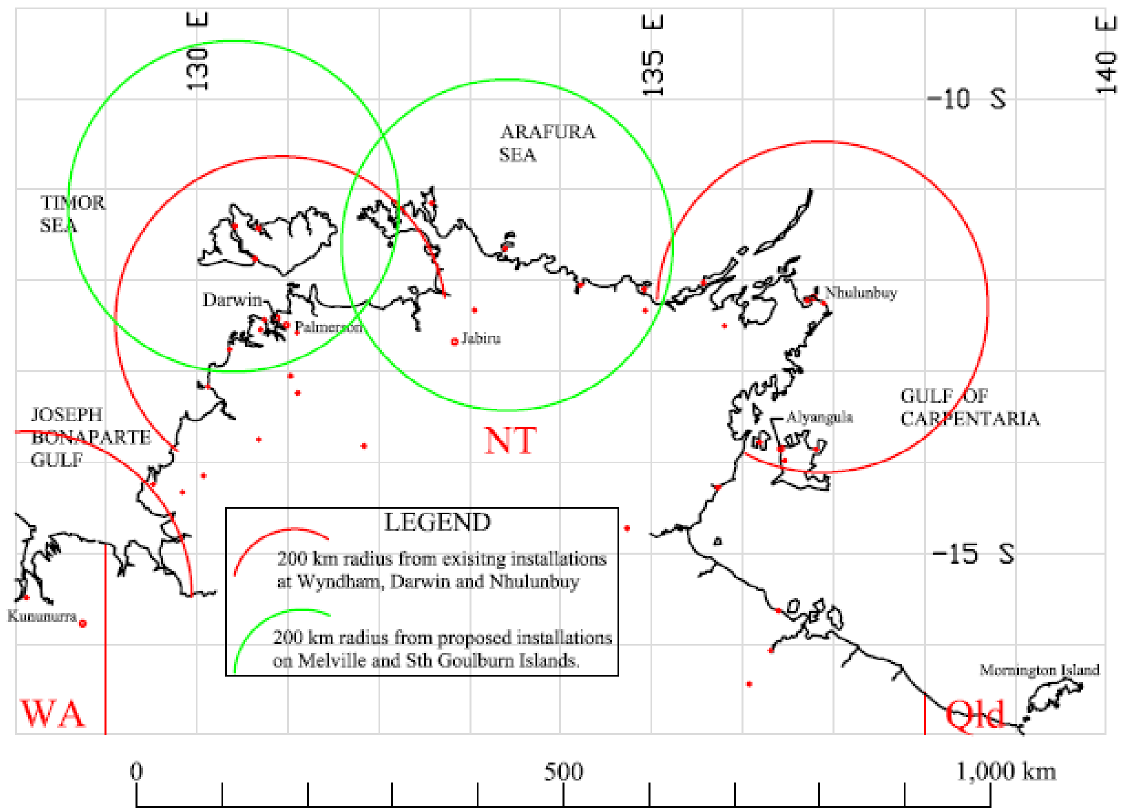


Figure A1 Existing radar ranges in red, proposed extension of system in green.

Appendix O

THE ‘TIM’ CYCLONES – JUST A CHANCE CLUSTER ?

Calculating the probability of getting three Category 5 cyclones in the space of just nine years

APPENDIX O THE 'TIM' CYCLONES – JUST A CHANCE CLUSTER ?

The passage of the Category 5 cyclones Thelma, Ingrid and Monica (the TIM cyclones) within 500 km of Darwin in the space of just nine years is unprecedented in recorded history.

An optimist might say that the TIM cyclones are just a chance grouping of rare events that will occasionally crop up in any random sequence of events. **The following analysis (1) suggests that there is at least a 90% probability that the optimist would be wrong.**

ANALYSIS

- if we assume that intense cyclones in the region have a known average recurrence interval but otherwise occur randomly with the occurrence of one having no bearing on the occurrence of another, then we are assuming that the occurrences conform to a Poisson Distribution

- there is no 'known' average recurrence interval but for the sake of this argument (and because it simplifies the mathematics) we will assume that the average recurrence interval is 9 years. The first satellite which could reliably detect cyclones night and day was probably the Nimbus 1 which went up in time for Australia's 1964/1965 cyclone season. There have been 5 intense cyclones pass within 500 km of Darwin since that time. November 1964 plus 45 years gives November 2009. Therefore, 9 years is a reasonable if optimistic estimate for the average recurrence interval (**R**).

- for the Poisson Distribution, the chance of having **'n'** events occurring within any period equal to R = 1/(e x n!) where e is a mathematical constant = 2..718…., and n! is factorial n

The calculations for different values of **n** are tabulated below.

Number of occurrences in 9 years (n)	Probability
0	1/(2.718 x 1) x 100 = 37%
1	1/(2.718 x 1) x 100 = 37%
2	1/(2.718 x 2 x1) x 100 = 18%
3	1/(2.718 x 3x 2 x1) x 100 = 6%
4	1/(2.718 x 4 x 3 x 2 x1) x 100 = 1.5%
5	1/(2.718 x 5 x 4 x 3 x 2 x1) x 100 = 0.3%

Table 2.4.1 Probability of n events occurring within 9 years when R = 9 years

The table shows that the probability of there being three or more cyclones during any nine year period is only (6% + 1.5% + 0.3% + ….) or somewhat less than 10%.

Therefore, anyone saying that the TIM cyclones were just a chance cluster could be well be correct – but the odds are 90% in favour of them being wrong and that some other factor was in play.

(1) The writer is indebted to Keith McGuinness, a statistician at CDU who came to similar conclusions to the above using alternative statistical methods.