Queensland Climate Change and Community Vulnerability to Tropical Cyclones

1998 - Extreme weather responsible for A$89 billion dollars in damages worldwide

CYCLONE HAZARDS ASSESSMENT - Stage 4

Report
September 2003

Development of a Cyclone Wind Damage Model for use in Cairns, Townsville and Mackay

Climate Change and Tropical Cyclone Impact on Coastal Communities' Vulnerability

Project with: Queensland State Government's Department of Natural Resources and Mines and the Department of Emergency Services
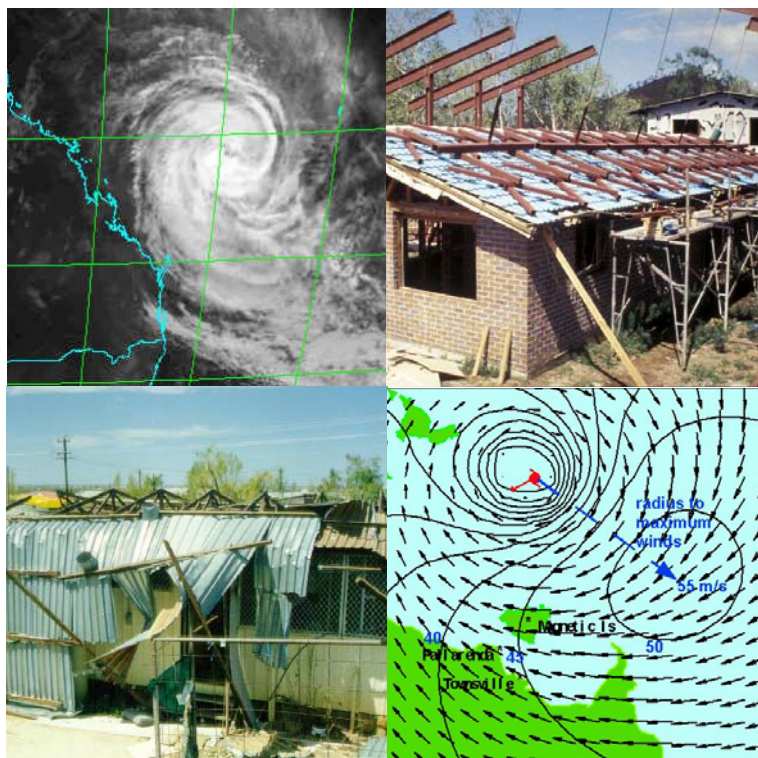
by JCU Cyclone Testing Station in association with Systems Engineering Australia Pty Ltd

Queensland Government
Department of **Emergency Services**
Department of **Natural Resources and Mines**

SEA

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LIMITATIONS OF THE REPORT

The information contained in this report is based on the application of conceptual models of cyclonic winds and house elements and provides an estimation only of the likely impacts of such events with respect to wind damage to houses. The results should be interpreted by persons fully aware of the assumptions and limitations described in this report and who are familiar with statistical concepts and the variability of such predictions.

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Executive Summary

The purpose of the study is to assess the amount of wind damage likely to occur in the major coastal communities of Townsville, Cairns and Mackay, and to obtain a distribution of that damage over each township for a cyclone of given intensity and path. This study focuses on houses and flats (i.e. domestic construction) as they represent the shelter mainly used during cyclone events. For this reason, knowledge of housing performance (resilience) is crucial for agencies involved in disaster mitigation and response, as it serves to target disaster amelioration.

Towns have a mixture of house types. Differences in size, shape, window size, cladding type, roof shape, age, and methods of construction have an effect on the resilience of the house to resist wind forces. Houses also have varying degrees of exposure to wind forces, with those dwellings located in a suburban environment gaining shelter from surrounding structures as distinct from those exposed houses near the sea or in open terrain. Topographical features such as hills can concentrate or divert wind flow. Wind speeds impacting on a community will vary according to a tropical cyclone's intensity, size and distance from the community. Therefore an assessment of the wind resistance of housing requires knowledge of house types and their distribution throughout the community.

The concept of assessing the vulnerability of housing in the community is to combine these effects of the varying wind forces on the population of houses of different shape, size, construction and age that comprise the township. All of these factors make it difficult to accurately predict the likely damage to a community's housing from the cyclonic winds.

The study is not about trying to assess the performance of individual houses or even small groups of houses but more a general estimation or indication of potential damage from a particular cyclone event.

As the different geometries and house elements react to the impact wind in different ways, the distribution of the pertinent housing parameters across the community is required. Comprehensive data surveys of the external features of housing were carried out for Cairns, Townsville and Mackay as part of the Tropical Cyclone Coastal Impacts Program (TCCIP). The data collection for Cairns and Mackay was conducted by AGSO Cities project for the TCCIP. Mackay City Council and Cairns City Council provided the TCCIP housing survey and spatial data to the Cyclone Testing Station (CTS). The CTS conducted the physical attribute housing survey for Townsville along with detailed structural inspections of houses.

From knowledge of the development of the towns forming this study, a review of current and superseded building regulations, detailed house inspections, and an overall survey of the housing stock, the methodology was to categorise the various house styles into six general classes based on overall geometry and construction technique, covering houses from the 1860's through to present day forms.

Because a house frame is a very complex structure it does not lend itself to a straightforward structural analysis, as there are a multitude of building elements providing load sharing and in some cases redundancy. The CTS developed housing wind resistance models used here are to give an estimate of the likely failure mode and failure load for a representative proportion of houses. Findings from full scale house testing, and component joint tests, have been incorporated in the estimation of failure capacities.

The CTS housing wind resistance models focus on the chain of connections from the roof cladding fixings down to the wall tie-down. Findings from damage surveys and full scale house testing results conclude that the predominant mode of failure is associated with the lower load capacity of the joints in the house structure. Five failure modes (at cladding, at cladding to batten connection, at batten to truss/rafter connection, at truss/rafter to wall connection, and of wall tie down connection) were derived for each of the six house models for the two primary wind orientations for both full and partial internal pressure.

When sudden internal pressurisation of the house occurs, such as that caused by a breach in the building envelope by wind driven debris breaking a window or by a blown in door, the load can be dramatically increased on the structure. Failures of house elements add to the debris field impacting on down wind houses that increases their risk of failure leading to higher probabilities of further failures down wind (eg a snowball effect). The report demonstrates the sensitivity of the model output to the estimation of houses subjected to full internal pressure and also highlights the importance of mitigating the risk of full internal pressure (sound structure, window protection, securing potential debris prior to the cyclone, etc).

The deterministic wind field model SEACATd was amalgamated with the CTS housing wind resistance models to provide a user-friendly software interface to estimate the number of houses suffering wind induced damage from a cyclone of given parameters (track, intensity, radius etc). In the wind model framework, topographic factors such as ground height, surrounding terrain and neighbouring structures were represented in accordance with the boundary layer coefficients as detailed in the Australian Wind Load Standard AS1170.2-1989.

As a verification check, the output of the combined SEACATd and CTS housing wind resistance model has been calibrated against real data. This is not an easy task, because there is a dearth of damage survey data available since, thankfully, severe cyclones are rare events. Tropical Cyclone Althea, which hit Townsville in 1971, is the one event that can be used to calibrate the output from the wind model and pre 1970's house models. Althea caused overall damage levels in the order of 16 % and a damage level of 68 % for an exposed coastal suburb, which were published in a JCU report on Cyclone Althea. For pre 1970s housing the CTS model estimated the percentage of houses damaged at 15 % for a shielded suburb and 71% for an exposed coastal suburb, which compares favourably with the reported damage. There are no other events in the survey areas that can be used for the calibration of the complete system. However, damage investigations following cyclones Tracy and Vance for example, have been used for validation of specific data points.

The model generated output is intended to give an estimate of the number of houses sustaining wind damage when subjected to a derived wind speed. Limitations, assumptions and variability in the house resistance models, house class distribution, wind speed model, and terrain models should all be considered when assessing the model output. The report and model results are of a sensitive nature and care should be taken in the interpretation of the output and findings.

Variations in model parameters such as the assessed construction quality of the housing stock, the composition of the housing wind resistance models, and the estimated proportion of houses that might be susceptible to full internal pressure can play a large factor in the model's estimation of overall damage numbers.

Results from the study detail, for defined districts within the modelled community, the estimated numbers of houses suffering damage and give a broad-brush classification of the types of structural failures, using varying winds from a generated cyclone or a blanket wind speed across all districts. In running the model with various cyclone scenarios, areas of housing stock within the modelled districts are shown to have varying relative vulnerability through combinations of topographic and building class features.

The study has shown that the modelled region of Cairns is estimated to have a lower relative overall vulnerability of its housing stock to wind loads than the other modelled regions of Townsville and Mackay, because it has a greater proportion of housing built following the introduction of engineered house building requirements in the early 1980's.

In varying the house model parameters, the report highlights the potential reduction in damage to houses by protecting the house envelope to reduce the probability of subjecting the structure to full internal pressure.

The project has demonstrated a practical yet advanced methodology for combining multiple CTS house wind resistance models, representing real communities, with the SEA tropical cyclone wind field modelling system. There is much opportunity to extend and improve upon the sophistication of the Housing wind resistance models and the cyclonic wind field model. However, the CTS and SEA are of the view that this work already represents the most advanced assessment of house performance in high winds yet undertaken in Australia.

1. Introduction

1.1   Background

In 1971, Category 3 Cyclone Althea damaged 16 % of the houses (JCU 1972). In 1974, Category 4 Cyclone Tracy devastated Darwin, destroying over 70 % of the houses. Walker (1975) reported that this high level of damage of houses was not reflected in engineered commercial structures. Cyclone Tracy was the catalyst for greater research into cyclones, wind loads on houses and the corresponding development of engineered design standards for domestic construction. Although Category 3 Cyclone Winifred damaged to 20 to 30% of housing built prior to the 1980s only minimal damage to the 1980s housing was observed (Reardon et al 1986).

Today, would a cyclone of similar intensity to Cyclone Tracy create a similar catastrophic loss to a coastal community in Queensland? How many houses are expected to be damaged? Will changes in cyclone parameters from climate change increase the communities' vulnerability?

The aim of this project is to develop and verify a methodology to assess the amount of damage likely to occur in the major coastal communities of Townsville, Cairns and Mackay, and to obtain a distribution of that damage over each township for a cyclone of given intensity and path. The study is not about trying to assess the performance of individual houses or even small groups of houses but more a general estimation/indication of potential damage from a particular event.

This study focuses on houses and flats, i.e. common forms of domestic construction as they represent the main forms of shelter accessed during cyclone events. For this reason houses have to be able to withstand up to a wind threshold with this knowledge crucial for agencies involved in disaster mitigation and response as it serves to target disaster amelioration.

Although housing damage risk studies have been conducted in recent years for DES (e.g. Harper 1999b) and the commercial insurance industry, all have lacked detailed data on house type and distribution throughout the region. Existing studies have also had to rely on empirical claims-based damage relationships essentially based on the industry experience of Cyclone Tracy. Because of the complex behaviour of buildings when subjected to high winds, the house structural resistance mechanisms have never been detailed or enmeshed in the modelling process, and there is a high uncertainty when making predictions. The present study seeks to understand the physical damage sequences in the first instance, hopefully leading to better economic loss analyses than presently available from the purely claims-based approach. This will lead to higher confidence in the damage estimates and the ability to explore the potential benefits of specific mitigation initiatives.

The three modelled communities of Townsville, Cairns and Mackay are located in cyclonic region C as defined by the Australian wind loading standard, AS1170.2-1989, shown in Figure 1.1. In broad terms houses, in cyclonic region C, that have been built since the early 1980s have been designed to standards with an underlying assumption that the design impact wind speed has a 5 to 10 % probability of exceedance in 50 years, as defined in the Building Code of Australia.

The proposed methodology is to estimate numbers of wind damaged houses by using several representative house types and their distribution within model districts of Townsville, Cairns and Mackay as shown in Figures 1.2, 1.3 and 1.4 respectively.

The extensive surveys of the distribution of houses within Townsville, Cairns and Mackay, detailed structural inspections of houses, and initial development of the housing wind resistance models were conducted under the auspices of the Tropical Cyclone Coastal Impacts Program (TCCIP).

The project deliverables are;
- Technical report describing the methodology, calibration, conclusions and recommendations
- A "demonstration" software program and associated input data files and user guide that will permit Emergency Managers to estimate the extent of damage likely to be produced across one of the nominated communities by a tropical cyclone of given parameters
- Model output files that will be compatible with GIS packages (postcode level ASCII)

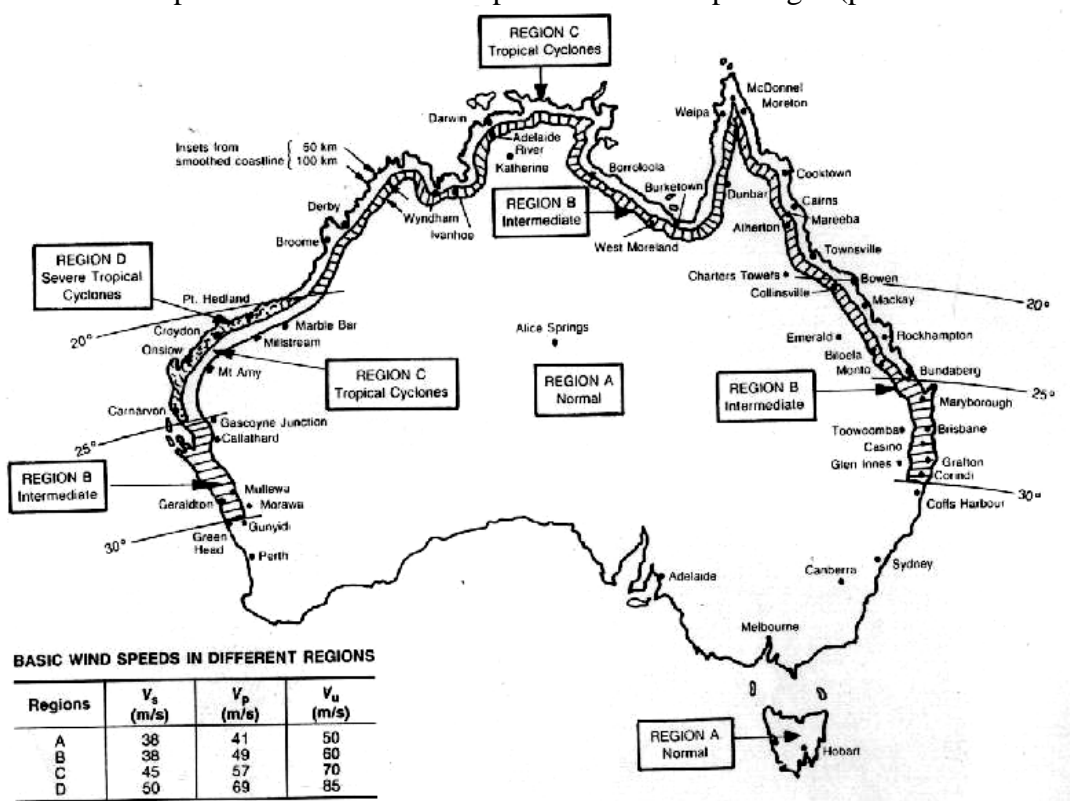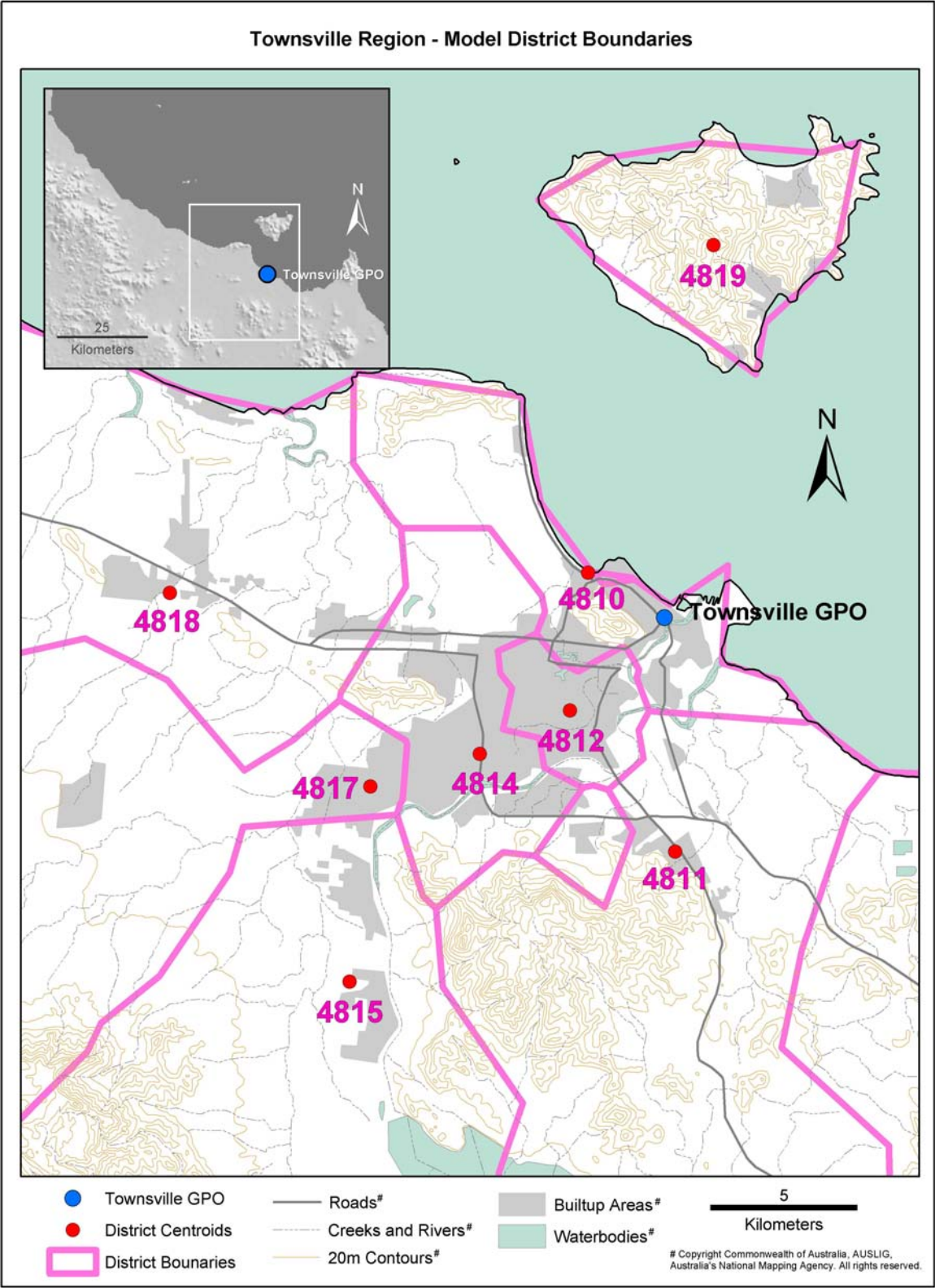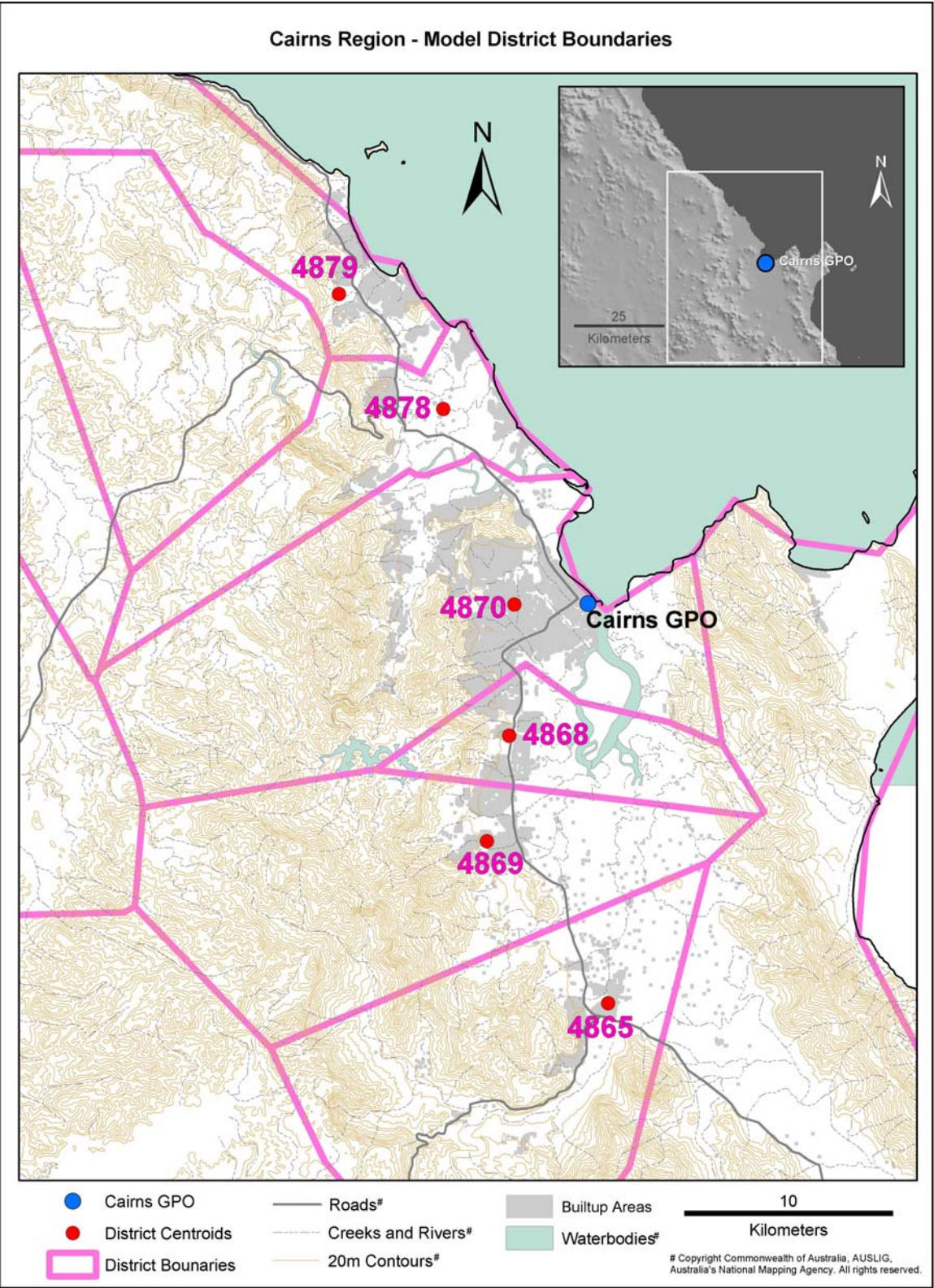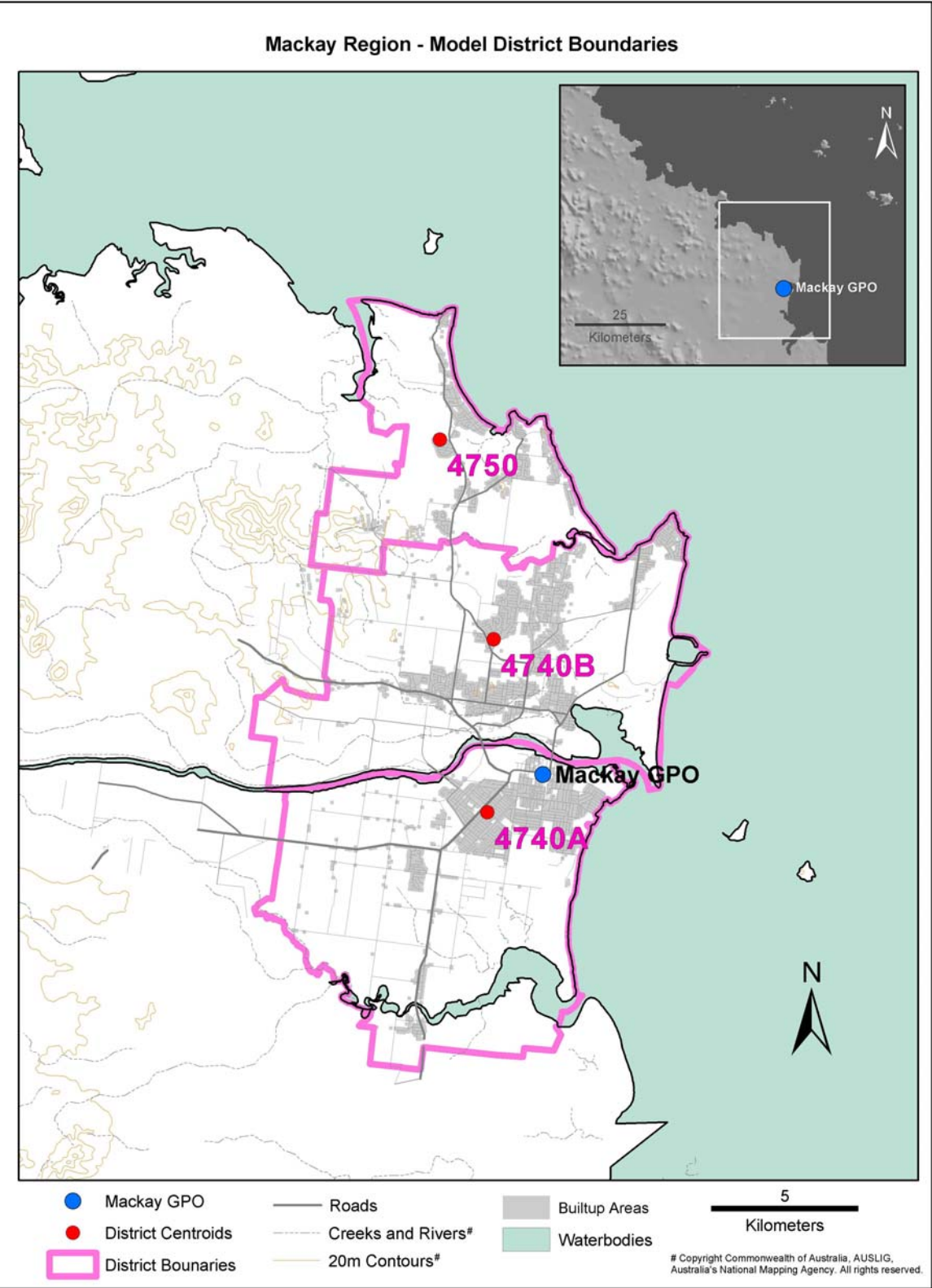**Figure 1.1: Wind regions of Australia (AS1170.2-1989)**

Figure 1.2: Location map of Townsville/Thuringowa modelled districts

Figure 1.3: Location map of Cairns modelled districts

Figure 1.4: Location map of Mackay modelled districts

1.2   Limits/Constraints on Use

The results contained within this report and output generated by the SEACATd computer package, incorporating the CTS house wind resistance models, are of a sensitive nature. This report's associated computer package is only for internal use by the Queensland State Government's Department of Natural Resources and Mines and the Department of Emergency Services.

Care should always be taken in the interpretation and dissemination of the output. The following factors should also be considered;
- The output is at a post code resolution, that is an amalgamation of adjoining suburbs giving a minimum of a few thousand houses.
- The output is expressed in terms of the estimated number of houses suffering damage from wind.
- The damage output in each district can vary from minor, like the loss of a roof cladding element, through to the collapse of the supporting structure.
- The output does not model the damage caused by the considerable problem of water ingress during a cyclonic event.
- The wind model is deterministic (Section 1.3.1).
- The house wind resistance models are probabilistic (Section 2.6).
- The peak wind speeds, not temporally varying speeds, generated by the wind model are used in estimating the number of houses suffering damage.
- The wind model uses the AS1170.2-1989 boundary layer wind flow (Section 3.2).
- The house wind resistance models use the AS1170.2-1989 pressure coefficients (Section 1.4).
- The only calibration/verification point for both the combined wind model and house wind resistance models is for cyclone Althea (Section 4).

1.3   Characteristics of Tropical Cyclones

The present study is concerned with estimating the impact of severe tropical cyclone winds on domestic classes of housing in North Queensland. Tropical cyclones are large scale and potentially very severe low pressure weather systems that affect the Queensland region typically between November and April, with an average incidence of 5.2 storms per year since 1959/60 (Harper 2001).

The tropical cyclone is an intense tropical low pressure weather system where, in the Southern Hemisphere, winds circulate clockwise around the centre. In Australia, such systems are upgraded to *severe* tropical cyclone status (referred to as hurricanes or typhoons in some countries) when average, or sustained, surface wind speeds exceed 120 km h^{-1}. The accompanying shorter-period destructive wind *gusts* are often 50 per cent or more higher than the *sustained* winds.

The destructive force of cyclones is usually expressed in terms of the strongest *gusts* likely to be experienced, which is related to the central pressure, speed of movement and internal structure of the storm system. The Bureau of Meteorology (1999) uses the five-category system shown in Table 1.1 for classifying tropical cyclone intensity in Australia. *Severe* cyclones are those of Category 3 and above.

Table 1.1 Australian tropical cyclone category scale.

Category	Maximum Wind Gust (km h^{-1})	Potential Damage
1	<125	Minor
2	125-170	Moderate
3	170-225	Major
4	225-280	devastating
5	>280	Extreme

1.3.1 Representing Tropical Cyclone Characteristics in a modelling framework

The main structural features of a severe tropical cyclone at the earth's surface are the eye, the eye wall and the spiral rain bands (refer satellite image in Figure 1.5). The eye is the area at the centre of the cyclone at which the surface atmospheric pressure is lowest. It is typically 20 to 50 km in diameter, skies are often clear and winds are light. The eye wall is an area of cumulonimbus clouds, which swirls around the eye. The rain bands spiral inwards towards the eye and can extend over 1000 km or more in diameter. The heaviest rainfall and the strongest winds, however, are usually associated with the eye wall. For any given central pressure, the spatial size of individual tropical cyclones can vary enormously. Generally, smaller cyclones occur at lower latitudes and larger cyclones at higher latitudes but there are many exceptions.
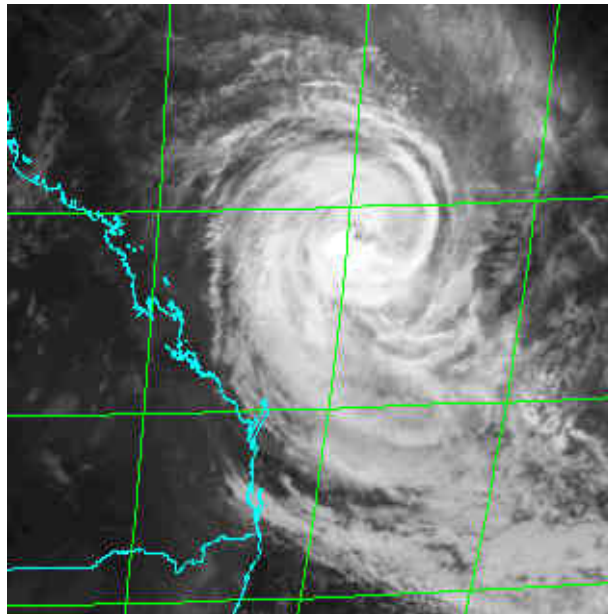
Figure 1.5: Severe tropical cyclone Fran (Category 3) approaching the Queensland coast in March 1992

In the present study, an analytical model of the tropical cyclone wind structure is used to estimate the spatial distribution of the maximum wind gust speed during the passage of a storm with specified parameters. In this sense, the model developed is termed *deterministic*, because it provides the answer to a specific scenario or "*what if*" question. Such models can also be extended to include *probabilistic* predictions (e.g. Harper 1999, 2001) by inclusion of tropical cyclone climatology statistics, but this aspect is not a part of the present study scope. Probabilistic models can account for the natural cyclone variability from one season to

another or between storms during the same season and be used to estimate the Average Return Period (or Average Recurrence Interval) between storm events equalling or exceeding a given wind speed intensity. Deterministic models, however, are useful tools for examining the underlying model behaviour, as training tools and for real-time impact and response forecasting and planning assessments.

1.3.2   Assessing the Impact of Possible Climate Change

A companion report to the present study by Harper (2001) entitled "Queensland Climate Change and Community Vulnerability to Tropical Cyclones: Stage 1 - Ocean Hazards Assessment" addresses the issue of potential climate change and its possible impacts on tropical cyclones in the Queensland region. Although that report considered a now superceded climate change statement (IPCC 1996), the conclusions of the assessment were based largely on the specialist WMO Commission for Atmospheric Sciences review by Henderson-Sellers *et al* (1998). Notwithstanding that an updated specialist review is yet to be prepared, these conclusions are generally deemed to still stand (Harper 2003).

Any significant modifications to the behaviour of tropical cyclones in a changed climate could have especially damaging impacts for regions of northern Australia. In the context of community housing, the potential exists for changing extreme wind environments to perhaps adversely affect existing infrastructure where design conditions that are embodied in the building regulations have been based on estimates from the historical dataset of "present" climate.

The principal issues arising from assessments of climate change with respect to tropical cyclones are whether there is likely to be any significant change in the Maximum Potential Intensity (MPI) of tropical cyclones and if the frequency or extent of cyclones is likely to change. Considering the various issues involved, this lead to recommendation 2 from Section 14 of Harper (2001), which stated:

It is recommended that the assessment of long-term storm tide risks to the Queensland coast should include allowance for the current estimates of enhanced Greenhouse sea level rise and a 10% to 20% potential increase in the MPI of tropical cyclones. Although no significant increase in frequency of occurrence or geographical coverage is anticipated, it is considered prudent to investigate the sensitivity of storm tide statistics to a 10% variation in these aspects of the climatology under an enhanced Greenhouse scenario.

This recommendation has been adopted by Stage 2 of the above project JCU (2003) whereby techniques have been developed to incorporate such allowances into the estimation of long term statistics of storm tide levels for the Hervey Bay and Sunshine Coast regions. Subsequent studies are planned that will extend these analyses along the east coast of Queensland.

Section 9 of the report includes recommendations as to how the present deterministic model might be readily adapted to make use of climate change scenario outcomes from other studies.

1.4   Wind loads on a house

The wind field within a cyclone is a highly turbulent environment. The dynamic fluctuating winds that impact on the house subjects the structure to a multitude of spatially and temporally varying forces (Ginger and Henderson 2003). Generally the design of the house structure uses the peak gust wind speed in determining the large positive and negative pressures pushing and pulling on the house. The wind duration and temporally varying forces are important in assessing elements of the house envelope and frame, such as roofing, battens and connections, that may suffer degradation from load cycle fatigue (Henderson et al 2001).

The peak gust wind speed, taken as the 3 second peak from the BOM, impacting on the house can be related to the pressures exerted on its elements through a series of coefficients defined in the wind loading standard AS1170.2-1989. These pressure coefficients for a large variety of building geometries have been determined over many years by researchers at facilities like the Cyclone Testing Station's boundary layer wind tunnel at JCU (Reardon and Holmes 1981, Holmes 2001). The pressure coefficients take into account many factors such as the buildings overall shape, height, length to breadth ratio, wind ward openings, roof geometry and slope, and orientation to the wind, to name a few.

The loads on a house roof can be analogous to that of the high uplift (suction) pressures acting on an aircraft wing. During a severe cyclone event such as cyclone Tracy, a typical truss or rafter support needs to be able to resist forces pulling up on it equivalent to the weight of a small car. Figure 1.6 and Figure 1.7 give a representation of the pressures acting on a house. The high suction pressures at the leading edge of the roof can be seen. If there is a breach in the building envelope on a windward face, the interior of the house is suddenly pressurised. These internal loads act in concert with the external pressures greatly increasing the load on the house cladding elements and structure. This is discussed further in Section 4.2 The building envelope includes windows and doors as well as the wall and roof cladding.
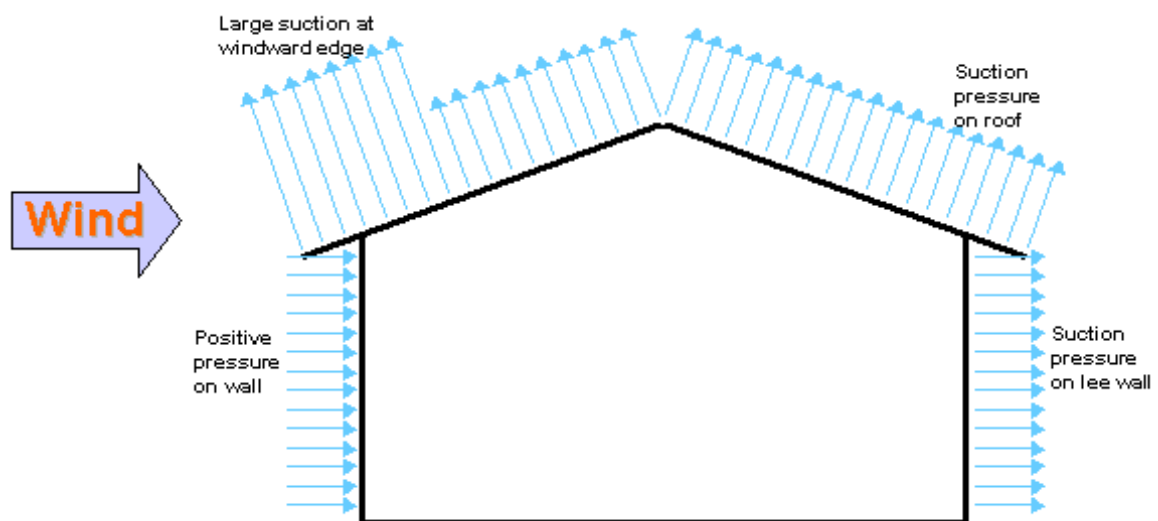
Figure 1.6: Representation of wind forces on a house
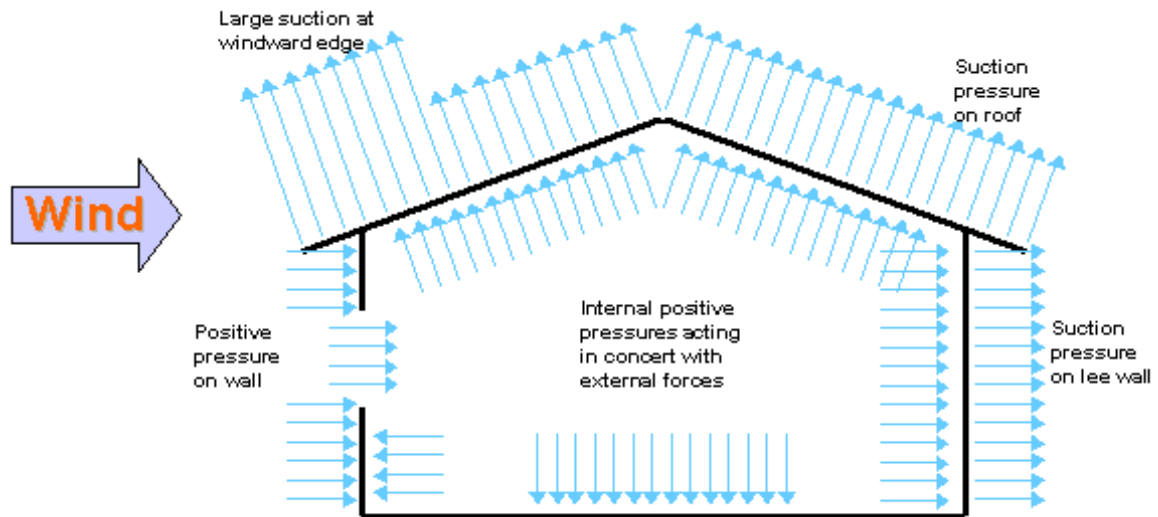
Figure 1.7: Wind forces with a dominant opening in windward wall

1.5   Houses

Houses are common and have elements based on traditional forms of construction. Traditionally, housing has evolved with the changes in building practice and materials, being slow relative to the maximum likely loads being frequent enough for errors to be highlighted before any serious disaster occurs. Walker (1975) notes that where changes in building practice has been rapid and where extreme events occur infrequently, the traditional approach can lead to a sense of false security and a disaster prone situation. This can be seen in the incredibly disproportionate amount of damage, caused by cyclones Althea and Tracy, to housing relative to engineered commercial buildings.

Houses, although common, are complex structures and do not lend themselves to simple structural analysis. Typical framed house construction has a multitude of elements and connections as shown in Figure 1.8. Through all these members and connections there is no easily identifiable load path. There is load sharing between multiple frame members and even between the frame and some cladding elements. However, full-scale house testing at CTS and damage investigations have shown that a house is only as strong as its weakest connection, "The weak link in the hold down chain". The CTS house wind resistance model uses this as its basis.
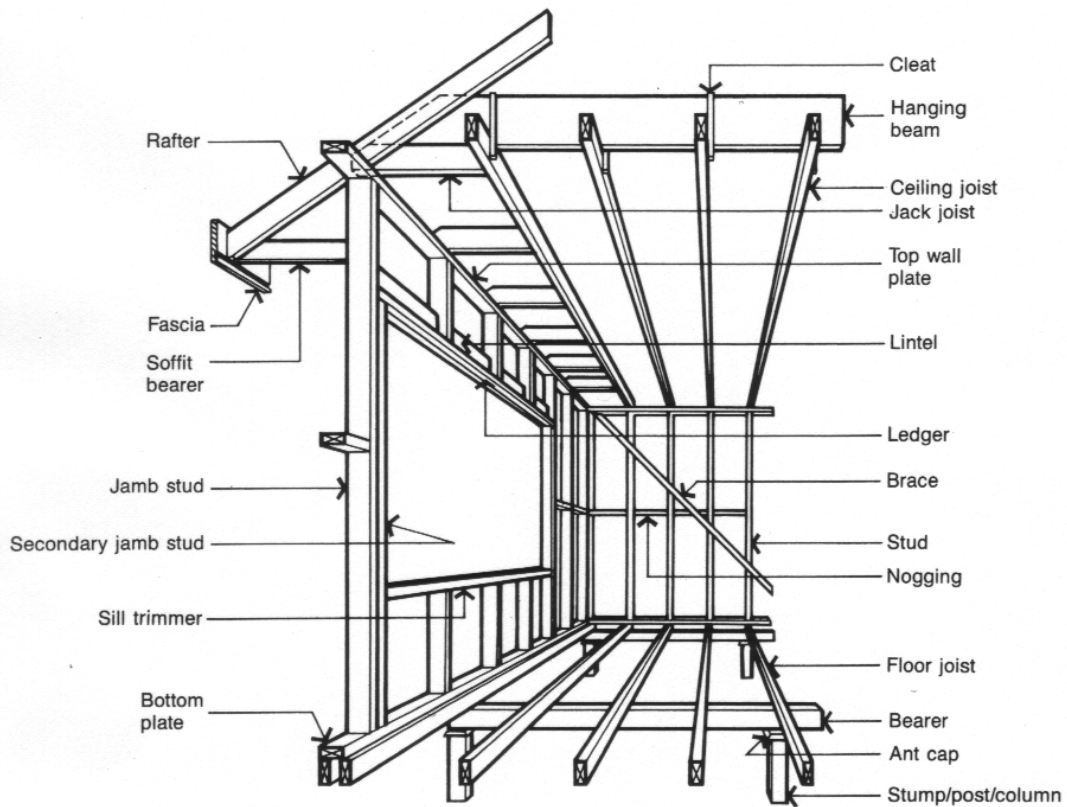
Figure 1.8: Multitude of components and connections in a house frame (from TRADAC Timber framing manual, 1990)

2. How strong is a house?

Nearly all towns comprise a mixture of house types. There are differences in size, shape, window size, cladding type, roof shape, age, and methods of construction. Each of these parameters can have an effect on the resilience of the house to resist wind forces.

Individual houses have varying degrees of exposure to wind forces with those dwellings located in a suburban environment gaining shelter from surrounding structures as opposed to houses near the sea or open terrain. Topographical features such as hills can concentrate or divert the wind flow. The wind speeds from a tropical cyclone impacting on a community will vary according to its intensity, size and distance from the community.

The concept of assessing the vulnerability of housing in the community is to combine these effects of the varying wind forces on the population of houses of different shape, size, construction and age that comprise the township.

The damage estimate is not given for the performance of an individual house or even small groups of houses. The aim of this project is to quantify the vulnerability of dwellings, from winds of known speed caused by a tropical cyclone, in terms of the likely overall distribution of damaged houses.

Therefore an assessment of the wind resistance of housing requires knowledge of house types/construction and their distribution throughout the community.

2.1   Types of Houses

Materials, size and shape of houses have a bearing on the resistance to wind forces and there are many different forms of house styles and construction. This study cannot hope to classify them all nor is it necessary as the study is looking at the proportion of damage to a population of houses and not at individual dwellings. From knowledge of the development of the towns forming this study, a review of current and superseded building regulations, detailed house inspections, and an overall survey of the housing stock, the various house styles have been generalized into common classes based on overall geometry and construction technique.

2.1.1   Early Queenslander

Houses built in the early part of the century were considerably smaller than current ones. A common style was to have a central square core with verandahs on two or three sides.

The roof of the core is high pitched and often pyramid shaped with no ridge line. Roof framing consists of rafters spanning from the top plates of the core walls to the apex or ridge. A king post typically provides the support from the apex down to ceiling joists or hanging beams. The roof of the verandahs have a lower pitch. Wall framing was mortice and tenon construction. Usually the only bolts included in the construction were used to attach the bearers to timber stumps.

In considering the total housing stock, there are not many of these older houses left. It is often argued that the remaining ones must be the strongest as they have resisted a number of cyclones and, as they have a high market value, are generally kept in good condition.

2.1.2   1930s to 1950s houses

Houses of this era were larger and more complex than their predecessors. They were no longer square, or even rectangular, in plan which resulted in complex roof shapes with multiple hips and gables. Their construction included mortice and tenon wall frames with bearers bolted to stumps as previously mentioned. But there were differences introduced into these houses. Most have tongue and grooved, vertically jointed (VJ) internal timber lining. External cladding is usually timber weatherboards.

This VJ lining plays a significant role in providing tie down for the roof structure against cyclone wind uplift forces. The timber boards are about 100 x 12 mm and extend from bottom wall plate to top wall plate. In addition, some boards continue upwards, being fastened to an overbatten on top of the rafter and directly over the wall, and downwards to the subfloor where it was fastened to a joist or bearer. The spacing of these boards provides strong tie down around the perimeter of the house. Some houses have cyclone rods, but mainly in the corners. It is not uncommon to have the eaves vented by using timber slats as opposed to eaves lining used in later construction.

2.1.3   1960s and 1970s houses

Unfortunately, VJ timber lining became too expensive and was replaced in the post war era by flat sheet internal lining material that was easier to fix and provided a smooth surface for painting. But it did not provide the structural strength of VJ lining. In these houses cyclone rods are present in perimeter walls at about 3 m spacing. Alternatively a specific number of rods were stipulated for a house. Sometimes the rods are extended to overbattens, but the holding nuts interfered with the roofing and are often embedded in the batten, weakening it severely.

A typical house of this period for Townsville was of rectangular shape, timber framed, elevated on stumps about 2.5 m high, with external walls clad with fibre cement or timber weatherboards and internal lining of either hardboard or plasterboard. The roofing was usually metal sheeting on a relatively low to flat pitch. Another common style is single storey brick veneer construction with the roofing typically metal sheeting on a relatively low to flat pitch. The fibre cement clad elevated houses are far less common in Cairns and Mackay.

2.1.4   1980s and 1990s houses

The Queensland Home Building Code (HBC) was introduced in 1982. It was formulated because of the extensive damage to housing caused by cyclone Tracy in Darwin in 1974 and to a lesser extent by Althea in Townsville in 1971, and the obvious need to provide adequate strength in housing. By 1984 it is reasonable to consider that houses in the cyclone region of Queensland were being fully designed and built to its requirements.

The predominant regional building style in this period was single storey construction with a truss roof of low to high pitch with metal roof cladding. In Cairns the external wall construction is typically reinforced masonry block, while in Mackay the greater proportion is by far brick veneer construction. Townsville has both forms. Metal roof cladding is common, although the percentage of tile roofs in Townsville is higher than Cairns or Mackay.

As opposed to the previous three house type groupings, there is a greater mix of the hip and gable roof shapes with a combination of both being common. The use of girder trusses enables larger living areas but also concentrates greater uplift forces requiring specific design solutions.

2.2   Housing survey

As the different geometries and house elements react to the impact wind in different ways, the distribution of the pertinent housing parameters across the community is required.

Comprehensive data surveys of the external features of housing were carried out for Cairns, Townsville and Mackay as part of the Tropical Cyclone Coastal Impacts Program (TCCIP). The aim was not to catalogue every house but to map the majority, typically over two thirds of the dwellings, in each suburb, so that the makeup of the suburb can be reasonably extrapolated. The uniformity/repeatability of the housing stock in newer suburbs is greater than the older.

The data collection surveys of Cairns and Mackay were conducted by AGSO Cities project for the TCCIP and are reported in "Community Risk in Cairns" (1999) and "Community risk in Mackay" (2000) reports. Cairns City Council and Mackay City Council provided the TCCIP housing survey and spatial data to CTS.

The Cyclone Testing Station conducted the physical attribute housing survey for Townsville. The methodology of the Townsville survey is described in Appendix A of this report.

2.2.1   Attributes surveyed

The housing survey collected data on those physical attributes of houses likely to affect their performance during a windstorm. The following data were recorded for each dwelling:
- address (for spatial accounting, not for assessment of actual house)
- number of units
- number of stories high
- orientation
- aspect ratio
- external wall cladding
- window size
- roof end shape
- roof slope
- roofing
- special features.

Figure 2.1: Recorded external features of housing

Because of the vast number of houses involved, all of the above data had to be recorded quickly (eg in less than one minute per house), so each of the data items was divided into predetermined categories, e.g. aspect ratio was either 1:1, 2:1 or 3:1. No other values were allowed.

Definitions of the surveyed attributes and survey procedure are discussed in Appendix A.

2.3   Age data

The age of houses is important in estimating their strength. It is not used to account for deterioration, but to gain an estimate of the likely form of construction. This is highlighted by the classification of house types described in Section 2.1.

However, it was not a straightforward task to obtain an accurate estimate of the age of houses.

For the Cairns and Mackay surveys, AGSO (1999) describes the determination of age data from building plaques, air photos and the expansion of the road network. It is noted that the house ages have been generally classed into pre 1980's and post 1980's.

For the Townsville region, the CTS explored various sources to determine the age of housing. These ranged from city council building permit data, real estate listing data, sewage connection date, and historical photos. The best overall source of data that was obtainable in electronic format was the date of subdivision from the Department of Lands (DOL), which was kindly made available. While it is acknowledged that this age data does not provide an accurate estimate for all of the housing stock, it does represent an upper bound value.

Figure 2.2 gives an indication of the accuracy of the subdivisional data for older housing
when compared with site surveys of Townsville. The survey data points include no houses
newer than 1975. The agreement is much better for newer subdivisions than for older ones
as newer suburbs have been populated at a higher rate and there has not been enough time
for houses to have been replaced.
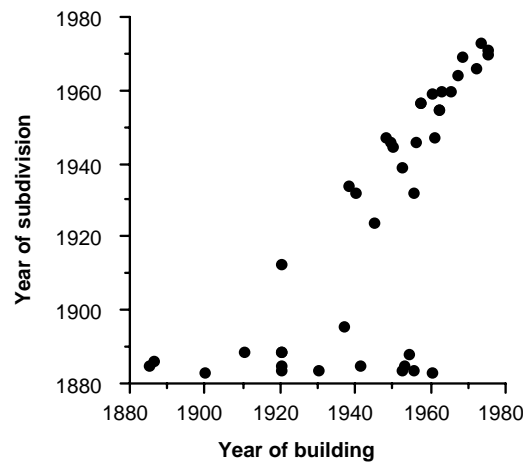
Figure 2.2: DOL age versus age of house

The outlying values in the graph are due to a number of causes. The main underlying cause
is in the typical blanket subdivision of a relatively large area of land in the initial stages of
development of the town. It took several decades to populate these areas and some of the
older housing has now been replaced with newer housing or units. A secondary expansion
of large suburb development also occurred in the 1960s. **Figure 2.3** shows the DOL ages
classified into age brackets, for a Townsville suburb.
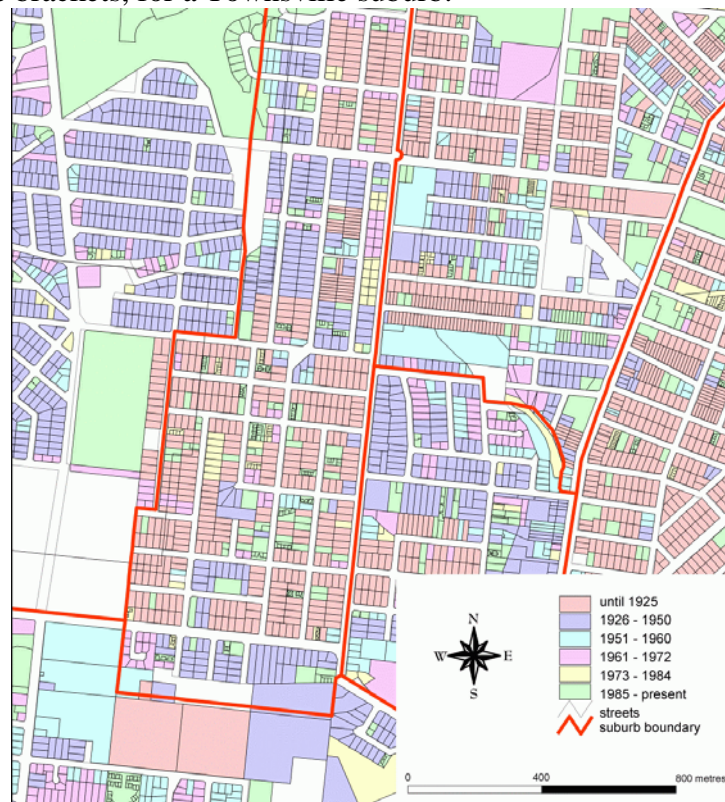
Figure 2.3: DOL age distribution for a Townsville suburb

To refine the age estimate based on date of subdivision, the descriptions of the houses from the housing survey database were used. As an example, a concrete block construction house with a tiled roof on a 1955 block of land would not be classed as a 1950's house but given a minimum estimate of late 1970s construction. The house could of course have been built quite recently.

This methodology, using the majority of the house external features in various combinations, was employed on selected suburbs in the Townsville house survey database to refine the age estimate. The results for a Townsville suburb are given in Table 2.1. The proportioning of house ages will be used to enhance the age allocations of the various house Groups, for the model regions.

Table 2.1: Comparison of DOL age with age modified by external features

Age	< 1925	1925 < 1950	1950 < 1960	1960 < 1972	1972 < 1984	> 1984
Model Suburb	188	166	56	67	104	252
DOL Suburb	411	196	39	81	74	202

2.4   Building regulations

An estimate of age is not of much value in itself, unless it can be related to the typical methods of construction of the time.

The Queensland Home Building Code (HBC) was introduced in 1982. It was essentially a set of deemed-to-comply provisions for house building to resist specific permissible stress design wind speeds, 33 m/s and 42 m/s. These wind speeds specifically related to suburban areas that were in non-cyclone regions and cyclone-prone regions respectively.

At about the same time, the Timber Research and Development Advisory Council of Queensland (TRADAC) introduced a set of manuals giving details of timber construction to resist a range of permissible stress design wind speeds up to 60 m/s. These were complemented by industry brochures showing construction details for bracing walls, for hollow concrete masonry construction and for roofing for various wind speeds. In the latter part of this period, hollow concrete masonry construction on a concrete slab replaced timber framing as a more popular form of housing.

In general, houses built in the 1980s and 1990s in North Queensland represent properly engineered forms of cyclone resistant construction.

Although not regulations as such, recommendations, such as those made by Walker (1972) on design and framing details following Cyclones Althea and Tracy were implemented by many local building authorities, up until the introduction of the HBC in the early 1980s.

Copies of building regulations for Queensland dating back to about 1960 (NSB, 1962) and for Australia from about 1950 (CSB, 1949) were also obtained. Their requirements are very general compared with those of today. Plans of typical houses have also been obtained for houses dating back to about 1970, but the structural details are sparse.

No regulations were available for houses built prior to 1950.

2.5   Inspections of connections

As building regulations alone cannot provide enough information on construction details, especially for older houses, detailed inspections of the structure of nearly 70 houses in Townsville and several from Cairns, of various ages were conducted. Typical connection and framing details from these inspections have been included in the descriptions of the housing types in 'Types of Houses', section 2.1 .

The CTS mounted a media campaign requesting the public of Townsville to offer pre-1970 houses for inspection. The campaign was very successful, as in excess of 50 houses were offered for inspection and nearly 40 individual inspections were made. The age of the houses ranged from 30 to 100 years old. Some houses built in the 1970s for government employees were made available by Queensland Government authorities and analysed by Waqainabete (1997).

Overall inspections included measuring the approximate plan of the house, and recording all external features. Detailed inspections included recording the size and spacing of principal structural members as well as details of tie down and bracing where available. Sub-floors were inspected for attachment of members to stumps/piers and tie down of the wall frames. As most houses had a manhole in the ceiling, inspection of the roofing members and their tie down to the walls was possible.

Unfortunately, these inspections still did not provide full details of some of the critical joints between members in the roof structure. In most instances the fixings for batten-rafter joints and in some cases the rafter-top plate joints were not obvious. To augment the inspections of older houses, inspections were made of houses in the process of having their sheet roofing replaced. This provided invaluable data on fastenings at joints. Although all the detailed house inspections have provided a significant pool of data, they are still only a tiny fraction of the total housing stock modelled. This highlights the importance, as with any model of keeping in mind the underlying assumptions when interpreting the output.

In the structural analysis, assumptions on the fabrication of these joints were made, based on the authors' experience. For the 1960s era high-set house defined in Section 2.1 , it is considered reasonable to assume that batten rafter joints consist of a pair of nails and that the rafters are attached to the top wall plate by a pair of nails, but with additional connection to an adjacent ceiling joist.

The vast majority of the housing surveyed was in a serviceable condition but there were some examples of degradation via insect attack or rot. In some of the houses surveyed, structural integrity had been weakened by subsequent modifications, eg through the removal of bracing, or tie down support by putting in openings, or the addition of roof area for carports etc fixed to the house structure, with no apparent consideration to the effects of the wind loading on the structure. However in an overall sense, this is somewhat balanced by older houses having tie down connections upgraded when approved re-roofing to local council regulations is carried out.

2.6   Estimation of wind resistance

A house frame is a very complex structure and does not lend itself to a straightforward structural analysis, as there is a multitude of building elements providing load sharing and in some cases full redundancy. The housing wind resistance models proposed here are NOT intended to be used for the design of the structure. They are also NOT for determining the most efficient joint or member size, but for an assessment of the likely failure mode and estimated failure load for a representative proportion of houses. Where appropriate, findings from full scale house testing, such as load sharing (Boughton and Reardon 1984) and fatigue (Reardon 1996), and component joint tests, have been incorporated in the estimation of failure capacities.

The models of the housing wind resistance focus on the chain of connections from the roof cladding fixings along to the wall tie-down. Findings from damage surveys and full scale house testing results conclude that the predominant mode of failure is associated with the load capacity of the joints in the house structure.

2.6.1   House wind resistance groups

The housing population for each of the study regions has been divided into six groups, detailed in Table 2.2. The groupings are based primarily on construction technique, which align reasonably with the house's age and external features.

Table 2.2: House wind resistance groups

Group	Built during
1	1865 – 1925
2	1926 – 1950
3	1951 – 1960
4	1961 – 1972
5	1973 – 1984
6	1985 – present

For each of the housing wind resistance Groups a determination of the likely failure load for the following structural elements was made;
    Roofing elements under cyclic loading,
    Roof fixing to batten,
    Batten/rafter joint,
    Rafter/ridge joint,
    Collar tie joint (where applicable),
    Rafter/top plate joint (with ceiling joist where applicable),
    Truss hold down, and
    Wall tie down
The failure modes have been assessed through physical testing and structural engineering theory with reference to full scale house tests and damage investigations.

2.6.2   House models

The uplift pressure needed to cause failure of an element in a house is calculated and converted into a horizontal impact wind speed, which is taken to be the wind speed acting on the building at eaves height. Within each house Group there is a spread of construction practices, spans and materials used, such as one nail at a collar tie joint or a 3"x1" instead of a 4"x2". Therefore there is no single value of the failure load for a connection type, but a spread of possible outcomes.

By using the data collected on the various element and joint details from building regulations, drawings and the house inspections a mean and standard deviation was determined for five failure modes for each of the six house Groups.
> Failure at cladding
> Failure at cladding to batten connection
> Failure at batten to truss/rafter connection
> Failure at truss/rafter to wall connection
> Failure of wall tie down connection

The statistical parameters for each of the five failure modes determined for each Group of houses are the basis of the damage prediction technique.

In analysing physical data where negative values are impossible (eg length, mass, time and wind speed) statistical distributions other than the Gaussian (normal) are generally used. A lognormal (skewed) probability distribution is the simplest of these, and has been used for these models. Holmes (2001) employed a similar method using a lognormal probability distribution for the derivation of a theoretical wind speed vulnerability curve for engineered steel structures. Leicester and Reardon (1976) used a lognormal distribution in the analysis of damage level and type for structures in Darwin following cyclone Tracy.

A lognormal cumulative frequency distribution of impact wind speeds for each wind resistance element was attributed to each failure mode within each house Group for wind directions parallel and perpendicular to the roof ridge line, and for low (0.2) and full (0.7) internal pressures. The wind model has not been configured to report change in wind direction at this time, as the study is examining a large population of housing, the parallel and perpendicular orientation wind resistance models were combined in equal proportion.

Figure 2.4 describes the house group models. As an example, Figure 2.5 details the probability of damage versus impact wind speed for Group 6.

The ten curves in Figure 2.5 represent the predicted damage envelopes for the Group 6 houses. A wide variety of houses were analysed in the development of these curves. The Group 6 houses represent both masonry block construction and timber framed, typically with brick veneer, construction. The majority of the house parameters used were for C1 wind classification, as defined in AS4055-1992. This applies to housing in a typical suburban environment. Alternatively, if a majority of C2 classification (exposed, open terrain) houses had been used, it is expected that the resulting calculated resistance curves would be slightly higher as the houses would have been designed for higher winds.

The roof framing for this group is predominantly timber trusses. Roof cladding is a mixture of tiles and metal. As mentioned previously, the wind resistance of individual houses can

vary dramatically. In one inspection on a new house, no tile clips were observed along an exposed gable edge. Batten spacings for metal cladding ranged from conservative to exceeding manufacturers recommendations. Accordingly, the variation of strength in the roof cladding can be seen by the flatness of the 'wind_Roof_fix_2' curves, while the steepness of the 'wind_Bat_rft' represents a smaller variability (coefficient of variation).
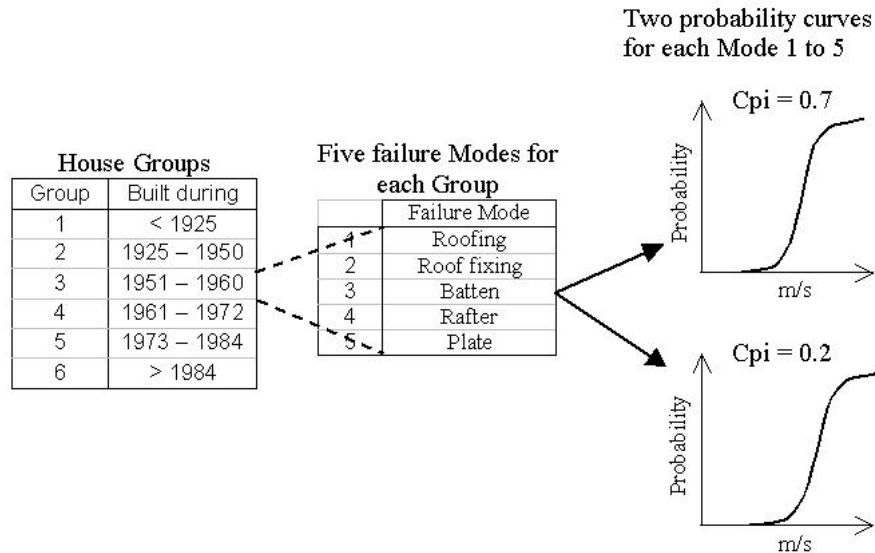
Figure 2.4: Representation of the house Group models

As discussed in the house types section, for this project analysis, the various types of construction (masonry block, timber frame, tile, etc) have been combined into Group 6. They were combined in a proportion reflective of the distribution derived from the house survey database.
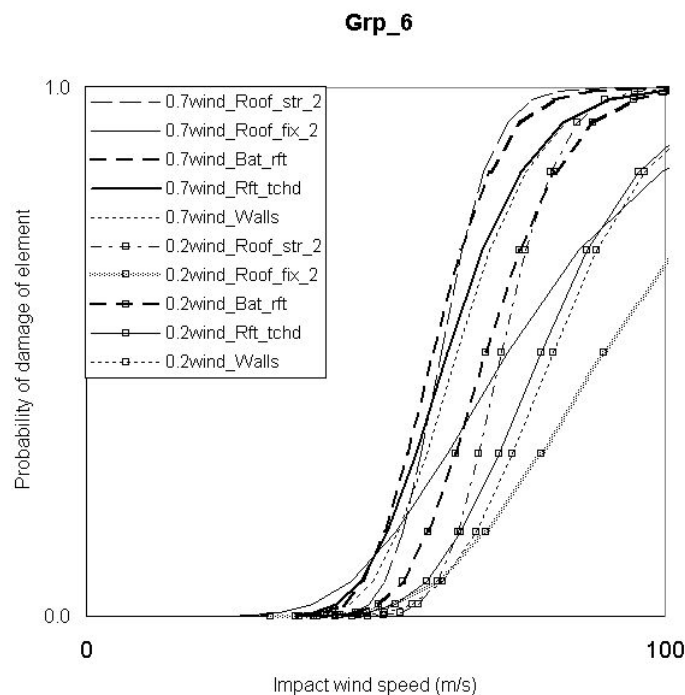
Figure 2.5: House model for Group 6

Generally the probability of damage versus impact wind speed curves show a trend whereby the Group 4 perform the worst while Group 6 is the best. Groups 1, 2, 5 and 3 fall in between. The lower performance of Group 4 can be attributed to its shape and poor roof tie-down. Group 4 has a predominance of flat/low pitch gable roofs, which means larger uplift pressures for both wind directions than the higher pitched and generally hip shaped roofs of Groups 1, 2, and 3. Typically, use of skew nails and notched over battens with bolts at large centres, form the majority of rafter top plate connections.

3. SEA Tropical cyclone wind model

Systems Engineering Australia Pty Ltd provided its proprietary deterministic wind risk catastrophe model SEACATd for use in this project. This specific model is a derivative of some 10 years of development by SEA of the fully probabilistic model MIRAM, used in insurance loss estimation studies for a number of major Australian home and contents insurers.

The SEACATd risk model provides the means to describe the vulnerability of a community in a physically consistent manner and for the user to construct a specific storm scenario to impact that community. A model tropical cyclone is generated and passes along the prescribed track relative to the community. The maximum wind speed experienced at any of a number of nominated locations (e.g. postcode or suburb centroids etc) are then recorded. The model then reports the community impacts in terms of the estimated number of damaged houses, which can vary across a region depending on the changing wind speed experienced, local topographic effects, and the house strength characteristics.
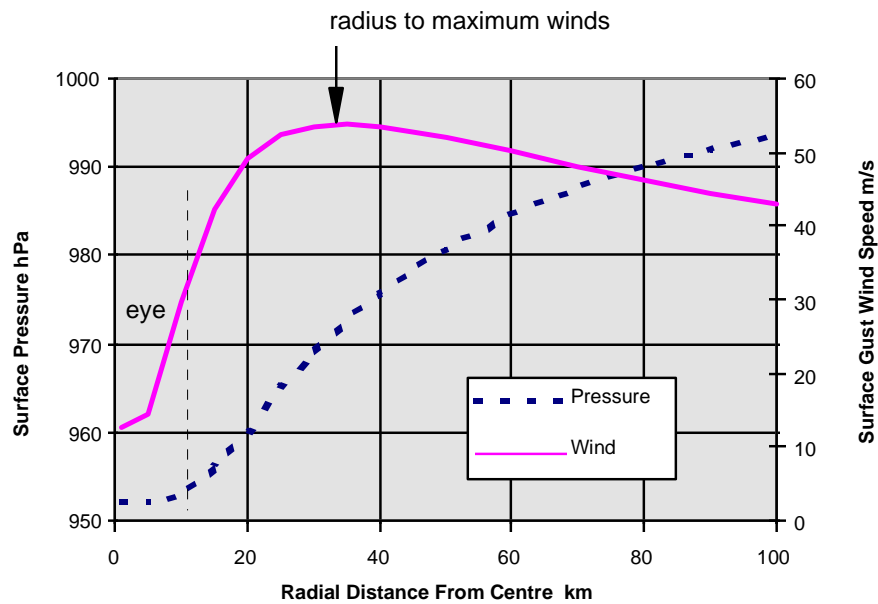
3.1   Tropical Cyclone Winds

The analytical cyclone wind field model after Holland (1980) is used as the basis for the estimation of tropical cyclone generated wind speeds. The Holland model (Harper 2001) has been used extensively for risk assessment studies in the Australian offshore oil and gas industry for West Australian cyclones where 100s of detailed model calibrations have been undertaken and the model is also used by many international weather services, including Australia and the USA.

Primary parameters considered by the Holland model (Harper and Holland 1999) include the central pressure, ambient pressure, radius to maximum winds, forward speed, track and wind profile peakedness. Using these values the model can construct a representation of the wind and pressure fields surrounding the cyclone that accounts for planetary boundary layer effects (causing a reduction in winds close to the surface and the spiralling pattern towards the eye) and the asymmetry due to forward speed effects. Harper (2001) provides details of the tropical cyclone wind model.

Figure 3.1a shows how the model represents the radial variation in mean sea level (MSL) central pressure and peak 3 second wind gusts at +10m relative to sea level. The example shown is for Tropical Cyclone *Althea* whose centre crossed the coast about 50 km north of the city of Townsville in December 1971. *Althea* had an estimated central pressure of 952 hPa and a recorded peak wind gust of 55 ms^{-1} (200 km h^{-1}) at Townsville Airport.

The plan view of model-generated wind vectors in Figure 3.1b shows how the radius of maximum winds (in this case estimated as 35 km) separates the eye of the storm from the area of maximum destruction, here causing the highest winds to pass directly over the city. *Althea* was relatively fast moving at 9 ms^{-1} (32 km h^{-1}) and this results in a strong asymmetry in wind speeds around the eye so that the winds to the left (south) of the storm track are much stronger than to the right (north) in this case.

(a) Radial Wind and Pressure Variation

radius to maximum winds

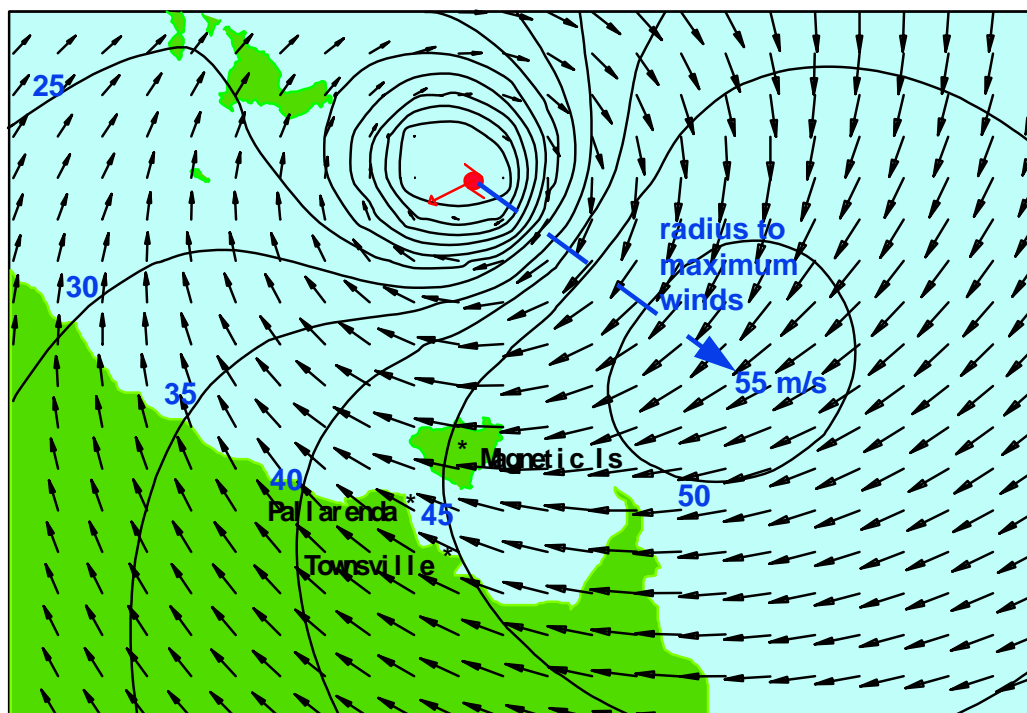## (b) Vector Wind Field

Figure 3.1 Example SEA windfield model of tropical cyclone *Althea*.

3.2   Regional and Local Wind Speed Patterns

The Holland model delivers wind speeds that are deemed representative of over-ocean conditions far from the influence of land. However, this study needs to also consider the degree to which wind speeds may vary over the land as a function of the local surface roughness and topography. These variations are based on the guidelines in the Australian Standard Wind Loading Code AS1170.2 (1989), whereby terrain categories are defined ranging from "2", representing flat open land such as airfields (and over-water), through "3" for residential areas or forests and finally "4" for high-rise CBD area. Local wind speeds decrease with increasing terrain category roughness for a given structure height. Likewise local winds are also affected by the presence of hills where acceleration can occur which is a function of the slope of the hill. Figure 3.2 illustrates in a schematic way how the wind speed variations are handled by the SEACATd model.

The model performance can be tested against the experience in cyclone Althea which caused widespread damage in Townsville in December 1971. Figure 3.3 shows how the modelled wind speeds compare with actual on-the-ground measured values at Townsville Airport. The top trace shows model and measured 10 minute mean wind speeds, the middle shows 3 second wind gusts and the bottom trace compares mean sea level pressures. In all cases the model does an excellent job of matching the peak conditions. Away from the actual passage of the storm, however, it is less accurate due to the fact that the model does not represent the ancillary squalls, which might accompany the storm.

There are many other examples available, which show that the windfield model can readily reproduce measured wind speeds using Bureau of Meteorology estimates of track and intensity plus estimates of radius to maximum wind from radar or satellite and appropriate values for the wind profile peakedness. Appendix B provides details of the tropical cyclone parameters required to operate the risk model.

3.3   Detailed Terrain and Topography Modelling

The regional variability in terrain and topography influences for Cairns, Townsville and Mackay have been previously assessed by SEA using satellite-derived LANDSAT imagery combined with a digital elevation model to map the city areas according to their relative wind exposure (Harper 1999). Wind speeds derived from the Holland model are then converted to local winds on this basis for individual postcode districts at a spatial resolution of 30m (about the size of individual house blocks). SEA made these earlier proprietary analyses available for use in the present project.

The terrain and topographic classification system used in SEACATd follows AS1170.2 (1989) in defining the variability in winds due to terrain and topography changes across the region under broad scale fully mixed conditions typical of tropical cyclones. The following 3 second gust wind speed multipliers are used:

$M_{z,cat}$ - Height and terrain category-dependent multiplier (z=house height).
M_t - Topographic multiplier, dependent on ground slope.
M_s - Shielding multiplier, dependent on the proximity of houses.
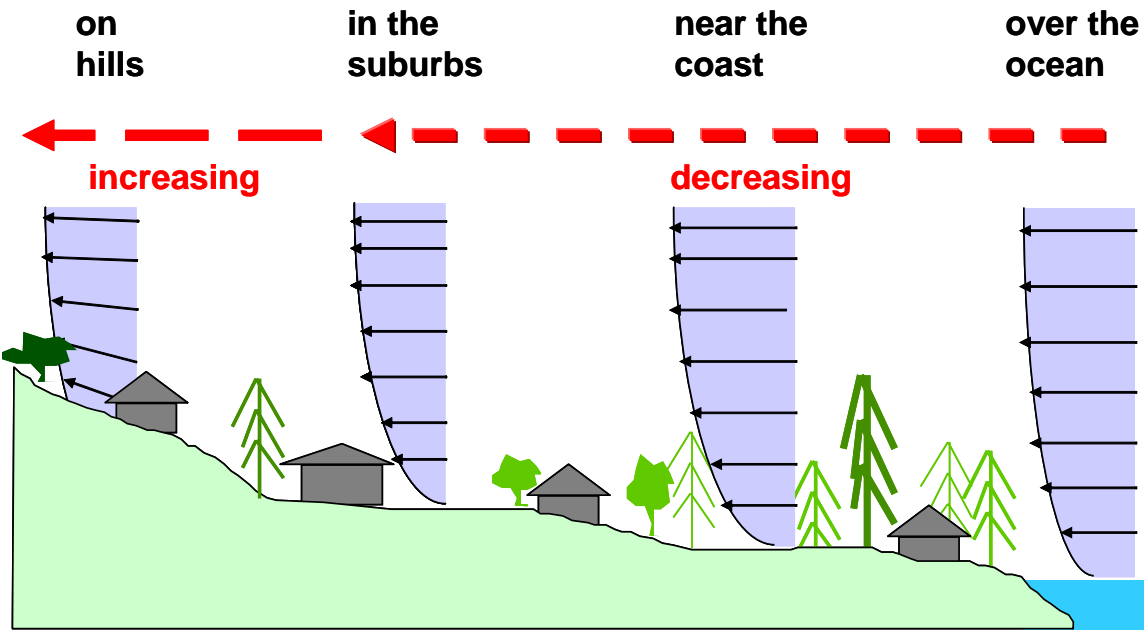
Figure 3.2: Schematic of SEA model terrain and topography influences.
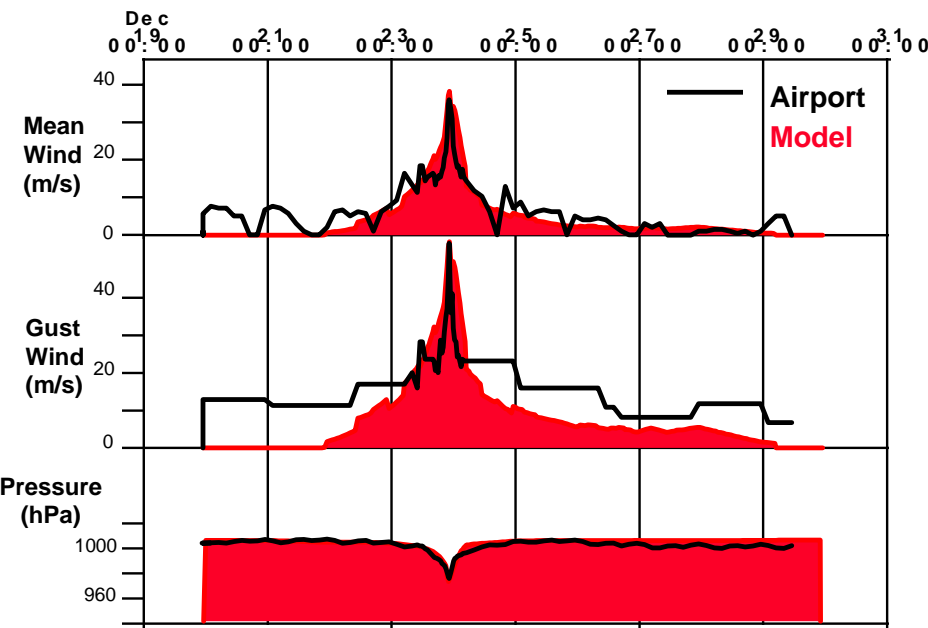

Figure 3.3: SEA wind model calibration against cyclone *Althea*.

The wind speed at any location is calculated as the predicted +10m Category 2 gust wind speed $V3_{10,2}$ (=Vref) from the Harper and Holland (1999) wind model, multiplied by the above local parameters, viz

$$V3_{z,cat} = Vref \times M_{z,cat} \times M_t \times M_s$$

The local surface roughness required to define $M_{z,cat}$ was estimated by SEA across each of the Cairns, Townsville and Mackay regions from the thematic analysis of the LANDSAT data, ground-truthed to each of 4 roughness classes based on definitions in AS1170.2, as follows:

1. uncut grass, airfields, rough open water   Terrain Category 2
2. open savannah, long grass, crops   Terrain Category 2.5
3. suburban areas, wooded regions   Terrain Category 3
4. town centres, city buildings   Terrain Category 4

The SEA analysis further allowed for buffering and boundary layer transition of 1 km between each of these roughness zones on the basis of an omni-directional wind influence. Accordingly, this classification is expected to be conservative, thus tending to slightly overestimate the exposure of housing in some regions.

Figure 3.4 provides an example of the SEA terrain and topography analysis. The top image is a false-colour image of Townsville and the surrounding Thuringowa suburban regions. The prominent Castle Hill can be seen near the port area, surrounded by the older suburban areas and the CBD. The bottom image shows the result of processing by SEA that has allocated a different colour to each of many hundreds of possible wind speed zones, depending on the local terrain roughness, the ground slope and whether there are houses or simply open country. The number of pixels of a specific colour is then counted within the postcode boundaries to determine the proportion of each postcode that is subject to a particular wind speed.

For the present analysis, the full SEA terrain and topography descriptions were reduced to three terrain classes (2.0, 2.5 and 3.0) and 7 slope classes. Some manual updating and additions were also undertaken by the CTS as outlined in Section 5, and the shielding multiplier M_s has been separated from the terrain description to allow it to be wind speed dependant as required by the CTS house damage assessment module.
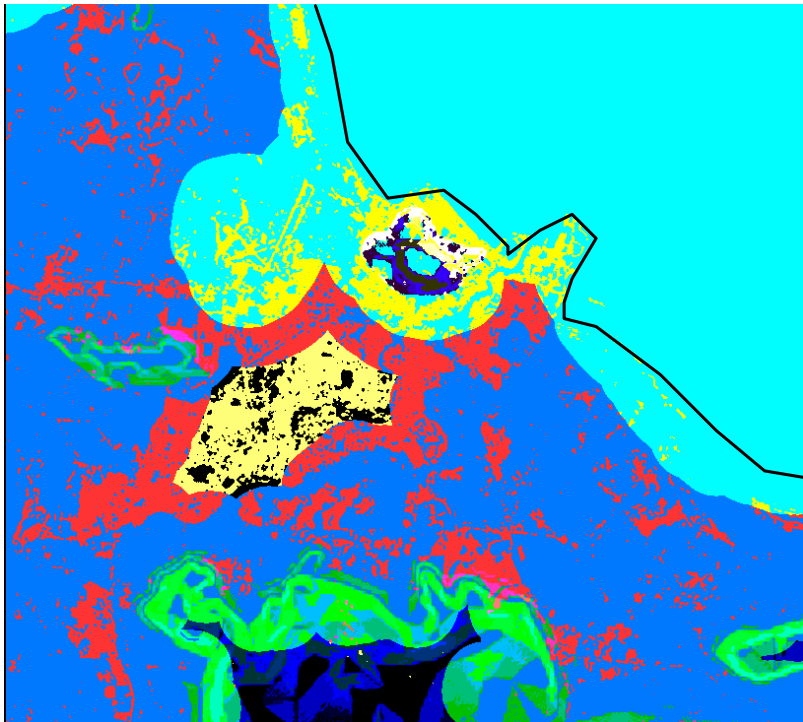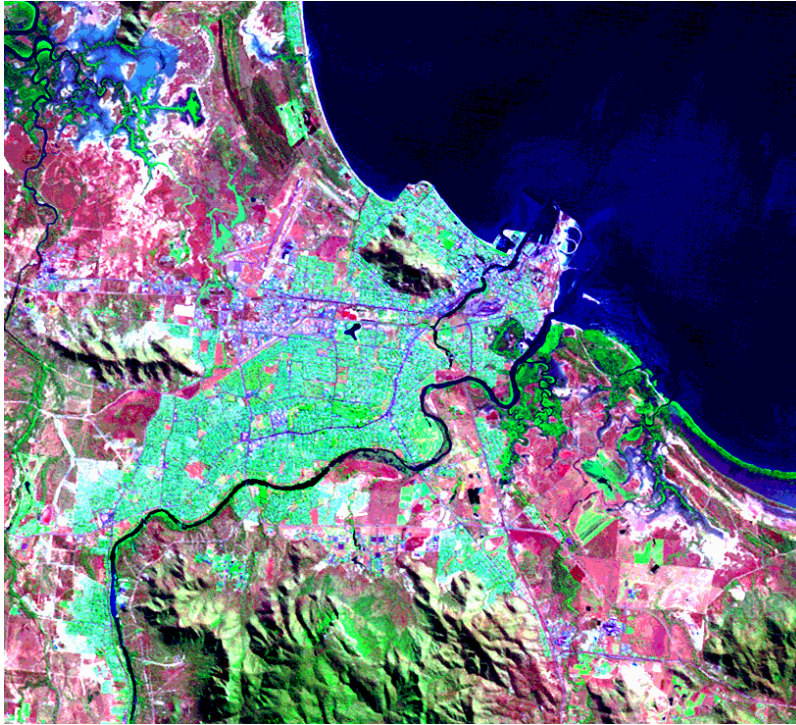
Figure 3.4: Example of SEA terrain and topography mapping for Townsville.

4. Calibration of housing damage models

As a verification check, the output of the housing wind resistance models and wind field model has been calibrated against real data. This is not an easy task for cyclone risk assessment. There is a dearth of damage survey data available since, thankfully severe cyclones are rare events. Tropical Cyclone Althea, which hit Townsville in 1971, is the one event that can be used to calibrate the output from the wind model and house models (only pre 1970's). Reported overall damage levels were 16 % while a damage level of 68 % was reported for an exposed suburb (JCU 1972).

There are no other events in the survey areas that can be used for the calibration of the complete system. However, damage investigations following cyclones Tracy and Vance for example, can be used for validation of specific data points.

Estimates of damage from overseas events such as Hurricane Andrew in Miami could be used, but the strength of the housing stock is not necessarily the same as in Australia. Reardon (1994) highlighted significant differences in house construction between hurricane regions of Florida and cyclone regions of Queensland. Similar failure modes of poor tie down and instability of framing after loss of roof structure were reported, but as the construction methods were different, care needs to be taken in using the damage levels for calibrating the CTS house wind resistance models in this study.

4.1 Methodology

The types and percentage of damage generated by the housing wind resistance models for given impact wind speeds needs to be assessed for each Group and also the overall damage to the housing population.

In using the amounts and types of damage reported in various damage investigations, care is needed in interpreting the impact wind speed for use in calibrating the damage numbers. The wind speeds given in the reports are typically for a wind at +10 m height in flat open terrain. Adjustments are required to convert this 10 m high wind speed into the actual wind speed impacting on the housing stock for comparison with the wind resistance models. Factors taken from the Australian wind standard AS1170.2 (1989) are used to account for height of houses, shielding from adjacent houses, and reduction in wind speed from terrain type such as a suburban environment as opposed to beach frontage.

Example:
Cyclone Althea's peak gust wind speed at Garbutt aerodrome was recorded as 54.5 m/s at a height of +10 m (JCU 1972). In estimating impact wind speed on a single storey house in a suburban environment, say in the middle of the suburb of Pimlico, the wind speed is modified for;
      Eaves height = 3 m
      Terrain and height factor Mzcat = 0.8
      Shielding Ms = 0.85
Therefore impact wind speed on a single storey house is estimated to be 37 m/s. For interest, this is approximately 45 % of the wind force generated by a 54.5 m/s wind at that height.

For a nearby high set house located at the edge of Pimlico next to a park;

        Eaves height = 6 m
        Terrain and height factor Mzcat = 0.89
        Shielding Ms = 1.0

Therefore impact wind speed is estimated to be 49 m/s. For interest this is approximately 80 % of the wind force generated by a 54.5 m/s wind at this height.

However, if the reported maximum wind gust from Althea approached from the opposite direction to the park, the impact wind speed on the above high set house would be estimated as;

        Eaves height = 6 m
        Terrain and height factor Mzcat = 0.81
        Shielding Ms = 0.9

Therefore impact wind speed is estimated to be 40 m/s. For interest this is approximately 55 % of the wind force generated by a 54.5 m/s wind at this height.

The above example highlights the detail required to hopefully calibrate/verify the house strength models against impact wind speed when using overall data from damage surveys. In using overall damage statistics, an estimate of the type and proportion of houses affected by the varying terrain effects is required.

4.1.1   Overview

Conclusions drawn from the varied damage investigations report that the predominant failure of a house structure is associated with the inability of the connections to transfer the applied wind load to the next element. This statement helps to verify the methodology of the house wind resistance model as it is based on the failure of an element along the load path in the house structure tie down chain. These failures at the connections were observed in both the older and newer construction, with separation of battens from rafters and rafters from top plates as just two of many such examples (Walker 1975, Henderson et al 1999).

4.1.2   Housing model groups 1 - 3

Predominantly timber framed with high pitched roofs.

Category 3 Cyclone Althea crossed the coast approximately 40 km north of Townsville, in December 1971. A maximum wind speed of 54.5 m/s was measured at the Garbutt aerodrome at the standard reference height of 10 m. As described earlier, the majority of housing in Townsville would not have been subjected to this wind speed. The overall damage level to domestic construction, not including Magnetic Island, was reported (JCU 1972) as 16% (0.7% demolished, 1.7% not habitable, 13.3% damaged but habitable). For the exposed suburb of Pallarenda, the damage level was significantly higher at 68%. However from the Department of Lands age data, the majority of the houses in Pallarenda would have been constructed after 1960.

The predominant reported damage type observed for the badly damaged houses was a failure of the rafter connections at the ridge or top plate. The predominant predicted failure mode for house model groups 1 and 2 is failure of the rafter connection at ridge or top plate. Whereas in house model group 3 the predominant predicted failure mode is mostly shared between the batten rafter connection and the rafter ridge or top plate connection.

The Cyclone Althea report (JCU 1972) states that the survival of so many structures with this common connection method is probably attributed to the high variability in strength of timber structures and the fact that the majority would not have been exposed to the maximum wind loads due to windward windows remaining intact and shielding obtained from neighbouring houses. The report postulates that if the peak wind had come from North, on which side there is a majority of large windows, damage could have been much more wide spread.

4.1.3   Housing model groups 4 - 5
Predominantly flat/low pitch gable roofs.

The Althea report notes that for the exposed suburb of Pallarenda, the damage level of 68% (8% demolished, 22% not habitable, 38% damaged but habitable) was significantly higher than the majority of Townsville. The majority of housing in Pallarenda would have been built in the mid to late 60's.

The report describes results of inspections made on 34 damaged houses built in the five years prior to Althea. Failure of windows (and/or doors) through inadequate strength preceded the loss of roof for nearly 58 % of the houses. Roof first failures accounted for 26% with a further 16% attributed to wind and debris. This implies that 75 % of the damaged houses were subjected to full internal pressure. The report discusses the subsequent collapse of walls in a quarter of the detailed inspections, through loss of wall top plate support due to the failure of the roof structure. Typically these were external walls of the lounge/dinning areas at one end of the house. Walker (1975) details many examples of this mechanism following Cyclone Tracy. The house wind resistance models do not yet estimate the collapse of walls as a subsequent failure from the loss of support from roof structure, but this could be pursued in future development.

It was noted that the then recently introduced engineered nail plate trusses performed well but there were examples of failure of the connections to roof battens.

Revisions to home building standards to include cyclone resistant construction methods, such as required numbers and connections for cyclone bolt tie down, screw fixing for roofing, purlin straps etc, were introduced following the Cyclone Althea Report. However, Leicester and Reardon (1976) noted that the high set houses in Darwin that showed the poorest performance following Cyclone Tracy, were post 1972 and had incorporated the structural reinforcing features that houses elsewhere in Australia rely on to resist cyclone winds. Although, Sneath (1975) observed a number of poor construction practices in these high set houses in Darwin following Cyclone Tracy, and infers that these practices were wide spread. He noted that detailed supervision of construction was not practicable in Darwin.

Category 4 Cyclone Tracy made a direct hit on Darwin in December 1974. The peak wind gusts were estimated in the order of 65 to 70 m/s (Walker 1975). It had a slow forward movement, subjecting the buildings to high peak wind speeds over a long period of time. As the eye passed over the town there would also have been a large change of angle in the wind direction.

Walker (1975) reported extreme damage to domestic construction at 70% (53% destroyed, 16% roof and walls damaged) with two thirds of the remaining houses suffering some roof

cladding damage, as shown in Figure 4.1. He stated that there appeared to be considerable correlation between damage and age, with the degree of damage increasing in the more modern northern suburbs. The study conducted by Leicester and Reardon (1976) reinforced this conclusion. Leicester and Reardon (1976) show percentages of houses damaged, where damage is loss of half roof cladding through to loss of structure, for elevated, low set brick and low set asbestos cement clad houses as 95 %, 80 % and 85 % respectively.

There was extensive loss of light gauge metal roof cladding. The cause, detailed by Morgan and Beck (1977), was low cycle fatigue of the cladding adjacent to its fasteners. That is, cracking of the cladding allowed the cladding to pull over one fastener, leading to an avalanche effect of overloading and failing of the cladding at adjacent fasteners, as shown in Figure 4.2.

Figure 4.1: Extreme damage to high set houses following Cyclone Tracy

Figure 4.2: Extensive failure of cladding during Cyclone Tracy

As in Townsville following Althea, hip roofs performed better than gable framed roofs. The hip roofs have a better aerodynamic shape (subject to less uplift) and the roof framing builds in an inherent bracing to the roof structure. Similar gable end failures in Miami following Hurricane Andrew, were noted by Reardon (1994).

Cyclone Winifred crossed the coast south of Innisfail, February 1986 with maximum three second gust winds reported in the order of 50 to 55 m/s at Kurrimine Beach. The severe topographical features in the area are considered to have influenced wind patterns.

Reardon et al (1986) reported damage to 20 to 30% of housing built during 1960 to 1980 with only minimal damage observed to modern housing. The most common type of failure in the older housing was loss of roofing with battens still attached. There was little evidence of flying debris damage or of racking failure of walls. Where walls had collapsed it was from loss of stability from loss of roof structure. It was suggested that the improvements of upgrading the fixing of the roof cladding to battens (replacing lead heads with power driven screws) had improved performance but shifted the failure to the next element, the batten rafter connection.

An interesting observation by Boughton (1987) reporting on the minor levels of damage following Category 2 Cyclone Connie, was that although very low levels of damage were experienced overall, failures of the house frame were observed in buildings that had survived previously more stronger cyclonic events. These failures were attributed to corrosion of metal or deterioration of timber due to splitting, rot or insect attack or low levels of damage initiated in previous cyclones.

4.1.4   Housing model group 6

Category 5 Cyclone Vance impacted on the West Australian town of Exmouth in March 1999. The cyclone did not pass directly over the town but to the east. This meant that the maximum wind speeds, although still very severe, at Exmouth were not in the category 5 range, but were in the order of 60 to 65 m/s. With the fast forward motion of the cyclone, the whole storm passed relatively quickly so fatigue effects on the cladding and other elements would be greatly reduced.

Henderson et al (1999) reported that approximately 70 % of all houses had no or negligible structural damage, which is much better than in Darwin after cyclone Tracy and Miami after Hurricane Andrew for similar wind speeds. The better performance reflects the advances in our understanding the effects of cyclonic winds on houses, improvements in building regulations and the success in implementation of those regulations. However the vast majority of houses suffered from considerable water ingress which caused damage to the interior linings and contents and distress to the householders.

Boughton (1999) reported structural damage from Vance was observed in 5 to 7 % of the newer housing for the entire town. He also noted that 35 % of the newer housing was subjected to high internal pressure from the failure of fascias, soffits, windows etc.

Extracting data from the CTS survey records for the newer housing in the northern part of Exmouth shows 20 % of the houses were observed with failure of the building envelope through debris impact or failure of roller door/soffit/flashings etc. It is noted that prior to the cyclone season Exmouth has high community participation in cleaning up potential debris

and there was a higher proportion of effective screen protection of windows than in the regions considered in this study.

Four percent of the newer houses in the northern part of Exmouth suffered damage with loss of cladding and battens, and were a subset of the houses with damage to the building envelope. The impact wind speed at eaves height for these houses was estimated in the order of 50 to 55 m/s.

4.2   Internal pressure variability

Any breach of the building envelope on a windward wall, which includes doors and windows, leads to a sudden increase in load on the structure. This is shown in Figure 4.3 with the failure of the roof and end wall connections from a combination of internal pressure plus external suctions. Depending on the geometry of the house and the structural element under consideration, the increase in load can range from 40 % to over 100 %. Failure of the building envelope can be by a broken window from wind driven debris, failure of door lock, or loss of some cladding.

Flying debris associated with windstorms is also applied to buildings in addition to the wind load as shown in Figure 4.4. Windward walls and the upwind slope of steep pitch roofs are especially susceptible to debris impact damage. Resulting dominant openings in the envelope can generate large internal pressures and an increased possibility of more serious damage. The flying debris damage potential in a windstorm is dependent upon the available upwind debris, its impact velocity and the resistance provided by the building envelope.

Figure 4.3: Failure of kit house in Exmouth

Figure 4.4: Severely damaged older house with impact damage to newer house

The failure of elements disengaging from the house structure, such as roofing, fascias, gutters, battens, garden sheds etc, leads to a snowball effect as the failed components add to the wind borne debris field, increasing the potential for full internal pressure in other houses downwind resulting in more debris, and so on. Research is ongoing at the Cyclone Testing Station to quantify sources and types of debris and quantify likely impact speeds and resultant envelope damage for the different types.

4.2.1   Estimating percentage of houses with full internal pressure

With the large increase in load associated with full internal pressurization to be resisted by the house, there is a higher probability of failure of the building elements. Therefore, a critical element for the prediction of damage levels is estimating the number or proportion of houses subjected to internal pressure during the event.

As described in Section 2.6.2, the house wind resistance models incorporate parameters for both full internal pressure (Cpi=0.7) and minimal internal positive pressure (Cpi=0.2) for each house group. A module was developed to combine the two internal pressure cases in varying proportions depending on the modeled house group and the wind speed. Therefore for a given wind speed one modeled house group may have a higher proportion of houses with full internal pressure than another.

Consideration was given to different housing types having different features, such as large windows/doors, type of wall cladding or vented eaves, which can increase or reduce the potential for full internal pressure. Reference was also made to values given in damage assessment reports and from experience in conducting damage surveys. Because progressive element failure of the house with increasing wind speed over time and direction is not currently modeled, factors were included to account for debris generation from the different house model groups. An assumption was made that because the model house groups are generally based on age, they tend to be situated together and so the house groups that fail earliest generate debris which impacts on the same house group.

As a point of interest, Post 1984 houses in cyclonic Region C and D, that have been designed using the TRADAC manuals or the Australian Standard 4055 Wind loads for housing, incorporate full internal pressure in the design loads. This is not the case for Region A or B house design loads.

4.3   Comparisons between model output and damage surveys

Table 4.1 shows some comparisons of the house wind resistance model predictions with actual reported percentage damage from surveys.

Table 4.1: Comparisons of reported damage with model

House group	Event	Vref (m/s)	Major terrain	% single storey	Model damage estimate	Actual reported damage
Pimlico	Althea	55	2.5/3	30 %	15 %	16 %
Pallarenda	Althea	55	2	30 %	71 %	68 %
4	Tracy	65	2.5	0	97 %	93 %
5	Tracy	65	2.5	0	66 %	93 %
5	Winifred	55	2.5	30 %	26 %	20 – 30 %
3	Winifred	55	2.5	30 %	24 %	20 – 30 %
6	Vance	60	2.5	95 %	4 %	4 %
6	(Theory)	70	2.5/3	95 %	17 %	(?)

The house groups for Pimlico consist of 1, 2, 3, and 4 while Pallarenda has a majority of group 4 with some 2 and 3. The group proportions were taken from the modified DOL analysis.

It is thought that the better modelled performance of Group 5 housing over the reported 93 % damage is a function of the Group 5 houses incorporating better practices following Cyclone Tracy and better building inspections than Darwin experienced prior to Cyclone Tracy, as noted in Section 4.1.3. This also affects the internal pressure module of the model as the internal pressure ratio of the Group 5 houses is less than the Group 4 houses.

For Group 6, broadly speaking, engineering ultimate limit state (ULS) theory typically has for a structure's design 'life' a 5 % probability of exceedance of the design event, in this case 70 m/s. It is unlikely that a probability of exceedance relates directly to damage as there may or may not be a failure, depending on the stress levels of the elements concerned. However this limit is not meant to include errors in construction practice as noted in Section 2.6.2. The modelled damage estimate of 17 % highlights the greater variability of house construction and materials over that of larger fully engineered and inspected structures.

4.3.1   Comparisons with insurance loss damage curves

Several risk studies for the insurance industry have been conducted in recent years, many of these being conducted by SEA, but all have lacked detailed data on house type and distribution throughout the region. The assumed insurance damage curves for housing versus wind speed in such studies have been developed generally through analysis of claims data, empirical observation and extensive experience and understanding of the performance of housing subjected to severe winds. Examples are by Leicester and Beresford (1978) and the Walker curves (Stewart 2002). The Walker curves represent housing construction built prior to the introduction of the HBC (pre-1984) and the houses built after its introduction (post-1984). These have been used by researchers and insurance companies in Australia and overseas, as well as for previous community damage assessments in Queensland (Harper 1999b, Jones *et al* 2001).

Insurance loss damage curves are based on the estimated repair or replacement cost for the affected housing. Therefore comparison with the developed CTS house wind resistance models is not a straightforward task and care is required in relating the two measures.

However in a broad overall comparison of the Walker curves with the CTS models, it is interesting to note the similar lower bound wind velocity and the delineation between the pre and post 1980s house construction. The CTS models represent a finer range of housing types and are therefore expected to be able to better replicate the distribution of housing damage across the modelled districts.

5. Model input for Townsville, Cairns, Mackay

5.1   Regions

The three communities of Townsville/Thuringowa, Cairns and Mackay form the three regions for the present model investigation. They each are coastal centres located in cyclone region C, as defined in the Australian Standard for wind loads (1989). All were founded around the end of the nineteenth century. Similar house construction methods were used in the three regions with the majority of the housing situated on flat terrain.

5.2   Districts

Each region was divided into districts. For this study the districts are based nominally on postcode boundaries. However, because the postcode area for Mackay covers most of the region under consideration, it was subdivided into two sections, north and south of the Pioneer River. Figure 1.2, Figure 1.3 and Figure 1.4 show the three modelled regions with their associated districts.

Table 5.1: District names

Region Townsville model districts	Region Cairns model districts	Region Mackay model districts
4810 Townsville	4870 Cairns	4740A Mackay
4811 Wulguru	4865 Gordonvale	4740B North Mackay
4812 Hermit Park	4868 White Rock	4750 Bucasia
4814 Aitkenvale	4869 Edmonton	
4815 Kelso	4878 Machans Beach	
4817 Kirwan	4879 Clifton Beach	
4818 Bohle		
4819 Magnetic Island		

5.3   Housing stock

As discussed in Section 2.2 , detailed surveys of the external features of the housing stock were conducted by the CTS for Townsville and by the AGSO Cities Project for Cairns and Mackay. The results are summarised in Table 5.2: Townsville, Table 5.3: Cairns, and Table 5.4: Mackay. The totals given in the Number of houses column represent the approximate total number of domestic structures located in those districts and not just the surveyed houses or flats.

Townsville and Mackay have a similar percentage of Post 1984 houses, which is two thirds that of Cairns. It can be noted that Post 1984 houses are predominantly low set construction for all regions. For Townsville the Pre 1984 houses have a majority of high set construction while Mackay is mostly low set.

Table 5.2: Townsville

Region Townsville model districts		Number of Houses	Percentage of housing stock		Percentage Low set
			Pre 1984	Post 1984	
4810	Townsville	5442	74%	26%	40%
4811	Wulguru	3018	75%	25%	50%
4812	Hermit Park	6420	85%	15%	40%
4814	Aitkenvale	12342	61%	39%	65%
4815	Kelso	5630	49%	51%	70%
4817	Kirwan	6732	43%	57%	70%
4818	Bohle	3065	48%	52%	85%
4819	Magnetic Island	1016	47%	53%	65%
Total		43665	62%	38%	

Table 5.3: Cairns

Region Cairns model districts		Number of Houses	Percentage of housing stock		Percentage Low set
			Pre 1984	Post 1984	
4870	Cairns	16473	54%	46%	70%
4865	Gordonvale	1671	60%	40%	85%
4868	White Rock	4016	25%	75%	95%
4869	Edmonton	3570	3%	97%	82%
4878	Machans Beach	3502	39%	61%	84%
4879	Clifton Beach	3234	26%	74%	89%
Total		30733	43%	57%	

Table 5.4: Mackay

Region Mackay model districts		Number of Houses	Percentage of housing stock		Percentage Low set
			Pre 1984	Post 1984	
4740A	Mackay	7776	75%	25%	85%
4740B	North Mackay	8538	60%	40%	90%
4750	Bucasia	2385	35%	65%	90%
Total		18699	63%	37%	

5.4   Input Terrain data

As part of the collaboration for this study, proprietary terrain data for the three regions was provided by SEA. In joint consultation, modifications were made by CTS to Townsville district 4819 to reduce the SEA slope percentages and to the partitioning of the Mackay model region. The terrain for each district was classed into three categories, described in Table 5.5.

Table 5.5: Description of Terrain categories

Terrain Category	Description (from AS4055-1992)
TC 2	Open terrain including sea coast areas, airfields, and grassland with few obstructions.
TC 2.5	Terrain with a few trees, isolated obstructions, cane fields. Category represents the terrain in developing outer urban areas.
TC 3	Terrain with numerous closely spaced obstructions having the size of houses.

6. Model output

6.1   Assessment of model output

The model generated output is intended to give an estimate of the number of houses sustaining damage when subjected to a derived wind speed. Limitations and variability in the house resistance models, house class distribution, wind speed model, and terrain models should be considered when assessing the model output.

The generated output is a function of more than a 100 parameters, examples of which include;

- The assessment of the failure capacity of element joints extrapolated over the housing stock for a community,
- An assumption of the percentage of houses subjected to internal pressure, based on damage surveys and the estimated amount of wind driven debris.
- The use of the wind speed modifying factors as detailed in the Australian wind loading standard, which assumes a boundary layer wind profile for cyclonic winds.

Variability in the generated output from variations in the input parameters is discussed in Section 7.7 .

6.2   Definition of Damage

The model generated output is the estimated number of houses in each district that suffer some form of damage resulting from wind loading. The output is also presented as a percentage of the estimated housing stock and aggregated across each region.

Cladding damage includes loss of one or two cladding sheets through to the loss of the majority of the cladding, as shown in Figure 6.1.

Roof structure damage encompasses failure of a roof batten connection (Figure 6.2) to the truss or rafter through to the failure of the truss or rafter hold down connections. Failure of the major framing connections can lead to collapse of walls through loss of support from roof structure, as shown in Figure 6.3.

Figure 6.1: Failure of cladding (tiles) at the high suction regions on gable end

Figure 6.2: Failure at batten truss connection

Figure 6.3: Extensive damage with loss of all roof structure and collapse of walls

6.2.1   Output categories

The region under investigation is divided into districts. For each district the housing stock is classified into numbers of houses in each of the six housing resistance groups and the percentage of high set and low set houses.

Output is in two main classes;
- Pre 1984 - housing built prior to the current building regulations introduced in the early 1980's, and
- Post 1984 - housing built to the current building regulations.

Each class, Pre 1984 and Post 1984, is further detailed with two sub classes;
- low set
- and high set.

6.3   Output wind speed (Vref)

For each district, the SEACATd model calculates a reference maximum wind speed (Vref), which represents the maximum 3 second gust wind speed for standard exposure and applicable to +10 m above ground level experienced at the nominal location of the district during the passage of a tropical cyclone. Vref is then factored up or down to apply to those proportions of houses that are shielded, on slope, two storey etc.

Three second gust wind speeds ranging from 47 m/s to 74 m/s, with their annual probability of exceedance for cyclonic region C as defined in AS/NZS 1170.2:2002, are shown in Table 6.1. Based on this defined annual probability of exceedance level, the probabilities of the tabled wind speeds being exceeded once in 10 years and once in 50 years have been calculated.

Table 6.1: Probability of exceedance

Probability of wind speed (Vref) being exceeded			
Vref (m/s)	Annual probability of exceedance	Probability of exceedance in 10 years	Probability of exceedance in 50 years
47	1:20 (5 %)	40 %	92 %
55	1:50 (2 %)	18 %	64 %
59	1:100 (1 %)	10 %	40 %
69	1:500 (0.2 %)	2 %	10 %
74	1:1000 (0.1 %)	1 %	5 %

The Australian Building Codes Board sets the societal risk for the ultimate limit state strength of a structure, in the Building Code of Australia (2002). From Table 6.2, the design level for housing (Importance level 2) is to be a minimum annual probability of exceedance of 1:500.

The wind speed at ultimate limit state is the design level that the structure is meant to withstand and still protect its occupants. It is interesting to note that the Vref wind speed for a 1:500 probability is 69 m/s. This is in the range of gust wind speeds for a Category 4 cyclone. Cyclone Tracy was classed as a Category 4 cyclone.

Table 6.2: Table B1.2a and B1.2b from Building Code of Australia (2002)

Importance levels of Buildings and Structures		Annual Probability of Exceedance
Level	Building Type	Cyclonic Regions
1	Buildings or structures representing a low degree of hazard to life and other property in the case of failure.	1:200
2	Buildings or structures not included in Importance levels 1, 3 and 4.	1:500
3	Buildings or structures that are designed to contain a large number of people.	1:1000
4	Buildings or structures that are essential to post disaster recovery or associated with hazardous facilities.	1:2000

7. Model output for Townsville, Cairns, Mackay

The model estimate of the number of houses damaged, includes minor levels of damage such as loss of some roofing elements, through to severe damage and collapse of roof structure. This study does not differentiate between degrees of damage. These estimates have been generated using modelled cyclones with parameters similar to those of Althea and Tracy as well as a range of constant Vref wind speeds for all districts in each region. Although it is unlikely that a cyclone impact would generate the same Vref for all districts, it enables an effective comparison between individual districts and each of the three regions.

7.1   Number of houses damaged versus wind speed

The estimated number of houses sustaining damage for the three modelled regions has been generated using an increasing reference velocity (Vref). The curves for the three regions detailing damage per district are given in Figures 7.1, 7.2, and 7.3.

From the curves it is clear that different districts suffer different percentages of damaged houses for the same Vref wind speed. As discussed in Section 5, the districts vary in the proportion of terrain roughness, slopes, shielding and house heights leading to a range of impact wind speeds for each district Vref. The various house classes also suffer differing amounts of damage for the same impact wind speed. The general overall shape of Figures 7.1 to 7.3, reflects the underlying house resistance curves described in Section 2.6.2.

The effects of terrain classification and resulting modification to Vref can be seen in the higher estimates of damage in model district 4810 compared with those in 4812. Both have a high percentage of older house construction and the same percentage of single storey house construction. However, model district 4810 has over 60 % of houses classed in terrain category 2, whereas model district 4812 has over 90 % of houses in a shielded intermediate to suburban terrain environment.
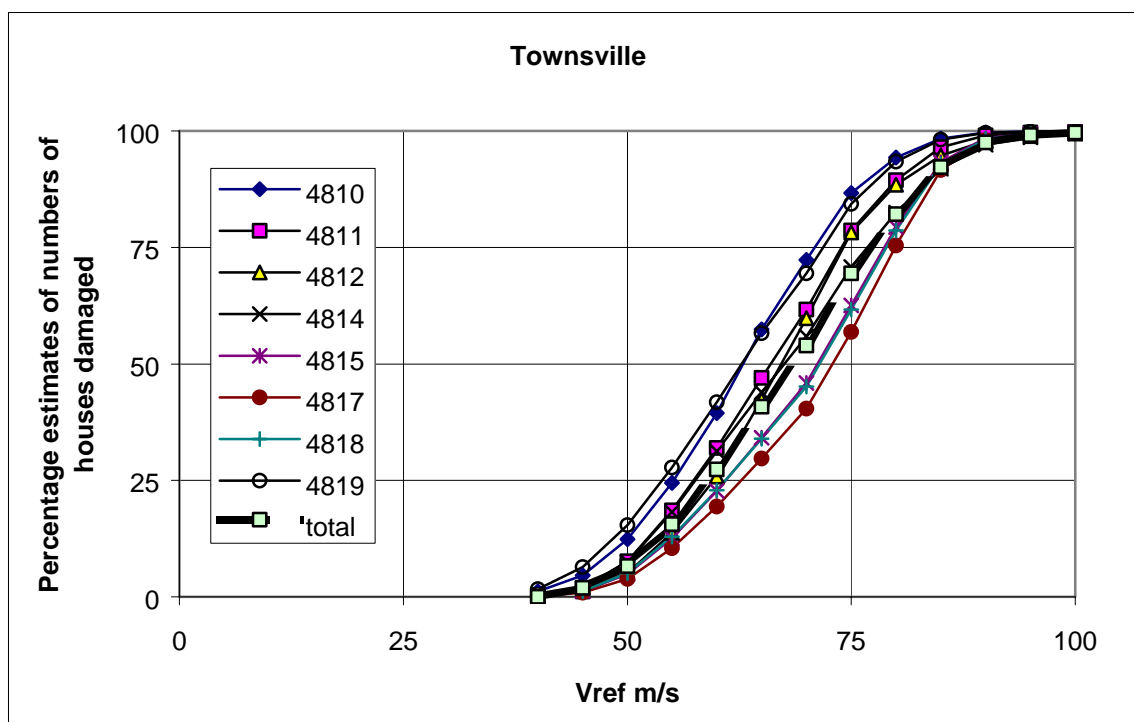
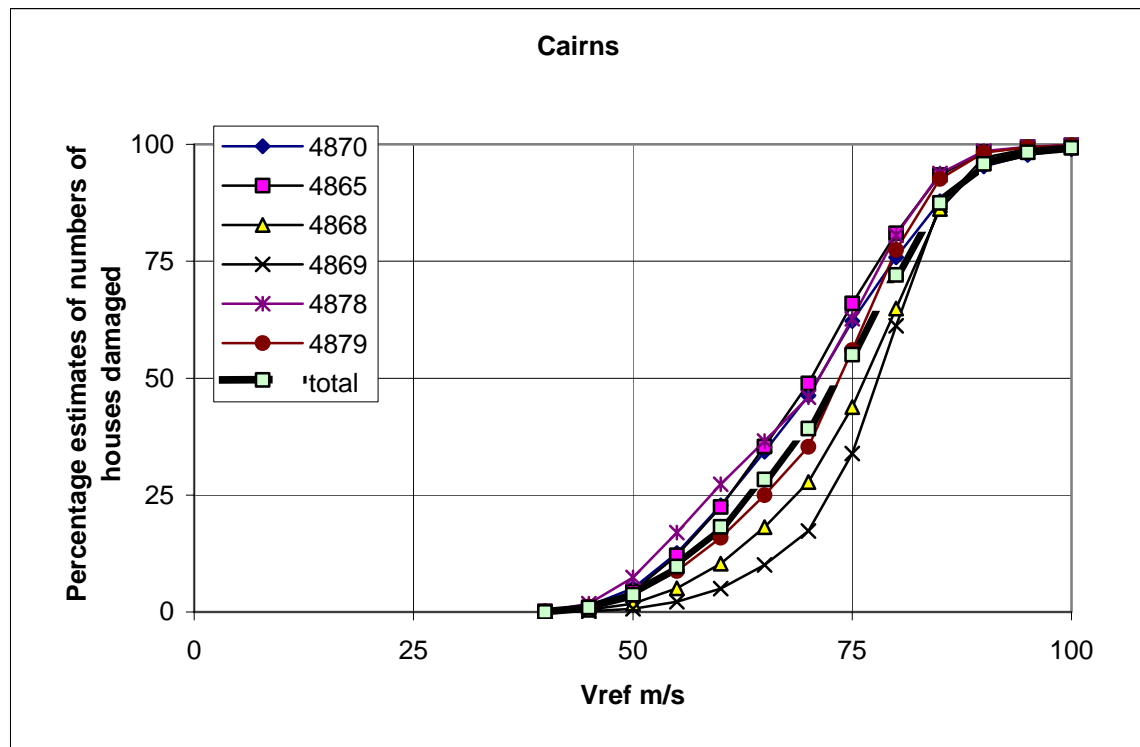**Figure 7.1: Percentage estimates of damaged houses for Townsville districts**

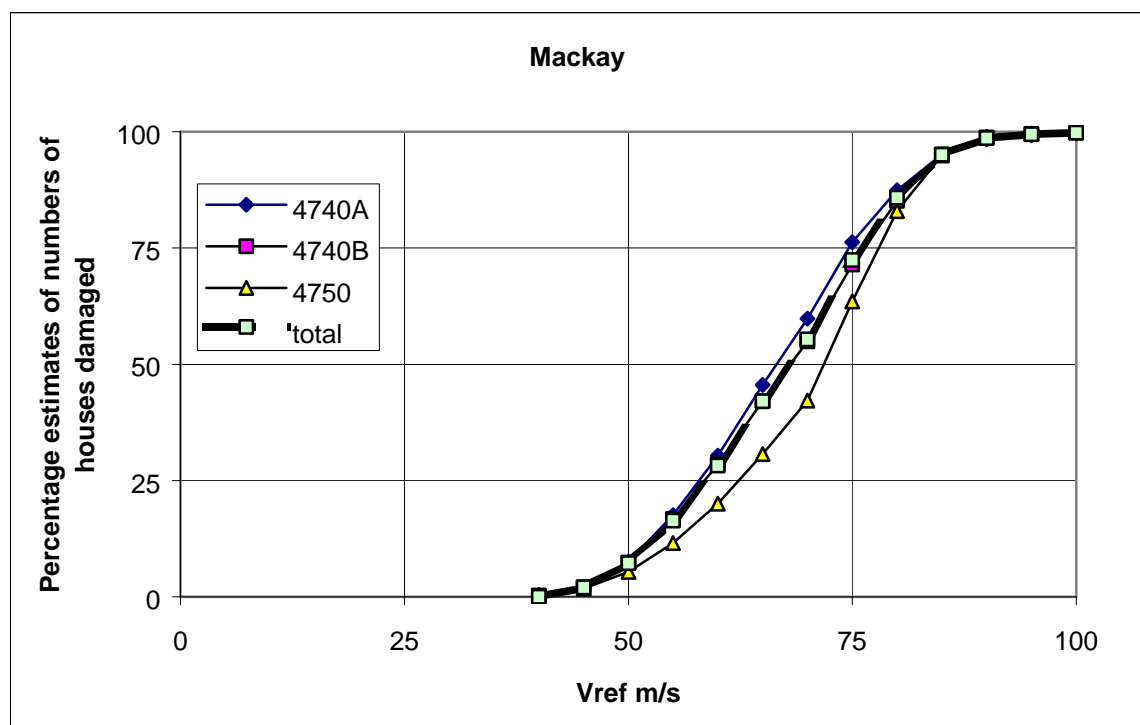**Figure 7.2: Percentage estimates of damaged houses for Cairns**

Figure 7.3: Percentage estimates of damaged houses for Mackay Districts

7.2   Number of houses damaged versus house group

Figures 7.4, 7.5, and 7.6 show the proportion between the numbers of older and newer housing damaged for increasing values of Vref. Clearly from these estimated numbers of damaged houses, the pre 1984 construction suffers more damage than the post 1984 construction. The different construction groups and implementation of the revised building requirements in the early 1980s are discussed in Section 2.
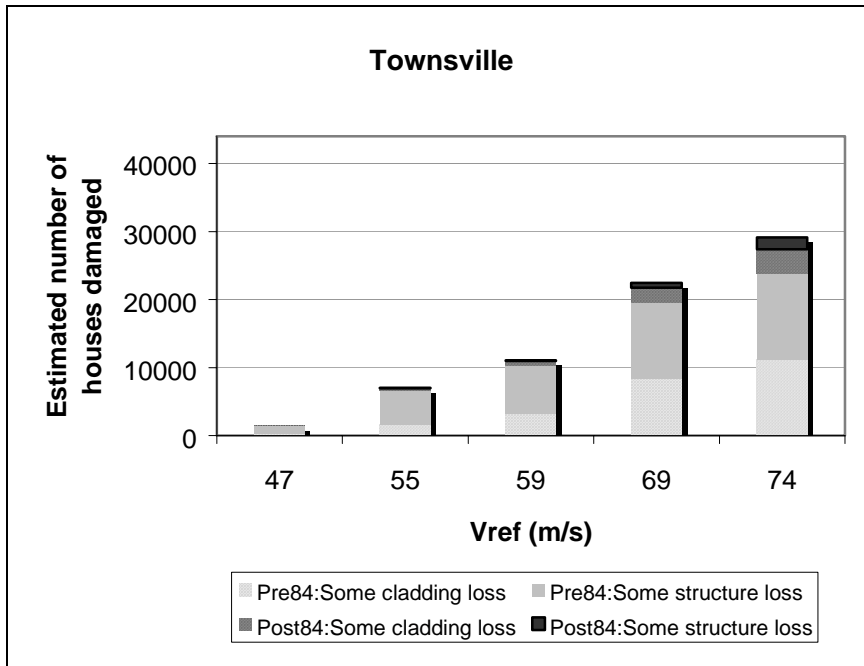
Figure 7.4: Damage proportions for Townsville
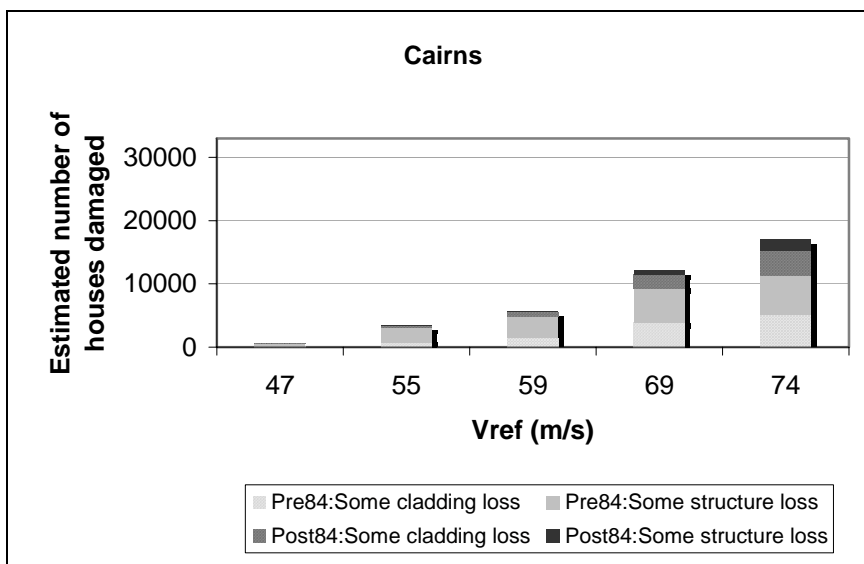
Figure 7.5: Damage proportions for Cairns
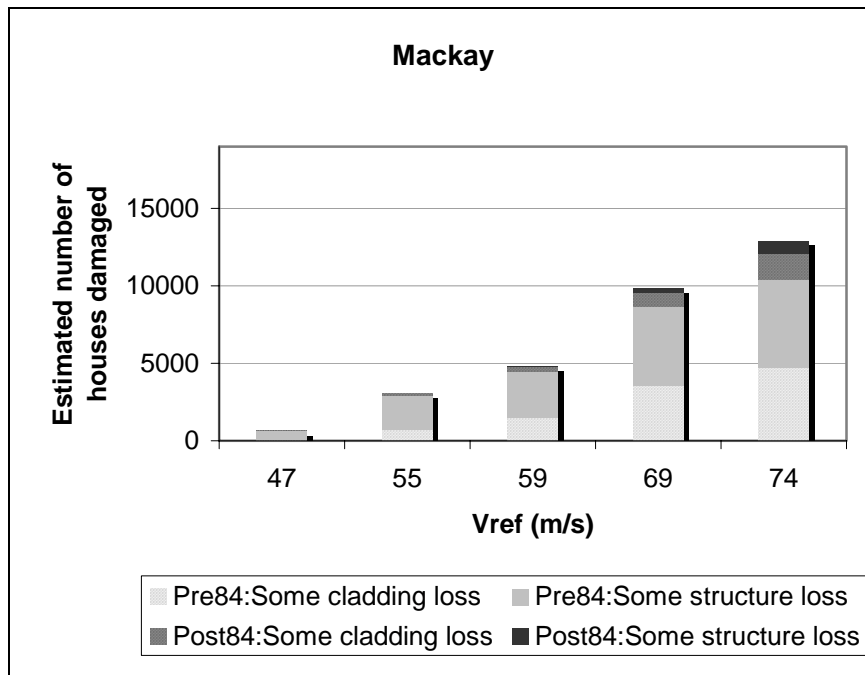
Figure 7.6: Damage proportions for Mackay

7.3   Houses damaged versus house height

The estimated percentage of high set houses damaged is greater than low set houses as shown in Table 7.1. With increasing building height comes increasing wind loads through higher wind speed and reduced shielding. For comparable roof shapes, the increase in wind load for the additional storey can be in the order of 10 to 20 %.

Table 7.1: Damage comparison for height of house

Townsville	Low set	High set
Vref (m/s)	3 m eaves height	6 m eaves height
47	3 %	5 %
55	14 %	19 %
59	23 %	29 %
69	48 %	57 %
74	63 %	73 %

7.4   Estimates of damage across districts

The modelled districts comprise varying proportions of house types, terrain categories and slopes, with the effects of these parameters noted previously. Table 7.2, Table 7.3 and Table 7.4 detail the percentage estimates of numbers of houses sustaining damage for increasing values of a blanket wind speed for Townsville, Cairns and Mackay, respectively.

7.4.1   Townsville

Table 7.2: Percentage estimates of houses sustaining damage - Townsville

	Constant wind speed Vref applied to all districts				
District	47 m/s	55 m/s	59 m/s	69 m/s	74 m/s
4810	7 %	24 %	35 %	68 %	83 %
4811	4 %	19 %	29 %	58 %	75 %
4812	2 %	14 %	24 %	57 %	75 %
4814	3 %	18 %	28 %	52 %	66 %
4815	2 %	12 %	20 %	43 %	59 %
4817	2 %	11 %	18 %	38 %	53 %
4818	2 %	12 %	21 %	43 %	58 %
4819	8 %	23 %	32 %	58 %	75 %
Total	3 %	16 %	25 %	51 %	67 %

The effect of the higher percentage of older construction for model districts 4811 and 4812, is seen in the approximately 35 % greater estimated number of houses damaged compared with the newer districts of 4815, 4817 and 4818. This difference would be even greater if it were not for the fact that 4811 and 4812 have greater proportions of houses ensconced in suburban terrain, with its lower impact wind velocity.

It is worth noting that the higher estimated number of damages for the district of 4810 and the island district of 4819 are due to the proportion of the houses in the district on elevated sloping terrain and in close proximity to coast. Although 4819 has a similar housing age proportion to 4815, its damage level is similar to the older suburb of 4811.

7.4.2   Cairns

Table 7.3: Percentage estimates of houses sustaining damage - Cairns

	Constant wind speed Vref applied to all districts				
District	47 m/s	55 m/s	59 m/s	69 m/s	74 m/s
4870	2 %	12 %	21 %	44 %	59 %
4865	2 %	12 %	20 %	46 %	63 %
4868	1 %	5 %	9 %	26 %	40 %
4869	0 %	2 %	4 %	16 %	29 %
4878	4 %	17 %	25 %	44 %	59 %
4879	2 %	9 %	14 %	33 %	51 %
Total	2 %	11 %	17 %	38 %	53 %

The older districts of 4870 and 4865 have higher estimated damage than the districts with higher proportions of post 1980 houses. The predominant terrain for both 4869 and 4865 was set as category 2.5. However the estimated damage is two to three times more for 4865. The model input for 4869 is almost totally new housing, while the age estimate of 4865 may need further refinement as a large percentage of the houses in the district were classed as "unknown" in the AGSO Cities Project survey and had no age or external feature data recorded. The proportions of housing age for 4870 were used for 4865. Although a large proportion of the northern beach districts is in exposed terrain, the newer construction helps offset the damage total.

7.4.3 Mackay

Table 7.4: Percentage estimates of houses sustaining damage - Mackay

District	Constant wind speed Vref applied to all districts				
	47 m/s	55 m/s	59 m/s	69 m/s	74 m/s
4740A	4 %	18 %	28 %	57 %	73 %
4740B	4 %	17 %	26 %	53 %	68 %
4750	3 %	12 %	18 %	40 %	59 %
Total	4 %	16 %	26 %	53 %	69 %

Model districts 4740B and 4750 have similar proportions of open and coastal terrain and the same percentage of single storey construction. However the larger numbers of damage for 4740B highlights the larger proportion of older houses. District 4740B has a higher damage in line with its higher proportion of older construction even though part of the district is in shielded suburban terrain.

7.5 Comparison of the three regions

To aid in comparing the three modelled regions, totals for the estimates of numbers of houses damaged as a percentage of the total housing stock in each region are given in Table 7.5, for Vref wind speeds.

Table 7.5: Percentage estimates of numbers damaged for the three modelled regions

Region	Constant wind speed Vref applied to all districts				
	47 m/s	55 m/s	59 m/s	69 m/s	74 m/s
Townsville	3 %	16 %	25 %	51 %	67 %
Cairns	2 %	11 %	17 %	38 %	53 %
Mackay	4 %	16 %	26 %	53 %	69 %

The overall wind damage estimates are similar for Townsville and Mackay, whereas Cairns total damage estimates are approximately 30 % less. Cairns' surge in growth from the 1980s and redevelopment of older districts results in a lower proportion of older house construction than Mackay and Townsville and has had a marked effect on the modelled estimates of damage.

With the higher proportion of low set construction in Mackay, it might be expected that the damage estimates would be less than Townsville. However, Mackay has a greater proportion of housing in more exposed terrain than does Townsville.

7.6 Output from simulated cyclonic events

Figures 7.7, 7.8, and 7.9 for Townsville, Cairns and Mackay respectively, show percentage totals of the estimated number of damaged houses for a cyclone of similar parameters to that of Cyclone Althea. The modelled cyclone was given the same track and the same starting reference from each region's reference point. The figures also show the calculated Vref for each district.
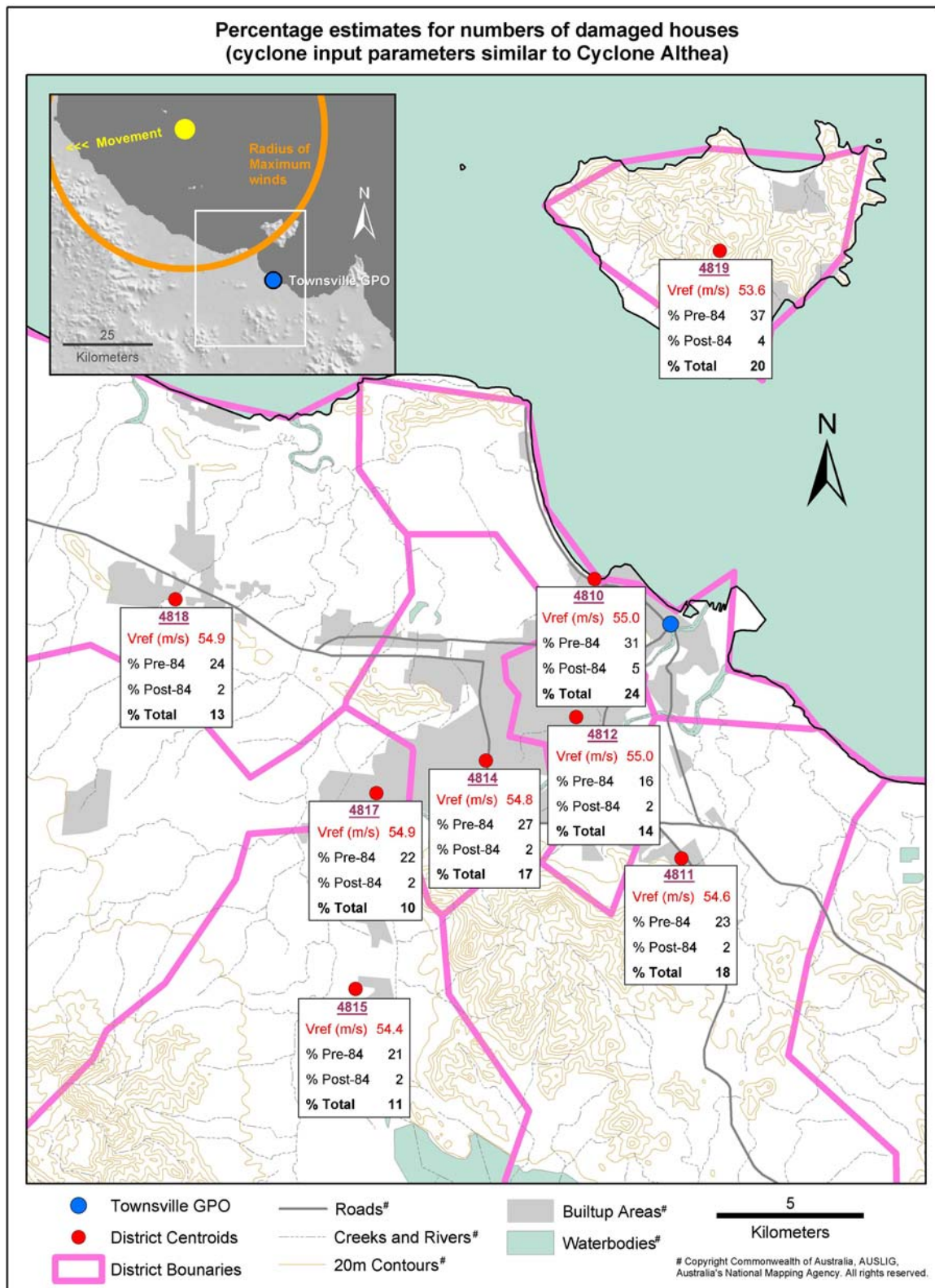
Figure 7.7: Percentage estimates of numbers of damaged houses for Townsville from a modelled cyclone with parameters similar to Cyclone Althea
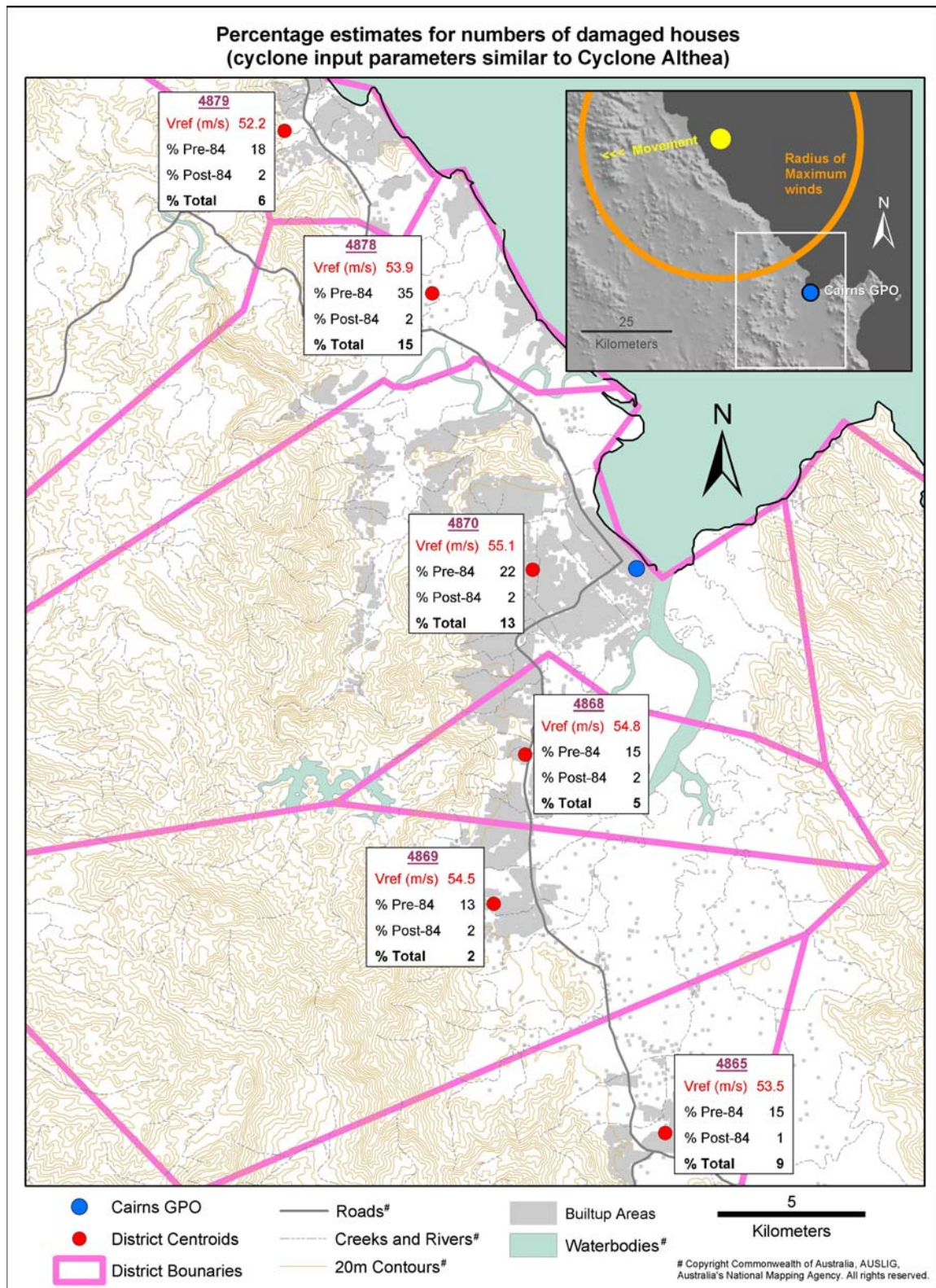
Figure 7.8: Percentage estimates of numbers of damaged houses for Cairns from a modelled cyclone with parameters similar to Cyclone Althea
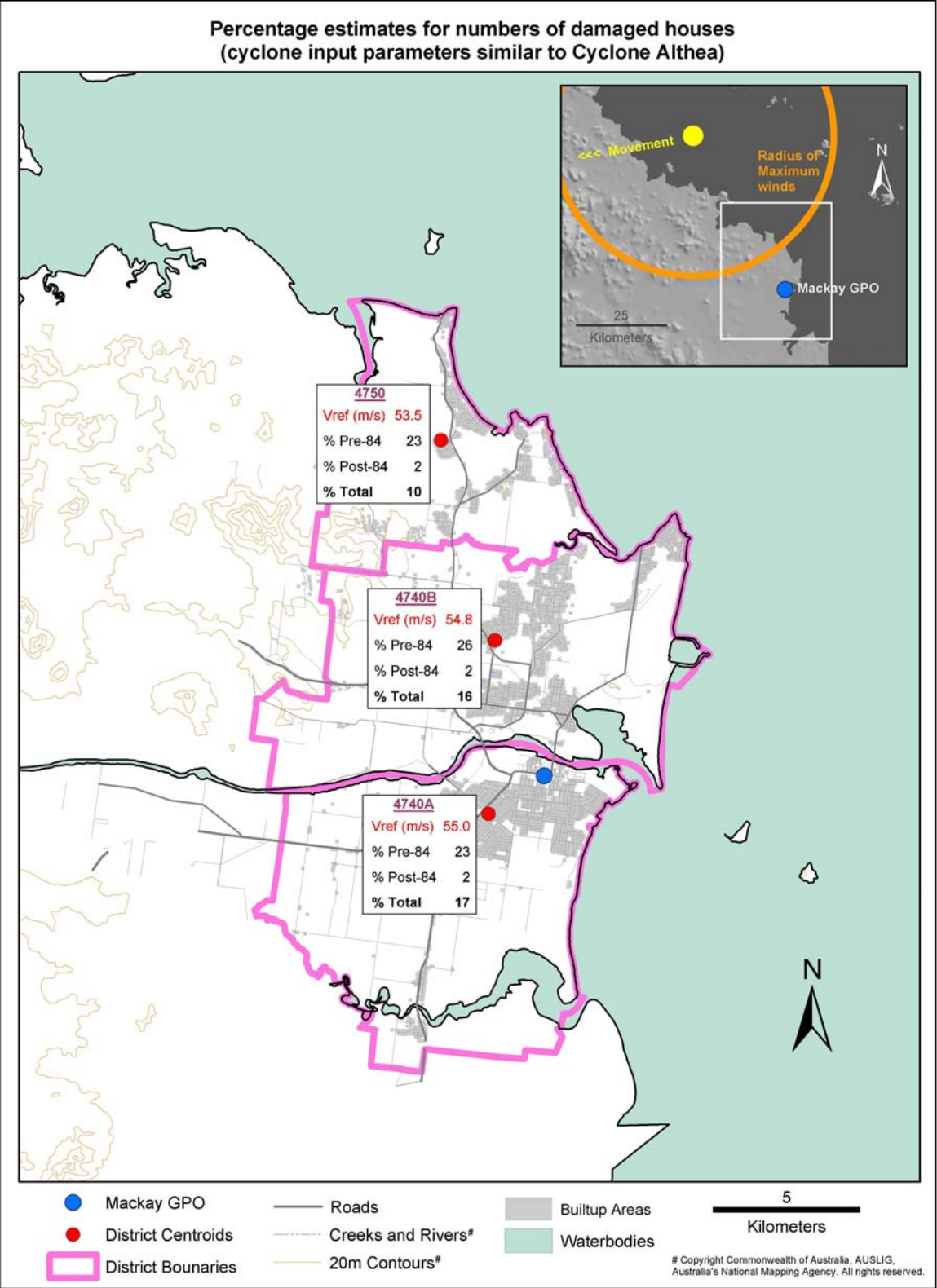
Figure 7.9: Percentage estimates of numbers of damaged houses for Mackay from a modelled cyclone with parameters similar to Cyclone Althea

In line with Section 7.5 Cairns performs more favourably than the other two regions. Fig 7.8 shows a greater range of Vref than Fig 7.7. The distribution of houses in Cairns is situated along a long front almost perpendicular to the simulated cyclone track as compared to Townsville with an 'inland' spread roughly in line with the area of maximum winds. The relationship of the track needs to be kept in context with the generated output. A probabilistic model involving the simulation and analysis of many hundreds of possible runs would enable better quantification of relative levels of risk.

7.7   Sensitivity of model output to input parameters

7.7.1   Wind model – Cyclone track parameters

Figures 7.10 and 7.11 for Townsville, show percentage totals of the estimated number of damaged houses for a cyclone of similar parameters to that of Cyclone Tracy. The two runs have the same radius to maximum winds and movement direction but the tracks are 14 km apart. The overall estimate of damage changed from 35 % to 20 %, with district totals swinging from a severe 55 % to 15 % and 4 % to 39 % for 4810 and 4811 respectively.

In interpreting the output, care needs to be exercised in relating the cyclone input parameters to the estimated damage output.

7.7.2   House model – Internal pressure

As detailed in Section 4.2 full internal pressurisation of the house envelope can greatly increase the load that needs to be resisted by the critical connections in the house structure. The internal pressure module is an integral part of the house wind resistance model linking the partial and full internal pressure cases together.

Data is presented in Figure 7.12 for all houses with a partial internal pressure coefficient (Cpi) of 0.2, and for all houses with a full internal pressure coefficient (Cpi) of 0.7 in Figure 7.13, for a cyclone of similar parameters to that of Cyclone Althea. The overall estimated damage is summarised in Table 7.6. The effect of changing the ratio of houses that are subjected to full internal pressure is dramatic. Not only does this show a critical area in the model's performance but also highlights the value in pre-cyclone season debris cleanups and protecting the house envelope with effective screens etc.

Table 7.6: Effect of varying internal pressure ratio on estimated damage percentage

|	Mix of internal pressure across modelled housing stock	All modelled houses have Minimum internal pressure	All modelled houses have Full internal pressure
Cpi	Dependant on wind speed and house model type	All 0.2	All 0.7
Vref	54.7 m/s	54.7 m/s	54.7 m/s
Pre 1984	24 %	13 %	45 %
Post 1984	2 %	1 %	7 %
Total	16 %	8 %	30 %
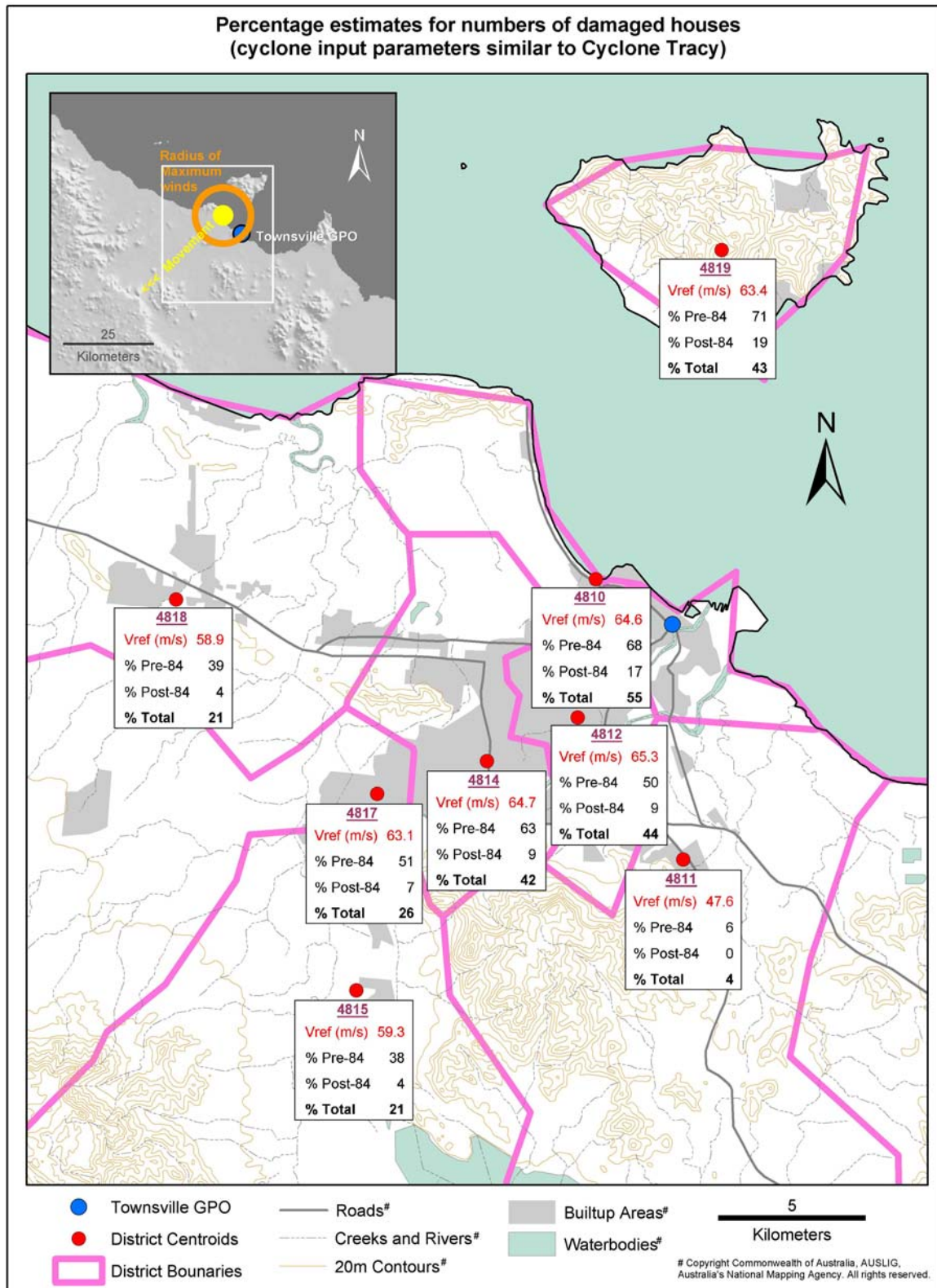
Figure 7.10: Percentage estimates of numbers of damaged houses for Townsville from a modelled cyclone with parameters similar to Cyclone Tracy – North track
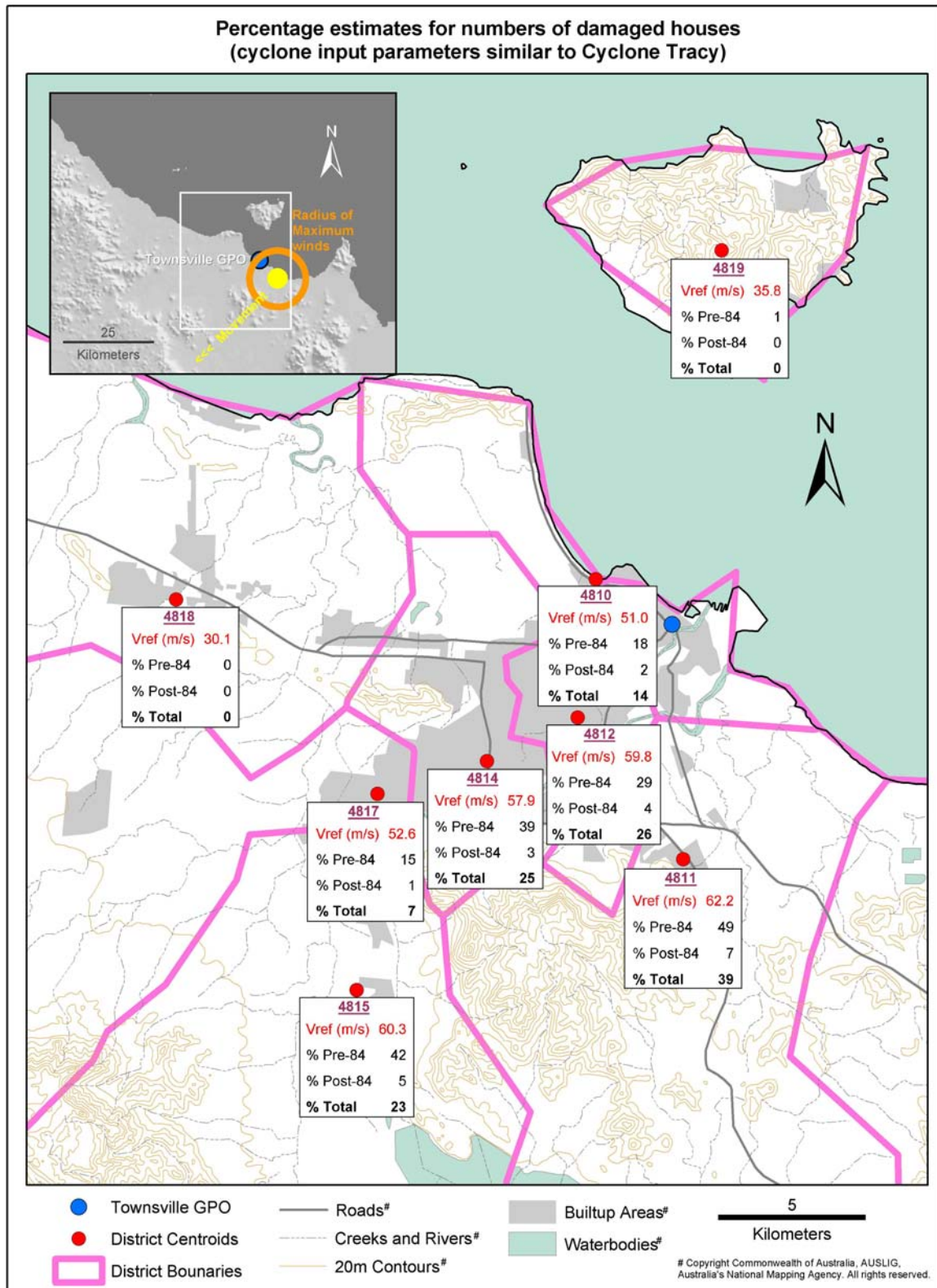
Figure 7.11: Percentage estimates of numbers of damaged houses for Townsville from a modelled cyclone with parameters similar to Cyclone Tracy – South track
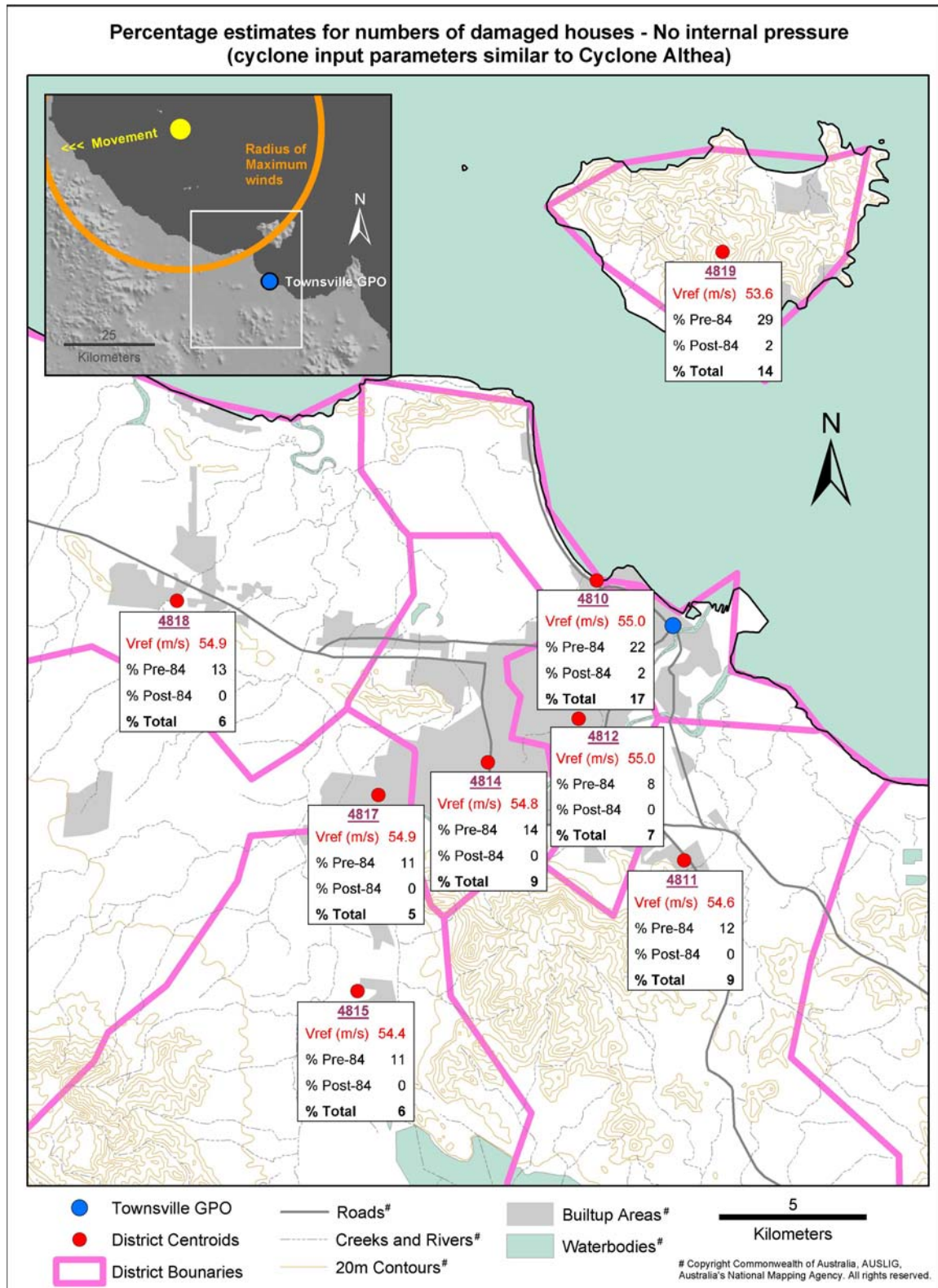
Figure 7.12: Percentage estimates of numbers of damaged houses for Townsville from a cyclone with parameters similar to Cyclone Althea – all houses Cpi=0.2
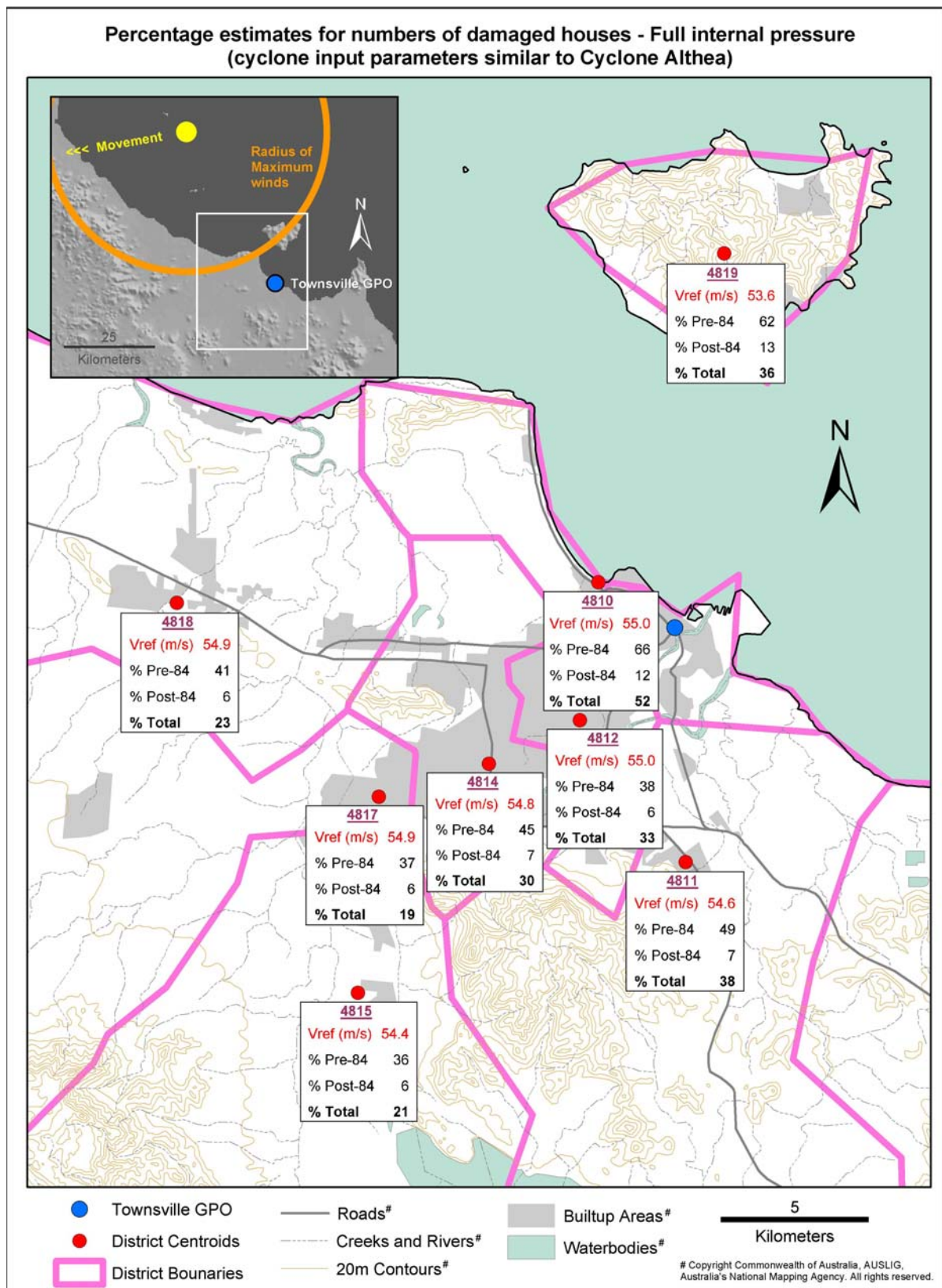
Figure 7.13: Percentage estimates of numbers of damaged houses for Townsville from a cyclone with parameters similar to Cyclone Althea – all houses Cpi=0.7

7.7.3   House model – Wind speed sensitivity

The outputs of estimated damage are sensitive to changes in wind speed. In an overall sense, this can be seen in Figure 7.1, with a 1 m/s increase giving approximately a 3 % increase in estimated damage. Therefore, small changes of 1 or 2 m/s in the wind speed envelope curves for the house wind resistance models (Section 2.6.2) will have a corresponding 3 to 5 % change in estimated damage.

7.7.4   House model – Age distribution across terrain categories

The wind model assumes house groups are equally distributed over the district in their defined proportions. So if a district has 40 % old and 60 % new and an equal proportion of TC 2 and TC 3 terrain then half of the old houses will be assigned TC 2. The majority of the surveyed houses might have been in terrain category 3 with the corresponding 15 % reduction in wind speed. However this effect can work the other way as well and is such not considered an issue until further refinement of the wind and house models is undertaken.

7.7.5   Wind model – Terrain analysis

The supplied SEACATd model terrain data assumes the worst case for all directions. In quantifying the significance that this inbuilt conservatism might play in the final result two Townsville districts were analysed. A 1 km grid was superimposed on the district to divide it into subdistricts. For the four compass directions, N, S, E and W, the terrain class was determined using the original SEA 1 km buffer zones for TC 2 and TC 2.5. The terrain classes for each subdistrict were totalled.

In comparing the average percentage damage with that calculated using the SEA terrain areas the difference is roughly 4 % at 55 m/s and 7 % at 70 m/s. In taking the worst wind direction for 4814 the difference is 5 % at 70 m/s.

8. Conclusions

The purpose of the study is to assess the amount of wind damage likely to occur in domestic housing in the major coastal communities of Townsville, Cairns and Mackay, and to obtain a distribution of that damage over each township for a cyclone of given intensity and path. The study has demonstrated a practical yet advanced methodology for combining multiple house wind resistance models, representing real communities, with a tropical cyclone wind field model to estimate numbers of houses likely to be damaged by specified cyclonic events.

The SEACATd software system from SEA has proven to be a highly practical way of assembling the various CTS housing wind resistance assessment (CTSWhrap) models into a user-friendly and efficient modelling system, which also has the capacity to grow and adapt to include new features.

The study has shown that the modelled region of Cairns is estimated to have a lower relative overall vulnerability of its housing stock to wind loads than the other modelled regions of Townsville and Mackay, because of its much greater proportion of post 1984 housing.

The assessed construction quality of the housing stock plays a large factor in the model's estimation of overall damage numbers. Further refinement of this aspect and the estimated proportion of houses that might be susceptible to full internal pressure is especially warranted. Notwithstanding this, the developed deterministic model sets a firm base for the development of a future probabilistic model.

In using the societal risk level set by ABCB for new housing design (BCA 2002), it could be inferred from the present modelling results that, in an overall community sense, there exists a much higher residual level of risk than is desirable, due to the proportion of housing built prior to the introduction of engineered house building requirements in the early 1980's.

There remains much opportunity to extend and improve upon the sophistication of the modelling presented in this report. However, the authors are of the view that this work already represents probably the most advanced assessment of house performance in high winds yet undertaken in Australia. It remains to ensure that the findings of this study can be turned towards practical improvements that will benefit the affected communities, especially within the context of potential climate change.

9. Recommendations

9.1   Recommendations based on model output

The model output highlights the relatively greater vulnerability of houses constructed pre 1980s and authorities should consider what steps can be made to better inform the public of this situation. Methods of upgrading older houses are detailed in the Standards Australia HB132.2 guidelines and Councils typically require some form of upgrading when re-roofing or renovating houses.

The house survey exercise showed some cases of current house construction having incorrect specification and construction of some structural details. House construction and design is an evolving process with new materials, techniques and styles, with the majority aimed at reducing the house cost. A more comprehensive survey is therefore recommended to determine specific areas of increasing concern, with a follow-up education campaign directed towards manufacturers, designers, builders and inspectors in the understanding of wind loads and the correct implementation of design recommendations.

In varying the house model parameters, the report highlights the potential reduction in damage to houses, by protecting the house envelope to reduce the probability of subjecting the structure to full internal pressure. This could be by pre-cyclone season debris cleanups, effective debris screens, shutters, etc. Increased community awareness of the importance and implications of reducing wind driven debris is therefore recommended.

None of these issues are new, with some of these same recommendations being made in almost all wind damage investigation reports. However, with the computer program SEACATd, incorporating the CTSWhrap models, being available to DNR and DES to explore varying scenarios, this may assist in developing policies to further reduce levels of wind vulnerability to communities.

It is recommended that the supplied computer model SEACATd, incorporating the CTSWhrap models, should only be used by persons fully aware of the assumptions described in this report.

9.2   Recommendations for model development

The sensitivity analysis showed the critical modelling issues to be the determination of the wind speed distribution, the composition of the housing wind resistance models, and the estimated proportion of houses subjected to full internal pressure. Research is recommended in the areas of wind driven debris to determine likely debris sources and potential damage.

The house wind resistance models have the capacity for a finer resolution of damage type suffered by a house through examining the process of progressive failure by load-shedding. This will become feasible with the incorporation of time varying wind speed and direction and through further refinement of the internal pressure module.

Currently the model districts are based on a postcode size area, with housing numbers varying from 2000 to over 10,000. To enable a finer resolution of district size, say census

collection district, all areas of the model need to be refined to match. For example, there would be an advantage in dividing the current house groups into subclasses such as brick veneer construction and reinforced masonry construction for Group 6, to reduce the coefficient of variation in some of the modelled elements. Further detailed structural assessments should be made for each of the modelled regions to refine the assumed regionally-based house groups.

The modelled terrain files should also be recalculated for smaller district sizes and for different wind directions, as described in Section 7.7.5. This would permit a more detailed approach to determine the amount of shielding afforded to the houses.

Engaging local government support for an extended vulnerability analysis may enable greater scope for data collection and therefore improvements to the house type and age groupings.

The SEACATd software system incorporating the CTS house wind resistance assessment models, has the capacity to provide increased functionality in all these respects and it is recommended that support for future development of both model components be considered. Further development of SEACATd user interface and presentation features should also be considered.

9.3   Climate Change Considerations

Section 1.3.2 provides a brief overview of associated studies that have considered the possible impacts of changing climate on tropical cyclone characteristics in Queensland. If presently planned statistical studies can be adapted or extended to include an assessment of the possible changes in cyclone climatology for Cairns, Townsville and Mackay, then the deterministic housing damage model developed in this study may be used to directly assess the possible impacts of climate change.

Depending on the exact outputs from the statistical studies, the present model could be used for comparative impact studies using either different sets of parameter scenarios or to match specific peak wind speeds. For example, a statistical study might indicate that the return period of a specific storm intensity within some nominal area of influence of the site in question will shift under changed climate conditions. The community damage levels due to that intensity may then be assessed within that context of changing risk, all other aspects being equal (e.g. track etc). Alternatively, the impact of a change in the Return Period of a specific wind speed at a specific location could be assessed by devising a series of scenarios that match those expected peak wind speeds – i.e. with and without climate change.

Ideally, the present model would be extended to a full probabilistic basis that will integrate the various elements in an appropriate way and provide a fully consistent risk statement, not just regarding climate change *per se* but also in the context of "present" climate. This would provide statistical information useful for justifying the economic advantages of long-term mitigation planning.

10.　Acknowledgements

11.   References

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Appendix A - Housing Survey for Townsville

Attributes surveyed

The housing survey collected data on those physical attributes of houses likely to affect their performance during a windstorm. The following data were recorded for each dwelling:
  address
  number of units
  number of stories high
  orientation
  aspect ratio
  external wall cladding
  window size
  roof end shape
  roof slope
  roofing
  special features.

Because of the vast number of houses involved, all of the above data had to be recorded in less than one minute per house, so each of the data items was divided into predetermined categories, e.g. aspect ratio was either 1:1, 2:1 or 3:1. No other values were allowed.

Address
The address was recorded to relate the survey data to location within suburb, and house age data, which came from a different source and had to be cross-referenced. The actual house does not get specifically included in the model.

Number of units
The "number of units" differentiated single-family houses from blocks of multiple dwellings.

Stories high
The "number of storeys high" becomes a little complicated because of the North Queensland tradition of high set houses. Five categories were chosen;
  1,
  2,
  3 or more storeys,
  high set open underneath (designated as 1H)
  and high set built in underneath (designated as 2H).
The 2H category was meant to differentiate between the form of construction used for a conventional two storey house and that used to build a conventional high set house (1H) which in later years had the lower section enclosed.

The differences in construction between a 2 and a 2H house relate to the performance in racking resistance and tie down techniques.

Orientation
"Orientation" of the house is recorded so that the angle of attack of the wind relative to the house in question can be taken into account when determining the likely strength of the houses.

This is also important if the surrounding terrain is not the same from each direction.

Aspect ratio
"Aspect ratio" is the length to breadth ratio and in concert with the "Orientation" affects the external wind pressures on the building.

External wall cladding
"External wall cladding" is predefined as brick, concrete block, timber, or fibre cement. As there is very little cavity brick construction in North Queensland, all brick external cladding is defined as brick veneer. All concrete block external cladding is assumed to be reinforced masonry construction.

Window size
Although it is acknowledged that maximum internal pressure can be developed through the breaking of a small window, the survey differentiates between large and small windows. It is assumed that large windows are more likely to be broken than smaller ones.

Roof end shape
The "roof end shape" is classified as hip, gable or skillion. Gable ends are subjected to higher uplift pressures than hip ends. For houses with combinations of roof types, the dominant one is chosen.

Roof slope
"Roof slope" is defined as flat, low or high pitch. The slope of a flat roof is about 2° or 3°. All flat roofs are assumed to be gable ended. Low slopes are up to about 15° and high ones are more than that.

Roofing
"Roofing" is predefined as metal, fibre cement or tile. Metal tiles are classified as metal roofing, but the survey does not differentiate between cement and terra cotta tiles. All tiled roofs are considered to be high pitched.

Special features
"Special features" include anything that may affect the performance of the building during a wind storm. They include L-shaped or U-shaped plans, external studs, pole houses, A-frames, poor maintenance or alterations judged to cause a strength reduction, e.g. removing diagonal bracing from beneath a high set house.

Survey process

A team of two driving slowly along suburban streets collected the data. A maximum of one minute per house was allowed, but up to 600 houses were surveyed in an eight-hour day. The driver described the features of each house while the passenger entered the data into a lap top computer. A computer program was developed to handle and store the data. The computer screen showing classifications is given in Figure A.1. The data in the figure shows that the house at that address was single storey, width parallel to the street, square, with timber cladding, small windows, with fibre cement roofing on a steeply sloped hip ended roof.

As a pool of six people was used to gather the data, calibration runs were made at the beginning of the project, and at intervals throughout it, to ensure that the judgemental decisions within the group were constant. Each person in turn recorded the data for a street of about 50 houses. The results were compared and discussed, and adjustments were made where necessary.

Figure A.1: Survey input data screen

Appendix B - Operation of the SEACATd Risk Model

General

SEACATd is an interactive program that operates under 32 bit Microsoft Windows™ operating systems (e.g. Windows 2000 and XP). As outlined in the schematic overview in Figure B.1 it relies on a series of three input files for its operation, as follows:

- Project file (*.prj) created by the user, defining the study region and the cyclone scenario file to be used;
- Regional definition file (*.rdf) supplied by CTS-SEA;
- Cyclone scenario file (*.cyc) created by the user.
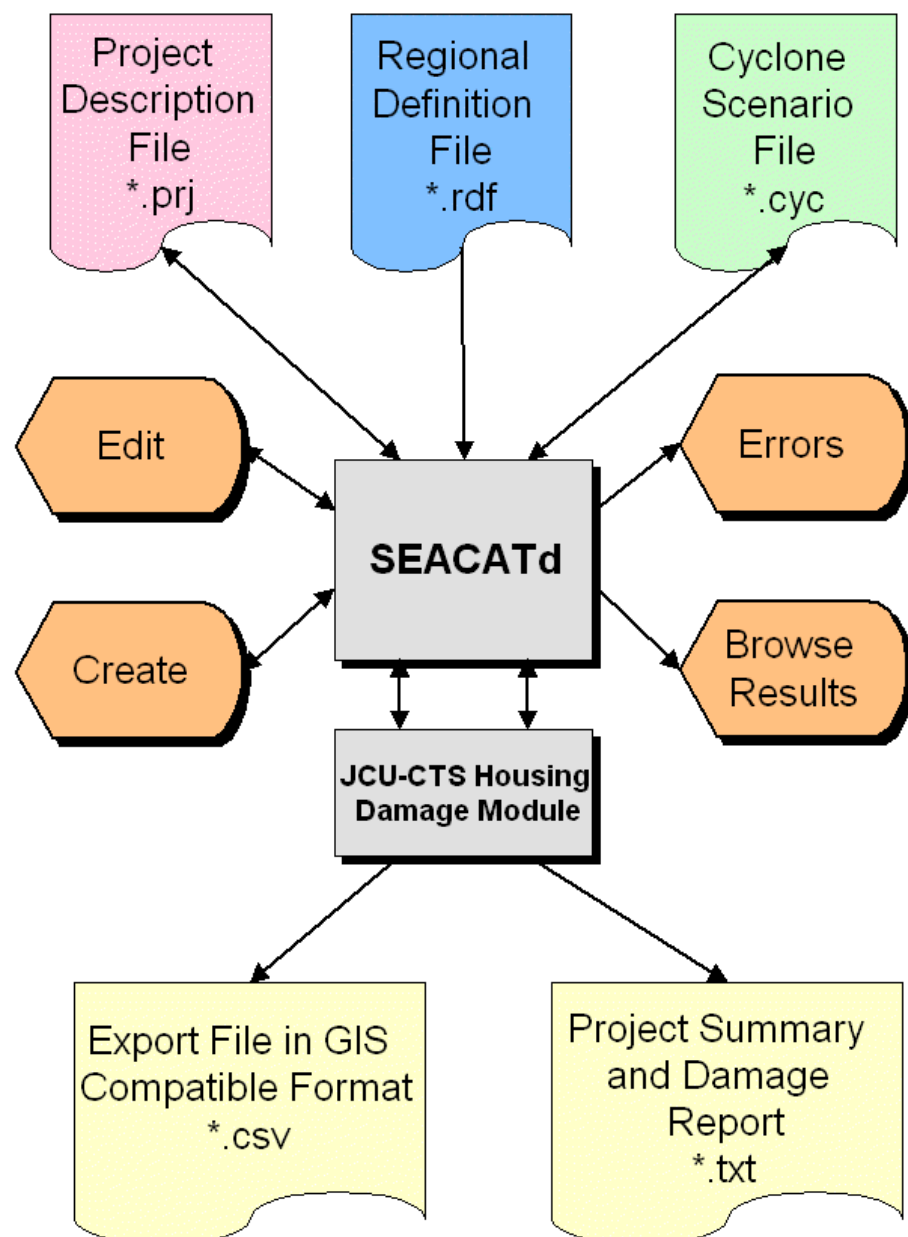
Figure B.1: Schematic Overview of SEACATd Operation.

None of the input files are designed for direct editing by the user, their content is updated automatically by SEACATd in response to user requests. The rdf files are provided as an output from the present study for each of the regions, i.e. Cairns, Townsville and Mackay. These files are complex descriptions of the detailed district information, comprising numbers and types of houses at risk, terrain and topography data and parameters used by the model damage functions. Accordingly the rdf files are provided in a binary format and <u>should not be printed</u>.

The principal output from the model is the project summary and damage report, which can be printed either directly from within the model or externally as required. The secondary output is the export GIS compatible file, which includes spatial information to allow overplotting within a GIS context. The export file is in comma delimited format and may also be imported into a spreadsheet program.

The model operates within the context of having <u>only one</u> active project file at any time and <u>only one</u> active cyclone scenario file, as indicated by the project file. While many such files may be available, only one of each is considered active. Any changes to project or scenario files by the user also results in the <u>automatic saving</u> of those changes unless a "save as" action has been requested.

Installation

The model comes complete with an installation wizard which will ask for the installation directory. This directory will be assigned an environment variable (SEACATD) which is written to the Windows Registry to enable the program to locate its essential files.

Operation of the Model

The model operation is described here in terms of a series of screen shots:

1. Startup

The licence details are displayed momentarily while the main program loads.

During this time, the program will look to recover details of the last model session to facilitate user interaction. This includes the directory paths and filenames of the last used prj and cyc files etc. If unsuccessful, a dialog will appear to prompt the user to change to a preferred directory path for the commencement of the session.

2. Wizard

A wizard dialog is automatically launched to assist the inexperienced user in setting up or choosing project and/or scenario files.
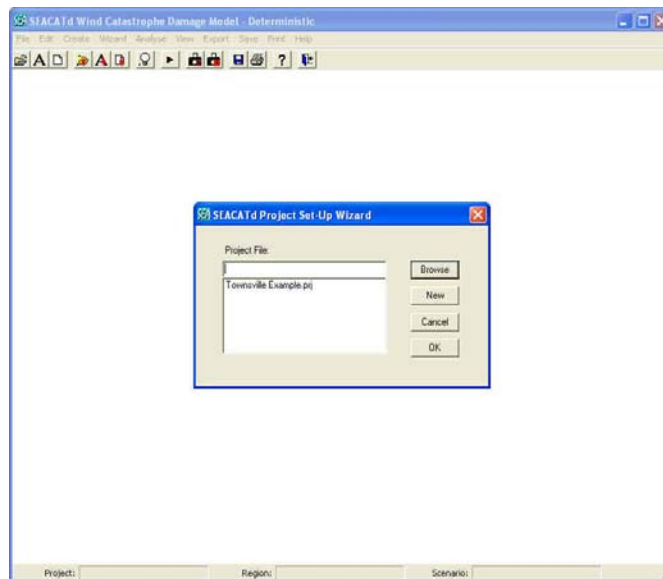
This displays a list of the currently available project files in the nominated directory and allows the user to browse to another directory or create a new project file.
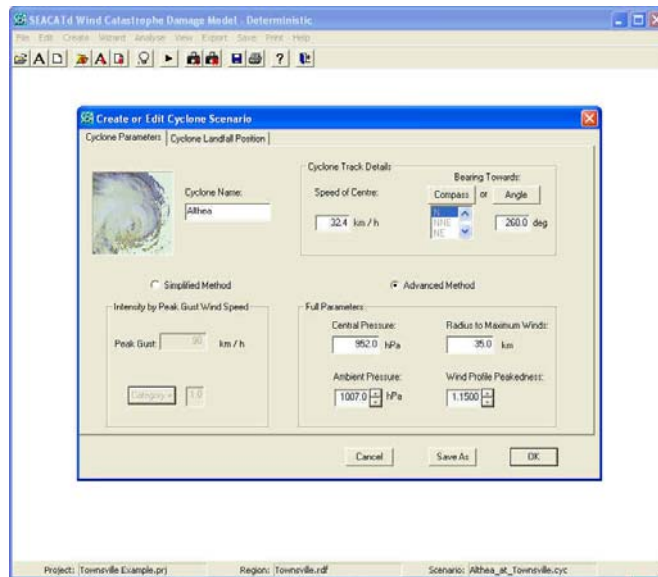
3. Edit or Create a Project File

This dialog displays or accepts changes to a project file details:
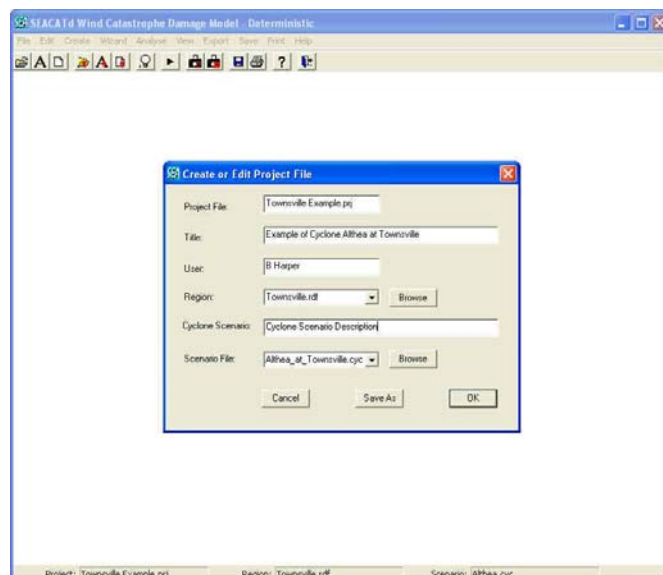
The cyclone scenario file must be nominated in the project file, together with any other descriptive information.

4. Edit or Create a Cyclone Scenario

This dialog displays or accepts changes to the cyclone scenario file details:

This is a tabbed dialog, the first tab of which is shown above, addressing the specification of the cyclone specific parameters such as name, track and intensity information. Two options are provided for specifying the intensity 1) a simplified method whereby only the estimated peak gust wind speed is entered (for example derived from Bureau of Meteorology advisories) or 2) an advanced method whereby the user must provide all the required parameters. In the case of the simplified method, the nominal cyclone category scale can be confirmed by pressing the indicated button. In this case, a set of regional default parameters are provided that will match the specified gust wind speed.

The second tab of the dialog allows specification of the location of the cyclone:
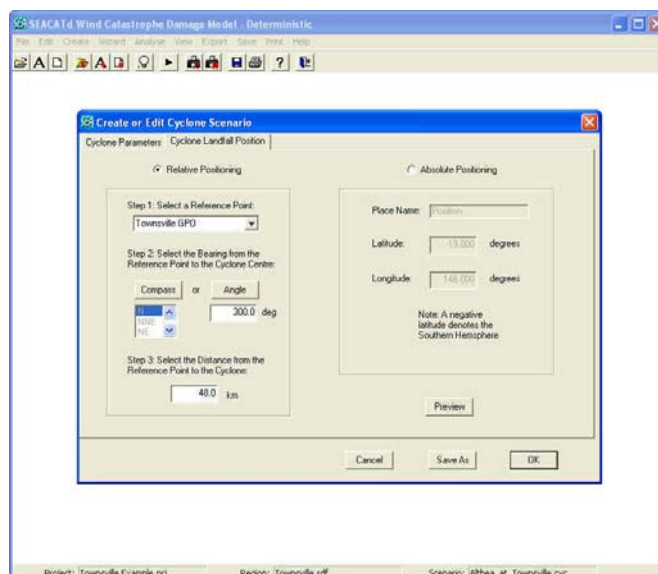
There are also two separate options in this case. Either the storm landfall position can be given as a bearing and distance from a reference location or as an absolute position.

5. Analysis and Viewing of Results

The damage analysis is then invoked via the main menu option or the toolbar button provided. When complete, the user may then either view the results through an on-screen browser (which is cut and paste enabled) or print a summary report to a file, which can also be printed directly from the program.

An example of the on-screen browser is:

6. Export in GIS Compatible Format

The model will also export all of the relevant spatially-tagged damage results into comma-delimited (csv) format files that can be imported by GIS software.