NORTHERN TERRITORY
DEPARTMENT OF LANDS, HOUSING
AND LOCAL GOVERNMENT

TROPICAL CYCLONE STORM SURGE RISK
FOR THE GREATER DARWIN REGION
VOLUME 2 - MAIN REPORT

Final Report

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SUMMARY

This Report, Volume 2 of the Greater Darwin Storm Surge Risk Study, documents the complete results of an evaluation of the tropical cyclone storm surge risk for the Greater Darwin Region.

The study ...

- was commissioned by the Northern Territory's Department of Lands, Housing and Local Government and supervised by the N.T.'s Department of Transport and Works.

- was carried out by Vipac Engineers & Scientists Ltd (Sydney), the Special Services Unit (SSU) of the Bureau of Meteorology (Melbourne) and Global Environmental Modelling Services Pty Ltd (Melbourne), under the guidance of Acer Vaughan Darwin Pty Ltd.

The analysis of storm surge risk includes the effects of cyclone wave set-up and the contribution of astronomical tide and covers Darwin Harbour and the nearby coastline stretching between Point Blaze to the southwest and Point Stephens to the northeast.

- The estimation of cyclone storm surge, that is, the sea level change brought about by surface wind stress and surface pressure, is made using a deterministic regional ocean model which allows the use of nested fine grid zones within the overall large scale grid covering the region.

- The estimation of cyclone wave set-up, the secondary effect of water being piled up on the shore as a result of wave action, is made by running a third generation wave model in open waters combined with analytical-empirical techniques in shallow water areas.

Both of these analytical-empirical cyclone simulation models, use as input, the important climatological parameters of central pressure, Radius of Maximum Winds, storm translation speed, storm direction and track location.

- The variation of cyclone surge plus cyclone wave set-up with return period is then evaluated using probability estimates associated with various cyclone climatological parameters, combined with the annual occurrence rate of storms in the area of interest.

This method takes into account the fact that an intense cyclone crossing the coast some distance from the point of interest may produce a similar surge to that produced by a weaker cyclone crossing closer to this point.
The effect of tidal variation is determined by running a tidal model over the full tidal cycle to establish the probability distribution of tidal height versus return period.

Finally, the cyclone surge plus cyclone wave set-up plus astronomical tide probability distributions are combined to create a total still water elevation probability distribution, termed the cyclone storm tide.

The study was broken up into the following phases:

- **Phase 1**
  - Five bathymetric grids spanning the study area were set up to run the numerical simulation model generating cyclone surge plus cyclone wave set-up estimates.
  - The simulation model was verified against historical observations recorded during major Australian tropical cyclone events, in particular Cyclone Tracy (December, 1974).
  - Darwin area historical cyclone data records were analysed to obtain a statistical representation of the storm parameters of interest.

- **Phase 2**
  - A set of 300 "model" cyclones was defined from the range of meteorological parameters (central pressure, translation speed, direction of motion etc.) representative of the historical cyclones which have affected the Darwin area.
  - The cyclone surge and wave simulation models were run for the 300 representative "model" cyclones on each of the five study grids (a total of 1500 separate cyclone simulation runs).
  - Empirical relationships defining surge and wave set-up heights, at localities of interest around the Darwin area, were determined as functions of any particular combination of cyclone storm climatological parameters.

- **Phase 3**
  - The combined probability distribution of cyclone storm surge plus cyclone wave set-up was determined from the results of the numerical simulation runs.
  - The probability distribution governing astronomical tide fluctuations in the Darwin area was determined separately.
  - Finally, the total probability of peak sea level elevation combining cyclone surge plus cyclone wave set-up plus tidal contribution, i.e. the so-called "storm tide" risk was integrated using the joint probability method.
The individual study location points are shown below in Figure 1.

**STUDY LOCATIONS**

1. Point Blaze
2. Fog Bay
3. Native Point
4. Bynoe Harbour
5. Masson Point
6. Charles Point
7. West Point
8. West Arm
9. Channel Island
10. Wickham Point
11. East Arm
12. Seawall
13. Fannie Bay
14. Casuarina Beach
15. Lee Point
16. Shoal Bay
17. Gunn Point
18. Point Stephens

**Figure 1 Location Map Showing the Sites Where Peak Tropical Cyclone Storm Tides Have Been Evaluated**
The cyclone storm tide extremes obtained in the present study at the individual study locations are summarised below.

### Table 1

**PEAK COMBINED SEA LEVEL PREDICTIONS**  
( metres A.H.D. )

Cyclone Storm Surge + Cyclone Wave Set-Up + Astronomical Tide

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
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<tbody>
<tr>
<td></td>
<td>10</td>
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<tr>
<td>1. Point Blaze</td>
<td>3.9</td>
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<tr>
<td>2. Fog Bay</td>
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<tr>
<td>3. Native Point</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td>4.0</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td>4.2</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td>3.7</td>
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<tr>
<td>7. West Point</td>
<td>4.0</td>
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<tr>
<td>8. West Arm</td>
<td>3.9</td>
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<tr>
<td>9. Channel Island</td>
<td>3.8</td>
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<tr>
<td>10. Wickham Point</td>
<td>3.8</td>
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<tr>
<td>11. East Arm PORT</td>
<td>3.7</td>
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<tr>
<td>12. Darwin South SEAWALL</td>
<td>3.8</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td>4.0</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td>4.0</td>
</tr>
<tr>
<td>15. Lee Point</td>
<td>3.6</td>
</tr>
<tr>
<td>16. Shoal Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td>3.7</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td>3.6</td>
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</table>
The present study predictions vary somewhat from previous estimates made in the GDSSS (1983) and a comparison of the 100-year and 1000-year return period estimates is shown below in Table 2.

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
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<tr>
<td></td>
<td>100 Vipac (1994)</td>
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<tr>
<td>Bynoe Harbour</td>
<td>5.3</td>
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<tr>
<td>Masson Point</td>
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<tr>
<td>Charles Point</td>
<td>4.6</td>
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<tr>
<td>West Point</td>
<td>5.1</td>
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<tr>
<td>West Arm</td>
<td>5.1</td>
</tr>
<tr>
<td>Channel Island</td>
<td>5.1</td>
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<tr>
<td>East Arm PORT</td>
<td>4.9</td>
</tr>
<tr>
<td>Darwin South SEAWALL</td>
<td>5.0</td>
</tr>
<tr>
<td>Fannie Bay</td>
<td>5.2</td>
</tr>
<tr>
<td>Casuarina Beach</td>
<td>5.3</td>
</tr>
<tr>
<td>Shoal Bay</td>
<td>5.1</td>
</tr>
<tr>
<td>Gunn Point</td>
<td>4.5</td>
</tr>
<tr>
<td>Point Stephens</td>
<td>4.2</td>
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</tbody>
</table>

The present estimates are both higher and lower than the previous GDSSS estimates at comparable locations. The reasons for this are discussed in detail in this Report.

In fact, there were substantial differences in individual components of the prediction process between the two models, i.e. the numerical simulation outputs, the climatological probabilities assumed etc. These however contributed to both increasing and decreasing the final estimates, and hence the uneven nature (higher and lower extremes) of the results of the two studies.
ACKNOWLEDGEMENTS

This evaluation of the long-term cyclone storm surge risk for the Greater Darwin Region was commissioned and funded by the Northern Territory's Department of Lands, Housing and Local Government, and supervised by the Northern Territory's Department of Transport and Works.

Much valuable information relating to previous studies of Darwin area cyclones and their effects was provided by both Departments. The assistance, guidance and enthusiasm of Mr Hermann Mouthaan (Lands, Housing & Local Government) and Mr Phill Piper (Transport & Works) are gratefully acknowledged.

The evaluation of Darwin cyclone characteristics carried out as part of the cyclone parameter statistical analysis was made possible through reference material and internal cyclone records provided by Mr Jim Arthur, Regional Director, Bureau of Meteorology, Darwin Office. The T.R.G. Historical Cyclone Data Tape was kindly provided by Mr Frank Woodcock of the Bureau's Severe Weather Warning Program, Melbourne Office.

A great deal of labour expended in this study was carried out by staff members of the Bureau of Meteorology's Special Services Unit in Melbourne. The efforts of Mssrs. Steve Oliver and Stuart Smith stand out.

Finally, from the outset, the study was coordinated by Acer Vaughan's Darwin staff who were responsible for gathering and documenting information and providing local support for the whole team. The guidance and patience of Acer's Mr Paul Grigg and the efforts of Mr Stephen Pendle have been an outstanding feature of the team's effort in this study.

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GEMS (formerly SSU)
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GLOSSARY OF TERMS AND SYMBOLS

Astronomical Tide, $T$  
the variation in sea level arising from the combined gravitational effect of the moon and sun. The **Full Tidal Cycle** is any period during which the full range of tidal elevations is experienced.

Australian Height Datum (A.H.D.)  
0.0 m A.H.D. is equivalent to 0.14 m Mean Sea Level

Tropical Cyclone  
a rotating tropical low pressure system with maximum winds greater than gale force strength

Central Pressure, $P_C$  
minimum pressure value at the centre of a cyclone

Central Pressure Difference, $\Delta p$  
difference between the central pressure in a cyclone and the peripheral value (nominally taken as 1010 hPa)

Radius of Maximum Winds, $R_{MAX}$  
distance from the cyclone centre to the area of maximum winds, lying just outside the cyclone eyewall

Translation Velocity, $V_T$  
forward speed of a cyclone over the earth's surface

Minimum Approach Distance, $D_{MIN}$  
minimum perpendicular distance from a site of interest to the cyclone track

Approach Angle, $\theta$  
direction from which a cyclone is travelling, i.e. a north approach angle cyclone moves towards the south

Surge, $S$  
elevation of sea caused by the effects of surface wind stress and surface pressure

$H_{S-w}$  
significant wave height, offshore

$\zeta_{MAX}$  
wave set-up height along the coastline, related to the significant wave height

Combined Storm Tide Level, $H_C$  
elevation of sea above A.H.D. caused by the combined effect of the cyclone surge and wave set-up plus tidal contribution

Probability Density  
probability of occurrence of a particular event

Return Period  
length of time during which an event might be expected to occur on average once every period
1 INTRODUCTION

In the southern hemisphere, tropical cyclones are clockwise rotating low pressure systems which originate in the tropics and in which the 10-minute mean or average winds exceed 63 km/hr or 34 knots (17 m/sec). The tropical cyclone season in Australia occurs typically from November to April.

There is characteristically a large area of convective cloud and heavy rain associated with tropical cyclones. In well-developed storms there is also a clear region, the eye, situated near the centre. The strongest winds in a cyclone, located at the Radius of Maximum Winds, \( R_{\text{max}} \), lie in a tight band surrounding this eye although, within the eye itself, winds are usually very light.

- **Storm surge** is the elevation in sea level which accompanies the movement of a cyclone particularly near, or over, a coastline, attributed to a cyclone's intensity and wind stress build-up. The height of the storm surge is dependent upon, amongst other factors, the local bathymetry, the intensity of the cyclone and its speed and direction of movement.

The intensity of a cyclone is usually indicated by the lowest barometric pressure in the centre of the system, the central pressure, \( P_c \). Lower pressures will result in stronger winds. The difference between the central pressure of a cyclone and the peripheral pressure at the outer edge of the storm is termed the central pressure difference, \( \Delta P \).

Units of both \( P_c \) and \( \Delta P \) are either hPa (hectoPascals) or mbar (millibars). In the absence of actual data, the peripheral pressure for Australian region cyclones is nominally taken to be 1010 hPa.

- A further contribution to the resulting elevation of the sea at the coast is the effect of wave action. In particular, breaking waves cause an elevation of the sea level by a process known as wave set-up.

- The level of the seas during the passage of a tropical passage also depends on the tidal cycle. Hence, the peak sea surface elevation associated with a particular cyclone will depend, not only on its intensity, location etc., but also on the tide at the time it passes.

The combined effect of cyclone surge plus cyclone wave set-up plus astronomical tide represents the so-called combined storm tide elevation, \( H_c \).

It is this peak combined water level, and its components, which have been evaluated in this investigation. Throughout this Report, both the cyclone surge, wave set-up and tide levels are reported with respect to the Australian Height Datum (A.H.D.).
2 METHODOLOGY

2.1 Study Area

Storm tide estimates for tropical cyclones affecting the Greater Darwin region were determined for the locations shown in Figure 2.1. The study area stretches between Point Blaze to the southwest and Point Stephens to the northeast.

- The extent of the study area necessitated the use of four separate coarse grid model domains to be established along the open coastline for the coastal stations, plus a fifth fine grid model domain to cover the locations studied within Darwin Harbour.

The estimation of peak tropical cyclone storm tide levels around each individual site was limited to cyclones whose Radius of Maximum Winds passed within approximately 100 kilometres of the site concerned. This however varied according to the direction of motion of cyclones crossing the coastline to the east or west of Darwin and for storms moving parallel to the coast.

- For example, a large storm approaching from the northwest and making landfall to the south of Darwin would have a much greater impact than an identical storm, also approaching from the northwest but making landfall the same distance away from Darwin to the north.

Locations within Darwin Harbour itself experience complex storm surge and wave set-up effects compared to open coastal locations as a result of the rapid turning of winds accompanying a cyclone passage and the confined fetch of water at interior locations for different cyclone approach directions.

- For example, a storm moving directly towards the Darwin CBD area from the west and producing local north-northwest winds would be driving water up against Casuarina Beach, prior to making landfall. At the same time, the winds might be off-land at the proposed site of the Darwin South Seawall even though water was being generally driven into the Harbour area.
Figure 2.1 Location Map Showing the Sites Where Peak Tropical Cyclone Storm Tides Have Been Evaluated
2.2 Model Bathymetry/Topography

The study was carried out using five model grids.

Four "coarse grids" (CG1–CG4) with a resolution of 3 kilometres were set up along the coast to establish the cyclone surge plus wave set-up at the specified locations on the open coastline from Point Blaze to Point Stephens. These are shown in Figures 2.2(a)–(d) respectively.

A "fine grid" (FG) was set up with a resolution of 300 metres covering Darwin Harbour and the immediate ocean area and was nested inside CG3. This is shown in Figure 2.2(e).

- **CG1** was used to evaluate Point Blaze, Fog Bay and Native Point.
- **CG2** was used to evaluate Bynoe Harbour, Masson Point and Charles Point.
- **CG3** covered an area of approximately 200 km of coastline with Darwin in the centre and extending to the north past Bathurst and Melville Islands. Nested within this grid was FG which covered the Harbour and the open ocean just outside the Harbour entrance.

This nesting was carried out in order to provide an open ocean surge on the coarse grid which could then propagate up the harbour on the fine grid.

- **CG3 plus FG** were used to evaluate West Point, West Arm, Channel Island, Wickham Point, East Arm Port, Darwin South Seawall and Fannie Bay.
- **CG4** was used to evaluate Casuarina Beach, Lee Point, Shoal Bay, Gunn Point and Point Stephens.

Bathymetry for the open ocean grids was obtained from Admiralty Charts. Bathymetry for the fine resolution Darwin Harbour grid was initially obtained from Patterson Britton & Partners, who were at the time carrying out a detailed modelling study of the circulation in Darwin Harbour. At a later stage in the present study, these data were supplemented with an improved data set generated from the relevant Admiralty Chart and local sounding data provided by the Department of Transport and Works and Acer Vaughan.
Figure 2.2(a) The Fog Bay Coarse Grid Bathymetry (CG1)

Figure 2.2(b) The Bynoe Harbour Coarse Grid Bathymetry (CG2)
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Figure 2.2(c) The Darwin Harbour Coarse Grid Bathymetry (CG3)

Figure 2(d) The Shoal Bay Coarse Grid Bathymetry (CG4)
2.3 Tropical Cyclone Storm Surge

In estimating the elevation changes above and below a datum during the passage of a tropical cyclone, it is necessary to accurately determine a number of contributing effects, and in defining the resulting peak combined storm tide, it is the convention to treat these effects explicitly:

- cyclone-induced storm surge,
- cyclone-induce wave set-up, and
- astronomical tide.

Storm surge, the piling up of water due to high winds and low pressure, is directly dependent on the characteristics of the cyclone, including its intensity and size (as measured by its central pressure and Radius of Maximum Winds), and path and forward translation speed.

For a given cyclone, the storm surge component will also be highly dependent on the local bathymetry.
The storm surge model used in this study is the Hubbert et al. [1990,1991] storm surge hydrodynamic model. This is an updated version of the model used operationally on the Bureau of Meteorology's tropical cyclone workstations. The model is a depth-integrated ocean-current model developed specifically to simulate currents and sea surface elevations on the Australian continental shelf.

Surface wind speeds and pressures which provide the driving mechanism for generating sea surface elevation changes are derived by means of an analytical-empirical tropical cyclone model based on Holland's [1980] cyclone windfield model.

These are described in detail in subsequent sections and in the technical papers which have been included with this Report (see Appendices D, E and F).

2.4 Tropical Cyclone Wave Modelling

Theoretical studies and field measurements indicate that the maximum wave set-up, designated $\zeta_{\text{MAX}}$, during a cyclone passage occurs at the shoreline. Furthermore, numerous field studies, discussed further in this Report, indicate that there is a close relationship between $\zeta_{\text{MAX}}$ and $H_{\text{s,\infty}}$, the so-called "significant wave height" in deep water (open ocean). Numerous field studies have yielded data which fit the relationship:

$$0.14 < \frac{\zeta_{\text{MAX}}}{H_{\text{s,\infty}}} < 0.17$$

and for the present study, $\frac{\zeta_{\text{MAX}}}{H_{\text{s,\infty}}} = 0.15$ was chosen as being a representative value.

Thus, the prediction of wave set-up accompanying a tropical cyclone requires the prediction of the wave field generated by a moving cyclone system and, in particular, predictions of the significant wave height near coastal locations of interest.

In the present study, the significant wave height is estimated using the so-called "WAM" model, a third generation ocean wave prediction model [Hasselmann et al, 1988]. This model is run on the coarse ocean grid to determine offshore significant wave heights for individual cyclone events. The wave model has been adapted to the PC environment where it is driven by the Holland analytical tropical cyclone windfield model.

The WAM model has been verified for water depths greater than about 20 metres and is now providing operational forecasts on a one degree grid for the Australian region driven by winds from the Bureau's operational numerical weather prediction model. For shallow depth areas, and specifically for the Darwin Harbour study locations, empirical relationships were used to convert significant wave height predictions at the Harbour entrance to wave set-up estimates at inner Harbour points, taking into wind stresses and the rate of change of wind approach angle for particular storm paths.
3 MODEL DESCRIPTIONS

The cyclone storm surge and significant wave height forecasting system [Hubbert et al., 1990, 1991] used in this study has been developed specifically for use in the Australian region. The model is driven by wind stresses, atmospheric pressure gradients, and bottom friction.

- The primary requirement therefore for modelling cyclone storm surge and wave set-up is an accurate description of the surface wind and atmospheric pressure fields accompanying the storm.

- In this study, surface wind speeds and pressures are inferred from an adaptation of the analytical–empirical profile model of Holland (1980). This model has been used extensively in national forecasting offices both in Australia and elsewhere and has been found to provide a good representation of the windfield in the vicinity of a cyclone, particularly around the eyewall in the region of maximum winds.

3.1 Windfield Model

There are usually insufficient data to allow a direct analysis of the central region of most tropical cyclones and currently available numerical weather prediction models do not adequately represent the small–scale features found in these storms, e.g. rainbands etc. Surface wind speeds and pressures are therefore derived using an adaptation of the analytical–empirical profile model of Holland (1980). A detailed description of the analytical model together with verifying data is given in Hubbert et al (1991) (see Appendix E) and only a brief description of the major features is given here.

The pressure, \( P \) (hPa), at radius, \( r \), in the cyclone is defined as:

\[
P = P_c + (P_o - P_c) \cdot \exp[-(R_{\text{max}}/r)^B]
\]

Eqn.(1)

where \( P_c \) is the central pressure, \( P_o \) is the peripheral pressure (the climatological mean for the region and month), \( R_{\text{max}} \) is the Radius of Maximum Winds and "\( B \)" is a scaling parameter for the pressure profile shape. The parameter, \( B \), is empirically defined by:

\[
B = 1.5 + (980 - P_c)/120
\]

Eqn.(2)

The symmetric, gradient–level azimuthal wind component, \( V \), at radius, \( r \), out from the centre of the storm is estimated as:

\[
V = \{ B \cdot (R_{\text{max}}/r)^B \cdot (P_o - P_c) \cdot \exp[-(R_{\text{max}}/r)^B]/\rho - (rf/2)^2 \}^{1/2} - rf/2
\]

Eqn.(3)

In the above expression, \( \rho \) is the air density and \( f \) is the Coriolis parameter.
A first order asymmetry is included by adding the cyclone translation to the symmetric field and rotating the windfield so that the maximum wind is 70° to the left (right in the Northern Hemisphere) of the direction of cyclone motion. The radial windfield is constructed by rotating the flow to a constant inflow angle of 25° outside the Radius of Maximum Winds.

It is important to note that the tropical cyclone model is not expected to represent the full field of synoptic scale features typically found in tropical cyclones, including localised rainbands etc.. The critical aspect from the point of view of storm surge and wave forcing is that the model can reproduce well the mesoscale forcing in the vicinity of the maximum winds.

### 3.2 Storm Surge Model

Although baroclinic effects have a significant influence on deep ocean circulation over long time-scales, the main short term variations in ocean circulation during tropical cyclones, particularly on a continental shelf, are due to the surface wind stress and the surface pressure. As a result, baroclinic effects can generally be neglected for the purpose of predicting the direct ocean response to a tropical cyclone. Hence a depth-integrated model has been adopted for storm surge prediction.

The storm surge model and the numerical solution scheme used in this study are described in detail in Hubbert et al. (1990, 1991) (see Appendices D–F), together with a stability analysis. The major features of the model are:

- the shallow water equations are solved on an Arakawa C-grid
- non-linear advection terms are included
- an efficient time-splitting finite difference scheme is used, which yields accurate and stable results and a faster solution than standard explicit techniques (three different time steps are used to solve the gravity wave, advective and the physics components of the equations)
- the model is driven by wind stresses, atmospheric pressure gradients, tides and quadratic bottom friction
- the resolution and the map projection are variable
- a radiation condition which solves for the group velocity is used to compute open boundary values
- a high resolution global bathymetry file is used, and the model can incorporate local very high resolution bathymetric data if available
- the model can be nested inside itself
- output consists of sea surface elevations, depth-integrated ocean currents and individual station time series at any number of locations

The storm surge model used in the present study, together with the cyclone windfield model, currently form the basis of the Bureau of Meteorology's operational storm surge forecasting system.
For most applications the storm surge model runs take less than an hour on modern personal computers. High resolution nested runs take longer and are used for environmental studies rather than for forecasting. The storm surge model has been used for a number of storm surge coastal impact studies and also for research studies such as modelling the propagation of coastally trapped waves along the continental shelf.

3.3 Model Nesting

Errors can be generated in nested model simulations if the change in grid resolution is substantial and the open boundaries are in a region of sharp bathymetric variation, e.g. across a continental shelf edge. The nesting techniques used in the present study are those adopted in all of the Bureau of Meteorology's operational forecasting models.

The test of successful transfer from a coarse grid to a fine grid is not a comparison of sea levels at the edge of the fine grid. By definition, these will be the same. Rather, an appropriate test is to examine the transfer of energy from one grid to another. The present model uses this energy transfer comparison as a check to accept or reject model output results when nesting is utilised.

The energy transfer acceptance criterion was utilised in the validation of the model with Cyclone Tracy (Dec., 1974) (see Section 4.3), and resulted in the original Fine Grid, FG, being moved further out to sea to finally encompass the area shown in Figure 2.2(e).

3.4 Wave Model

Observations have shown that the maximum mean shoreline water elevation in relatively exposed areas, where wave energy is dissipated as surf, is greater than in calmer areas. This difference cannot be explained in terms of storm surge height alone.

Theoretical studies and field measurements indicate that the maximum wave set-up at the shoreline, designated $e_{\text{MAX}}$, during the passage of a tropical cyclone is closely related to the significant wave height of the storm in the near coastal vicinity.

The model used to predict the significant wave height generated by a tropical cyclone in the present study is the so-called "WAM" model, a third generation ocean wave prediction model [Hasselmann et al, 1988]. This model is run on the coarse ocean grid to determine offshore significant wave heights for individual cyclone events.

The WAM model is now providing operational forecasts on a one-degree grid for the Australian region driven by winds from the operational numerical weather prediction model. For tropical cyclone studies it has been adapted to run in a menu-driven interactive mode in conjunction with the tropical cyclone model.
The extension of wave set-up theory to cover incident wave spectra [Battjes, 1978] involves assumptions about the distribution of wave heights and the energy lost during the breaking process. Guza and Thornton [1981] have pointed out that these models are only weakly dependent on details of the offshore incident wave spectra and to variations in beach slope.

Both theory and laboratory experiments have shown that:

$$0.14 < \zeta_{\text{MAX}} / H_{s,w} < 0.21$$

where $H_{s,w}$ is the significant wave height in deep water [Battjes, 1974].

Field data collected by Guza and Thornton showed $\zeta_{\text{MAX}} / H_{s,w}$ to be 0.17 for swell waves. Battjes [1974] and Vincent and Grosshopf [1982] have shown that wave set-up increases with decreasing wave steepness for a given value of $H_{s,w}$. It then follows that, during a tropical cyclone event, when waves are comparatively steep, the appropriate value should be somewhat less than 0.17.

In light of the above discussion and following the approach taken by other studies, it was assumed that:

$$0.14 < \zeta_{\text{MAX}} / H_{s,w} < 0.17$$

and for the present study, $\zeta_{\text{MAX}} / H_{s,w} = 0.15$ was chosen as being a representative value.

Thus, the prediction of wave set-up accompanying a tropical cyclone requires the prediction of the wave field generated by a moving cyclone system and in particular the significant wave height near coastal locations of interest.

The combined surge plus wave set-up for each of the "primary" cyclone types is thus determined by assuming that $\zeta_{\text{MAX}} / H_{s,w} = 0.15$.

The WAM model (developed by the WAM group [Hasselman et al, 1988]), is a third generation wave prediction model which computes the evolution of the directional surface wave spectrum over the area covered by the model grid by solving the energy balance equation

$$\frac{\partial}{\partial t} \phi + \nabla \cdot (c \phi) = s(u)$$

Eqn.(4)

where the source term $s(u)$ is defined by:

$$s(u) = s_H(u) + s_{nl} + s_{de} + s_{bf}$$

Eqn.(5)
and where:

\[ \phi(z,t,f,\theta) \]

is the spectral density at frequency, \( f \), and direction, \( \theta \), evaluated at position, \( z \), on the globe at time, \( t \)

\( C_g \)

is the group velocity

\( \phi \)

represents the three-dimensional spectrum of sea surface waves

\( S_h \)

is the source term representing the flux of energy from the atmosphere to the surface waves expressed as a function of the local friction velocity

\( S_a \)

is the source term representing the exchange of energy of waves in one frequency–direction bin with waves in other frequency–direction bins due to weak non-linear interactions

\( S_w \)

is the source term representing whitecapping dissipation

\( S_bf \)

is the source term representing dissipation due to bottom friction

The 2-D spectrum at each grid point is represented in the model as a function of discrete frequency–direction bins with frequencies ranging from 0.042 to 0.45 Hz. There are three time steps which can be varied to suit the application. The wind time step is usually set to one hour for tropical cyclone studies. At each integration time step the source terms are integrated locally and then at the end of a propagation time step advection is computed for each bin separately. The propagation time step can take values up to 30 minutes depending on the CFL criterion.

The WAM model applies to water depths greater than about 20 metres. For shallow depth areas, and specifically for the Darwin Harbour study locations, empirical relationships were used to convert significant wave height predictions at the Harbour entrance to wave set-up estimates at inner Harbour points, taking into account wind stresses and the rate of change of wind approach angle for particular storm paths.

The WAM Model requires much larger computer running time than the storm surge predictions model and, in the present study, this precluded making as many simulation model runs to predict waves as for the surge component of the study. Thus, separate model simulation runs were made with varying cyclone intensities, directions and tracks to define the range of resultant significant wave heights and resulting cyclone wave set-up in the coastal areas of interest.

### 3.5 Tidal Predictions

Actual total sea elevation relative to datum during the passage of a tropical cyclone is dependent on the occurrence of the cyclone–induced surge plus wave set-up with respect to the tidal cycle. A separate tidal probability distribution has been determined by running a tidal height prediction model (Foreman, 1980) for the study region over the full astronomical cycle (18.6 years). The probability distribution for discrete values of tidal elevations throughout the entire tidal range was then determined and is discussed in subsequent sections.
4 MODEL VERIFICATION

4.1 Published Studies

Verification of model hindcasts of sea-surface elevations and depth-averaged currents driven by a typical extratropical cold front has been presented previously in Hubbert et al. (1990). The results of several tropical cyclone studies reported in Hubbert et al (1991) are reproduced in Table 4.1 shown below.

Table 4.1
Comparison of PREDICTED Model Surge Heights with OBSERVED Surge Records for Tropical Cyclones (reproduced from Hubbert et al [1991])

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Location</th>
<th>Sea Surface Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>Winifred</td>
<td>Clump Point</td>
<td>1.6</td>
</tr>
<tr>
<td>Aivu</td>
<td>Upstart Bay</td>
<td>2.8</td>
</tr>
<tr>
<td>Jason</td>
<td>Karumba</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Burketown</td>
<td>3.5</td>
</tr>
<tr>
<td>Hazel</td>
<td>Carnarvon</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Geraldton</td>
<td>0.7</td>
</tr>
</tbody>
</table>

* - estimated observations from beach surveys

It can be seen that the comparison of peak predicted surge height compares very favourably with the observed heights for the above storms.
4.2 Cyclone Orson

Cyclone Orson passed within 4 kms of Woodside's North Rankin gas platform on the Australian northwest shelf, at 1600 hours UTC on April 23, 1989, on its way to a coastal crossing five hours later.

As Cyclone Orson passed North Rankin ...

- The central pressure was measured as 905 hPa, the lowest ever recorded in the Australian region.
- The peak 10-minute mean wind at 38 metres elevation was measured as 74 m/s. Using a representative boundary layer reduction factor the maximum surface wind would have been approximately 56 m/s.
- The wave rider buoy at North Rankin measured a peak significant wave height of approximately 10 metres before it was damaged and stopped recording. This measurement is believed to have been the maximum.
- Ocean currents measured by the current meter at mid-depth at North Rankin peaked at 1.10 m/s.

Fortunately astronomical tides were falling as Cyclone Orson approached the coast and the effect of the storm surge was reduced. At the time of landfall the predicted tidal height at King Bay near Dampier was only 1.6 metres, substantially less than the highest astronomical tidal level of 5.1 metres.

- The sea level measured by the tide gauge at King Bay was 4.7 metres, indicating a storm surge of 3.1 metres.

Results of the simulation of Cyclone Orson have been published previously by Hubbert (1991) (see Appendix F) and the major results are summarised below.

*Sea Level Winds and Pressures* ...

Cyclone Orson was simulated using the tropical cyclone model with a "B" parameter value of 1.5, a peripheral pressure of 1005 hPa and the "best track" data for position, central pressure and radius of maximum winds. The best track data is the cyclone track derived from a re-analysis of all data after the event – radar, aircraft reconnaissance etc.

The maximum wind speed generated by the present study model at North Rankin platform was 55 m/s compared with the measured peak 10-minute average wind speed of 56 m/s.
Storm Surge and Ocean Currents ...

The storm surge model was then run, using as input, the hourly winds and atmospheric pressures from the tropical cyclone model. The model surge reached a maximum of 3.0 metres at the nearest grid point to King Bay, which is in good agreement with the measured peak surge of 3.1 metres above astronomical tide.

The peak depth-averaged ocean current at North Rankin produced by the model was 0.96 m/s, compared with the observed mid-depth current of 1.10 m/s. This agreement is good in view of the fact that the depth-averaged current and the mid-depth current are not necessarily the same.

Simulation of Ocean Surface Waves ...

The wave model was also run, driven by the hourly winds from the tropical cyclone model. The peak significant wave height produced by the model at North Rankin was 10.2 metres compared with the measured peak height of approximately 10 metres. It is of interest that the overall peak significant wave height produced throughout the simulation of Cyclone Orson was 12 metres.

Finally, it should be noted that King Bay, in Mermaid Sound on the north-west shelf, where Cyclone Orson's storm surge was measured and where the simulation model domain had to be defined, is a region of extremely complex bathymetry, with small inlets, islands and shallow water.

4.3 Cyclone Tracy

Cyclone Tracy is one of the best remembered tropical cyclones in Australia due to the devastating results of its passage over Darwin on Christmas Day, 1974.

- Tracy was an extremely small cyclone with a Radius of Maximum Winds near landfall of only 6 km, whilst its lowest central pressure was recorded as 955 hPa.

- The tide gauge at Stokes Hill Wharf in Darwin Harbour recorded a peak storm surge of 1.6 metres, and

a post-storm visual appraisal of debris suggested that the storm surge along Casuarina Beach was in the range 3 to 4 metres.
The ability to accurately simulate the Darwin Harbour response to Cyclone Tracy was critical from the point of view of verifying both:

- the reliability of the cyclone windfield and storm surge plus wave set-up models in the general domain area, and
- the accuracy of the nested grid storm surge modelling system set up for grids CG3 and FG.

The tropical cyclone model was run using values of central pressure, translation speed, \(R_{MAX}\), approach direction etc. documented in the Bureau of Meteorology's Report on Cyclone Tracy [A.G.P.S., 1977]. Figure 4.1 below shows the simulation Cyclone Tracy windfield distribution at the start of the model run, 18 hours prior to landfall being made.

Using this windfield as the initial input, the storm surge model was run on the Darwin coarse grid, CG3, to generate surges along the open coastline. The storm surge model was then run on the nested fine grid of Darwin Harbour, FG, to propagate the open ocean surge into the Harbour and model the response of the Harbour itself.

![Figure 4.1 Cyclone Tracy Windfield - 18 Hours Prior to Landfall](Wind Speed in knots; Forecast Starts at 0900-24.12.1974)
Achieving a successful simulation of the ocean response to Cyclone Tracy proved to be a major challenge. Initially, the coarse grid results agreed with the observation of a possible 3 metre surge along Casuarina Beach. However, the model was initially unable to generate a sufficiently large surge in Darwin Harbour itself. A major effort was undertaken to ascertain the cause of this problem.

Two contributing factors were identified:

- One major cause was the original Darwin Harbour bathymetric file which had been provided from concurrent work being undertaken to model the circulation in Darwin Harbour. When it was scrutinised in detail, many significant discrepancies from the Admiralty Chart and the available sounding data were identified.

  The Darwin Harbour bathymetric file was corrected on the basis of the available Chart data and soundings provided by Acer Vaughan taken specifically for the project in a number of key locations, e.g. East Arm and the proposed Seawall.

- A second contributing factor was the small radius of the Cyclone Tracy windfield vortex, which resulted in large wind gradients across the overlapping nesting region of the coarse and fine grids.

  Some minor modifications were then made to the nesting transition from coarse to fine grid. This included extending the original fine grid (FG) for the Harbour further out to sea within its parent coarse grid, CG3.

The results improved significantly. The Tracy model run generated a peak storm surge level of 1.56 m (taking into account the small contribution from wave set-up at the tide gauge site). This value agreed well with the observed 1.6 metre residual water elevation (excluding tidal effects) at Stokes Hill Wharf.

Figure 4.2 shows the sea-surface elevations as the model Cyclone Tracy storm approached Darwin at approximately 7 hours before landfall. This was near the time that the maximum surge was being recorded at the Stokes Hill Wharf location.

Figure 4.3 indicates the time profile of residual sea level registered during the Cyclone Tracy model run at Stokes Hill Wharf as well as the actual recorded gauge data. The tidal components have been excluded in these data.
**Figure 4.2** Cyclone Tracy Sea Surface Elevation – 7 Hours Prior to Landfall

**Figure 4.3** Comparison of Model (Solid Line) versus Actual (Dashed Line) Surface Heights at Stokes Hill Wharf During the Passage of Cyclone Tracy (Tidal Component Removed)
5 CYCLONE CLIMATOLOGY

This section presents the results of a climatological analysis of tropical cyclones affecting the Darwin region. This analysis was used to develop appropriate probability distributions and joint probabilities describing the cyclone meteorological parameters of interest used as input variables to the cyclone surge and wave set-up model.

The results are based partly on a previous analysis of Darwin region tropical cyclones documented in Vipac Report No. 36499 (1992). An amended excerpt from this study has been included as Appendix A of this Report.

The original study identified 44 tropical cyclones which passed within 300 km of Darwin during the period of cyclone seasons 1957/1958 to 1989/1990. Cyclone occurrences prior to the 1957/58 season were not considered because of deficiencies in the data gathering processes (e.g. no radar, satellite data etc.) used to compile the existing historical record for the area.

In the present study, several storms were eliminated from the data base because of their distance from, or orientation with respect to, Darwin. The remaining storm data base, comprising 33 tropical cyclones, coincidentally gives an occurrence rate of one per year.

Some of the remaining 33 storms would still be considered to be too far away, i.e. 200 km from Darwin, to have had a serious impact on cyclone surge and waves in the vicinity.

However, the basis of the joint probability approach adopted in this study is to reproduce as exactly as possible the whole climatology of cyclones in any given area, not just the most severe events. As long as the corresponding probabilities of occurrence for the less severe events are maintained at the correct levels, the final extreme predictions will be reliable.

The subset of 33 cyclones comprising the basic storm data set for the present study has been listed on the following page in Table 5.1.

The track positions through the Darwin area region of the original 44 storm data set are shown in Appendix A, Figures A.2(a)–(e).

From the track paths, it is convenient to subdivide the tropical cyclones affecting the Darwin area into five basic directional groups:

- east/northeast storms (i.e. approaching from the east/northeast)
- east/northeast storms, but forming to the west of Darwin
- northerly storms, initially northeast but gently recurving towards the south
- westerly storms
- northwest storms, e.g. Tracy (1974) and/or recurving storms, e.g. Selma (1974)
# Table 5.1

**PRESENT STUDY DATA SET**

33 Tropical Cyclones Passing Within 200 km of Darwin in the Period 1957/58 - 1989/90

<table>
<thead>
<tr>
<th>Name</th>
<th>Date at Time of Closest Approach</th>
<th>Storm Direction (deg.)</th>
<th>Minimum Distance (kms)</th>
<th>Translation Speed (m/sec)</th>
<th>Minimum Central Pressure (mbars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.1</td>
<td>14 Jan. 1959</td>
<td>270</td>
<td>170</td>
<td>4.3</td>
<td>1004</td>
</tr>
<tr>
<td>U.3</td>
<td>4 Apr. 1959</td>
<td>190</td>
<td>−80</td>
<td>3.1</td>
<td>992</td>
</tr>
<tr>
<td>U.5</td>
<td>22 Mar. 1960</td>
<td>280</td>
<td>60</td>
<td>7.0</td>
<td>999</td>
</tr>
<tr>
<td>U.7</td>
<td>27 Jan. 1962</td>
<td>220</td>
<td>n.a.</td>
<td>1.3</td>
<td>998</td>
</tr>
<tr>
<td>Carmen</td>
<td>8 Mar. 1964</td>
<td>210</td>
<td>−60</td>
<td>3.3</td>
<td>996</td>
</tr>
<tr>
<td>Flora</td>
<td>2 Dec. 1964</td>
<td>180</td>
<td>80</td>
<td>2.9</td>
<td>996</td>
</tr>
<tr>
<td>Judy</td>
<td>25 Jan. 1965</td>
<td>170</td>
<td>240</td>
<td>7.3</td>
<td>1002</td>
</tr>
<tr>
<td>Marie</td>
<td>28 Feb. 1965</td>
<td>220</td>
<td>50</td>
<td>3.8</td>
<td>998</td>
</tr>
<tr>
<td>Amanda</td>
<td>28 Dec. 1965</td>
<td>230</td>
<td>60</td>
<td>3.1</td>
<td>997</td>
</tr>
<tr>
<td>Betty</td>
<td>10 Feb. 1966</td>
<td>270</td>
<td>120</td>
<td>3.6</td>
<td>998</td>
</tr>
<tr>
<td>Bertha</td>
<td>20 Jan. 1968</td>
<td>230</td>
<td>0</td>
<td>3.8</td>
<td>997</td>
</tr>
<tr>
<td>Bonnie</td>
<td>23 Feb. 1968</td>
<td>250</td>
<td>220</td>
<td>1.7</td>
<td>1003</td>
</tr>
<tr>
<td>Audrey</td>
<td>4 Mar. 1969</td>
<td>240</td>
<td>90</td>
<td>5.2</td>
<td>994</td>
</tr>
<tr>
<td>Glynis</td>
<td>26 Jan. 1970</td>
<td>250</td>
<td>90</td>
<td>4.1</td>
<td>1000</td>
</tr>
<tr>
<td>Beverley</td>
<td>1 Dec. 1970</td>
<td>260</td>
<td>−100</td>
<td>2.7</td>
<td>998</td>
</tr>
<tr>
<td>Kitty</td>
<td>5 Dec. 1971</td>
<td>240</td>
<td>−100</td>
<td>3.9</td>
<td>1000</td>
</tr>
<tr>
<td>Madge</td>
<td>6 Mar. 1973</td>
<td>250</td>
<td>180</td>
<td>4.9</td>
<td>995</td>
</tr>
<tr>
<td>Ines</td>
<td>19 Nov. 1973</td>
<td>260</td>
<td>−160</td>
<td>2.8</td>
<td>993</td>
</tr>
<tr>
<td>Jenny</td>
<td>19 Mar. 1974</td>
<td>270</td>
<td>120</td>
<td>1.4</td>
<td>995</td>
</tr>
<tr>
<td>Selma</td>
<td>3 Dec. 1974</td>
<td>&quot;REC.&quot;</td>
<td>80</td>
<td>2.8</td>
<td>980</td>
</tr>
<tr>
<td>Tracy</td>
<td>24 Dec. 1974</td>
<td>120</td>
<td>0</td>
<td>1.9</td>
<td>950</td>
</tr>
<tr>
<td>Wilma</td>
<td>13 Mar. 1975</td>
<td>230</td>
<td>−150</td>
<td>3.0</td>
<td>985</td>
</tr>
<tr>
<td>Linda</td>
<td>17 Mar. 1976</td>
<td>90</td>
<td>n.a.</td>
<td>7.0</td>
<td>1000</td>
</tr>
<tr>
<td>Verna</td>
<td>2 May 1977</td>
<td>&quot;REC.&quot;</td>
<td>200</td>
<td>2.2</td>
<td>997</td>
</tr>
<tr>
<td>Brian</td>
<td>18 Jan. 1980</td>
<td>220</td>
<td>−180</td>
<td>6.7</td>
<td>1001</td>
</tr>
<tr>
<td>Doris</td>
<td>20 Mar. 1980</td>
<td>260</td>
<td>110</td>
<td>7.5</td>
<td>1003</td>
</tr>
<tr>
<td>Max</td>
<td>11 Mar. 1981</td>
<td>250</td>
<td>−20</td>
<td>3.9</td>
<td>990</td>
</tr>
<tr>
<td>Amelia2</td>
<td>3 Dec. 1981</td>
<td>270</td>
<td>−50</td>
<td>5.6</td>
<td>999</td>
</tr>
<tr>
<td>Bruno</td>
<td>15 Jan. 1982</td>
<td>250</td>
<td>100</td>
<td>5.6</td>
<td>993</td>
</tr>
<tr>
<td>Ferdinand</td>
<td>2 Mar. 1984</td>
<td>90</td>
<td>80</td>
<td>2.7</td>
<td>1002</td>
</tr>
<tr>
<td>Gretel</td>
<td>13 Apr. 1985</td>
<td>230</td>
<td>−20</td>
<td>3.5</td>
<td>984</td>
</tr>
<tr>
<td>Kay</td>
<td>10 Apr. 1987</td>
<td>270</td>
<td>−140</td>
<td>5.2</td>
<td>994</td>
</tr>
</tbody>
</table>
5.1 Darwin Cyclone Approach Angles

In attempting to allocate percentages to the storms affecting Darwin based on direction of motion, the choice of sub-division adopted for the modelling runs follows the broad groupings shown in Figures A.2(a)–(e) (see Appendix A). This split up the total number of cyclones affecting the Darwin area into five (5) groups, listed below in Table 5.2.

† The bulk of these cyclones are from the northeast quadrants. However, the storms which have inflicted the greatest historical damage on Darwin are the recurving storms such as Tracy (1974), which typically had an initial southwest path and recurred towards the southeast as they approached the Darwin area.

<table>
<thead>
<tr>
<th>Group</th>
<th>Approach Angle</th>
<th>Occurrence Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280°</td>
<td>10 %</td>
</tr>
<tr>
<td>2</td>
<td>320°</td>
<td>12 %</td>
</tr>
<tr>
<td>3</td>
<td>0°</td>
<td>8 %</td>
</tr>
<tr>
<td>4</td>
<td>40°</td>
<td>35 %</td>
</tr>
<tr>
<td>5</td>
<td>80°</td>
<td>35 %</td>
</tr>
</tbody>
</table>

5.2 Darwin Cyclone Translation Speeds

From the previous analysis of the historical data base of cyclone translation speeds (see Appendix A), the following three categories and corresponding probability densities were adopted to cover the range of representative forward speeds for Darwin area cyclones:

<table>
<thead>
<tr>
<th>Group</th>
<th>Translation Speed</th>
<th>Occurrence Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 m/sec</td>
<td>35 %</td>
</tr>
<tr>
<td>2</td>
<td>5 m/sec</td>
<td>50 %</td>
</tr>
<tr>
<td>3</td>
<td>8 m/sec</td>
<td>15 %</td>
</tr>
</tbody>
</table>
5.3 Frequency Distribution For $\Delta p$

Initially, the central pressures of the 33 cyclones comprising the Darwin region data base were converted to central pressure differences, $\Delta p$, assuming a representative periphery pressure of 1010 hPa.

- It has been previously documented by the N.T.'s Bureau of Meteorology, that the average periphery pressure for tropical cyclones in the general north Australia region tends to fall slightly in the middle of the season (January-February). However, in the present study, it was decided to retain the 1010 hPa value, since the actual periphery pressure at the time the database storms were passing by Darwin was not recorded, and is therefore unknown.

Georgiou and Davenport (1988) have found that the $\Delta p$ values of North Atlantic tropical cyclones (hurricanes) are best fitted by a Weibull distribution, while the log-normal distribution is preferred for Northwest Pacific tropical cyclones (typhoons).

In the present study, it was found that a Weibull type Extreme-Value Distribution fitted the data well in the range up to a $\Delta p$ value of about 60 hPa (the Cyclone Tracy value).

- Appendix A discusses how the probability associated with a particular cyclone is related to the annual probability of its occurrence via the distribution of the number of cyclones per year (or per season).

Recent research and physical considerations (e.g. the maximum achievable ocean water temperatures etc.) require a means to limit the values of $\Delta p$ of tropical cyclones in any particular area to realistic values at the very high return periods, i.e. return periods of thousands of years.

- This implies that the chosen distribution cannot be physically unbounded. While the Weibull distribution was found to yield a good fit for most of the observations it does not follow that it is a good fit to the "tail" (very low probabilities of exceedance) of the distribution (Moriarty, 1985).

This aspect of the problem was approached by developing an extreme value asymptote using the method of sextiles (Jenkinson, 1969). The asymptote was of the truncated Weibull type, implying the existence of an effective upper limit for $\Delta p$. The asymptotic form is:

$$ F(x) = \exp \left[ - \left\{ 1 - k.a.(\Delta p - u) \right\}^{1/k} \right] $$  

Eqn.(6)

where $k$, $a$ and $u$ are constants determined from the fit of the upper return period data.
The overall analysis of the complete data set (all 33 cyclones) yielded a central pressure value, $P_c$, of approximately 917 hPa for the 1000 year return period.

- A central pressure value of 950 hPa (e.g. Cyclone Tracy) would have a return period of just less than 50 years, which agrees reasonably well with the occurrence rate of severe storms affecting Darwin in the last two hundred years.

However, it was observed from the basic study data set and from the available historical records dating back to the 1800's, that tropical cyclones ...

- approaching Darwin from the northeast are generally mild, while
- virtually all of the historically severe storms which have impacted upon Darwin have approached from north and northwest quadrants (e.g. Tracy).

This is understandable given the fact that tropical cyclones derive their energy from warm ocean waters and, in the area of interest, cyclones approaching the coast from the northwest will have a greater part of their circulation, especially in the important front-left quadrant over open water.

Thus it was decided to use two slightly different conditional distributions in the model simulation runs to characterise the variation in $\Delta p$ value -- a stronger distribution, "A", (i.e. stronger relative to the above fitted curve) for northwest quadrant storms and a weaker distribution, "B", for northeast storms:

- $\Delta p$ Conditional Distribution "A" covers angles $280^\circ, 320^\circ$ and $0^\circ$
- $\Delta p$ Conditional Distribution "B" covers angles $40^\circ$ and $80^\circ$

Representative return period versus Central Pressure values for these two conditional distributions and the resulting combined distribution for the general Darwin area are listed below in Table 5.4. These are further discussed in Section 9, comparing the current model assumptions with the previous GDSSS (1983) study assumptions for $\Delta p$.

<table>
<thead>
<tr>
<th>Minimum Central Pressure</th>
<th>Distribution &quot;A&quot; Return Period (280°, 320°, 0°)</th>
<th>Distribution &quot;B&quot; Return Period (40° and 80°)</th>
<th>Combined Darwin Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>980 hPa</td>
<td>3 years</td>
<td>7 years</td>
<td>5 years</td>
</tr>
<tr>
<td>950 hPa</td>
<td>25 yrs</td>
<td>90 yrs</td>
<td>50 yrs</td>
</tr>
<tr>
<td>920 hPa</td>
<td>230 yrs</td>
<td>3870 yrs</td>
<td>665 yrs</td>
</tr>
</tbody>
</table>
5.4 Correlations Between Parameters

The Northern Territory's Bureau of Meteorology has conducted a number of recent studies into the correlation between various cyclone parameters of interest. This follows on from similar research conducted on North Atlantic and Northwest Pacific tropical cyclones. The qualitative results of these studies have been summarised below in Table 5.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\Delta p$</th>
<th>$R_{\text{max}}$</th>
<th>$V_T$</th>
<th>$\Theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p$</td>
<td>-</td>
<td>strong</td>
<td>weak</td>
<td>moderate</td>
</tr>
<tr>
<td>$R_{\text{max}}$</td>
<td>strong</td>
<td>-</td>
<td>$?$</td>
<td>$?$</td>
</tr>
<tr>
<td>$V_T$</td>
<td>weak</td>
<td>$?$</td>
<td>-</td>
<td>$?$</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>moderate</td>
<td>$?$</td>
<td>$?$</td>
<td>-</td>
</tr>
</tbody>
</table>

- There is good evidence that storm intensity and storm size are inversely related, i.e. more intense storms tend to have a "tighter" circulation with smaller Radius of Maximum Winds values.
- Looking at all tropical cyclones affecting northerly latitudes in the Northern Territory region, the Bureau has also found a weak correlation between storm intensity and storm speed.
- It was noted in the preceding section that there appears to be a reasonable correlation in the Darwin area between storm intensity and approach direction, with the more severe tropical cyclones affecting Darwin likely to come from north and northwest quadrants.
- There are too little data to comment on the possible relationship between storm size, i.e. $R_{\text{max}}$ and translation speed or approach angle, and between storm translation speed and approach angle, although data from other cyclone regions suggests that, at low latitudes, there should be little correlation between these parameters.
In the present study, some of the above correlations have been taken into account. Others have been overlooked, primarily on the basis of too little information upon which to make a reasonable decision.

- In the present study, no correlation is assumed between storm size and intensity. In fact, only one value of Radius of Maximum Winds, $R_{\text{max}}$, was used for all the model simulation storms, viz. $R_{\text{max}} = 15$ km.

  This would appear to be a conservative value for the more severe storms which have affected Darwin, e.g. Cyclone Tracy's $R_{\text{max}}$ value was less than half this value.

- The choice of two distributions, "A" and "B", to describe the central pressure difference value of Darwin storms, $\Delta p$, has been described in the previous section.

- Finally, it was decided that too little data exists within the Darwin area cyclone set to further sub-divide any of the basic groupings, i.e. the approach angle groupings, the "A" and "B" groupings etc., into generally faster and slower storms depending upon storm intensity.

  In other words, Darwin area storms were assumed to exhibit the same variation of translation speeds regardless of approach direction and regardless of intensity.
6 STORM SURGE MODELLING

6.1 Representative Track Locations, Storm Intensities and Translation Speeds

Examination of the historical cyclone records dictated the break-up of climatological parameters of interest used to characterise cyclone behaviour (surge and wave set-up) for the region.

On the basis of the groupings discussed in the previous section sets of 300 "primary" model cyclones were run on each of the five model grids using the following variables:

- Storm Direction ...

The five (5) directions from which the primary simulation storms approached the region were:

280°, 320°, 0°, 40°, 80°

where a 0° storm approaches Darwin from the north, a 320° storm approaches Darwin approximately from the northwest etc.

- Storm Point of Closest Approach ...

For each approach direction, five (5) parallel storm tracks were chosen which passed by the simulation grid central point at varying ratios of the $R_{MAX}$ value of the storm. Positive values imply that the simulation centre point was to the LEFT of the storm centre at its point of closest approach. Since for all model storms, the $R_{MAX}$ value was taken to be 15 km, the resulting distance of minimum approach, $D_{MIN}$ values were:

-15 km, 0 km, 15 km, 30 km, 75 km for the 280°, 320°, 0° storms
-30 km, 0 km, 15 km, 30 km, 75 km for the 40° storms
-45 km, -15 km, 0 km, 15 km, 60 km for the 80° storms

The 25 combinations of five storm approach angles x five minimum approach distances for the Darwin coarse grid CG3 are shown below in Figures 6.1(a)–(e). Note that these track points were displaced accordingly for the other three basic coarse grid runs (CG1, CG2 and CG4).
Figure 6.1(a) 280° Approach Angle Storms

Figure 6.1(b) 320° Approach Angle Model Storms
Figure 6.1(c) 360° (0°) Approach Angle Model Storms

Figure 6.1(d) 40° Approach Angle Model Storms
Tropical cyclones in the Darwin area exhibit a wide range of forward motion speeds or "translation speeds". Three representative values were chosen for the primary runs.

2.0, 5.0, 8.0 m/s

It is well known that storm surge and to a lesser extent wave set-up are roughly proportional to the value of central pressure difference, Δp. Given the likely maximum possible cyclone intensities able to occur within the Darwin area, the following four (4) values of Δp were chosen to span the 300 primary simulation runs.

980, 950, 920, 890 hPa

The above combinations resulted in a total of 300 primary model runs for each one of the model grid groupings, made up of:

5 Approach Angles x 5 Minimum Approach Distances x 3 Translation Speeds x 4 Central Pressure Differences
6.2 Simulation Model Results

The results for each of the 1500 model runs have been included in Appendix B, tabulated by individual station. The bar diagrams indicate the maximum surge at each of the 18 study locations during the passage of a cyclone with the 5 approach angles, 3 forward speeds and 5 minimum distances away from the grid centre. Storm surge at intermediate minimum distance values should be interpolated linearly.

Note that, in Appendix B, only the results for the 890 hPa intensity runs have been shown in the diagrams. For the great majority of cases, the predicted storm surges at the other lower Δp values were very close to being linearly related to the Δp value, e.g. the 950 hPa storm surges are effectively half the 890 hPa storm surges etc.

The resultant storm surges for the 950 hPa, 5 m/sec forward speed group of cyclones are shown on the following page in Table 6.1. The "e" superscript indicates the approach angle which generated the largest surge for that point.

Comments on Table 6.1 ...

- Peak storm surges occur for the majority of the stations, not unsurprisingly, from storms approaching the Darwin area from the northwest (280° and 320° storms).

- For 950 hPa intensity storms moving with a translation speed of 5 m/sec, storm surges are predicted to range from as low as 1.5 metres at Point Stephens to 3.5 metres at Channel Island.

Maximum surge predictions, for all approach angles, in Darwin Harbour are in the range 2.9 to 3.5 metres.

- Locations in concave bay areas experience larger storm surges than locations in nearby but geographically "exposed" areas. For example, compare the maximum surge of 3.3 metres at Casuarina Beach (950 hPa, 280°, 5 m/s cyclone) with the comparable value of 2.4 m/sec at Lee Point.

- Stations which "face" the northwest, e.g. Fannie Bay, experience the maximum surge for storms approaching from the west (280°).

Western side internal Harbour locations, e.g. West Arm, tend to experience the maximum storm surge for storms approaching from the northwest (320°).

- The additional wave set-up component of the simulation runs ranged from around 10–15% of the storm surge for internal Harbour locations to 20–25% for exposed bay areas (e.g. Casuarina Beach).
Table 6.1
Comparison of Model Predicted Storm Surge at all Stations for a 950 hPa Cyclone, Moving at 5 m/sec, and the Cyclone's Maximum Winds Passing Directly over the Station.

<table>
<thead>
<tr>
<th>Station</th>
<th>Approach Angle (deg)</th>
<th>280°</th>
<th>320°</th>
<th>0°</th>
<th>40°</th>
<th>80°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Point Blaze</td>
<td></td>
<td>2.6</td>
<td>2.7</td>
<td>2.4</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td>2. Fog Bay</td>
<td></td>
<td>2.9</td>
<td>2.9</td>
<td>2.7</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>3. Native Point</td>
<td></td>
<td>2.9</td>
<td>2.8</td>
<td>2.5</td>
<td>2.1</td>
<td>1.4</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td></td>
<td>3.0</td>
<td>3.1</td>
<td>3.1</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td></td>
<td>2.9</td>
<td>3.0</td>
<td>2.9</td>
<td>2.7</td>
<td>2.5</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td></td>
<td>2.5</td>
<td>2.3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>7. West Point</td>
<td></td>
<td>3.0</td>
<td>2.9</td>
<td>2.5</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>8. West Arm</td>
<td></td>
<td>2.9</td>
<td>3.4</td>
<td>2.9</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>9. Channel Island</td>
<td></td>
<td>3.1</td>
<td>3.5</td>
<td>3.2</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>10. Wickham Point</td>
<td></td>
<td>3.3</td>
<td>3.3</td>
<td>3.0</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>11. East Arm PORT</td>
<td></td>
<td>2.6</td>
<td>2.9</td>
<td>2.6</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>12. Darwin South SEAWALL</td>
<td></td>
<td>3.3</td>
<td>3.2</td>
<td>3.3</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td></td>
<td>3.1</td>
<td>2.7</td>
<td>2.5</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td></td>
<td>3.3</td>
<td>2.9</td>
<td>2.6</td>
<td>2.3</td>
<td>2.1</td>
</tr>
<tr>
<td>15. Lee Point</td>
<td></td>
<td>2.4</td>
<td>2.1</td>
<td>1.9</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>16. Shoal Bay</td>
<td></td>
<td>3.3</td>
<td>2.9</td>
<td>2.7</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td></td>
<td>2.5</td>
<td>1.9</td>
<td>1.5</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td></td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Some sample graphs are shown on the following pages for the resultant surge at various sites of interest to illustrate further the variations in storm surge with approach angle, Harbour location, cyclone translation speed etc. They are:

- Figure 6.1 • Darwin South SEAWALL 320° cyclones
- Figure 6.2 • Darwin South SEAWALL 40° cyclones
- Figure 6.3 • All Harbour Sites 320° cyclones
- Figure 6.4 • Darwin South SEAWALL 890 hPa cyclones
Explanatory Notes ...

Figure 6.1: SEAWALL; Approach Angle 320°; VT = 5 m/sec

The largest surge occurs at a minimum track distance of +15 km, i.e. the cyclone passes to the south of Darwin from the northwest, so that the Radius of Maximum Winds passes almost directly over the Seawall. It can be seen that there is a linear increase in surge with decreasing central pressure, P_c (increasing central pressure difference, Δp). The surge is maintained for storms passing well to the south of Darwin, but quickly becomes negligible as the storms pass well to the north of Darwin.

Figure 6.2: SEAWALL; Approach Angle 40°; VT = 5 m/sec

These are identical storms, except that they approach Darwin from the northeast. As in the previous case, the largest storm surge occurs when the Radius of Maximum Winds is able to pass directly over the site. It can be seen however that there is still substantial surge at the Seawall over a wide range of minimum track distance. The overall values however are approximately half those of the 320° storms.

Figure 6.3: All DARWIN HARBOUR Locations;
Approach Angle 320°; VT = 5 m/sec; P_c = 950 hPa

This figure indicates that there are substantial differences across the Harbour in the storm surge experienced for particular individual storms – in this case, a 950 hPa cyclone approaching from the northwest (320°) and travelling with 5 m/sec forward speed.

The largest inter-site variations are for a minimum track distance of 0 km, i.e. when the cyclone will be moving right through centre of the Harbour, to the south of the Darwin CBD area. In this case individual sites are located at quite different locations with respect to the storm centre and will experience rapid turning of the cyclone windfield during the storm’s passage through the Harbour.

Figure 6.4: SEAWALL; Approach Angle 40°; P_c = 890 hPa

This figure shows the variation in peak storm surge with translation speed (i.e. the cyclone forward speed through the area) for 890 hPa cyclones. The important variation indicated is that the storm surge does not increase linearly with increasing translation speed, and in fact, for some particular important directions, e.g. 320° and 0°, the surge appears to peak at VT = 5 m/sec and then decreases for the higher forward speed storms.

This non-linear behaviour was most obvious for internal harbour locations. In these cases, examination of the time history of the simulation runs indicated that, as the storm translation speed increased to high values (i.e. 8 m/sec or almost 29 km/hr) there simply is not enough time for the water to build up inside the Harbour, when the initial oncoming wind near the entrance to the Harbour experiences relatively rapid variations in direction.
Greater Darwin Cyclone Storm Surge Risk
Vipac Report 24113-2
Main Report
August 1994

Location: SEA WALL
Storm Dirn. = 320 deg, Speed = 5 m/s

Figure 6.1 Storm Surge at Darwin South SEAWALL - 320° cyclones

Location: SEA WALL
Storm Dirn. = 40 deg, Speed = 5 m/s

Figure 6.2 Storm Surge at Darwin South SEAWALL - 40° cyclones

N.T. Dept. of Lands, Housing & Local Government
Location: DARWIN HARBOUR SITES
950 hPa Storm: 320 deg: 5 m/s

Figure 6.3 Storm Surge at All Harbour Sites – 320° cyclones

Peak Storm Surge vs Forward Speed
Seawall – 890 hPa cyclones

Figure 6.4 Storm Surge at Darwin South SEAWALL – 890 hPa cyclones
7 DARWIN AREA TIDES

To estimate the peak sea levels included in the present Report, existing tidal gauge data obtained from Stokes Hill Wharf were used initially to estimate tidal heights over the full astronomical cycle.

As part of the coordinating efforts involved with this study, tidal data recorded over a three month period at Mandorah Jetty in late 1993 were obtained for analysis. This data was used to derive an updated tidal height probability distribution. The probability of occurrence for each 0.1 metre increment above or below mean sea level is shown in Figure 7.1.

![DARWIN HARBOUR TIDAL PROBABILITIES](image)

Figure 7.1 Darwin Harbour Tidal Probabilities
8 DARWIN EXTREME STORM TIDE ESTIMATES

8.1 Methodology

If it is assumed that each of the meteorological parameters of interest is described by continuous probability distribution functions, the total number of event types involving any particular combination of storm intensity, forward speed, approach direction etc. will be infinite. However, the problem is considerably simplified if discrete, representative intervals are assigned across the range of possibilities for each variable.

"Joint Parameter" Probabilities ...

Discrete intervals have in fact already been defined in the previous sections spanning the likely variation over possible values in cyclone approach direction (5 angles), translation speed (3 speeds) and minimum approach distance (5 values).

The probability of occurrence for each combination of these discrete event is given by:

\[
\text{Prob} \{ \theta, V_T, D_{MIN} \} = \text{the probability of occurrence associated with cyclones with approach direction, } \theta, \text{ moving with translation speed, } V_T, \text{ and passing by the model centre point at a minimum approach distance of } D_{MIN}.
\]

In the present study, it is assumed that each one of the individual probabilities concerned is independent of the other. For example, it is assumed that the variation of storm forward speeds is the same for northwest storms as for north storms, northeast storms etc. Thus:

\[
\text{Prob} \{ \theta, V_T, D_{MIN} \} = \text{Prob} \{ \theta \} \times \text{Prob} \{ V_T \} \times \text{Prob} \{ D_{MIN} \}
\]

The discrete parameter intervals assumed in the following discussion coincide with the model parameters of the 300 "primary" simulation runs.

Storm Surge plus Wave Set-up vs Intensity ...

For each one of the 75 combinations of the "joint parameters", \( \theta - V_T - D_{MIN} \), four storm \( \Delta p \) values were utilised in the 300 "primary" model runs to determine resulting cyclone surge plus wave set-up.

From these results, the relationship between cyclone surge plus wave set-up and central pressure difference, for a given \( \theta - V_T - D_{MIN} \) combination, is generated. For convenience sake, the model surge plus wave set-up output height were initially broken up into discrete intervals of 0.1 metres.
Thus, for each cyclone surge plus cyclone wave set-up 0.1 metre interval, $\Delta S+WS_i$, there is a corresponding interval of central pressure difference, $\Delta P_i$, with an associated probability of occurrence, $\text{Prob} \{ \Delta P_i \}$, for each individual $\theta-V_I-D_{\text{MIN}}$ combination.

**Total Surge Plus Wave Set-Up Probability** ...

The total probability of surge plus wave set-up height can then be determined by summing over all "events", i.e. the 75 model "primary" runs, which result in a surge height in that interval, that is:

$$\text{Prob}\{ S+WS_i \} = \sum \text{Prob} \{ \Delta P_i : \text{given } \theta, V_I, d_{\text{MIN}} \} \cdot \text{Prob} \{ \theta, V_I, d_{\text{MIN}} \}$$

**Tidal Probability** ...

A similar procedure is adopted to include variation of tidal probability in the analysis. The tidal range is also broken up into 0.1 metre increments and the probability associated with each increment, $\text{Prob} \{ T_{ij} \}$, determined from the tidal model (see Fig.10).

**Total Storm Tide Probability** ...

The probability of occurrence for some total storm tide level, $H_c$, representing the sum of the cyclone surge and wave set-up plus tidal contribution is then simply the sum over all possible combinations of the individual components which result in that total level.

i.e. ....

$$\text{Prob} \{ H = H_c \} = \sum_N \text{Prob} \{ S+WS = S_g \} \cdot \text{Prob} \{ T_{ij} = H_c-S_g \}$$

where the sum is over the number of discrete combinations, $N$, which can combine to produce a particular height, $H_c$.

In other words, the probability of experiencing a 5.0 metre total storm tide level during the passage of a cyclone, is the sum of ...

- the probability of a 0.1 metre surge plus wave set-up + 4.9 metre tide, PLUS
- the probability of a 0.2 metre surge plus wave set-up + 4.8 metre tide, PLUS
- the probability of a 0.3 metre surge plus wave set-up + 4.7 metre tide etc. etc.

Note: This computation is identical to the problem of determining the probability of throwing a total number, "9" say, with two dice. The answer is formed by summing over all possible combinations of the dice which will add up to a "9", e.g. a "6" plus a "3", a "5" plus a "4", a "4" plus a "5" etc..
Non-Cyclone Event Probabilities ...

The above "combined storm tide" estimates, which take into account the tidal variation during the cyclone passage, only give the predicted probability level of the sea surface elevation, given a cyclone occurrence.

They do not take into account the contribution to the sea surface elevation of the tide alone when there is no cyclone event. That is, the continuous probability estimates of sea level elevation must take into account the hours during the year when a cyclone is not occurring, but when clearly the tide is occurring. This is simply a function of the probability distribution of tide alone.

Thus the final probability estimates of extreme sea level elevations, H, are computed from:

\[ \text{Prob}_{\text{TOTAL}}(H) = \lambda_{\text{TIDE}} \cdot \text{Prob}_{\text{TIDE}}(T) + \lambda_{\text{S+W+T}} \cdot \text{Prob}_{\text{S+W+T}}(S+\text{W+T}) \]

where

- \( \lambda_{\text{TIDE}} \) = probability of tide only occurring
- \( \text{Prob}_{\text{TIDE}} \) = probability distribution of astronomical tidal height alone (18.6 year cycle)
- \( \lambda_{\text{S+W+T}} \) = probability of cyclone occurring
- \( \text{Prob}_{\text{S+W+T}} \) = probability distribution of surge plus wave taking into account the influence of tide

A Note about Return Periods ...

By convention, the "return period" of an event is the period of time over which the event might be expected, on average, to occur once.

In fact statistically speaking, the "100-year" event, should be rigorously interpreted as the event which has a \( \frac{1}{100} \) (or 1%) probability of occurrence in any one year.

There is nothing stopping two "100-year" events occurring one year after another. Over a long period of time however, i.e. many thousands of years, it would be expected that this event would occur on average once every 100 years. So, for example, over a one thousand year period, the "50-year" event would be expected to have occurred approximately 20 times.

Also, it should be noted that the present study extreme estimates are based on the statistics of a relatively short historical data base of cyclone climatology. Therefore, in the following sections, the accuracy of the extremes quoted should be treated accordingly. That is, the errors associated with the 10-year extreme predictions will be less than the errors with 100-year extremes, and much less than the errors with the 1000-year extremes, and so on.
8.2 Return Period Estimates

The individual extreme value distributions for the 18 study sites have been included in Appendix C. Figure 8.1 illustrates the return period versus peak still water level results for several study stations including two key locations surveyed in this Report – Darwin South Seawall and the East Arm Port Development area.

At low return periods (several years), the predicted combined sea surface elevation is dominated by the tidal only contribution. At higher return periods, the extremes are dominated by the cyclone contribution, i.e. cyclone surge + wave set-up + tide.

The return periods vary considerably from station to station. For example, the return period for an extreme sea level elevation of 6 metres (A.H.D.) varies between 330 years at Casuarina Beach to 600 years at the SEAWALL to 1000 years at East Arm PORT and almost 3,000 years at Lee Point. Following on from the previous discussion, these return periods indicate that in any one year, the probability of occurrence of a 6.0 metre (A.H.D.) event is 0.3%, 0.17%, 0.01% and 0.003% respectively for the above four localities.

![Extreme Sea Level Estimates Diagram](Figure 8.1 Example Peak Sea Level Extreme Estimates (Cyclone Surge and Wave Set-up plus Tide))
Discrete values of interest for all sites are shown below in Table 8.1 showing the variation between the different sites.

Table 8.1
PEAK COMBINED SEA LEVEL PREDICTIONS
(metres A.H.D.)
Cyclone Storm Surge + Cyclone Wave Set-Up + Astronomical Tide

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>1. Point Blaze</td>
<td>3.9</td>
</tr>
<tr>
<td>2. Fog Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>3. Native Point</td>
<td>4.0</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td>4.0</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td>4.2</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td>3.7</td>
</tr>
<tr>
<td>7. West Point</td>
<td>4.0</td>
</tr>
<tr>
<td>8. West Arm</td>
<td>3.9</td>
</tr>
<tr>
<td>9. Channel Island</td>
<td>3.8</td>
</tr>
<tr>
<td>10. Wickham Point</td>
<td>3.8</td>
</tr>
<tr>
<td>11. East Arm PORT</td>
<td>3.7</td>
</tr>
<tr>
<td>12. Darwin South SEAWALL</td>
<td>3.8</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td>4.0</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td>4.0</td>
</tr>
<tr>
<td>15. Lee Point</td>
<td>3.6</td>
</tr>
<tr>
<td>16. Shoal Bay</td>
<td>3.9</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td>3.7</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td>3.6</td>
</tr>
</tbody>
</table>

- 100-year return period estimates (A.H.D.) vary from 4.2 metres at Point Stephens to 5.5 metres at Masson Point. The 100-year estimates within Darwin Harbour are around 5.0 metres.
Similarly, 1000 year return period values inside Darwin Harbour range between 6.0 metres and 6.4 metres. The comparable estimates for Fannie Bay and Casuarina Beach are 6.4 and 6.6 metres respectively.

In general, it was found that sites located right on coastal promontories exhibited significantly lower values than nearby adjacent coastal locations, e.g. compare Lee Point to Casuarina Beach.

Closer examination of surge predictions with additional model runs showed that this "point" characteristic leading to lower surge levels at exposed coastal locations, was because of the ability of water to "escape" either to the east or southwest along the coast as the surge was building up, as opposed to locations in bay or harbour areas, where the water tended to "pile up".

Further additional model simulation runs showed that this "point" characteristic only occurred very close to the actual promontory at the coastline.

In order to avoid the misconception that the coastal "point" estimates of this study are representative of extended segments of nearby coastline, they were re-computed and this study reports the surge predictions at locations slightly away (at least one grid point) from these exposed coastal points, with the exception of Lee Point, Point Blaze and Point Stephens. In Table 8.1, the "point" names have been retained as the locality indicator.

The reader can thus interpolate prudently (i.e. conservatively) between study locations. For Lee Point, Point Blaze and Point Stephens, it should be assumed that the Table 8.1 elevations are applicable to only a short stretch of adjacent coastline.

Locations within Darwin Harbour itself experience complex storm surge and wave set-up effects compared to open coastal locations as a result of the rapid turning of winds accompanying a cyclone passage and the confined fetch of water at interior locations for different cyclone approach directions.

For example, a storm moving directly towards Darwin from the west producing local north-northwest winds would be driving water up against Casuarina Beach. At the same time, the winds might be off-land at the proposed site of the Darwin South Seawall even though water was being generally driven into the Harbour area.

It may be noted that the 100-year cyclone return elevations at the Seawall represent conditions which would be produced by a tropical cyclone of central pressure 920 hPa approaching from the northwest with a forward speed of 5 m/sec and passing by with its Radius of Maximum Winds directly over Darwin Harbour (no tidal contribution taken into account).
9 COMPARISON WITH PREVIOUS STUDIES

The present study predictions vary somewhat from previous estimates made in the GDSSS (1983) as shown in Table 9.1 below.

Table 9.1

<table>
<thead>
<tr>
<th>Location</th>
<th>Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 years</td>
</tr>
<tr>
<td>4. Bynoe Harbour</td>
<td>5.3</td>
</tr>
<tr>
<td>5. Masson Point</td>
<td>5.5</td>
</tr>
<tr>
<td>6. Charles Point</td>
<td>4.6</td>
</tr>
<tr>
<td>7. West Point</td>
<td>5.1</td>
</tr>
<tr>
<td>8. West Arm</td>
<td>5.1</td>
</tr>
<tr>
<td>9. Channel Island</td>
<td>5.1</td>
</tr>
<tr>
<td>11. East Arm PORT</td>
<td>4.9</td>
</tr>
<tr>
<td>12. Darwin South SEAWALL</td>
<td>5.0</td>
</tr>
<tr>
<td>13. Fannie Bay</td>
<td>5.2</td>
</tr>
<tr>
<td>14. Casuarina Beach</td>
<td>5.3</td>
</tr>
<tr>
<td>16. Shoal Bay.</td>
<td>5.1</td>
</tr>
<tr>
<td>17. Gunn Point</td>
<td>4.5</td>
</tr>
<tr>
<td>18. Point Stephens</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The reasons for the variations (both up and down) between the present estimates with respect to the previous GDSSS (1983) values lie in the following two areas:

- the current deterministic storm surge model are significantly different (lower) than the GDSSS (1983) model equivalent.
- the climatological input statistical parameters (occurrence rates, cyclone intensity, forward speed etc.) vary widely in the present study.
9.1 Comparison of Storm Surge Alone Estimates

The GDSSS (1983) storm surge estimates are calculated as follows:

\[ S_{\text{MAX}} = H_0 \cdot \phi(V_T) \cdot \phi(D_{\text{min}}) \cdot \phi(\text{local}) \]  

where:

- \( S_{\text{MAX}} \) = peak storm surge
- \( H_0 \) = basic surge height, determined as a function of approach direction and central pressure of the storm, from the GDSSS Numerical Cyclone Simulation Model
- \( \phi(V_T) \) = forward speed adjustment factor
- \( \phi(D_{\text{min}}) \) = track distance adjustment factor
- \( \phi(\text{local}) \) = local amplification factor

For example, for NORTHWEST storms:

\[ \phi(V_T) = 0.90 + 0.19 \cdot V_T \]
\[ \phi(D_{\text{min}}) = 0.4 \]
\[ \phi(D_{\text{min}}) = 0.7 \]
\[ \phi(D_{\text{min}}) = 1.0 \]
\[ \phi(D_{\text{min}}) = 0.9 \]
\[ \phi(D_{\text{min}}) = 0.6 \]
\[ \phi(\text{local}) = 1.21 \]
\[ \phi(\text{local}) = 1.14 \]
\[ \phi(\text{local}) = 0.085 \]

The values of storm surge alone (no wave set-up) have been calculated at Darwin Harbour, Fannie Bay and Charles Point for a 920 hPa storm, approaching Darwin from the northwest and with a translation (forward) speed of 5 m/sec.

The GDSSS estimated surges are compared to the present study asymptotes in Table 9.2 shown on the following page.
Table 9.2
Sample Comparison of Present Study Storm Surge Predictions
With GDSSS (1983) Storm Surge Predictions
Cyclone: $P_c = 920$ hPa, Speed = 5 m/s, Approach Direction = NORTHWEST
(Note: No Wave Set-up or Tidal Contribution)

<table>
<thead>
<tr>
<th>$D_{MIN}$</th>
<th>Darwin Harbour</th>
<th>Fannie Bay</th>
<th>Charles Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $R_{max}$</td>
<td>0.3</td>
<td>2.2</td>
<td>0.9</td>
</tr>
<tr>
<td>0</td>
<td>3.3</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>$R_{max}$</td>
<td>5.9</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>2 $R_{max}$</td>
<td>4.4</td>
<td>4.9</td>
<td>5.8</td>
</tr>
<tr>
<td>5 $R_{max}$</td>
<td>1.7</td>
<td>3.3</td>
<td>3.0</td>
</tr>
</tbody>
</table>

It can be seen that:

For the northwest approaching storms ...

- the present study estimates are close to the GDSSS (1983) estimates at the maximum overall values, i.e. when the cyclone passes with its Radius of Maximum Winds directly over the site.

- the present study estimates taper off much more quickly at distances greater than one Radius of Maximum Winds value away from the site.

The same comparison was made for northeast approaching storms, and it was found that the differences in the predictions were substantial, with even the peak values typically around 80% of the comparable GDSSS (1983) estimates, and the values greater $R_{max}$ values sometimes less than 50%.

Thus, it would appear that if both simulations had used the same meteorology (i.e. same climatological probabilities), the present extreme estimates would have been significantly lower.
9.2 Climatological Comparison of Current and GDSSS (1983) Study

There are significant differences in the probabilistic representation of cyclones affecting Darwin between the GDSSS (1983) study and the present study.

Occurrence Rate ...

The break-up of cyclones affecting the Darwin areas used in the long-term extreme surge estimates in the GDSSS (1983) study are compared below to the current estimates in Table 9.3. Included as well are data received from the Darwin Bureau of Meteorology (personal communication, Nov.1993) for all tropical cyclone occurrences north of 13°S latitude and between 70°E and 160°E longitude.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>13 %</td>
<td>10 %</td>
<td>12 %</td>
</tr>
<tr>
<td>Northwest</td>
<td>15 %</td>
<td>12 %</td>
<td>10 %</td>
</tr>
<tr>
<td>North</td>
<td>27 %</td>
<td>8 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Northeast</td>
<td>45 %</td>
<td>35 %</td>
<td>29 %</td>
</tr>
<tr>
<td>East</td>
<td>-</td>
<td>35 %</td>
<td>40 %</td>
</tr>
</tbody>
</table>

The above percentages indicate a break-up for West–Northwest–North cyclones and all other cyclones of 55% and 45% respectively in the GDSSS (1983) study. This compares with a comparable break-up in the current study of 30% and 70% respectively. The GDSSS (1983) study estimates therefore appear to be biased by storms from the west around to the north.

Storms from the northwest quadrants generally produce greater storm surges in the Darwin area than storms from the northeast quadrants. Hence, the above break-up suggests that the original GDSSS (1983) simulation family of cyclones would have been weighted by more storms from the directions which produce greater storm surges, i.e. leading to higher extreme estimates.
Central Pressure ...

Figure 9.1 shows the probability distribution functions of central pressure for the GDSSS (1983) and current studies. It can be seen that up to return periods of around 5,000 years the current study distribution predicts more intense storms for a given return period compared to the GDSSS (1983) distribution. Some sample return period comparisons are made below in Table 9.4. This suggests that the current simulation would generate given intensity storms more often than in the GDSSS (1983) simulation runs.

<table>
<thead>
<tr>
<th>Minimum Central Pressure</th>
<th>GDSSS (1983) Return Period</th>
<th>Current Study Return Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>980 hPa</td>
<td>9 years</td>
<td>5 years</td>
</tr>
<tr>
<td>950 hPa</td>
<td>112 yrs</td>
<td>50 yrs</td>
</tr>
<tr>
<td>920 hPa</td>
<td>1508 yrs</td>
<td>665 yrs</td>
</tr>
</tbody>
</table>

Figure 9.1 Variation of Central Pressure with Return Period For the Current and GDSSS (1983) Studies
Cyclone Translation Speed ...

The GDSSS (1983) study assumed that there is a moderate, linear, increasing variation in peak storm surge with storm forward speed. In the present study, the variation of storm surge (and wave set-up) with storm forward speed has been found to be quite complex, and highly dependent on location and storm approach direction.

As an example, Figure 9.2 shows the variation in peak storm surge level at Fannie Bay as a function of oncoming storm direction and for the three model storm forward speeds of 2, 5 and 8 m/sec. From this and all the 1500 model cyclone runs, it was found that:

- storms approaching Darwin from northwest quadrants generally produce increasing storm surge with increasing forward speed, especially for open coast locations. This can be attributed mainly to the extra component of the cyclone windfield in the area of maximum winds produced by the storm's own forward speed.

- storms approaching Darwin from northeast quadrants generally produce their peak storm surge for a forward speed at close to 5 m/sec and then the peak surge decreases. This is especially apparent at internal Harbour locations, e.g. the Darwin South Seawall.

In the latter situation, although the general cyclone windfield exhibits increased peak winds because of the added forward speed component, there is not enough time for the surge to develop with the limited fetch conditions in internal harbour areas.

![Cyclone Peak Surge vs Forward Speed](Cyclone Peak Surge vs Forward Speed.png)

**Figure 9.2** Variation of Peak Storm Surge with Cyclone Forward Speed For the Current Study
Summary ...

The differences between the current estimates and the GDSSS (1983) estimates appear to arise from a number of sources.

Factors leading to higher peak storm surge estimates in the GDSSS (1983) study:

- The GDSSS (1983) cyclone windfield model generated overall higher surge estimates compared to the present study model, especially for storms moving past a site at distances further away than the Radius of Maximum Winds, and at all distances for northeast quadrant storms.

- The occurrence probabilities used in the GDSSS (1983) simulation were biased towards cyclones from northwest quadrants, which produce generally higher storm surges. The GDSSS (1983) probabilities do not agree with observed storm occurrences in the Darwin area.

- The GDSSS (1983) surge model assumed that, regardless of location and approach direction, peak storm surge is linearly related to storm forward speed. This has been found in the present study not to be the case, through the 1500 model cyclone surge runs which have directly determined the influence of storm forward speed on resulting surge. In some cases, especially within Darwin Harbour, the surge actually decreases for the very high forward speed cyclones, as there is insufficient time to generate the water build-up in the Harbour during the cyclone passage.

It should be repeated, that in the present study, the variation of storm surge with forward speed has not been inferred, but computed directly by utilising the three different model storm speeds in the actual 1500 model cyclone runs.

Factors leading to lower peak storm surge estimates in the GDSSS (1983) study:

- The GDSSS (1983) central pressure distribution yields lower central pressure cyclones for the same return period as the current study. The current study central pressure estimates however agree qualitatively with the occurrence rate of major cyclones affecting Darwin over the last two hundred years.

The above have resulted in variations which produced both increases and decreases in the final extreme estimates. It is believed that the present results, through the simulation of so many more model storms represents a more accurate picture of the storm tide risk in the area.
REFERENCES


Greater Darwin Cyclone Storm Surge Risk  
Main Report  

This Report has been Prepared  
for the  
NORTHERN TERRITORY  
DEPARTMENT OF LANDS, HOUSING & LOCAL GOVERNMENT  

by  
VIPAC ENGINEERS & SCIENTISTS Ltd  
SPECIAL SERVICES UNIT – Bureau of Meteorology  
GLOBAL ENVIRONMENTAL MODELLING SERVICES Pty Ltd  
ACER VAUGHAN Pty Ltd  

Peter N. Georgiou, Ph.D.  
Manager  
Vipac – N.S.W.
APPENDIX A

DARWIN REGION TROPICAL CYCLONE CHARACTERISTICS
DARWIN REGION
TROPICAL CYCLONE CHARACTERISTICS

The following is a modified version of Section 5 of Vipac Report No. 36499 [1992]. This Report was a review study of the original GDSSS storm surge study [Lawson & Treloar, 1982].

A.1 Data Sources

The following analysis of Darwin regional tropical cyclone climatological characteristics has been carried out using the following resource material:


"Summary of Tropical Cyclones Affecting the Northern Region Since 1964", Bureau of Meteorology, Darwin Office, Internal Reference Report.


The Darwin Bureau Internal Reference Report covers the tracks of cyclones up to storm season 1986/87.

The Tropical Research Group's (TRG) Cyclone Data Tape is the version used by the TRG in all research studies relating to tropical cyclones. Some track information for example has been repeated within the tape incorporating revised information from satellite, radar or ship and land observation posts providing track position corrections etc.
A.2 Selection of Historical Time Period Used for the Darwin Area Cyclone Analysis

Holland [1981] carried out an analysis on the quality of the Australian cyclone data base covering the period 1909 to 1979, coinciding with the Lourensz [1981] data base. The historical data were sub-divided into three distinct periods based on the evolution of observation and analysis systems:

- **Period 1**: 1909 - 1939
- **Period 2**: 1939 - 1959
- **Period 3**: 1959 - 1975

In the initial period, 1909-39, there was a gradual increase in the coverage around the Australian coastline of surface observations. With the outbreak of war in 1939, there was a marked increase in observations of tropical cyclones particularly in the northern regions. During this second period, 1939-59, the number of ad hoc ship and flight observations grew constantly and was coupled, not uncoincidentally, by a move to the tropics by many meteorologists.

The next changes in observation mode came with the installation of weather-watch radar in cyclone areas and the arrival of satellite coverage of the Australian continent. A "277" 5cm weather-watch radar became operational in Darwin in October 1958 and the first satellite observations of an Australian tropical cyclone began in April 1960 (TIROS I).

Table A.1 taken from the Holland analysis gives the variation in annual tropical cyclones occurrence for three broad Australian cyclone areas, including a "northern" area covering the Darwin region.

<table>
<thead>
<tr>
<th>REGION</th>
<th>West of 130°E</th>
<th>130° - 142°E</th>
<th>East of 142°E</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERIOD</td>
<td>Mean</td>
<td>S.Dev.</td>
<td>Mean</td>
</tr>
<tr>
<td>1909 - 1939</td>
<td>1.1</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>1939 - 1959</td>
<td>1.8</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>1959 - 1975</td>
<td>2.5</td>
<td>1.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Figures A.1(a) and A.1(b), also taken from Holland, show the points of origin of tropical cyclones for two periods, 1909–49 and 1949–75, respectively. These data show a dramatic post-war increase in the number of recorded occurrences of tropical cyclones in the northern central Australian region.

- It is clear that a significant amount of tropical cyclone activity surrounding Darwin (particularly offshore) was missed prior to the advent of radar and satellite coverage in the area – hence the restriction enforced by the Bureau's Tropical Research Group on the time period of the cyclone data tape used for research purposes.

- The same conclusion was reached by Lourensz [1981] who recommended that the cyclone data included in his report could only be considered accurate enough for scientific use starting in the cyclone season 1959/60, coinciding with a combination of radar, aircraft data and satellite imagery.

In view of the above ...

- the current analysis of cyclone statistical behaviour has been restricted to the years covered in the TRG data tape, i.e. the 34–year period spanning the cyclone seasons 1957/58 to 1989/90.

- Climatological data contained in Refs.5–1,3,4 were also used to identify storm characteristics recorded during this period.
Figure A.1 Points of Origin of Tropical Cyclones (taken from Holland [1981])
(a) 1909–1949  (b) 1949–1975
A.3 Geographical Area of Influence for Darwin Regional Cyclones

While peak storm surge effects are normally limited to around a hundred kilometres either side of a tropical cyclone centre (depending upon storm orientation), winds and wave effects can extend much further.

With this in mind, it was decided to begin the present analysis of cyclone meteorological characteristics using the data base of all tropical cyclones passing within a circle of radius 300 km around Darwin. This is a relatively large area and represents a compromise between the following needs:

- To model each of the cyclone parameters of interest it is necessary to include an area large enough to yield a statistically adequate sample for fitting purposes.
- The sampling area cannot be so large that significant climatological differences in tropical cyclone activity are absorbed within the sampling area.

Table A.2 presents information on the characteristics of the forty-four (44) tropical cyclones passing within 300 km of Darwin in the period 1957/58 to 1989/90, representing a total of 33 cyclone seasons. Table A.2 includes the cyclone name, date at the time when the storm was at its closest point to Darwin and representative cyclone parameters - storm direction of motion, minimum distance to Darwin, translation speed and central pressure.

Notes Regarding Table A.2 ...

- Unnamed storms are numbered U.1, U.2 etc..
- The storm direction, speed, and intensity values were taken as those exhibited during the approximately 6-hour period when the cyclone was closest to Darwin.
- Three cyclones do not have a representative storm direction value and are noted as "REC." - these were storms which had double recurving tracks near their closest approach to Darwin and therefore could not be characterised as having a single representative storm direction when passing Darwin.
- The minimum distance value of each cyclone was defined as positive or negative depending on whether Darwin was to the right or left of the storm respectively looking in the direction of storm motion when the cyclone was closest to Darwin.

The 44 data cyclones have also been plotted in Figures 2(a)–(e), sub-divided on the basis of their general direction of motion.
### Table A.2
**Tropical Cyclones Passing Within 300km of Darwin in the Period 1957/58 – 1989/90**

<table>
<thead>
<tr>
<th>Name</th>
<th>Date at Time of Closest Approach</th>
<th>Storm Direction (deg.)</th>
<th>Minimum Distance (kms)</th>
<th>Translation Speed (m/sec)</th>
<th>Minimum Central Pressure (mbars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.1</td>
<td>14 Jan. 1959</td>
<td>270</td>
<td>170</td>
<td>4.3</td>
<td>1004</td>
</tr>
<tr>
<td>U.2</td>
<td>10 Jan. 1959</td>
<td>110</td>
<td>-290</td>
<td>6.5</td>
<td>995</td>
</tr>
<tr>
<td>U.3</td>
<td>4 Apr. 1959</td>
<td>190</td>
<td>-80</td>
<td>3.1</td>
<td>992</td>
</tr>
<tr>
<td>U.4</td>
<td>24 Dec. 1959</td>
<td>90</td>
<td>n.a.</td>
<td>6.5</td>
<td>992</td>
</tr>
<tr>
<td>U.5</td>
<td>22 Mar. 1960</td>
<td>280</td>
<td>60</td>
<td>7.0</td>
<td>999</td>
</tr>
<tr>
<td>U.6</td>
<td>16 Jan. 1961</td>
<td>260</td>
<td>-270</td>
<td>4.9</td>
<td>998</td>
</tr>
<tr>
<td>U.7</td>
<td>27 Jan. 1962</td>
<td>220</td>
<td>n.a.</td>
<td>1.3</td>
<td>998</td>
</tr>
<tr>
<td>U.8</td>
<td>14 Apr. 1963</td>
<td>&quot;REC.&quot;</td>
<td>-260</td>
<td>2.4</td>
<td>997</td>
</tr>
<tr>
<td>Carmen</td>
<td>8 Mar. 1964</td>
<td>210</td>
<td>-60</td>
<td>3.3</td>
<td>996</td>
</tr>
<tr>
<td>Katie</td>
<td>24 Mar. 1964</td>
<td>260</td>
<td>n.a.</td>
<td>4.5</td>
<td>1003</td>
</tr>
<tr>
<td>Flora</td>
<td>2 Dec. 1964</td>
<td>180</td>
<td>80</td>
<td>2.9</td>
<td>996</td>
</tr>
<tr>
<td>Judy</td>
<td>25 Jan. 1965</td>
<td>170</td>
<td>240</td>
<td>7.3</td>
<td>1002</td>
</tr>
<tr>
<td>Marie</td>
<td>28 Feb. 1965</td>
<td>220</td>
<td>50</td>
<td>3.8</td>
<td>998</td>
</tr>
<tr>
<td>Ruth</td>
<td>24 Mar. 1965</td>
<td>240</td>
<td>-280</td>
<td>1.9</td>
<td>1001</td>
</tr>
<tr>
<td>Amanda</td>
<td>28 Dec. 1965</td>
<td>230</td>
<td>60</td>
<td>3.1</td>
<td>997</td>
</tr>
<tr>
<td>Betty</td>
<td>10 Feb. 1966</td>
<td>270</td>
<td>120</td>
<td>3.6</td>
<td>998</td>
</tr>
<tr>
<td>Bertha</td>
<td>20 Jan. 1968</td>
<td>230</td>
<td>0</td>
<td>3.8</td>
<td>997</td>
</tr>
<tr>
<td>Bonnie</td>
<td>23 Feb. 1968</td>
<td>250</td>
<td>220</td>
<td>1.7</td>
<td>1003</td>
</tr>
<tr>
<td>Audrey</td>
<td>4 Mar. 1969</td>
<td>240</td>
<td>90</td>
<td>5.2</td>
<td>994</td>
</tr>
<tr>
<td>Glynis</td>
<td>26 Jan. 1970</td>
<td>250</td>
<td>90</td>
<td>4.1</td>
<td>1000</td>
</tr>
<tr>
<td>Beverley</td>
<td>1 Dec. 1970</td>
<td>260</td>
<td>-100</td>
<td>2.7</td>
<td>998</td>
</tr>
<tr>
<td>Kitty</td>
<td>5 Dec. 1971</td>
<td>240</td>
<td>-100</td>
<td>3.9</td>
<td>1000</td>
</tr>
</tbody>
</table>
### Table A.2 (contd.)

Tropical Cyclones Passing Within 300km of Darwin in the Period 1957/58 – 1989/90

<table>
<thead>
<tr>
<th>Name</th>
<th>Date at Time of Closest Approach</th>
<th>Storm Direction (deg.)</th>
<th>Minimum Distance (kms)</th>
<th>Translation Speed (m/sec)</th>
<th>Minimum Central Pressure (mbars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madge</td>
<td>6 Mar. 1973</td>
<td>250</td>
<td>180</td>
<td>4.9</td>
<td>995</td>
</tr>
<tr>
<td>Ines</td>
<td>19 Nov. 1973</td>
<td>260</td>
<td>-160</td>
<td>2.8</td>
<td>993</td>
</tr>
<tr>
<td>Jenny</td>
<td>19 Mar. 1974</td>
<td>270</td>
<td>120</td>
<td>1.4</td>
<td>995</td>
</tr>
<tr>
<td>Selma</td>
<td>3 Dec. 1974</td>
<td>&quot;REC.&quot;</td>
<td>80</td>
<td>2.8</td>
<td>980</td>
</tr>
<tr>
<td>Tracy</td>
<td>24 Dec. 1974</td>
<td>120</td>
<td>0</td>
<td>1.9</td>
<td>950</td>
</tr>
<tr>
<td>Wilma</td>
<td>13 Mar. 1975</td>
<td>230</td>
<td>-150</td>
<td>3.0</td>
<td>985</td>
</tr>
<tr>
<td>Amelia1</td>
<td>8 Apr. 1975</td>
<td>200</td>
<td>n.a.</td>
<td>3.7</td>
<td>990</td>
</tr>
<tr>
<td>Joan</td>
<td>30 Nov. 1975</td>
<td>210</td>
<td>-290</td>
<td>0.8</td>
<td>997</td>
</tr>
<tr>
<td>Linda</td>
<td>17 Mar. 1976</td>
<td>90</td>
<td>n.a.</td>
<td>7.0</td>
<td>1000</td>
</tr>
<tr>
<td>Verna</td>
<td>2 May 1977</td>
<td>&quot;REC.&quot;</td>
<td>200</td>
<td>2.2</td>
<td>997</td>
</tr>
<tr>
<td>Trudy</td>
<td>10 Jan. 1978</td>
<td>270</td>
<td>n.a.</td>
<td>10.0</td>
<td>1003</td>
</tr>
<tr>
<td>Brian</td>
<td>18 Jan. 1980</td>
<td>220</td>
<td>-180</td>
<td>6.7</td>
<td>1001</td>
</tr>
<tr>
<td>Dean</td>
<td>27 Jan. 1980</td>
<td>230</td>
<td>-250</td>
<td>2.2</td>
<td>999</td>
</tr>
<tr>
<td>Doris</td>
<td>20 Mar. 1980</td>
<td>260</td>
<td>110</td>
<td>7.5</td>
<td>1003</td>
</tr>
<tr>
<td>Max</td>
<td>11 Mar. 1981</td>
<td>250</td>
<td>-20</td>
<td>3.9</td>
<td>990</td>
</tr>
<tr>
<td>Amelia2</td>
<td>3 Dec. 1981</td>
<td>270</td>
<td>-50</td>
<td>5.6</td>
<td>999</td>
</tr>
<tr>
<td>Bruno</td>
<td>15 Jan. 1982</td>
<td>250</td>
<td>100</td>
<td>5.6</td>
<td>993</td>
</tr>
<tr>
<td>Ferdinand</td>
<td>2 Mar. 1984</td>
<td>90</td>
<td>80</td>
<td>2.7</td>
<td>1002</td>
</tr>
<tr>
<td>Hubert</td>
<td>10 Feb. 1985</td>
<td>270</td>
<td>n.a.</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td>Gretel</td>
<td>13 Apr. 1985</td>
<td>230</td>
<td>-20</td>
<td>3.5</td>
<td>984</td>
</tr>
<tr>
<td>Kay</td>
<td>10 Apr. 1987</td>
<td>270</td>
<td>-140</td>
<td>5.2</td>
<td>994</td>
</tr>
</tbody>
</table>
Figure A.2(a) North-East Cyclones: NE-1

Jean (1975)
Dean (1980)
Ruth (1965)
Ky (1997)
Ines (1973)
Kitty (1971)
Ul6 (1961)

DARWIN

Betty (1966)
Max (1981)
Bartha (1969)
U.9 (1981)
Audrey (1969)
U.S (1960)

Madge (1973)
Doris (1980)
Jenny (1968)

Bruno (1982)
U.I (1989)
Donnie (1968)

Amelia2 (1981)
Amanda (1981)

Bonnie (1968)
Jenny (1974)
Madge (1980)
Bruno (1982)
Audrey (1969)
Betty (1966)
Max (1981)
Bartha (1969)
U.9 (1981)

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Figure A.2(b) North-East Cyclones: NE-2
(1957/58 - 1989/90)
Figure A.2(c) North-East Cyclones: NE-3
(1957/58 - 1989/90)
Figure A.2(d) West Cyclones: W
(1957/58 - 1989/90)
Figure A.2(e) "Recurving" Cyclones: REC (1957/58 – 1989/90)
North-East Cyclones: NE-1 Fig.A.2(a)  No. of Cyclones = 23

These storms, termed "NE-1" cyclones, generally move in a southwest to westerly direction at the time of their closest approach to Darwin. There are slightly more storms which pass to the right of Darwin (looking in the direction of motion), i.e. on the ocean side, than to the left. The NE-1 cyclones do not exhibit significant changes in their direction of motion as they pass close to the Darwin area.

North-East Cyclones: NE-2 Fig.A.2(b)  No. of Cyclones = 5

The "NE-2" cyclones have the same general direction as the previous group but formed over water to the west of Darwin and immediately moved away from the Darwin area having minimal impact on Darwin itself.

North-East Cyclones: NE-3 Fig.A.2(c)  No. of Cyclones = 6

The "NE-3" cyclones typically have the same initial general direction as the previous groups but all exhibit a marked southward curvature at about the time they cross a latitude level with Darwin. Their track directions at the time they are closest to Darwin are typically south to south-west.

West Cyclones: W Fig.A.2(d)  No. of Cyclones = 4

The "W" cyclones move in an almost straight eastward direction. Two of these storms had minimal effect on Darwin – Cyclone U.4 (1959) formed well to the east of Darwin, while Cyclone U.2 (1959) just managed to pass within 300 km of Darwin and has been included mainly for completeness sake.

"Recurving" Cyclones: REC Fig.A.2(e)  No. of Cyclones = 6

This last important group of storms is made up of two sub-groups: normal recurving cyclones such as Cyclone Tracy (1974) which typically begin in a southwesterly direction and end up moving southeastwards, and double recurving cyclones, of which there are two striking examples, Cyclones Selma (1974) and Verna (1977).
A.4 Occurrence Characteristics for Darwin Area Tropical Cyclones

From the above data, it can be seen that cyclone activity ranged from years of no cyclone occurrence (1966/67, 1978/79, 1982/83, 1985/86, 1987/88–1989/90) to two instances when four cyclones were recorded in the same season (1964/65 and 1974/75).

Some of the 44 data cyclones in this set were too far away to cause significant wind, wave or surge effects in Darwin itself. Others such as the NE-2 category storms have had minimal impact on the historical cyclone effects seen in the Darwin area.

However, the basis of the joint probability approach is to reproduce as exactly as possible the whole climatology of cyclones in any given area, not just the most severe events. As long as the corresponding probabilities of occurrence for the less severe events are maintained at the correct levels, the final extreme predictions will be reliable.

Table A.3 shows the occurrence months, November to May, taken on the day when each of the 44 data cyclones was closest to Darwin. Two (2) cyclones were registered in November (Ines–1973, Joan–1975) and one (1) in May (Verna–1977), with the remainder (41 cyclones out of the 44 total) falling in the period December to April. The monthly occurrence data, also shown in Figure A.3 exhibit a striking drop off in cyclone activity during the month of February with two strong peaks in cyclone activity in December–January and March.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. Storms</th>
<th>Storm Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>November</td>
<td>2</td>
<td>Ines, Joan</td>
</tr>
<tr>
<td>December</td>
<td>9</td>
<td>U.4, Flora, Amanda, Beverley, Kitty, Selma, Tracy, Amelia2, U.9</td>
</tr>
<tr>
<td>January</td>
<td>11</td>
<td>U.1, U.2, U.6, U.7, Judy, Bertha, Glynis, Trudy, Brian, Dean, Bruno</td>
</tr>
<tr>
<td>February</td>
<td>4</td>
<td>Marie, Betty, Bonny, Hubert</td>
</tr>
<tr>
<td>March</td>
<td>12</td>
<td>U.5, Carmen, Katie, Ruth, Audrey, Madge, Jenny, Wilma, Linda, Doris, Max, Ferdinand</td>
</tr>
<tr>
<td>April</td>
<td>5</td>
<td>U.3, U.8, Amelia1, Gretel, Kay</td>
</tr>
<tr>
<td>May</td>
<td>1</td>
<td>Verna</td>
</tr>
</tbody>
</table>
Figure A.3 Darwin Cyclone Monthly Occurrence
(1957/58 - 1989/90)
The probability density function of cyclone occurrence is well fitted by a non-homogeneous Poisson Distribution, given by:

\[ f(x) = \lambda(t)^x \frac{\exp[-\lambda(t)]}{x!} \quad x=0,1,2,... \]

where the usual Poisson constant, \( \lambda \), the average annual occurrence value, can be represented instead by a deterministic function of time, \( \lambda(t) \), sometimes referred to as an intensity function. This can be Fourier fitted to accommodate the observed cyclic nature of cyclone occurrence within each season.

However, if the monthly occurrence variations are not of importance, the Poisson Distribution can be used with the constant annual occurrence rate, \( \lambda \).

### A.4 Minimum Central Pressure for Darwin Area Tropical Cyclones

The minimum central pressure is a key parameter in establishing the overall magnitude of the windfield strength in a tropical cyclone and hence significantly influences the resulting storm surge and wave set-up.

Figure A.4 shows the distribution of minimum central pressure of the 44 data cyclones. The "outlier" nature of Cyclone Tracy's minimum central pressure of 950 mb is evident against the body of data which is tightly grouped around the average value of 996 mbars.

The probability distribution describing all the available cyclone pressure data (a larger and more reliable data set) can be converted to an annual distribution predictor if the set of all minimum central pressures (regardless of when they occurred) is firstly fitted by a marginal distribution function, \( F_p \), and then converted to a (time related) total distribution function, \( F_\lambda \), by incorporating the annual frequency of cyclone occurrence, \( F_\lambda \), as follows:

\[ F_\lambda(value < p_c \text{, within period } T) = \frac{F_p(value < p \text{ given cyclone occurrence })}{F_\lambda(cyclone occurrence within period } T) \]

Figure A.5(a) shows the cyclone data set minimum central pressure, \( C_p \), values plotted assuming a Type I Extreme-Value Distribution variation. The best line fit is also included in the figure. The data have been plotted again in Figure A.5(b) using a scaling which would produce a linear fit in the data if the central pressure difference, \( \Delta p \), defined as \((1011-C_p)\) mbar, followed a Weibull Distribution.
Figure A.4 Darwin Cyclone Central Pressures
(1957/58 - 1989/90)
Figure A.5 Darwin Cyclone Central Pressures
(a) Type I Fit (b) Weibull Fit
In both cases a straight line fit to the data is made difficult by the presence of the Cyclone Tracy (1974) value, although the Weibull form appears to give a better fit than the Type I form.

The outstanding problem remains how to weight the best fit line with the Cyclone Tracy 950 mb value.

The outrider nature of Tracy's pressure value raises the possibility that the observed central pressure data may belong to more than one parent distribution of values. Although the suggested subdivision into "locally or remotely generated" storms does not have an obvious geographical basis, the idea itself bears examination.

It might be recalled that all three storms which have devastated Darwin in the last 100 years had southeasterly paths, approaching Darwin from the northwest.

To examine this hypothesis, all cyclones which had a minimum central pressure less than or equal to 985 mb at any track point within a 300 km radius circle around Darwin were separated out from the full cyclone data set. The eight (8) cyclones so chosen are indicated in Table A.4.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date at Time of Closest Approach</th>
<th>Storm Direction at Closest Approach (deg.)</th>
<th>Cyclone Direction Group</th>
<th>Translation Speed (m/sec)</th>
<th>Central Pressure (mbars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.4</td>
<td>24 Dec. 1959</td>
<td>90</td>
<td>&quot;W&quot;</td>
<td>6.5</td>
<td>985</td>
</tr>
<tr>
<td>Ines</td>
<td>19 Nov. 1973</td>
<td>260</td>
<td>&quot;NE-1&quot;</td>
<td>2.8</td>
<td>985</td>
</tr>
<tr>
<td>Selma</td>
<td>3 Dec. 1974</td>
<td>&quot;Rev.&quot;</td>
<td>&quot;DR&quot;</td>
<td>2.8</td>
<td>980</td>
</tr>
<tr>
<td>Tracy</td>
<td>24 Dec. 1974</td>
<td>120</td>
<td>&quot;FR&quot;</td>
<td>1.9</td>
<td>950</td>
</tr>
<tr>
<td>Wilma</td>
<td>13 Mar. 1975</td>
<td>230</td>
<td>&quot;NE-3&quot;</td>
<td>3.0</td>
<td>985</td>
</tr>
<tr>
<td>Verna</td>
<td>2 May 1977</td>
<td>&quot;Rev.&quot;</td>
<td>&quot;DR&quot;</td>
<td>2.2</td>
<td>985</td>
</tr>
<tr>
<td>Max</td>
<td>11 Mar. 1981</td>
<td>250</td>
<td>&quot;NE-1&quot;</td>
<td>3.9</td>
<td>980</td>
</tr>
<tr>
<td>Gretel</td>
<td>13 Apr. 1985</td>
<td>230</td>
<td>&quot;NE-3&quot;</td>
<td>3.5</td>
<td>984</td>
</tr>
</tbody>
</table>
This is not a large sample from which to make predictions with statistical confidence. However, it is noted that for these 8 severe tropical cyclones:

- They either occurred early or late in their respective cyclone seasons (no occurrences in January or February),
- They exhibited lesser translation speeds than the total cyclone data set – a mean value of 3.4 m/s versus 4.2 m/s for the remaining storms, and
- The direction of motion of the severe storms does not reflect the overall patterns seen for the total data set. In particular, half the severe storms fall into non-Northeast categories, e.g. West storms or Recurving storms, as opposed to less than one quarter (23%) for the total data set.

The key meteorological/geophysical data which may have produced these anomalies include:

- the location of Darwin and the NT coastline shape relative to the favoured areas of tropical cyclone genesis,
- monsoonal and environmental steering current variations,
- sea-surface temperature variations, and
- El-Nino effects.

### A.5 Translation Speed for Darwin Area Tropical Cyclones

Figure A.6 shows the distribution of cyclone translation speeds for the Darwin area cyclones. The distribution is positively skewed with an average value of 4.1 m/s (14.8 kph) and a standard deviation of 2.0 m/s (7.2 kph).

Suitable functions which have been found to model translation speeds well in most tropical cyclone regions include the log-normal and gamma functions.
Figure A.6 Darwin Cyclone Translation Speeds
(1957/58 – 1989/90)
A.6 Direction of Motion for Darwin Area Tropical Cyclones

Figure A.7 shows the distribution of tropical cyclone direction of motion during the time when each cyclone was closest to Darwin. Cyclones Selma (1974) and Verna (1977) have not been included because of their double recurving storm paths.

The distinction between two separate groups of infrequent easterly and southeasterly moving storms and the large group of south to westerly moving storms is clearly seen. The distribution of the latter group exhibits a strong negative skewness about its own mean value of 240° (west-southwest).

The storm direction data shown in Fig.A.7 are amenable to modelling by a number of asymmetric analytical distributions such as the gamma and beta functions which would then allow for the full spectrum of storm paths to be defined.

A.7 Minimum Distance to Darwin at Closest Approach

Rather than needing to define the occurrence of landfall to couple with the storm direction parameter, it is convenient to define a "minimum distance" parameter which is the perpendicular distance from the track to Darwin at the point of closest approach. Thus a given paired value of storm direction and storm minimum distance parameters completely define a cyclone track.

Figure A.8 shows the "minimum distance" parameter from each cyclone centre to Darwin at the time of closest approach for the three North-East Cyclones groups (38 storms). Positive and negative values are interpreted as Darwin being to the right and left of the track (as seen in the direction of motion) respectively as the storm is passing Darwin at its closest point.

The mean of these minimum distance values is approximately -30 km, indicating that, of the North-East Cyclone group, somewhat more storms pass to the right of Darwin, i.e. with the cyclone over open water, than to the left of Darwin (with an overland cyclone trajectory).

The other cyclone groupings (West Cyclones, Recurving Cyclones etc.) are too few to fit with an analytical model. However they suggest that there is an easterly bias to these storms, i.e. more cyclones making landfall to the east of Darwin than to the west when they approach from the west and northwest.
Figure A.7 Darwin Cyclone Direction of Motion
(1957/58 – 1989/90)
Figure A.8 Darwin Cyclone Minimum Approach Distance
(1957/58 – 1989/90)
APPENDIX B

STATION STORM SURGE PLUS WAVE SET-UP RESULTS
STORM SURGE MODEL PREDICTIONS

1. Point Blaze: 280 deg. 890 hPa

- Minimum Approach Distance (km)
  - VT = 2 m/s
  - VT = 5 m/s
  - VT = 8 m/s

Storm Surge (m)
STORM SURGE MODEL PREDICTIONS

1. Point Blaze: 320 deg. 890 hPa

![Bar chart showing storm surge predictions with minimum approach distance in km and wind speeds of 2, 5, and 8 m/s.](image)
STORM SURGE MODEL PREDICTIONS

1. Point Blaze: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
1. Point Blaze: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

1. Point Blaze: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

2. Fog Bay: 280 deg. 890 hPa

Minimum Approach Distance (km) vs. Storm Surge (m) for different wind speeds:
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

2. Fog Bay: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s

VT = 5 m/s

VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

2. Fog Bay: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

2. Fog Bay: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

-30 0 15 30 75

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

2. Fog Bay: 80 deg. 890 hPa

![Storm Surge Model Predictions Diagram]

- Minimum Approach Distance (km)
- Storm Surge (m)
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

3. Native Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

<table>
<thead>
<tr>
<th>VT = 2 m/s</th>
<th>VT = 5 m/s</th>
<th>VT = 8 m/s</th>
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</thead>
<tbody>
<tr>
<td>-15</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
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<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- VT = Wind Speed
STORM SURGE MODEL PREDICTIONS

3. Native Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
3. Native Point: 0 deg. 890 hPa

STORM SURGE MODEL PREDICTIONS

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

3. Native Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

3. Native Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

4. Bynoe Harbour: 280 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>VT = 2 m/s</th>
<th>VT = 5 m/s</th>
<th>VT = 8 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15</td>
<td></td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>0</td>
<td>2.0</td>
<td>3.0</td>
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</tr>
<tr>
<td>15</td>
<td>3.5</td>
<td>5.0</td>
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<tr>
<td>30</td>
<td>4.0</td>
<td>5.5</td>
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</tr>
<tr>
<td>75</td>
<td>4.5</td>
<td>6.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>
STORM SURGE MODEL PREDICTIONS
4. Bynoe Harbour: 320 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>Storm Surge (m)</th>
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<tbody>
<tr>
<td>0.0</td>
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<tr>
<td>2.0</td>
</tr>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>6.0</td>
</tr>
</tbody>
</table>

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

4. Bynoe Harbour: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

4. Bynoe Harbour: 40 deg. 890 hPa

Minimum Approach Distance (km) vs. Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

4. Bynoe Harbour: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

5. Masson Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

-15 0 15 30 75

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
5. Masson Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

5. Masson Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

5. Masson Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

5. Masson Point: 80 deg. 890 hPa
STORM SURGE MODEL PREDICTIONS

6. Charles Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s, VT = 5 m/s, VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

6. Charles Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
6. Charles Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s VT = 5 m/s VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
6. Charles Point: 80 deg. 890 hPa

![Bar graph showing storm surge predictions for Charles Point with different wind speeds.](image-url)
STORM SURGE MODEL PREDICTIONS

7. West Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

7. West Point: 320 deg. 890 hPa

Minimum Approach Distance (km) vs. Storm Surge (m):
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
7. West Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
7. West Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

7. West Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

8. West Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
8. West Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

-15  0   15  30  75

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

8. West Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

8. West Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s

Storm Surge (m)
STORM SURGE MODEL PREDICTIONS
8. West Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

9. Channel Island: 280 deg. 890 hPa

- Minimum Approach Distance (km)
  - VT = 2 m/s
  - VT = 5 m/s
  - VT = 8 m/s

- Storm Surge (m)
  - Values range from 0 to 8 m
STORM SURGE MODEL PREDICTIONS

9. Channel Island: 320 deg. 890 hPa

- Minimum Approach Distance (km)
- Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

9. Channel Island: 0 deg. 890 hPa

Storm Surge Model Predictions:

- Channel Island: 0 deg.
- Pressure: 890 hPa

Graph showing storm surge predictions for different velocity thresholds (VT) and minimum approach distances (km):

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s

The graph illustrates the storm surge heights in meters (m) at various minimum approach distances (km). The data points are color-coded to represent different wind velocities.
STORM SURGE MODEL PREDICTIONS

9. Channel Island: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
9. Channel Island: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
10. Wickham Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>VT (m/s)</th>
<th>-15</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
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<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
STORM SURGE MODEL PREDICTIONS

10. Wickham Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

10. Wickham Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
10. Wickham Point: 40 deg. 890 hPa

![Graph showing storm surge predictions for different wind speeds and minimum approach distances. The graph indicates the maximum storm surge heights (in meters) at various distances (in kilometers) from the coastline. The wind speeds considered are 2 m/s, 5 m/s, and 8 m/s. The graph shows the surge height increasing with distance from the coastline and higher wind speeds.]
STORM SURGE MODEL PREDICTIONS
10. Wickham Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

11. East Arm PORT: 320 deg. 890 hPa

Minimum Approach Distance (km)

-15 0 15 30 75

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
11. East Arm PORT: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
11. East Arm PORT: 40 deg. 890 hPa

- Minimum Approach Distance (km)
- Storm Surge (m)
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s

Graph showing storm surge predictions for different wind speeds and minimum approach distances.
STORM SURGE MODEL PREDICTIONS
11. East Arm PORT: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
12. Dar. Sth SEAWALL: 280 deg. 890 hPa

Minimum Approach Distance (km)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

12. Dar.Sth SEAWALL: 320 deg. 890 hPa

Minimum Approach Distance (km)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
12. Dar.Ssth SEAWALL: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
12. Dar.Sth SEAWALL: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
12. Dar.Sth SEAWALL: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
13. Fannie Bay: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
13. Fannie Bay: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

13. Fannie Bay: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

13. Fannie Bay: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
14. Casuarina Beach: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
14. Casuarina Beach: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
14. Casuarina Beach: 0 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>VT</th>
<th>Storm Surge (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m/s</td>
<td>15</td>
</tr>
<tr>
<td>5 m/s</td>
<td>15</td>
</tr>
<tr>
<td>8 m/s</td>
<td>15</td>
</tr>
</tbody>
</table>

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
14. Casuarina Beach: 40 deg. 890 hPa

The diagram illustrates storm surge model predictions for Casuarina Beach at 40 degrees latitude and 890 hPa pressure. The graph shows the minimum approach distance (km) on the x-axis and storm surge (m) on the y-axis. Three wind speed scenarios are represented: VT = 2 m/s, VT = 5 m/s, and VT = 8 m/s.
STORM SURGE MODEL PREDICTIONS
14. Casuarina Beach: 80 deg. 890 hPa

Minimum Approach Distance (km)

-45 -15 0 15 60

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

15. Lee Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s

Storm Surge (m)
STORM SURGE MODEL PREDICTIONS

15. Lee Point: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

15. Lee Point: 0 deg. 890 hPa

![Storm Surge Model Predictions Graph]

- Minimum Approach Distance (km)
- Storm Surge (m)

Legend:
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

15. Lee Point: 40 deg. 890 hPa

<table>
<thead>
<tr>
<th>Minimum Approach Distance (km)</th>
<th>Storm Surge (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>VT = 2 m/s</td>
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<tr>
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<td>VT = 5 m/s</td>
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<tr>
<td>15</td>
<td>VT = 8 m/s</td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
</tr>
</tbody>
</table>

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

15. Lee Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

16. Shoal Bay: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
16. Shoal Bay: 320 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>VT = 2 m/s</th>
<th>VT = 5 m/s</th>
<th>VT = 8 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15</td>
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<tr>
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</tbody>
</table>
STORM SURGE MODEL PREDICTIONS

16. Shoal Bay: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

-15 0 15 30 75

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

16. Shoal Bay: 40 deg. 890 hPa

Minimum Approach Distance (km)

-30  0   15  30  75

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
16. Shoal Bay: 80 deg. 890 hPa

Minimum Approach Distance (km)

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
17. Gunn Point: 280 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
17. Gunn Point: 0 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
17. Gunn Point: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

- Graph showing storm surge predictions at different minimum approach distances.
- Three different wind speeds (VT) are represented: 2 m/s, 5 m/s, and 8 m/s.
- The vertical axis represents storm surge in meters, ranging from 0 to 8 m.
- The horizontal axis represents minimum approach distances in kilometers, ranging from -30 to 75 km.
STORM SURGE MODEL PREDICTIONS

17. Gunn Point: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
18. Point Stephens: 280 deg. 890 hPa

Minimum Approach Distance (km)

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>VT = 2 m/s</th>
<th>VT = 5 m/s</th>
<th>VT = 8 m/s</th>
</tr>
</thead>
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<td>75</td>
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<td></td>
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</tr>
</tbody>
</table>
STORM SURGE MODEL PREDICTIONS
18. Point Stephens: 320 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

<table>
<thead>
<tr>
<th>VT = 2 m/s</th>
<th>VT = 5 m/s</th>
<th>VT = 8 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-15</td>
<td>0</td>
</tr>
</tbody>
</table>

VT = 2 m/s  VT = 5 m/s  VT = 8 m/s
STORM SURGE MODEL PREDICTIONS
18. Point Stephens: 0 deg. 890 hPa

Minimum Approach Distance (km) vs. Storm Surge (m) for different wind speeds:
- VT = 2 m/s
- VT = 5 m/s
- VT = 8 m/s
STORM SURGE MODEL PREDICTIONS

18. Point Stephens: 40 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s □
VT = 5 m/s □
VT = 8 m/s □
STORM SURGE MODEL PREDICTIONS
18. Point Stephens: 80 deg. 890 hPa

Minimum Approach Distance (km)

Storm Surge (m)

VT = 2 m/s
VT = 5 m/s
VT = 8 m/s
APPENDIX C

STATION STORM SURGE PLUS WAVE SET-UP RETURN PERIOD RESULTS
EXTREME SEA LEVEL ESTIMATES
Fog Bay

Return Period (years)

Peak Sea Level — A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES
Native Point

Peak Sea Level - A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES
Bynoe Harbour

Return Period (years)

Peak Sea Level – A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES
Masson Point

Peak Sea Level — A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES
Charles Point

Return Period (years)

Peak Sea Level – A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES
West Point

Return Period (years)

Peak Sea Level – A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES
West Arm

Peak Sea Level - A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES
Channel Island

Return Period (years)

Peak Sea Level – A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES
East Arm PORT

Peak Sea Level – A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES

Darwin South SEAWALL

Peak Sea Level – A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES
Fannie Bay

Peak Sea Level – A.H.D. (m)

Return Period (years)
EXTREME SEA LEVEL ESTIMATES
Casuarina Beach

Return Period (years)

Peak Sea Level - A.H.D. (m)
EXTREME SEA LEVEL ESTIMATES

Gunn Point

Return Period (years)

Peak Sea Level - A.H.D. (m)
APPENDIX D

"A STORM SURGE MODEL FOR THE AUSTRALIAN REGION"
(Hubbert et al., 1990)
A storm surge model for the Australian region

By G. D. HUBBERT, L. M. LESLIE and M. J. MANTON
Bureau of Meteorology Research Centre, GPO Box 1289K, Melbourne, Australia

(Received 5 May 1989; revised 25 September 1989)

SUMMARY
A depth-integrated ocean-current model is developed to simulate currents and sea surface elevations on the Australian continental shelf. The nonlinear advective terms are included and the equations of motion are solved using an efficient split-explicit finite difference scheme, which yields accurate and stable results. The model predictions are compared with observations over a four-day period of both surface elevations and currents in Bass Strait during the passage of a typical cold front in April 1984.

1. INTRODUCTION

The coupling between the atmosphere and the oceans extends over all time scales. There are transfers of momentum, heat and water across the air-sea interface, and all three fluxes influence the ocean structure over long time scales when baroclinic effects are dominant. For short-term predictions around a continental shelf, however, the main forcing on the ocean is due to the surface-wind stress and the atmospheric surface pressure. In this case the bulk behaviour of the ocean circulation can be estimated by neglecting baroclinic effects and considering the two-dimensional depth-integrated equations of motion. Numerical models based on the resulting shallow-water equations have been used successfully for almost 20 years to predict both tidal and wind-forced circulation in coastal regions (e.g. Flather and Heaps 1975; Flather 1984).

A large number of commercial and recreational activities in Australia take place in the waters of the surrounding continental shelf. An ocean-circulation model has been developed to provide short-range predictions of sea surface elevations in this region. The model includes the nonlinear advection terms so that large-amplitude storm surges can be simulated. The model is driven by wind stress, atmospheric pressure gradients, astronomical tides and quadratic bottom friction. The atmospheric forcing at the air-sea interface is derived from the lowest level of the BMRC limited-area atmospheric prediction model (Leslie et al. 1985) and the boundary-layer model of McIntosh and Hubbert* which accounts for variations in surface roughness and atmospheric instability. An efficient split-explicit time-differencing scheme is used to integrate the shallow-water equations. The system is nested so that a relatively-coarse-resolution grid (about 30 km) is used to cover the whole continental shelf, while a high-resolution grid (about 10 km) can be nested in any sub-region of the coarse-grid domain. Nesting of the model reduces the uncertainties associated with the specification of the boundary conditions at open boundaries.

This paper presents details of the model and its application to the prediction of atmospherically forced currents and sea-surface elevations in Bass Strait, a shallow shelf extending east–west between Tasmania and the mainland of Australia. Observations by Jones (1980) show that the Strait is well mixed for approximately eight months of the year so the limitations of a depth-integrated model should be reduced for that period. Although the vertical structure of coastal ocean currents can still be important, even when the waters are well mixed (Gordon 1982), previous studies have demonstrated that

* Details obtainable from G.D.H.
a linear depth-integrated model of Bass Strait can adequately predict the tidal response (Fan et al. 1985).

2. THE MODEL

The equations of motion for a nonlinear depth-integrated model are

\[
\frac{\partial U}{\partial t} = fV - mg \frac{\partial \zeta}{\partial x} - m \frac{\partial P}{\rho_w \partial x} - m \left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} \right) + \frac{1}{\rho_w H} (\tau_{sx} - \tau_{bx}) \tag{1}
\]

\[
\frac{\partial V}{\partial t} = -fU - mg \frac{\partial \zeta}{\partial y} - m \frac{\partial P}{\rho_w \partial y} - m \left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} \right) + \frac{1}{\rho_w H} (\tau_{sy} - \tau_{by}). \tag{2}
\]

The equation of continuity is:

\[
\frac{\partial \zeta}{\partial t} = -m^2 \left\{ \frac{\partial}{\partial x} \left( \frac{UH}{m} \right) + \frac{\partial}{\partial y} \left( \frac{VH}{m} \right) \right\} \tag{3}
\]

where \(x\) and \(y\) are the horizontal Cartesian coordinates in the plane of the chosen map projection of the undisturbed sea surface, \(U\) and \(V\) are the components of the depth-integrated current, \(\zeta\) is the sea surface elevation, \(H\) is the total water depth, \(f\) is the Coriolis parameter, \(P\) is the atmospheric surface pressure, \(\tau_{sx}\) and \(\tau_{sy}\) are the components of surface wind stress, \(\tau_{bx}\) and \(\tau_{by}\) are the components of bottom frictional stress, \(\rho_w\) is the density of water (assumed constant), \(g\) is the gravitational acceleration, \(m\) is the map factor for the chosen map projection.

The surface-wind stresses are computed using the quadratic relationship

\[
\tau_{sx} = C_D \rho_a (u_a^2 + v_a^2)^{1/2} u_a \tag{4}
\]

\[
\tau_{sy} = C_D \rho_a (u_a^2 + v_a^2)^{1/2} v_a
\]

where \(u_a\) and \(v_a\) are the horizontal components of wind velocity (m s\(^{-1}\)) 10 m above the sea surface, \(\rho_a\) is the density of air and \(C_D\) is the drag coefficient.

For wind speeds below 25 m s\(^{-1}\), \(C_D\) is given by the expression (Smith and Banke 1975):

\[
C_D = \{0.63 + 0.066(u_a^2 + v_a^2)^{1/2}\} \times 10^{-3}. \tag{5}
\]

For wind speeds above 25 m s\(^{-1}\) the dependence of \(C_D\) on wind speed is reduced and it is expressed as

\[
C_D = [2.28 + 0.033((u_a^2 + v_a^2)^{1/2} - 25.0)] \times 10^{-3}. \tag{6}
\]

The bottom stress is computed using the normal quadratic relationship with the depth-integrated current

\[
\tau_{bx} = \rho_w K (U^2 + V^2)^{1/2} U \tag{7}
\]

\[
\tau_{by} = \rho_w K (U^2 + V^2)^{1/2} V \tag{8}
\]

where \(K\) is the bottom friction coefficient which is assigned the value 0.0020. This value was chosen to be slightly lower than the more commonly used value of 0.0025 (e.g. Flather 1984) in view of the low values obtained experimentally by Dewey and Crawford (1988). The results of Mojfeld (1988) also support the use of a lower mean value and suggest further that the coefficient of bottom friction is depth dependent.

At coastal boundaries the normal component of velocity is zero. At open boundaries the component of current along the outward directed normal (\(U_n\)) is computed from the
sea surface elevation:

\[ U_n = (C/H) \zeta \]  \hspace{1cm} (9)

where \( C = (gH)^{1/2} \).

The sea surface elevation at open boundaries is obtained from

\[ \zeta = \zeta^T + \zeta^M \]  \hspace{1cm} (10)

where \( \zeta^T \) is the elevation due to the astronomical tides and \( \zeta^M \) is the elevation due to meteorological effects (winds and atmospheric pressure).

In this work only the effects of meteorological forcing are considered, but if \( \zeta^T \) is required it can be calculated from harmonic theory using known amplitudes and phases of the major tidal constituents. These values have been determined in a separate study with this model, and values throughout the Australian region will be published in the near future.

When the solution domain is nested in a larger region, \( \zeta^M \) is obtained from the coarse-mesh model; otherwise it is set equal to barometric displacement due to the deviation of the surface pressure from a specified mean value \( \bar{P} \) i.e.

\[ \zeta^M = (\bar{P} - P)/\rho_w g \]  \hspace{1cm} (11)

where \( \bar{P} \) is 1013 hPa.

The purpose of these boundary conditions is to allow the passage of information from the coarse-mesh model to the fine-mesh model and to prevent the generation of noise at the boundary. The first requirement is achieved through Eqs. (9) and (10). The second requirement is achieved by Eq. (9) and the occasional use of a filter which selectively removes two-grid-spacing waves.

3. Numerical Integration Procedure

(a) Finite difference equations

Equations (1)–(3) are solved on a square Arakawa C-grid (Mesinger and Arakawa 1976, p. 47). The numerical integration procedure is split into three separate explicit steps. This split-explicit approach is very efficient in oceanographic models with free surfaces because of the large disparity between advective speeds and gravity-wave phase speeds in deep water. The first step, which is usually referred to as the adjustment step, considers the effects of the gravity wave and Coriolis terms and solves the full continuity equation (the continuity equation is not split because large errors can be introduced by finite-difference schemes when local variations in bathymetry are very large). Then follows the advective step which accounts for the remaining nonlinear terms. Finally, the 'physics' step accounts for the effects of surface-wind stress, bottom-friction stress and atmospheric pressure. Details of the numerical method adopted for each of these steps are given below.

(i) Adjustment step. An efficient explicit technique for this step is the so-called forward-backward method in which the surface elevation is evaluated using a forward time-step

\[
\zeta_i^{t+\Delta t} = \zeta_i^t - m_i^2 \Delta t \left\{ \frac{(UH^r)^{i}_{ij}}{m_i^2} - \frac{(UH^r)^{i}_{i+1j}}{m_{i+1}^2} + \frac{(VH^r)^{i}_{ij}}{m_i^2} - \frac{(VH^r)^{i}_{i-1j}}{m_{i-1}^2} \right\}
\]  \hspace{1cm} (12)

where

\[ m_i^2 = (m_{ij} + m_{ij+1})/2 \quad m_i^2 = (m_{ij} + m_{ij+1})/2 \]

\[ H_i^r = (H_{ij} + H_{i+1j})/2 \quad H_i^r = (H_{ij} + H_{i+1j})/2. \]
In equation (12) the grid spacing at the standard latitude of the map projection is represented by $\Delta s = \Delta x = \Delta y$.

The velocity components are then computed using the latest values of the surface elevation in the implicit relationship

\begin{equation}
U_{ij}^* = U_{ij} + \Delta t \left\{ fV_{ij}^* - m_{ij}^n g \left( \frac{\partial \xi}{\partial x} \right)_{ij}^{t+\Delta t} \right\}
\end{equation}

\begin{equation}
V_{ij}^* = V_{ij} - \Delta t \left\{ fU_{ij}^* + m_{ij}^n g \left( \frac{\partial \xi}{\partial y} \right)_{ij}^{t+\Delta t} \right\}.
\end{equation}

Equations (13) and (14) may be rewritten directly in the explicit form to obtain the intermediate solutions $U^*$ and $V^*$:

\begin{equation}
U_{ij}^* = \frac{1}{(1 + f^2 \Delta t^2)} \left[ U_{ij} + m_{ij}^n g \Delta t \left( \frac{\partial \xi}{\partial x} \right)_{ij}^{t+\Delta t} + f \Delta t \left( V_{ij} - m_{ij}^n g \Delta t \left( \frac{\partial \xi}{\partial y} \right)_{ij}^{t+\Delta t} \right) \right]
\end{equation}

\begin{equation}
V_{ij}^* = \frac{1}{(1 + f^2 \Delta t^2)} \left[ V_{ij} - m_{ij}^n g \Delta t \left( \frac{\partial \xi}{\partial y} \right)_{ij}^{t+\Delta t} - f \Delta t \left( U_{ij} - m_{ij}^n g \Delta t \left( \frac{\partial \xi}{\partial x} \right)_{ij}^{t+\Delta t} \right) \right]
\end{equation}

where

\begin{aligned}
\overline{U}_{ij} &= (U_{ij} + U_{i+1j} + U_{i-1j} + U_{i-1j+1})/4 \\
\overline{V}_{ij} &= (V_{ij} + V_{i+1j} + V_{i-1j} + V_{i+1j+1})/4.
\end{aligned}

(ii) **Advective step.** Equations (12), (15) and (16) are solved $N_a$ times so that the adjustment step advances the intermediate solution to the values $U^*$ and $V^*$ at time $t + \Delta t_a$, where $\Delta t_a = N_a \Delta t$. The numerical scheme chosen for the advective step is the two-time-level method of Miller and Pearce (1974). This scheme alternates the Euler and Euler backward (Matsuno) schemes at odd and even advective time-steps and has the major advantage of an amplification factor that is almost exactly unity for the Courant numbers that are found in ocean models (see stability analysis below).

On the odd advective time-steps the updated intermediate solutions $U^{**}$ and $V^{**}$ are

\begin{equation}
U_{ij}^{**} = U_{ij}^* + \Delta t_a F(U_{ij}^*_a)
\end{equation}

\begin{equation}
V_{ij}^{**} = V_{ij}^* + \Delta t_a G(V_{ij}^*_a)
\end{equation}

where the advective operators $F$ and $G$ are defined by

\begin{aligned}
F(U_{ij}^*_a) &= - \frac{m_{ij}^n}{4 \Delta s} \{ U_{i+1j}^* + U_{i-1j}^* - 2U_{ij}^* \} + (U_{ij}^* + U_{i-1j}^*)(U_{ij}^* - U_{i-1j}^*) + \\
&\quad + (V_{i+1j}^* + V_{i-1j}^*)(U_{ij}^* - U_{i-1j}^*) + (V_{i+1j}^* - V_{i-1j}^*)(U_{ij}^* - U_{i-1j}^*)
\end{aligned}

\begin{aligned}
G(V_{ij}^*_a) &= - \frac{m_{ij}^n}{4 \Delta s} \{ V_{i+1j}^* + V_{i-1j}^* - 2V_{ij}^* \} + (U_{ij}^* + U_{i-1j}^*)(V_{ij}^* - V_{i-1j}^*) + \\
&\quad + (V_{i+1j}^* - V_{i-1j}^*)(U_{ij}^* + U_{i-1j}^*) + (V_{i+1j}^* - V_{i-1j}^*)(V_{ij}^* - V_{i-1j}^*)
\end{aligned}

On the even advective time-steps the two-step Euler–backward scheme is applied instead of Eqs. (17) and (18). On the second iteration the values of $U$ and $V$ obtained after the first iteration are substituted into the advective operators $F$ and $G$ to obtain the final values of $U^{**}$ and $V^{**}$. 
(iii) Physics. The adjustment and advective integration cycle is carried out \( N_p \) times so that the interim solution is now \( U^{**} \) and \( V^{**} \) at time \( t + \Delta t_p \), where \( \Delta t_p = N_p \Delta t_a = N_p N_s \Delta t \). At this time the solution cycle is completed with the inclusion of the physics terms using a numerical technique similar to that described for the adjustment step. The final value of \( U \) is therefore

\[
U_{ij}^{\Delta t_p} = U_{ij}^{**} + \frac{\Delta t_p}{\rho_w} \left\{ \frac{1}{H_{ij}^s} (\tau_{sx} - \tau_{tx}) - \frac{m_{ij}^s}{\Delta s} (P_{i+1,j}^a - P_{ij}^a) \right\}
\]

\[
= U_{ij}^{**} + \frac{\Delta t_p}{\rho_w} \left\{ \frac{\tau_{sx}}{H_{ij}^s} \frac{\rho_w}{H_{ij}^s} K U_{ij}^{\Delta t_p} (U^{**2} + V^{**2})^2 - \frac{m_{ij}^s}{\Delta s} (P_{i+1,j}^a - P_{ij}^a) \right\}.
\]

This can be rewritten in explicit form as

\[
U_{ij}^{\Delta t_p} = U_{ij}^{**} + \frac{\Delta t_p}{\rho_w} \left\{ \frac{\tau_{sx}}{H_{ij}^s} - \frac{m_{ij}^s}{\Delta s} (P_{i+1,j}^a - P_{ij}^a) \right\} \left\{ 1 + \frac{\Delta t_p}{H_{ij}^s} K (U^{**2} + V^{**2})^{1/2} \right\}.
\] (19)

Similarly

\[
V_{ij}^{\Delta t_p} = V_{ij}^{**} + \frac{\Delta t_p}{\rho_w} \left\{ \frac{\tau_{sx}}{H_{ij}^s} - \frac{m_{ij}^s}{\Delta s} (P_{i+1,j}^a - P_{ij}^a) \right\} \left\{ 1 + \frac{\Delta t_p}{H_{ij}^s} K (U^{**2} + V^{**2})^{1/2} \right\}.
\] (20)

The numerical scheme therefore is split-explicit and consists of three distinct time steps \( \Delta t \), \( \Delta t_a \) and \( \Delta t_p \) where \( \Delta t \leq \Delta t_a \leq \Delta t_p \). For a typical run of the nested fine-mesh model with \( \Delta s = 11 \text{ km} \) and maximum depth of \( D = 5.5 \text{ km} \), the three time-steps used for a stable solution are

\[ \Delta t = 30 \text{ s} \quad \Delta t_a = 180 \text{ s} \quad \text{and} \quad \Delta t_p = 360 \text{ s}. \]

(b) Stability analysis

The time scheme may be analysed (linearly) for stability in each stage of the integration.

(i) Adjustment step. Standard linearized stability analysis (see, for example, Mesinger and Arakawa 1976, p 54) applied to the forward–backward scheme shows that the scheme is stable and neutral provided that

\[ \Delta t \leq \Delta s/(2gH)^{1/2} \]

(ii) Advective step. The amplification factors for the Euler scheme and the forward–backward (Matsuno) scheme are given by

\[ |\lambda_E| = (1 + p^2)^{1/2} \]

and

\[ |\lambda_M| = (1 - p^2 + p^4)^{1/2} \]

respectively (Mesinger and Arakawa 1976, pp. 12–13), where \( p \) is the advective Courant number

\[ p = U_{\text{max}} \Delta t/\Delta s \]

where \( U_{\text{max}} \) is the maximum absolute advective velocity.
The amplification factor for the Miller and Pearce scheme is therefore given by

$$|\lambda| = |\lambda_E||\lambda_M| = (1 + p^6)^{1/4}.$$  

The scheme is very weakly unstable. However typical values of $p$ are $p \approx 0.02$, so that $|\lambda|$ is almost exactly unity and the instability is so weak that the scheme is sufficiently stable for very long integrations.

(iii) Physics step. The physics step utilizes a backward implicit scheme which is stable for all values of $\Delta t$.

4. NUMERICAL SIMULATION OF SEA SURFACE ELEVATIONS AND CURRENTS IN BASS STRAIT

In order to test the accuracy of the present model, it is used to simulate the wind-driven currents in Bass Strait (a region of complex bathymetry) forced by a typical extratropical front. The case study corresponds to a period when observations from tide gauges and current meters are available at a number of sites in the Strait.

Bass Strait (see Fig. 1) is located in the south-east corner of Australia and it separates Tasmania from the mainland. Its geometry is unusual in that it consists of a shallow

Figure 1. Bathymetric contours for the fine-mesh model in Bass Strait. Observation stations are also marked. (TG = tidal station. CM = current meter station. M = meteorology station at Marrawah).
region approximately 350 km wide, 500 km long and no more than 100 m deep which shelves abruptly at either end to depths greater than 4000 m. This region supports a significant amount of commercial activity (such as oil and gas extraction, fishing and shipping) and recreational activity (such as yachting, small boats and surfing) and yet is one of the most dangerous stretches of water in the Australian region.

(a) Observations

An experiment designed to study the net mass flux through Bass Strait and to determine the forcing factors controlling the longer-period circulation in the Strait was carried out from April to July of 1984. In these months the shelf waters are well mixed. A six-day period of the experiment (20-25 April 1984) has been chosen for the model simulation as it contained the passage of a moderately strong cold front across the Strait resulting in winds of 15 to 20 m s\(^{-1}\) and a surge along the Victorian coastline of approximately 0.3 m. This surge was typical of those observed during the three-month experiment, as shown by Fig. 2 which shows the complete record of residual sea surface elevations observed at Stony Point.

The experimental data-set contains quarter-hourly data from current meters which were deployed at stations across the western entrance to the Strait and tide gauges which were distributed around the entire Bass Strait region. Meteorological data from the Australian Bureau of Meteorology stations, known to produce reliable data, provided atmospheric forcing data. For this case study, data from four tidal stations (Portland, Point Lonsdale, Stony Point and Rabbit Island) along the Victorian coastline were chosen to study the propagation of the surge along the coast. Data from five current meter stations in the western entrance to Bass Strait were also chosen to study the currents entering the Strait. The location of these observation stations is given in Fig. 1. All oceanographic data used in this study were reduced to hourly residuals by extracting the component due to the astronomical tide.
(b) Atmospheric forcing

The primary data requirements for modelling storm surges are accurate wind and atmospheric pressure fields. Except for cases involving intense mesoscale depressions, the Australian region numerical weather prediction (NWP) model (Leslie et al. 1985) together with the BMRC marine boundary-layer model (McIntosh and Hubbert*) provide a good source of atmospheric forcing data at the sea surface. For this case study the NWP model was started with archived analyses and run for the six-day period nested in archived analyses which were updated every twelve hours. The output from the lowest level of the NWP model was then reduced to surface data with the boundary-layer model, resulting in an atmospheric-forcing data-set containing six days of three-hourly surface pressures and winds at 10 m.

(c) Model simulations

In order to study the effects of resolution and boundary conditions the ocean circulation along the Victorian coastline and in Bass Strait was simulated by three different configurations of the storm-surge system. A coarse grid which mapped the whole Australian continental shelf on a Lambert grid with a 30 km resolution was used in the first simulation. The bathymetry for this grid is shown in Fig. 3. The second simulation was carried out on a fine grid which covered the continental shelf along the Victorian and Tasmanian coastlines on a Mercator grid with a mean resolution of 11 km (Fig. 1). Both of these simulations were carried out with surface elevations at open boundaries derived from the variations in atmospheric surface pressure. The third simulation was carried out with the fine-grid model nested within the coarse-grid model to obtain realistic boundary conditions (surface elevations) for the fine-grid model. The nesting was one-way and was carried out at multiples of complete coarse-grid time-steps.

Figure 3. Bathymetric contours for the coarse-mesh Australian continental-shelf model.
Coarse-grid values were obtained at fine-grid points using standard interpolation routines. The model, forced by surface pressures and winds at 10 m, was run for the six days of the case study in each of the three configurations. The parameters for the coarse grid (141x161 grid points) were

\[ \Delta t = 75 \text{s} \quad N_a = 3 \quad N_p = 2 \]

requiring a total central processor time on the Australian Bureau of Meteorology's FACOM M200 of approximately 400 s in 24 hours. The parameters for the fine grid (76x76 grid points) were

\[ \Delta t = 30 \text{s} \quad N_a = 6 \quad N_p = 2 \]

requiring a total central processor time of approximately 360 s in 24 hours.

There are different truncation errors in the split-explicit and the standard-explicit time-differencing techniques. Care was taken not to extend the splitting of the solution so that it diverged significantly from the solution obtained using the standard (but less efficient) explicit scheme. Each of the model runs was therefore compared with a purely explicit run and the results were virtually identical for the stated splitting parameters.

(d) Results

The first two days of the six-day model runs were regarded as the spin-up period and model results are compared with observations for the last four days, which contained the passage of a mid-latitude cyclone with an associated cold front through Bass Strait. The synoptic charts which were used for the four days of the model simulation are given in Fig. 4.

The first verification requirement was to assess the quality of the meteorological data-set used to force the storm-surge model. The results of this verification are seen in Fig. 5 where observations of wind speed and atmospheric pressure at Marrawah are compared with the corresponding values from the atmospheric-forcing data-set. These results were typical of the results obtained at the other three meteorological stations (Cape Otway, King Island and Flinders Island). The results show that good agreement is obtained between model and observation except that the NWP model produces a local maximum in the wind speed after about 12 hours, when the observations suggest a local minimum. This difference in wind speed is matched by a corresponding difference in surface pressure at that time. The anomalous wind-maximum leads to an overestimation of the surface forcing in the first day of the simulation. For the remainder of the simulation period, which included the passage of the front, the agreement is very good, and after the first day only, reasonably small errors could be introduced into the simulations from the atmospheric-forcing data-set.

In the model simulations the wind stress, which is predominantly from the west, drives a corresponding current around the continental shelf and across Bass Strait. In response to the geostrophic pressure gradient the sea-surface elevation tends to become aligned with a maximum along the Victorian coastline. The development of the sea-surface elevation along the Victorian coastline in the simulation, with the nested fine-mesh model, can be seen in Fig. 6 which shows the elevations at 24-hourly intervals. The associated depth-integrated currents are shown at 24-hourly intervals in Fig. 7. The peak response in both elevation and currents occurs on day 2, following the passage of the front from the west. Maximum surface elevations of about 0.3 m are observed along the Victorian coastline and currents of up to 60 cm s\(^{-1}\) into the Strait are produced in the entrance between north-west Tasmania and King Island. It is of interest that the wind surge on day 1 leads to a current surge that continues to propagate along the western and southern coasts of Tasmania as a coastally trapped wave.
Predictions from the nested fine-resolution model are compared with observations in Figs. 8 and 9. Figure 8 shows the sea surface elevations at four locations along the Victorian coastline, whilst Fig. 9 shows depth-integrated residual currents through the western entrances of Bass Strait. The effect of the anomalous atmospheric forcing during the first day of the simulation can be seen in both Figs. 8 and 9 where the model predictions are generally larger than the observations. Apart from this discrepancy the agreement between prediction and observation in Figs. 8 and 9 is good.
To obtain a quantitative assessment of the performance of the model and to demonstrate the effects of resolution and boundary conditions, an error analysis of several model runs was carried out. Tables 1 and 2 give a summary of the root mean square (r.m.s.) errors and mean errors, for sea surface elevations and currents respectively, at each station. The errors presented in these tables provide a comparison of the results obtained for the nested fine-resolution model, the non-nested fine-resolution model and the coarse-resolution model.

The analysis shows that the nested fine-mesh model results are significantly better than both the non-nested fine-mesh and the coarse-mesh results. The difference is most significant in the error analysis for sea surface elevations where the mean r.m.s. error
for the nested fine-mesh model is 0·04 m with a mean error of 0·02 m indicating a small degree of over-forecasting. The coarse-mesh model r.m.s. error is 0·06 m and the mean error is −0·04 m whilst the non-nested fine-mesh model mean r.m.s. error is 0·08 m with a significant under-forecasting mean error of −0·06 m. The error analysis for depth-integrated currents shows a similar trend. The mean r.m.s. error for the nested fine-mesh model was 0·05 m s⁻¹, compared with r.m.s. errors of 0·06 m s⁻¹ for both the non-nested fine-mesh model and the coarse-mesh model.

The fine-mesh model results are very encouraging and are more accurate than both the non-nested fine-mesh model and the coarse-mesh model. This result indicates that to accurately resolve surges and depth-integrated currents produced by typical meteorological fronts passing along south-east Australia a resolution of between 30 km and 11 km is required together with a realistic specification of boundary conditions.
TABLE 1. SEA SURFACE ELEVATION FORECAST ERRORS

<table>
<thead>
<tr>
<th></th>
<th>R.m.s. error (m)</th>
<th>Mean error (m)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Nested</td>
<td>Alone</td>
</tr>
<tr>
<td>Portland</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>Point Lonsdale</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>Stony Point</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Rabbit Island</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Mean</td>
<td>0.04</td>
<td>0.08</td>
</tr>
</tbody>
</table>
TABLE 2. EASTWARD VELOCITY COMPONENT FORECAST ERRORS

<table>
<thead>
<tr>
<th></th>
<th>R.m.s. error (m s⁻¹)</th>
<th>Mean error (m s⁻¹)</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td>Mean</td>
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<td>0·06</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

A fully nonlinear storm-surge model has been developed which utilizes a fast and accurate split-explicit time-differencing scheme. The model can be nested at finer resolutions and can be employed in any region of the globe. The numerical scheme also makes this model particularly suitable for vectorization and a fully vectorized version is being developed on the Australian Bureau of Meteorology ETA-10(P) supercomputer.

The effects of both resolution and nesting were examined and it has been shown that the model, when run at a resolution of 11 km in a nested-grid system, can satisfactorily simulate the sea surface elevations and depth-integrated currents produced by a moderate front passing through Bass Strait in south-eastern Australia. The fine-mesh model without nesting, and the coarse-mesh model with a resolution of 30 km, produced significantly greater errors.
Figure 9. Forecasts of the eastward component of depth-integrated current (solid lines) from the nested model compared with observations (broken lines) at five current-meter stations (labelled CM1 to CM5 in Fig. 1) in the western entrance to Bass Strait.

ACKNOWLEDGEMENTS

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REFERENCES


APPENDIX E

"A REAL TIME SYSTEM FOR FORECASTING TROPICAL CYCLONE STORM SURGES"
(Hubbert et al., 1991)
A Real-Time System for Forecasting Tropical Cyclone Storm Surges

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ABSTRACT

The depth-averaged, numerical storm-surge model developed by Hubbert et al. (1990) has been configured to provide a stand-alone system to forecast tropical cyclone storm surges. The atmospheric surface pressure and surface winds are derived from the analytical-empirical model of Holland (1980) and require only cyclone positions, central pressures, and radii of maximum winds. The model has been adapted to run on personal computers in a few minutes so that multiple forecast scenarios can be tested in a forecast office in real time.

The storm surge model was tested in hindcast mode on four Australian tropical cyclones. For these case studies the model predicted the sea surface elevations and arrival times of surge peaks accurately, with typical elevation errors of 0.1 to 0.2 m and arrival time errors of no more than 1 h. Second order effects, such as coastally-trapped waves, were also well simulated. The model is now being used by the Australian Tropical Cyclone Warning Centres (TCWC's) for operational forecasting. It will also be released as part of a tropical cyclone workstation that has recently been recommended for use by WMO member nations.

1. Introduction

Operational numerical models of storm surges, ocean currents, and astronomical tides are employed on a routine basis in several locations around the world, such as the North Sea (Flather 1976), the Gulf of Mexico, and the Atlantic Coast (Jelesnianski and Chen 1979). Sophisticated inundation models also are available for engineering and disaster planning purposes, but these require very detailed surveys and require too much computer time to be of general operational use. These models are reviewed in Murty (1984) and Jelesnianski (1989).

Most forecasting offices do not have access to sufficient computing power to run the above models routinely, especially to test multiple forecast scenarios. In these offices, the forecasts of storm surges associated with tropical cyclones are based on the nomogram methods of Jelesnianski (1972), which have been developed from modelling studies of a large number of bathymetries and storm approach angles.

The advent of powerful personal computer (PC) technology has opened up the possibility of direct use of dynamical models running on PC-based workstations in operational centers. This was recognized by the Second WMO International Workshop on Tropical Cyclones, (WMO 1990), which recommended that stand-alone storm-surge models be adopted for use on personal computers in developing countries. A PC-based Workstation (the Automated Tropical Cyclone Forecasting System, ATCF) has been in operation at the Joint Typhoon Warning Center, Guam for the past few years. The Bureau of Meteorology Research Centre (BMRC), together with the Bureau Severe Weather Program Office, has been developing an Australian workstation for tropical cyclone forecasting (the Australian Tropical Cyclone Workstation, ATCW) that contains dynamical atmospheric and oceanic models as integral components. Our aim in this paper is to describe the adaptation of the BMRC surge model (Hubbert et al. 1990) for use on this workstation.

A brief description of the model and of the numerical solution method is given in section 2, the atmospheric forcing is described in section 3, and four case studies of the tropical cyclones shown in Fig. 1 are analyzed in sections 4-6. The first two cases investigate the oceanic response along the north-east coast to tropical cyclones Winifred (1986) and Aivu (1989). Meteorological observations from a Bureau station were available near the radius of maximum winds of Winifred as it crossed the coast, providing a good data set for the verification of the atmospheric forcing. The third case examines the sea surface elevations associated with tropical cyclone Jason (1987) which occurred during the Australian Monsoon Experiment (AMEX). In addition to simulating the surge from the actual cyclone track a number of extra simulations are carried out, involving variations to the track and central pressure, in order to understand the discrepancy between the actual and forecast storm surges. The fourth case examines the effects of tropical cyclone Hazel (1979), which moved polewards along the north-west coast of...
Australia and generated a coastally-trapped surge that propagated polewards. The Hazel simulations also show the complex surge that can be generated inside a large bay with islands.

2. Atmospheric forcing

The primary data requirement for modelling storm surges is accurate surface wind and atmospheric pressure fields. In the extratropical case study reported in Hubbert et al. (1990) the meteorological forcing at the air–sea interface was derived from the lowest-level of the BMRC limited-area atmospheric prediction model (Leslie et al. 1985).

There are insufficient real-time data to allow a direct analysis of the central region of most tropical cyclones, and the resolution of currently available numerical weather prediction models is too coarse to resolve the important small-scale features adequately. Surface wind speeds and pressures therefore are inferred from an adaptation of the analytical-empirical profile model of Holland (1980). This approach has the additional advantage that the model can be used in a stand-alone mode in forecast offices without access to extensive observations.

a. Pressure field

The pressure field asymmetries are assumed negligible over the region of interest (Shea and Gray 1973), and the pressure field is derived following Holland (1980) as follows:

\[ P = P_c + (P_n - P_c) \exp[-(r_m/r)^b], \]  

(1)

where \( P \) is the atmospheric pressure at radius \( r \), \( P_c \) is the central pressure, \( P_n \) is the environmental pressure (defined in these studies as the climatological mean for the region and month), \( r_m \) is the radius of maximum winds, and \( b \) provides a scaling on the profile shape. The parameter \( b \) is empirically defined by

\[ b = 1.5 + (980 - P_c)/120, \]  

(2)

where \( P_c \) is in hPa.

b. Surface wind field

The symmetric, gradient-level azimuthal wind component is estimated (Holland 1989) by

\[ v = \{b(r_m/r)^b(p_n - P_c) \exp[-(r_m/r)^b]/\rho \]  

\[ - r^2f^2/(4)\}^{1/2} - rf/2, \]  

(3)

where \( \rho \) is the air density and \( f \) is the Coriolis parameter. A first order asymmetry is included by adding the cyclone translation to the symmetric field and rotating the field so that the maximum wind is 70° to the left (right in the Northern Hemisphere) of the direction of cyclone motion (Shapiro 1983). The radial wind field is constructed by rotating the flow to a constant inflow angle of 25° outside the radius of maximum winds (Shea and Gray 1973). Following Powell (1980), and after making allowances for the Australian standard of 10 minute average winds, the surface winds are then derived using a constant reduction of 0.7.

c. Verification of the tropical cyclone output

The tropical cyclone model has been used extensively in forecasting offices both in Australia and elsewhere, and has been found to provide a good indication of the flow in data-sparse regions (Martin, personal communication from Joint Typhoon Warning Center 1989). An independent test by G. Foley and K. Lovell (personal communication 1989) on a range of tropical cyclones off the north-west Australian coast showed excellent agreement with observations.

It is important to note that we do not expect the tropical cyclone model to represent the full field of synoptic scale features with a high degree of accuracy. The critical aspect as far as the storm surge forcing is concerned is that the model parameterizes the mesoscale forcing in the vicinity of the maximum winds reasonably well. The meteorological observations at Cowley Beach during tropical cyclone Winifred (1986) are the only station observations close to the radius of maximum winds of the four cyclones studied. The Cowley Beach observations therefore provide the best opportunity to test the accuracy of the meteorological forcing derived using the tropical cyclone model. The observed and modelled atmospheric pressures and surface winds are compared in Figs. 2a and 2b. A timing discrepancy of 1 h between the published best track and the observations at Cowley Beach has been removed.
The results show that good agreement is obtained between model and observations during the cyclone's approach to the coast. Because of its inability to accommodate the large changes that occur following landfall (e.g., Powell 1982), the model produces an unrealistically large second wind maximum (Fig. 2b). Thus, the atmospheric forcing should be reliable during the build-up to maximum surge height during cyclone landfall, but may be quite wrong after landfall. This is of little consequence, however, as the surge height generally decays rapidly following landfall. Care will need to be taken with interpreting the results for cyclones that move very slowly, or stall, at the coast.

Other discrepancies between observations and the tropical cyclone model may arise from the neglect of potentially important features such as non-linear changes associated with different cyclone translation speeds (Shapiro 1983). However, such effects cannot be analyzed with the available data base for most parts of the world. It is expected that these effects are of second order and generally can be neglected.

d. Surface wind stresses

The surface wind stresses are computed using the quadratic relationship:

\[ \tau_{x} = C_D \rho_w (u^2 + v^2)^{1/2} u, \]
\[ \tau_{y} = C_D \rho_w (u^2 + v^2)^{1/2} v, \]

where \( u \) and \( v \) are the horizontal components of wind velocity (m s\(^{-1}\)) 10 m above the sea surface, \( \rho_w \) is the density of water and \( C_D \) is the drag coefficient.

For wind speeds below 25 m s\(^{-1}\), \( C_D \) is given the value defined by Smith and Banke (1975):

\[ C_D = (0.63 + 0.066(u^2 + v^2)^{1/2}) \times 10^{-3}, \]

where \( u \) and \( v \) are in m s\(^{-1}\).

For wind speeds above 25 m s\(^{-1}\) the dependence of \( C_D \) on wind speed is not well known, although it is commonly believed that this dependence is not as strong as for lower wind speeds (e.g., Frank 1984). A fifty percent reduction in the Eq. 5 dependence on wind speed therefore was adopted for winds in excess of 25 m s\(^{-1}\); that is

\[ C_D = (2.28 + 0.033 [(u^2 + v^2)^{1/2} - 25]) \times 10^{-3} \]


e. Input data

The standard input data to the tropical cyclone model are latitude and longitude of the cyclone center, radius of maximum winds, and central pressure of the cyclone. A modification has recently been included to enable the option of specifying maximum wind data as used in the United States instead of defining the central pressure. In Australia, these input data are determined by the duty forecasters in the relevant TCWC. When the cyclone approaches the coast, the radius of maximum winds can be determined from radar and the central pressure is estimated from analysis of satellite and surface observations. Due to the uncertainty of forecast tracks, several forecast options can be determined and the surge model run for each of these options.

3. Storm surge model

The storm surge forecasting system has been developed for use either in the ATCW or as a menu-driven stand-alone system. The applications described here are for the Australian region only, but the system has been generalized for use anywhere there are tropical cyclones.

Although baroclinic effects have a significant influence on deep ocean circulation over long time-scales,
the main short term variations in ocean circulation, particularly on a continental shelf, are due to the surface wind stress and the surface pressure. As a result, baroclinic effects can be neglected for predictions of ocean circulation over periods of a few days on the continental shelf. Hence a depth-integrated model has been adopted for the surge prediction. The model and the numerical solution scheme are described in detail in Hubbert et al. (1990), together with a stability analysis. Only a brief description of specific features are presented here.

The model is driven by wind stresses, by atmospheric pressure gradients, and by quadratic bottom friction. Nonlinear advection terms are included in the results presented in this paper. We have since found that they have very little effect on the final result, and therefore for operational applications, the nonlinear terms are normally left out to save integration time. Any grid spacing or map projection may be chosen depending on the particular application. For these studies a Lambert conformal projection, with a grid spacing of 15 km is used. Station time series can be output at the nearest grid point for any number of specified locations.

a. Integration procedure

The model solves the nonlinear shallow water equations, which are integrated forward in time on a Arakawa C-grid (Mesinger and Arakawa 1976, p. 47) using a split-explicit finite difference scheme. The split-explicit approach is very efficient in depth-integrated oceanographic models because of the large disparity between gravity wave phase speeds and advective speeds.

The numerical solution is split into three explicit steps, each with its own time step. First, the adjustment step solves the full continuity equation and considers the effects of the gravity wave and Coriolis terms in the momentum equations using the forward-backward method. Next follows the advective step that solves the remaining non-linear terms using the two-time-level method of Miller and Pearce (1974). This scheme alternates the Euler and Euler-backward (Matsuno) schemes at odd and even advective time steps. It has the major advantage of an amplification factor that is almost exactly unity for the Courant numbers in the advective terms of this model. Finally, the “physics” step accounts for the effects of surface wind stress, bottom friction stress, and atmospheric pressure using the forward-backward method.

b. Bottom stress

The bottom stress is computed from the depth-integrated current using a quadratic relationship with a constant coefficient of 0.0020. This value was chosen to be slightly lower than the more commonly used value of 0.0025 (e.g., Flather 1984) in view of the low values obtained experimentally by Dewey and Crawford (1988) and of the work by Mojfeld (1988).

c. Boundary conditions

At coastal boundaries the normal component of velocity is zero. The external, open boundaries use a radiation condition which solves for the group velocity (Miller and Thorpe 1981) to compute the velocity components. The sea-surface height at the open boundaries is set at the atmospheric barometric displacement. Astronomical tides can be modelled but are not included in these studies since the major forecasting requirement is for surge heights above local tides.

d. Bathymetry

The bathymetry used in the forecast system is derived from a global data file with a latitude and longitude resolution of 5 min. To reduce the processing time, a subset of the global data set, covering the region of interest is first derived and stored as a permanent record. Any sub-region then can be selected using an easy to follow screen-based menu. The Australian region bathymetric data set is shown in Fig. 3, together with the sub-regions selected for the studies presented in sections 4 and 5.

e. Operating procedure

The forecast model is run from a screen menu with pop-up windows that can be called from within ATCW or used in a stand-alone mode. A typical procedure would be as follows. First the user sets up the forecast domain by executing the appropriate window and entering the latitudes and longitudes of the domain limits. The user also is prompted to provide an arbitrary
number of stations for time series display of surge heights. The system then sets up a Lambert conformal grid, and extracts bathymetry data from a 5-min global topography file (higher resolution local files may be substituted). This process takes 2–3 min on a 20 MHz 386 computer with a maths co-processor and is set for the duration of the forecast period.

The user is next prompted to provide cyclone positions, central pressures, and radii of maximum winds at any time interval (typically every 3 h for 24 h). The environmental pressure is pre-defined in these studies by its climatological mean. The tropical cyclone model is then run for the required forecast period (typically 24 h) and it produces hourly forecasts of surface winds and sea-level pressures at each grid point. The user is given the opportunity to examine these via a menu driven screen display package before proceeding further. This process takes a further 2–5 minutes to set up a 24-h data set.

The final step is to run the surge model, which takes 3–5 min. The output from this consists of the domain bathymetry field, hourly sea-levels (above the astronomical tide) and current fields and station time series with a 10-min resolution. These fields may be displayed in any order or combination from the menu. The user may zoom in to any part of the domain to provide higher resolution as needed.

One of the major advantages of the Australian storm surge forecast system is that it enables an investigation of multiple forecast scenarios to be made in real-time. For example, four 24-h forecasts can be carried out on a 20 MHz 386 personal computer in around 15 min. As the cyclone approaches the coast and the forecast becomes more accurate, updated forecast tracks can then be used.

f. Verification

Verification of model hindcasts of sea-surface elevations and depth-averaged currents driven by a typical extratropical cold front has been presented previously in Hubbert et al. (1990). In the present studies, sea-surface heights above the predicted astronomical tide are compared with observations from local tide gauges where possible, or with beach survey estimates. There were no observations of ocean currents in the vicinity of the tropical cyclone case studies presented here.


Severe Tropical Cyclones Winifred and Aivu both crossed the densely populated east coast of Australia (Fig. 1).

Cyclone Winifred gradually intensified while moving south-west and crossed the Queensland coast at maximum intensity on 1 February 1986 near Cowley Beach (Fig. 4c). The Brisbane TCWC estimated a central pressure of 957 hPa (from satellite surface observations analysis) and a radius of maximum winds of 27 km at landfall (from radar). Observations of peak sea surface elevations were obtained at Clump Point (Fig. 4c) just south of Cowley Beach.

A 4-day simulation of the ocean response to Winifred was commenced at 2300 UTC on 29 January. The atmospheric forcing was derived using a constant radius of maximum winds of 27 km and was updated every hour using the best track position and central pressure provided by the Brisband TCWC. The atmospheric surface pressures and winds and the model sea surface elevations and currents near to the time that Winifred crossed the coast are shown in Fig. 4. The model surge reached a maximum of 1.5 m at the nearest grid point to Clump Point compared with the maximum of 1.6 m above the astronomical tide measured by a local tide gauge (Table 1). The timing of the peak surge coincided with the observed time (Table 2).

Cyclone Aivu approached the coast of Queensland from the Coral Sea in the first week of April 1989 with destructive winds exceeding 60 m s⁻¹ and a minimum central pressure of 935 hPa. Aivu, thus, was one of the most severe tropical cyclones ever to affect the east coast of Australia. It caused widespread damage to several coastal communities. The radius of maximum winds of Aivu when it crossed the coast was estimated by the Brisbane TCWC to be 30 km from radar; and the maximum storm surge was focused in the area of Upstart Bay (Fig. 5), where peak storm-surge estimates were made.

The storm surge model was run in hindcast mode for the four days prior to the landfall of Aivu. The atmospheric surface forcing was derived using a constant radius of maximum winds of 30 km and updated every hour from the best track positions and central pressures provided by the Brisbane TCWC. The model sea surface elevations and currents near to the time that Aivu crossed the coast are shown in Fig. 5. The model surge reached a maximum of 2.6 m at the nearest grid point to Upstart Bay coincident with the estimated peak surge of 2.8 m above the astronomical tide (Tables 1 and 2).

The slightly low surge simulation is considered to be due to the small size of Upstart Bay. At a resolution of 15 km, Upstart Bay is barely resolved. Thus the model obtains a surge indicative of that along a more open coastline, which would be expected to be less than that occurring inside an inlet the size of Upstart Bay.

5. Tropical Cyclone Jason (1987)

a. Best track

During the Australian Monsoon Experiment (AMEX), Severe Tropical Cyclone Jason (Fig. 1) threatened the coastal community of Karumba (Fig. 6c) in the south-eastern corner of the Gulf of Carpentaria. The bathymetry of this region is particularly
FIG. 4. Model results at landfall of Tropical Cyclone Winifred (0900 UTC 1 February 1986): (a) surface pressures (4 hPa contours), (b) surface winds (10 m s⁻¹ contours and vector arrows up to 60 m s⁻¹), (c) sea surface elevations (0.2 m contours), and, (d) depth-integrated currents (0.2 m s⁻¹ contours). Note that the domain has been zoomed to higher resolution for the last two panels and the Winifred track has been added to panels (a) and (c) for reference.
TABLE 1. Observed and model maximum storm surge magnitudes.

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Location</th>
<th>Observed</th>
<th>Model</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winifred</td>
<td>Clump Point</td>
<td>1.6</td>
<td>1.5</td>
<td>-0.1</td>
</tr>
<tr>
<td>Aivu</td>
<td>Upstart Bay</td>
<td>2.8*</td>
<td>2.6</td>
<td>-0.2</td>
</tr>
<tr>
<td>Jason</td>
<td>Karumba</td>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Jason</td>
<td>Burketown</td>
<td>3.5*</td>
<td>3.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>Hazel</td>
<td>Carnarvon</td>
<td>1.3</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Hazel</td>
<td>Geraldton</td>
<td>0.7</td>
<td>0.6</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

* Estimated observations from a beach survey.

suited to large surge generation. Operational forecasts of a direct hit at maximum intensity with a 5 m surge near high tide forced the evacuation of Karumba. The large surge did not occur, however, as the cyclone turned from the forecast track and crossed the coast approximately 150 km west of Karumba early on 13 February 1979. It is therefore of interest to compare the model surges from the actual and forecast tracks. We also conducted a series of sensitivity experiments to test the effects of differing tracks and central pressures on surge heights at Karumba.

At landfall, the central pressure and radius of maximum winds were estimated at 975 hPa and 27 km, respectively. The minimum central pressure of 965 hPa occurred approximately 24 h before landfall. No observations of the maximum storm surge were obtained on the uninhabited coast where the cyclone crossed. The maximum surge above the astronomical tide observed at Karumba by a local tide gauge was 2 m. The simulations of Jason commenced at 2300 UTC on 10 February and continued for four days with a constant radius of maximum winds of 27 km. The position and central pressure were updated hourly following the best track.

Figure 6 shows the atmospheric pressures and wind speeds and the model sea surface elevations and currents at about the time Jason crossed the coast. These plots illustrate the effects of a large bay. Strong spatial gradients in sea-level are generated near the center of the cyclone as a result of a concentrated cyclonic gyre which is established in the south-east corner of the Gulf. The peak model surge at the nearest grid point to Karumba coincided with the observed maximum of 2.0 m (Table 1). The timing of the peak surge at Karumba also coincided with the observed time (Table 2). The maximum simulated surge was 3.3 m just east of the landfall point (Fig. 6c). Fig 6e compares the predicted surge above the astronomical tide with observations from the Karumba tide gauge.

b) Sensitivity to track and central pressure

Four additional simulations were carried out to determine what the surge would have been if Jason had followed the forecast track and whether the forecast peak surge of 5 m could have been achieved, and if so, under what conditions. Accordingly, we examined the sensitivity of surges in the Karumba region to variations of track and central pressure by varying the track
parameters in the 24 h before landfall. These simulations also provide an indication of the manner in which the system would be used in operations, when a number of forecast scenarios would typically be tried. The simulations chosen were the forecast track and central pressure (965 hPa) for the last 24 h into the coast, the forecast track with a much more intense (920 hPa) and a weaker (995 hPa) cyclone, and a track crossing the coast 150 km to the east of Karumba but retaining the best track central pressure.

FIG. 6. Model results at landfall of tropical cyclone Jason (0500 UTC 12 February 1987): (a) surface pressures (4 hPa contours), (b) surface winds (10 m s$^{-1}$ contours and vector arrows up to 60 m s$^{-1}$), (c) sea surface elevations (0.2 m contours), (d) depth-integrated currents (0.2 m s$^{-1}$ contours), and, (e) comparison of the model and observed sea-surface elevation above the astronomical tide at Karumba. Note that the domain has been zoomed to higher resolution for panels (c) and (d).
The time series of surge heights at Karumba for these simulations plus the best track case are shown in Fig. 7. There was little difference between the surge height simulations up to approximately 8 h before landfall, but substantial divergence occurred as the cyclones approached the coast. The forecast track and central pressure produced a simulated surge of 3.0 m at Karumba, which is significantly less than the forecast of 5.0 m issued at the time based on nomograms. The close agreement between the observed and predicted maximum surge when the best track data was used indicates that the maximum surge which would have occurred if Jason had followed the forecast track would indeed have been nearer to 3 m than 5 m. The intense cyclone simulation shown in Fig. 7 indicates that a 5 m storm surge would require a cyclone making landfall with a central pressure of 920 hPa.

### 6. Tropical Cyclone Hazel (1979)

When a tropical cyclone moves with the coast on the left (Southern Hemisphere) near to the propagation speed of a coastally-trapped wave, resonant amplification of the sea surface elevation can occur. The contributions of these waves to tropical cyclone surge generation have been described previously by Jelesnianski (1967). This is a particular problem off the Australian west coast, where the conditions for such resonant amplification are regularly met and, as noted by Fandry et al. (1984), the resulting surface elevation can propagate for thousands of kilometers after the cyclone has decayed.

We tested the model capacity to simulate both resonant amplification and free propagation of coastally-trapped waves using Severe Tropical Cyclone Hazel (Fig. 1). Hazel moved parallel to the north-west coast of Australia in a poleward direction over a number of days. During the 12 h before landfall, Hazel also accelerated to a speed of over 15 m s⁻¹, so that the conditions for resonance with coastally-trapped waves were met. For this reason, Hazel was one of the cyclones chosen by Fandry et al. (1984) in their study of coastally-trapped wave generation. Tidal data also were available at Carnarvon (Fig. 8) and Geraldton (approximately 500 km south of Carnarvon). Hazel reached a minimum central pressure of 936 hPa near Carnarvon, with an estimated radius of maximum winds of 30 km from shore-based radar. The maximum surge above the astronomical tide observed by the Carnarvon tide gauge was 1.3 m and the Geraldton tide gauge measured a surge of 0.7 m in spite of the fact that Hazel crossed the coast 400 kms north of this location.

The simulation of Hazel started at 2300 UTC on 10 March and continued to 2300 UTC on 14 March, or 12 h after landfall. Best track cyclone positions and central pressures were used and the radius of maximum winds was held constant throughout at 30 km. The integration domain was on a 15 km Lambert conformal grid over the region shown in Fig. 3. The amplification and progression of a surge wave down the coast is shown by the four panels in Fig. 8. As Hazel moved obliquely towards the coast, a region of positive surge first developed. A region of negative surge then formed and moved ahead of the amplifying positive surge wave, with the zero line staying slightly ahead of the cyclone position.

The details of the surge structure near the time of maximum surge at Carnarvon is shown in Fig. 9. We note, in particular, that the current has split into two branches: one flowing along the coast into the shallow Shark Bay to the south of Carnarvon, the other following the sharp gradient of bathymetric contours across the mouth of the bay (Fig. 3). Substantial amplification of the surge wave was simulated in Shark Bay, with heights of over 3 m above the astronomical tide. The second branch continued to propagate down the coast, resonating with the decaying Hazel (Fig. 1) and producing significant surge effects. In a separate simulation, in which the cyclone was rapidly weakened at landfall, the second branch evolved into a freely propagating coastally-trapped wave, with amplitude of around 10 cm.
This simulation accurately predicted both the timing and amplitude of the observed surge heights at Carnarvon and Geraldton (Tables 1 and 2). The amplitude of the simulated negative surge at Carnarvon was much larger than observed, however. This can be seen in Fig. 9c which compares the predicted surge above the astronomical tide with observations from the Carnarvon tide gauge.

We tested the degree of resonant amplification by a separate integration with a storm of the same characteristics as Hazel but approaching perpendicular to the coast near Carnarvon. Consistent with the analytical
study of Fandry et al. (1984), the peak generated surge of 0.8 m was much weaker than observed, implying that the resonant amplification was responsible for a significant part of the observed surge at Carnarvon. We are investigating these aspects further in a companion study.

7. Concluding remarks

We have described the development of a tropical cyclone surge forecasting system that runs in a few minutes on a personal computer. The surge forecasts are based on the depth-integrated numerical storm surge model of Hubbert et al. (1990). The atmospheric forcing was provided by an adaptation of the analytical-empirical model of Holland (1980). The only requirements are for tropical cyclone positions, central pressures, and radii to maximum winds at arbitrary time intervals leading up to landfall. The system can be readily adapted to any tropical cyclone region and is operated via a screen menu that provides for an arbitrary selection of forecast domain. Output consists of the derived cyclone wind and pressure fields, ocean elevations, and ocean currents; and a zoom feature allows focusing on the regions of most interest. A surge time series also may be displayed for any point in the domain.

We have shown in these four case studies that the model, when run at a resolution of 15 km, can simulate accurately the sea surface elevations and arrival times of the peak surge generated by tropical cyclones in proximity to the Australian coastline. A series of sensitivity experiments demonstrated the capacity of the system to handle multiple forecast scenarios. The model has been shown to be applicable in regions of complex bathymetry, where large local gradients in surge height occur. It also can simulate the effects of forced and free coastally-trapped waves when cyclones move parallel to the coast.

The forecast system is designed to run either on the Australian Tropical Cyclone Workstation or in a standalone mode. It is now used for operational storm surge

Fig. 9. Model results at the time of peak Carnarvon surge for Tropical Cyclone Hazel (1400 UTC 13 March 1979): (a) sea surface elevations (0.2 m s⁻¹ contours), (b) depth-integrated currents (0.2 m s⁻¹ contours), and, (c) comparison of the model and observed sea-surface elevation above the astronomical tide at Carnarvon.
forecasting in Australian TCWC's. Following a recommendation by the Second WMO International Conference on Tropical Cyclones (Manila, November 1989), it is to be utilized in many of the tropical cyclone forecasting centers around the globe.

Acknowledgments. This research has been conducted in the BMRC as a joint program with the Bureau Severe Weather Office and has been partially supported by the US Office of Naval Research under contract N-00014-89-J-1737. Part of the development of the tropical cyclone model used was carried out by one of us (G. J. Holland) under contract to Woodside Offshore Petroleum Ltd. G. Foley (Perth TCWC) and J. Davidson (Brisbane TCWC) provided important track data for the tropical cyclones used in this study. D. Pike provided valuable assistance in the preparation of figures.

REFERENCES


APPENDIX F

"NUMERICAL MODELLING FOR COASTAL ENGINEERING AND ENVIRONMENTAL STUDIES: TROPICAL CYCLONE STORM SURGES AND WAVES" (Hubbert, 1991)
Numerical Modelling for Coastal Engineering and Environmental Studies
Part 1: Tropical Cyclone Storm Surges and Waves

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SUMMARY - A numerical forecast system has been developed to study and predict storm surges and surface waves resulting from tropical cyclones. The system incorporates an adaption of the analytical tropical cyclone model of Holland (1980), the numerical storm surge model of Hubbert et al (1990, 1991) and an adaption of the third generation numerical wave model developed by the WAM group (WAMDI, 1988). The components of the system are described and the results of a case study of the effects of the 1989 tropical cyclone Orson are given. Orson passed near the North Rankin platform on the Australian northwest shelf and had the lowest recorded central pressure (905 hPa) in any Australian region tropical cyclone. At the Woodside North Rankin gas platform the maximum surface wind measured was 56 m/s, the maximum mid-depth ocean current was 0.96 m/s and the peak significant wave height measured was approximately 10 m. The corresponding results obtained with the numerical forecast system were 55 m/s, 1.15 m/s and 10.2 m respectively. The peak storm surge measured at King Bay near Dampier was 3.1 m, whilst the storm surge model simulation produced a peak surge of 3.0 m. The system has been used for a number of tropical cyclone studies and similarly good results are obtained. The system provides a reliable method of determining the likely extreme marine response to tropical cyclones.

1. INTRODUCTION

A regional numerical forecast system has been developed for the purpose of studying and predicting mesoscale meteorology, storm surges, tides, ocean currents, ocean temperatures and ocean waves in any region of the globe. The system provides a strong basis for environmental impact studies and coastal engineering applications. The system runs on modern workstations and includes five model components:

a) a high resolution primitive equation atmospheric model,
b) an analytical tropical cyclone model,
c) a non-linear depth-integrated storm surge model,
d) a three-dimensional primitive equation regional ocean model and
e) a third generation ocean wave model.

Part 1 of this paper describes models (b), (c) and (e) and reports on their application to the study of the effects of tropical cyclones on the coastal marine environment. In part 2 of the paper the primitive equation atmospheric and ocean models are described and results of simulations of ocean currents and temperatures are reported.

2. MODEL DESCRIPTIONS

2.1 Tropical Cyclone Model

There are usually insufficient data to allow a direct analysis of the central region of most tropical cyclones and currently available numerical weather prediction models do not adequately represent the small-scale features. Surface wind speeds and pressures are therefore derived using an adaption of the analytical-empirical profile model of Holland (1980). A detailed description of the analytical model together with verifying data is given in Hubbert et al (1991) and only a brief description of the major features are given here.

The pressure $P$ (hPa) at radius $r$ is derived as follows:

$$P = P_c + (P_n - P_c) \exp[-(r_m/r)^b],$$  \hspace{1cm} (1)

where $P_c$ is the central pressure, $P_n$ is the environmental pressure (the climatological mean for the region and month), $r_m$ is the radius of maximum winds and $b$ provides a scaling on the profile shape. The parameter $b$ is empirically defined by

$$b = 1.5 + (980 - P_c)/120.$$ \hspace{1cm} (2)

The symmetric, azimuthal wind component at the top of the boundary layer is estimated by
\[ v = \left( b(r_0/e)^2 (P_e - P) \right) \exp\left( -(r_0/e)^2 / r^2 + 4 \right) - rf/2, \]  

where \( \rho \) is the air density and \( f \) is the Coriolis parameter.

A first order asymmetry is included by adding the cyclone translation to the symmetric field and rotating the field so that the maximum wind is \( 70^\circ \) to the left (right in the Northern Hemisphere) of the direction of cyclone motion. The radial wind field is constructed by rotating the flow to a constant inflow angle of \( 25^\circ \) outside the radius of maximum winds.

It is important to note that the tropical cyclone model is not expected to represent the full field of synoptic scale features with a high degree of accuracy. The critical aspect for storm surge and wave forcing is that the model parameterises the mesoscale forcing in the vicinity of the maximum winds reasonably well.

### 2.2 Storm Surge Model

Although baroclinic effects have a significant influence on deep ocean circulation over long time-scales, the main short term variations in ocean circulation during tropical cyclones, particularly on a continental shelf, are due to the surface wind stress and the surface pressure. As a result, baroclinic effects can be generally be neglected for the purpose of predicting the direct ocean response to a tropical cyclone. Hence a depth-integrated model has been adopted for storm surge prediction.

The storm surge model and the numerical solution scheme are described in detail in Hubbert et al. (1990, 1991), together with a stability analysis. The major features of the model are:

- the shallow water equations are solved on the Arakawa C-grid defined in Mesinger and Arakawa (1976)
- the non-linear advection terms are included
- an efficient time-splitting finite difference scheme is used, which yields accurate and stable results and a faster solution than standard explicit techniques (three different time steps are used to solve the gravity wave, advective and the physics components of the equations)
- the model is driven by wind stresses, atmospheric pressure gradients, tides and quadratic bottom friction.
- the resolution and the map projection are variable
- the coastal boundary moves as a function of the sea level to account for inundation or drying
- a radiation condition which solves for the group velocity is used to compute open boundary values
- a high resolution global bathymetry file is used
- the ability to read local very high resolution bathymetric data is included
- the model can be nested inside itself
- the model output consists of sea surface elevations, depth-integrated ocean currents and station time series at any number of locations.

The storm surge model, together with the tropical cyclone model, forms the basis of the present Bureau of Meteorology operational storm surge forecasting system. The system was developed for use in a menu-driven stand-alone system and it has been generalised for use anywhere in the globe. For most applications the storm surge model runs in a few minutes on modern personal computers. High resolution nested runs take longer and are used for environmental studies rather than for forecasting. The storm surge model has been used for a number of storm surge coastal impact studies and also for research studies such as modelling the propagation of coastally trapped waves along the continental shelf.

### 2.3 Wave Model

The third generation ocean wave model (commonly known as the "WAM" model) has been adapted to the workstation environment where it is driven by the analytical tropical cyclone winds. The WAM model is a third generation wave prediction model developed by the WAM group (WAMDI, 1988) which computes the evolution of the directional surface wave spectrum over the area covered by the model grid by solving the energy balance equation

\[ \frac{\partial \phi}{\partial t} + \nabla \cdot (C_g \phi) = S(u) \]  

where the source term \( S(u) \) is defined by

\[ S(u) = S_{f1}(u) + S_{n1} + S_{de} + S_{bf} \]

and

\[ \phi(z,f,\theta) \] is the spectral density at frequency \( f \) and direction \( \theta \) evaluated at position \( z \) on the globe at time \( t \).

- \( C_g \) is the group velocity.
- \( S_n \) is the source term representing the flux of energy from the atmosphere to the sea surface waves expressed as a function of the local friction velocity.
- \( S_{sd} \) is the source term representing the exchange of energy of waves in one frequency-direction bin with waves in other frequency-direction bins due to weak non-linear interactions.
- \( S_{sw} \) is the source term representing whitecapping dissipation.
- \( S_{bf} \) is the source term representing dissipation due to bottom friction.

The WAM model applies to water depths greater than 20 m. The two-dimensional spectrum at each grid point is represented in the model as a function of discrete frequency-direction bins with frequencies ranging from 0.042 to 0.45 Hz.

There are three time steps which can be varied to suit the application. The wind time step may be 3 hours for synoptic scale studies but for tropical cyclone studies hourly winds are required. At each integration time step the source terms are integrated locally and then at the end of a propagation time step advection is computed for each
The WAM model is now providing operational forecasts on a one degree grid for the Australian region driven by winds from the operational numerical weather prediction model. For tropical cyclone studies it has been adapted to run in a menu-driven interactive mode in conjunction with the tropical cyclone model.

3. VERIFICATION RESULTS

Verification of model hindcasts of sea-surface elevations and depth-averaged currents driven by a typical extratropical cold front has been presented previously in Hubbert et al. (1990). The results of several tropical cyclone studies reported in Hubbert et al (1991) are reproduced in Table 1.

Table 1: Observed and model maximum storm surge magnitudes (reproduced from Hubbert et al (1991))

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Location</th>
<th>Sea surface elevation (metres)</th>
<th>observed</th>
<th>model</th>
<th>error</th>
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</thead>
<tbody>
<tr>
<td>Winifred</td>
<td>Clump Point</td>
<td>1.6</td>
<td>1.5</td>
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<td></td>
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<tr>
<td>Aivu</td>
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<tr>
<td>Jason</td>
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<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Jason</td>
<td>Burkstown</td>
<td>3.5*</td>
<td>3.3</td>
<td>-0.2</td>
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</tr>
<tr>
<td>Hazel</td>
<td>Carnarvon</td>
<td>1.3</td>
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<td>Geraldton</td>
<td>0.7</td>
<td>0.6</td>
<td>-0.1</td>
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</tr>
</tbody>
</table>

* = estimated observations from a beach survey

Wave heights during tropical cyclones derived using the Australian version of the WAM model have not been reported previously. The typical root mean square error observed on the west coast of Tasmania with the one degree Australian region operational version of the model is 0.7 m.

4. TROPICAL CYCLONE ORSON

Since the adoption of the WAM model to tropical cyclone wave height forecasting the system has been used in several environmental impact studies (e.g. near Darwin, Mornington Island and Port Hedland). This paper reports the results of a case study of the ocean response to tropical cyclone Orson along the northwest coast of Australia. Orson passed within 4 kms of the Woodside North Rankin gas platform on the Australian northwest shelf at 1600 hours UTC on April 23, 1989 on its way to a coastal crossing five hours later. As Orson passed North Rankin the central pressure was measured as 905 hPa (the lowest ever recorded in the Australian region) and the peak 10 minute mean wind at 38 m was measured as 74 m/s. Using a logarithmic boundary layer reduction factor the maximum surface wind was therefore 56 m/s.

The wave rider buoy at North Rankin measured a peak significant wave height of approximately 10 m before it was damaged and stopped recording. This measurement is believed to have been the maximum. Ocean currents measured by the current meter at mid-depth at North Rankin peaked at 1.10 m/s.

Fortunately astronomical tides were falling as Orson approached the coast and the effect of the storm surge was reduced. At the time of landfall the predicted tidal height at King Bay near Dampier was 1.6 m, substantially less than the highest astronomical tidal level of 5.1 m. The sea level measured by the tide gauge at King Bay was 4.7 m giving a storm surge of 3.1 m.

4.1 Simulation of Sea Level Winds and Pressures

Tropical cyclone Orson was simulated using the tropical cyclone model with a "b" parameter value of 1.5, an environmental pressure of 1005 hPa and the "best track" data for position, central pressure and radius of maximum winds. The best track data, which was obtained from the Perth office of the Bureau of Meteorology, is the cyclone track derived from a re-analysis of all data after the event.

The tropical cyclone was simulated for a period of eighteen hours prior to crossing the coast. The resultant wind fields produced by the model as Orson passed North Rankin platform and again at the coastal crossing are shown in Figures 1a and 1b. The maximum wind speed generated by the model at North Rankin platform was 55 m/s compared with the measured peak 10 minute average wind speed of 56 m/s.

4.2 Simulation of the Storm Surge and Ocean Currents

The storm surge model was run for the eighteen hour period forced by the hourly winds and atmospheric pressures from the tropical cyclone model. The model sea surface elevations near to the time that Orson crossed the coast are shown in Figure 2. The model time series of surge heights is compared with measurements at King Bay in Figure 3. The model surge reached a maximum of 3.0 m at the nearest grid point to King Bay which is in good agreement with the measured peak surge of 3.1 m above the astronomical tides. The depth-averaged ocean currents as Orson passed North Rankin are shown in Figure 4. The model time series of depth-averaged currents at North Rankin is shown in Figure 5.

The peak depth-averaged ocean current at North Rankin produced by the model was 0.96 m/s compared with the observed mid-depth current of 1.10 m/s. This agreement is quite good in view of the fact that the depth-averaged current and the mid-depth current are not necessarily the same.
Figure 1a. Surface wind speed contours (m/s) and directions from the tropical cyclone model near North Rankin platform.

Figure 1b. Surface wind speed contours (m/s) and directions from the tropical cyclone model near King Bay.

Figure 2. Sea surface elevation contours (m) from the storm surge model at landfall of tropical cyclone Orson.

Figure 3. Comparison of storm surge time series (in metres) from the model (solid line) with observations at King Bay (dashed line) on April 23, 1989.
Figure 4. Depth-averaged ocean current speed contours (m/s) and directions as tropical cyclone Orson passed North Rankin platform.

Figure 5. Time series of depth-averaged ocean current speeds (m) at North Rankin platform on April 23, 1989.

Figure 6a. Significant wave height contours (m) from the wave model as tropical cyclone Orson passed North Rankin platform.

Figure 6b. Significant wave height contours (m) from the wave model as tropical cyclone crossed the coast.
4.3 Simulation of Ocean Surface Waves

The wave model was also run for the eighteen hour period forced by the hourly winds from the tropical cyclone model. The significant wave heights near to the time that Orson passed North Rankin and five hours later at the time Orson crossed the coast are shown in Figures 6a and 6b. The peak significant wave height produced by the model at North Rankin was 10.2 m compared with the measured peak height of approximately 10 m. The peak significant wave height produced throughout the simulation of Orson was 12 m.

5. CONCLUSIONS

A tropical cyclone forecasting system has been described that models the cyclone winds and pressures and the ocean sea-surface elevations, depth-integrated currents and surface waves. The system runs on modern 80386 or 80486 personal computers or on Unix workstations. The atmospheric forcing is provided by an adaption of the analytical-empirical model of Holland (1980). The surge forecasts are based on the depth-integrated numerical storm surge model of Hubbert et al. (1990). The wave forecasts are based on a wave model adapted from the WAM model developed originally by the WAMDI group (1988).

The system is operated via a screen menu that provides for an arbitrary selection of forecast domain anywhere on the globe. The input requirements for tropical cyclone case studies are positions, central pressures and radii of maximum winds at arbitrary time intervals leading up to landfall.

It has been shown that the system provides a highly reliable method of determining the likely extreme marine response to tropical cyclones. In the case study of tropical cyclone Orson the system, when run at a resolution of 10 km, accurately simulated the cyclone winds and pressures in the vicinity of the centre of the cyclone as it passed North Rankin platform.

The maximum mid-depth ocean currents and the peak significant wave height at North Rankin together with the peak storm surge at King Bay were also simulated accurately. The storm surge results confirm the accuracy of the system reported in Hubbert et al (1991).

6. REFERENCES


