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# Tropical Cyclone Surge Penetration Across The Great Barrier Reef

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SUMMARY. An evaluation of the impact of the Great Barrier Reef on tropical cyclone storm surge development and propagation on to Australia's Coral Sea coast is presented. The physical processes involved in the meteorological forcing and the hydrodynamic response in the presence of coral reefs are first discussed. Confirmation and quantification of this behaviour follows from a series of numerical experiments with a numerical hydrodynamic model of the cyclone "Althea" storm surge near Townsville in December, 1971. The Reef was found to have a major influence on the continental shelf flow patterns but only a relatively minor influence on the magnitude and timing of the peak surge.

## 1 INTRODUCTION

The continental shelf along Australia's Coral Sea coast is dominated by the 1900 km Great Barrier Reef, a continuous chain of quite separate coral reef clusters located near the edge of the continental shelf. The separate reefs are often exposed at low tide, the inner fringe of the clusters ranges from 10 km offshore north of Cairns to 200 km offshore near Rockhampton and the outer fringe is typically some 50 km further offshore, beyond which the ocean bed drops rapidly away. These reefs clearly provide some protection from *ocean wave* penetration from the Coral Sea as short period waves would normally break on the reefs, dissipating a significant amount of energy before reforming inside the inner fringe.

The influence of these reefs on *long wave* penetration however is quite different. Wave breaking would be unlikely as incident wave lengths are quite long (of order 100 km for storm tides, even greater for astronomical tides) and hence wave steepness would be very small. They most probably act as some form of partial flow barrier, allowing only a relatively small flow over the top in addition to unimpeded flow between the individual coral reefs.

The quite considerable variation in astronomical tide characteristics along the Queensland coast has yet to be explained. They vary from mixed semi-diurnal and diurnal with a mean springs range of under 2 m at the Gold Coast, through essentially semi-diurnal with a range of over 6 m at Broad Sound and Mackay, and back to mixed tides with a range of 2.5 to 3 m at Townsville and Cairns. Tide penetration from the Coral Sea might be sufficient to excite resonant oscillations on the continental shelf between the Reef and coastline. Alternatively or even additionally the behaviour might result from rotating Kelvin waves about possible amphidromic points in the Coral Sea. While there is no evidence at present to support either of these possibilities, there is at least sufficient reason to anticipate the possibility of unusual meteorological tide response in this area.

Australia has yet to experience a really devastating storm tide, although the serious loss to life and property in Holland 1953 and Bangladesh 1973 serve as a grim reminder of what we may have in store. Certainly some tropical cyclones in the Coral Sea region have resulted in meteorological tides of significant magnitude. The 1899 Bathurst Bay cyclone "Mahina" (915 mb) was accompanied by a substantial surge, reportedly 14 m, although this figure must include wave run-up. During cyclone "Althea" (952 mb) in December 1971 the Townsville Harbour Board tide gauge recorded water levels up to 2.9 m above the predicted astronomical tide. The influence of the Great Barrier Reef on the generation and propagation of a tropical cyclone storm surge is not immediately clear. The hydrodynamic forcing is local (but still large scale) and direct in contrast with the astronomical tide where forcing is remote and somewhat indirect in its local manifestation.

This paper begins with a qualitative discussion of what might be the hydrodynamic response to the passage of a landfalling tropical cyclone from the Coral Sea across the Great Barrier Reef and the continental shelf. This is followed by a more detailed quantitative evaluation, using a numerical hydrodynamic model, of surge penetration across the Reef and the continuing generation and propagation on the continental shelf.

## 2 STAGES IN THE DEVELOPMENT OF THE STORM TIDE

The tropical cyclone (or hurricane or typhoon) is essentially an atmospheric phenomenon,developing over tropical seas in mid to late summer. Extremely low central pressures (<960 mb at M.S.L.), high vortex winds (> 40 $ms^{-1}$) and the presence of an eye are the dominant features of the atmospheric flow structure (Ref. 1). The aerodynamics of the tropical cyclone and the hydrodynamics of the underlying water body are coupled at the water surface by the atmospheric pressure and wind shear stress. The M.S.L. pressure and the sustained wind both change significantly with distance from the eye, which itself moves forward, typically in a south-westerly direction in the Coral Sea region, and perhaps changing speed and direction in the process. The hydrodynamic response is clearly a rather complex and transient long wave motion.

The two components of the applied stress at the water surface act in quite different ways. The characteristic vee-structure of the atmospheric pressure profiles induces a superelevated mound of water, the so-called inverse barometer effect, that broadly mirror-images the pressure profile. For a stationary cyclone the build-up of this mound of water requires a radial inflow to satisfy mass conservation. As the cyclone moves the situation becomes much more complicated but some general trends are apparent. This pressure surge is essentially a hydrostatic effect and is independent of depth. In the deep water beyond the Reef (see Fig. 1) the total storm tide is predominantly pressure surge and the accompanying radial inflow of water towards the eye results in an initial draw-down of the water surface along the stretch of coastline closest to the eye; further to the right (north) and left (south) of the projected path this effect is not so apparent. It would appear that the presence of the Great Barrier Reef might attenuate the offshore flow and reduce the initial draw-down. With the passage of the eye across the Reef and continental shelf the onshore flow might now be impeded. In the relatively confined region of the shelf, the low central pressures in the eye region might tend to induce longshore currents from the north and south, although it would be expected that the total surge inside the Reef would be largely dominated by the wind tide.

The influence of the surface wind shear is largely confined to the shallower waters of the shelf. It is well established (e.g. from a comparison of the water surface gradient and wind shear terms of the momentum conservation equations given below) that the wind tide is depth-dependent, the water level in general increasing with decreasing depth for an onshore wind. Fig. 1 shows a typical cross-section through the continental shelf bathymetry (Section A-A is located on Fig. 4); depths increase rapidly beyond the Reef and it is clear that surface wind shear effects will be significant only within the continental shelf. Wind speeds decay relatively slowly away from the eye-wall and wind effects will be experienced on the shelf well before the cyclone actually crosses the Reef. The clockwise vortex winds would result in an initial longshore flow to the north along the shelf, that the Reef might confine to some extent to the shelf region. As the eye approaches and crosses the Reef the vortex structure of the wind forces an onshore flow and wind set-up along the coast to the south of the path and an offshore flow and wind set-down to the north. The Reefs would impede this developing circulation pattern, perhaps increasing the horizontal scale of the circulation. As the eye approaches and crosses the coast the wind tide increases rapidly in magnitude in the shallower near-shore waters. As already mentioned the reefs would be expected to reduce the initial draw-down along the coast, leaving perhaps more (deeper) water on the continental shelf, which in turn might have the effect of marginally reducing the surge levels at the coast around the time of cyclone landfall. The extended scale of the circulation pattern might simultaneously broaden the longshore extent of the surge wave.

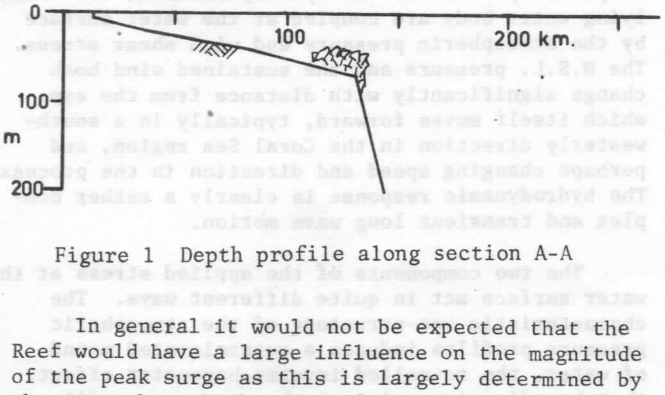



Figure 1 Depth profile along section A-A

In general it would not be expected that the Reef would have a large influence on the magnitude of the peak surge as this is largely determined by the near-shore bathymetry of the continental shelf. One would anticipate however that perhaps the timing and longshore extent of the coastal surge and certainly the overall flow pattern would be significantly influenced by the Great Barrier Reef.

## 3 THE NUMERICAL HYDRODYNAMIC MODEL

A numerical hydrodynamic model SURGE that describes the development and propagation of tropical cyclone storm surge has been developed within the Department of Civil and Systems Engineering at James Cook University. Full details of this model are given in Ref. 2 and only a brief summary of the relevant aspects are given here.

Surge wave propagation is described by the Long Wave Equations, expressing respectively the conservation of mass and the conservation of momentum in spatial directions x and y:

$$\frac{\partial\eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{U^2}{h+\eta}\right) + \frac{\partial}{\partial y}\left(\frac{UV}{h+\eta}\right) - fV$$
$$= -g(h+\eta)\frac{\partial\eta}{\partial x} - \frac{h+\eta}{\rho_w}\frac{\partial p_s}{\partial x} + \frac{1}{\rho_W}(\tau_{xs} - \tau_{xb}) \qquad (2)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\frac{UV}{h+\eta}\right) + \frac{\partial}{\partial y}\left(\frac{V^2}{h+\eta}\right) + fU$$
$$= -g(h+\eta)\frac{\partial\eta}{\partial y} - \frac{h+\eta}{\rho_W}\frac{\partial p_s}{\partial y} + \frac{1}{\rho_W}(\tau_{ys} - \tau_{yb}) \qquad (3)$$

The x-y datum plane is located at the mean water level with the z-axis directed vertically upwards. The water surface elevation with respect to datum is $\eta(x,y,t)$, the sea bed is $h(x,y)$ below datum, and U and V are depth-integrated flow velocities or discharges per unit width.

The forcing influence of the tropical cyclone is represented through the surface wind shear stress vector $\underline{\tau}_s(x,y,t)$, resolved into components $\tau_{sx}$ and $\tau_{sy}$, and the x and y gradients of the M.S.L. atmospheric pressure $p_s(x,y,t)$. The adopted spatial variations of both $\underline{\tau}_s$ and $p_s$ relative to the moving eye of the storm essentially follow the recommendations of the U.S. Weather Bureau (Ref. 3), where the spatial fields for sustained wind speed at height 10 m and M.S.L. pressure at a particular time are expressed in terms of the four parameters that are commonly assumed to characterise a tropical cyclone:

(a) Central pressure $p_o$ at Mean Sea Level.
(b) Maximum sustained wind $V_{10}$ at a height of 10 m above M.S.L.
(c) Radius of maximum winds R.
(d) Speed $V_E$ and direction of eye.

SURGE allows all four parameters to be varied continuously (after each time step $\Delta t$ if necessary) to represent changes in cyclone intensity and track. The recommendations in Ref. 3 for the relationship between the vector surface shear stress and the sustained wind field have been modified slightly in accordance with more recent work by Wu (Ref. 4).

The flow field, coastal details and offshore bathymetry (including the Reef) are represented on a square grid of typical unit dimension $\Delta x$ (=$\Delta y$) of 5 n miles (see Figs. 4 and 6 for typical details). The Long Wave Equations are integrated in time by an explicit finite-different procedure similar to that used in the numerical simulation of storm tides in Galveston Bay, Texas, by Reid and Bodine (Ref. 5). Solutions over the computational field are accomplished only at discrete points ($i\Delta x$, $j\Delta y$, $n\Delta t$), that are located on a space and time staggered grid, with water levels $\eta$ (or H in FORTRAN) and depths at points ($i,j,n+\frac{1}{2}$), x-direction flows U at ($i+\frac{1}{2},j,n$) and y-direction flows V at ($i,j+\frac{1}{2},n$), where i,j and n now can have only integer values. The finite-difference approximation to the continuity equation (Eq.1) is centred at (i,j,n), the x-momentum equation (Eq.2) at ($i+\frac{1}{2},j,n+\frac{1}{2}$) and the y-momentum equation (Eq.3) at ($i,j+\frac{1}{2},n+\frac{1}{2}$). If the convective accelerations and the bed friction terms are omitted (but these terms are definitely included in SURGE), the finite-difference equations are represented by the computational molecules shown in Figs. 2a and 2b respectively.

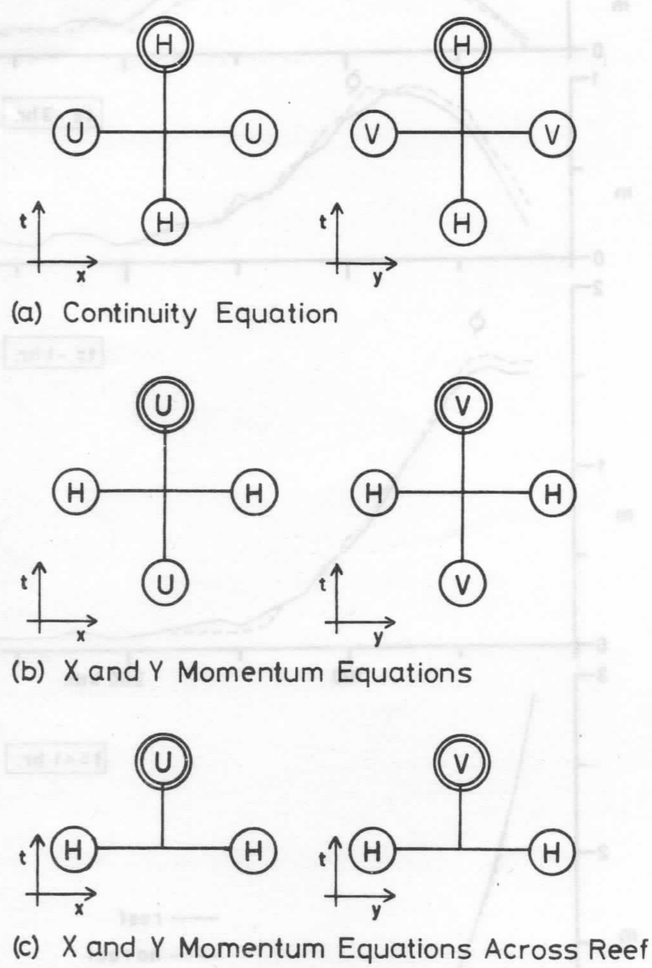



Figure 2 Computational molecules

The coastline is represented by no flow conditions U = 0 or V = 0 depending on the orientation of the boundary. Open boundary conditions (typically to the north, east and south for the Coral Sea) are somewhat more complicated as the geophysical scale of the meteorological forcing normally exceeds the area that can feasibly be modelled on a digital computer. The forcing influence of the tropical cyclone outside the computational field must be included in the open boundary conditions and this was found to be most satisfactorily accomplished (Ref. 6) by adopting as the open boundary water levels the local (quasi-static) bathystrophic storm tide. Flow constraints within the computational field imposed by islands (no flow) and reefs (see Section 4) are also included in SURGE. In most cases these boundary conditions require some interpretation in terms of the general finite-difference equations; two or more constraints could apply at the same point and in many cases the spatial coverage of the general finite-difference schemes needs to be restricted in the vicinity of a constraint. All this information is supplied to the model by the systematic specification of sixty different flag conditions.

## 4 MODEL REPRESENTATION OF A CORAL REEF

Topographic details on the Great Barrier Reef are somewhat sketchy; typically plan dimensions of separate reefs exceed several kilometers, and the reef crests are exposed at low tide. In terms of long wave propagation it would seem appropriate (Fig. 3) to represent their influence within the flow field as a submerged broad-crested weir, a broad-crested weir or a total flow barrier, depending on the crest elevation of the reef with respect to the instantaneous water levels on both sides.

The weir equations for discharge per unit width in each case are (Ref. 7):

(a) Submerged broad-crested weir,

when $H_u > H_d > Z_{crest}$:

$$q = C_1[\tfrac{1}{2}(H_u+H_d) - Z_{crest}][g(H_u-H_d)]^{\frac{1}{2}} \qquad (4a)$$

where $C_1$ can be taken as approximately $(2)^{\frac{1}{2}}$.

(b) Broad-crested weir,

when $H_u > Z_{crest} > H_d$:

$$q = C_2\ (H_u - Z_{crest})\ [g(H_u - Z_{crest})]^{\frac{1}{2}} \qquad (4b)$$

where $C_2$ can be taken as $(\frac{2}{3})^{1.5} \doteqdot 0.5$

(c) Total flow barrier,

when $Z_{crest} > H_u$ and $H_d$:

$$q = 0. \qquad (4c)$$

Coral reefs are located through U and/or V points with Eq.4 interpreted in terms of the adjacent H points, replacing either Eq.2 at a U point or Eq.3 at a V point. Fig. 2c shows the resulting computational molecules at both U and V points.

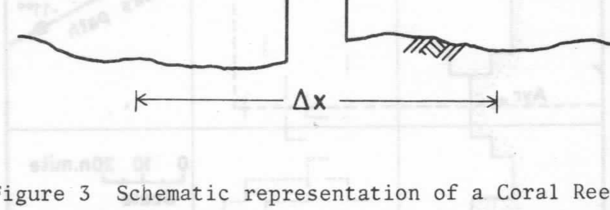



Figure 3 Schematic representation of a Coral Reef

A significant problem remains in the specification of realistic reef crest elevations $Z_{crest}$. Navigation charts give little detail other than statements such as "awash at half-tide" and "heavy breakers" and precise levelling in such a situation is very difficult. A uniform reef crest level of

-1m to M.S.L. datum has been adopted as a representative elevation. Comparative computations were undertaken with reef crests at M.S.L. and the differences in the computed flow fields were quite minor; crest elevation above M.S.L. would be rare. Figs. 4 and 6 show the model representation of the Great Barrier Reef off Townsville.

## 5 SURGE PENETRATION ACROSS THE REEF

A series of numerical experiments were conducted at several locations along the Coral Sea coast with a view to quantifying the influence of the Great Barrier Reef on surge development and propagation. As preliminary experiments had indicated that a realistic plan representation of the gaps between separate coral reefs was very important it was considered appropriate to relate the experiments as closely as possible to real situations.

The offshore bathymetry around Townsville is reasonably typical of the Coral Sea coast. To the north the Reef is closer to the coast, to the south further away. Fig. 4 gives an indication of the extent and the scale of the flow field considered, the broken lines representing the Great Barrier Reef. The tropical cyclone adopted was cyclone "Althea" (December, 1971), as described in Ref. 8. Two separate cases have been chosen to illustrate the trends:

(a) Reef fully modelled, crest height at -1m to M.S.L. datum, and

(b) Reef omitted.

Figs. 5 and 6 show some typical results during the passage of the cyclone from the Coral Sea across the coast north of Townsville. Zero time refers to the time of landfall.

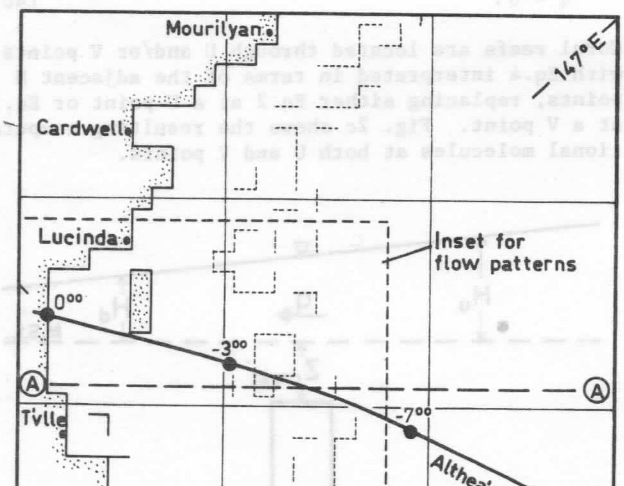



Figure 4 Townsville model grid

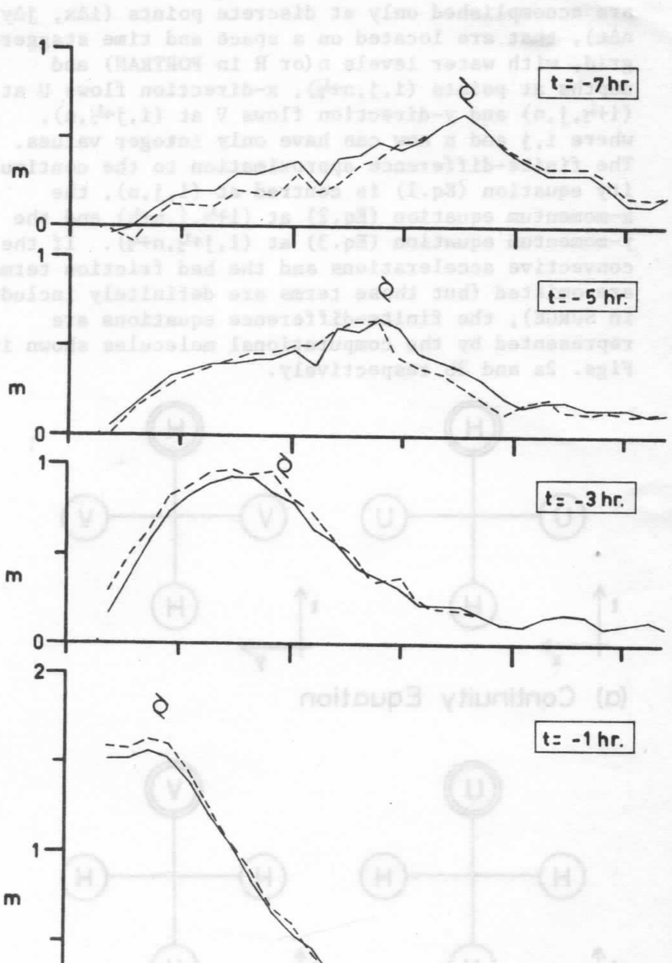
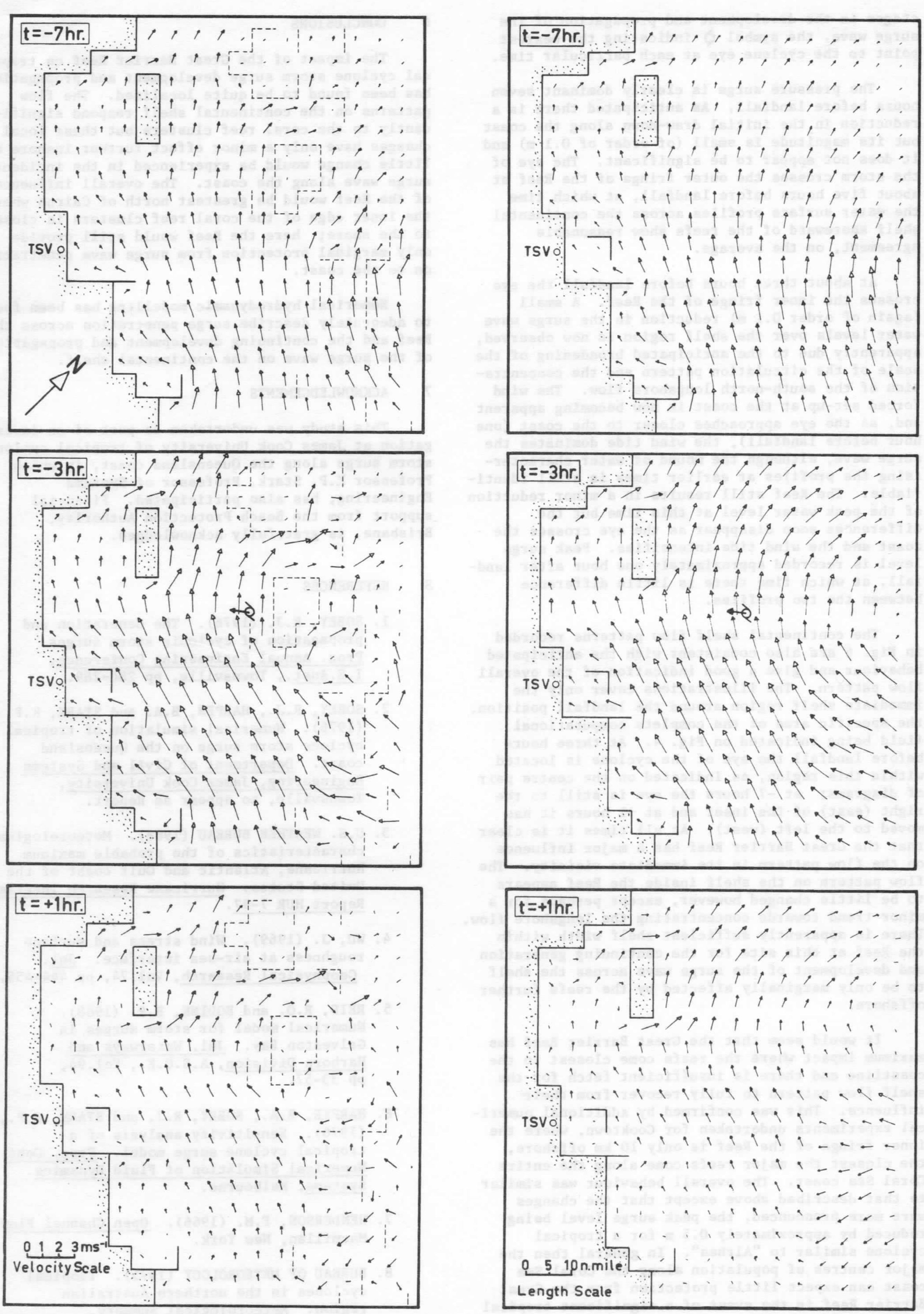



Figure 5 Water surface profiles along section A-A

Computed water surface profiles along Section A-A through Black River north of Townsville (see Fig. 4 for location) are shown in Fig. 5 for times ranging from seven hours before cyclone landfall to one hour after landfall. Black River is not far from the peak surge location and the cyclone path roughly follows the chosen cross-section. These results generally support the behaviour anticipated in Section 2 and provide good illustrations of the




(a) Including Reef (b) Excluding Reef

Figure 6 Continental Shelf flow patterns stages in the development and propagation of the surge wave, the symbol ϭ indicating the nearest point to the cyclone eye at each particular time.

The pressure surge is clearly dominant seven hours before landfall. As anticipated there is a reduction in the initial draw-down along the coast but its magnitude is small (of order of 0.1 m) and it does not appear to be significant. The eye of the storm crosses the outer fringe of the Reef at about five hours before landfall, at which time the water surface profiles across the continental shelf shoreward of the reefs show reasonable agreement, on the average.

At about three hours before landfall the eye crosses the inner fringe of the Reef. A small (again of order 0.1 m) reduction in the surge wave water levels over the shelf region is now observed, apparently due to the anticipated broadening of the scale of the circulation pattern and the concentration of the south-north longshore flow. The wind forced set-up at the coast is now becoming apparent and, as the eye approaches closer to the coast (one hour before landfall), the wind tide dominates the surge wave, although the mound of water characterising the profiles at earlier times is still identifiable. The Reef still results in a minor reduction of the peak water level at this time but the differences soon disappear as the eye crosses the coast and the wind tide intensifies. Peak surge level is recorded approximately one hour after landfall, at which time there is little difference between the two profiles.

The continental shelf flow patterns recorded in Fig. 6 are also consistent with the anticipated behaviour and give a good indication of the overall flow pattern. The illustrations cover only the immediate shelf region around the landfall position, the specific area of the complete computational field being indicated on Fig. 4. At three hours before landfall the eye of the cyclone is located within this region, as indicated on the centre pair of diagrams; at -7 hours the eye is still to the right (east) of the inset and at +1 hours it has moved to the left (west). At all times it is clear that the Great Barrier Reef has a major influence on the flow pattern in its immediate vicinity. The flow pattern on the shelf inside the Reef appears to be little changed however, except perhaps for a minor trend towards concentrating the longshore flow. There is apparently sufficient shelf width within the Reef at this site for the continuing generation and development of the surge wave across the shelf to be only marginally affected by the reefs further offshore.

It would seem that the Great Barrier Reef has maximum impact where the reefs come closest to the coastline and there is insufficient fetch for the shelf flow pattern to fully recover from their influence. This was confirmed by additional numerical experiments undertaken for Cooktown, where the inner fringe of the Reef is only 10 km offshore, the closest the major reefs come along the entire Coral Sea coast. The overall behaviour was similar to that described above except that the changes were more pronounced, the peak surge level being reduced by approximately 0.5 m for a tropical cyclone similar to "Althea". In general then the major centres of population along the Coral Sea coast can expect little protection from the Great Barrier Reef in the event of a significant tropical cyclone storm surge.

## 6 CONCLUSIONS

The impact of the Great Barrier Reef on tropical cyclone storm surge development and propagation has been found to be quite localised. The flow patterns on the continental shelf respond significantly to the coral reef clusters but these local changes have only a minor effect further inshore and little change would be experienced in the incident surge wave along the coast. The overall influence of the Reef would be greatest north of Cairns where the inner edge of the coral reef clusters is closest to the shore; here the Reef would still provide only marginal protection from surge wave penetration on to the coast.

Numerical hydrodynamic modelling has been found to adequately describe surge penetration across the Reef and the continuing development and propagation of the surge wave on the continental shelf.

## 7 ACKNOWLEDGEMENTS

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