CHAPTER SIXTEEN

SIMULATION OF TIDES AND STORM SURGES IN THE GREAT BARRIER REEF REGION

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The Great Barrier Reef Region which constitutes the north-eastern continental shelf waters of Australia, is an area that is subject to both large astronomical tides and the passage of tropical cyclones (hurricanes). One section of this area, centred on Mackay, is characterised by particularly high tides, with a springs range of order 10 metres. Numerical hydrodynamic modelling is used in the present study to: (a) simulate the M tide to investigate possible effects of the reef barrier on tidal amplification; (b) simulate the passage of a tropical cyclone across the continental shelf; (c) investigate the effect and consequences of non-linear surge/tide interactions. The recent discovery of a major shipping route through the reef in this area and the continuing development of natural resources makes a much more detailed understanding of the region's hydrodynamics essential for coastal engineering.

INTRODUCTION

The Great Barrier Reef (GBR) extends in an almost unbroken chain along some 1200 miles of the Queensland coast of Australia. The area between the coastline and reef (the 'lagoon') is of key importance to engineers, oceanographers, development consultants and shipping; it is of unique biological importance and supports significant fishing and tourism industries. The area of particular interest to the present study is centred on the city of Mackay, with the model's location and extent being delineated in Fig. 1. This area's hinterland is rich in natural resources and this has resulted recently in an upsurge of development, particularly in the exploitation of massive nearby coal reserves. The possibility also exists of large scale development of extensive shale-oil deposits in the longer term.

Shipping within the GBR Region is therefore very important and coastal engineering projects range from the development of port and harbour facilities, and the construction of deep-water ports to consideration of environmental problems associated with potential shipping disasters. The newly-discovered shipping channel through the main reef, Hydrographer's Passage, is also shown in Fig. 1. This provides much easier and more economical access for international shipping to Mackay.

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<u>Fig. 1</u> Model region with solid rectilinear boundaries of computational region superimposed on the actual coastline. Dashed curves depict bathymetry (m); dashed rectilinear elements represent reef and low barriers. The hatched region is Hydrographer's Passage. Also shown is the cyclone track through the region. Latitude and longitude of the region are indicated.

However, it is also clear that although the initial shipping traffic through the new passage will be relatively small, it will be necessary to evaluate the additional risks, environmental and ecological, that will be superimposed on the region. Such evaluations require a detailed understanding of the hydrodynamic interactions of the complex tidal and meteorological forcing mechanisms that apply in this area.

In this southern (Mackay) section of the GBR Region, the pattern of the astronomical tides is of considerable scientific and applied interest. Tides are much higher than, and exhibit large phase lags relative to areas to the north and south. Spring tides can have a range of up to 10 metres. Recent numerical studies by the authors have lent weight to the hypothesis [first proposed, incidentally, by the maritime explorer Matthew Flinders in 1814], that the reef chain itself plays a key role in the attainment of such large water levels (1). The area is also subjected to the influence of strong and persistent longshore winds for a large part of the year. In addition, the occasional incidence of the passage of tropical cyclones means that such extreme meteorological forcing and the associated water levels and currents, must be included in any coastal engineering assessment of the area.

Aims and Objectives

The work to be discussed in this paper comprises three parts. The first is an investigation of the factors which lead to the large amplification of the semi-diurnal astronomical tides. In particular the role played by the dense reef barrier in the tidal dynamics is considered by means of numerical modelling. The second part of the work considers the effect of the passage of a tropical cyclone through this area. In view of the extremely large water levels that are attainable from each of these forcing mechanisms, the ultimate effect of surge/tide interactions on the total water level and currents could well be considerable and should be incorporated in the design of important coastal engineering works in this area, since variations of fractions of a metre in levels could have significant economic implications. This aspect of the coastal hydrodynamics is often neglected and forms the third part of the study.

METHOD OF SOLUTION

The above cases are treated numerically by the solution of the two-dimensional (depth-integrated) long wave equations. Solution techniques for such models are by now more or less conventional and will not be referred to in any detail. Further details of the model can be found in Refs. (1,7,11,12). The equations of motion to be solved are:

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x} (\frac{U^2}{H}) + \frac{\partial}{\partial y} (\frac{UV}{H}) - fV = -H\frac{\partial}{\partial x} [g \eta + \frac{P_a}{\rho}] + \frac{1}{\rho} (\tau_{sx} - \tau_{bx}) , \qquad (1)$$

$$\frac{\partial \mathbf{V}}{\partial t} + \frac{\partial}{\partial \mathbf{x}} (\frac{\mathbf{U}}{\mathbf{H}}) + \frac{\partial}{\partial \mathbf{y}} (\frac{\mathbf{V}^2}{\mathbf{H}}) + \mathbf{f} \mathbf{U} = -\mathbf{H} \frac{\partial}{\partial \mathbf{y}} [\mathbf{g} \ \eta + \frac{\mathbf{p}_a}{\rho}] + \frac{1}{\rho} (\tau_{\mathbf{s}\mathbf{y}} - \tau_{\mathbf{b}\mathbf{y}}) , \qquad (2)$$

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t x, y = $\eta = $ H = g P a τ sx τ v V = U = η	$\eta(\mathbf{x})$ $h(\mathbf{x})$ $h + \mathbf{y}$ \mathbf{y} \mathbf{y} \int_{-h}^{h}	,y,t ,y) η	-)		tlsutCgawccccwa	im cend or and transformer of he	e, al is io is io io io io io io io io io io io io io	horizontal Cartesian co-ordinates, arface elevation, referred to M.S.L. datum, curbed water depth, water depth, lis parameter, assumed constant tational acceleration, pheric pressure density, assumed constant, nents of surface stress $\tau_{\rm b}$, nents of bottom stress $\tau_{\rm b}$, nents of horizontal transport per unit width of section, defined by u is the average velocity and \bar{u} the depth ged mean velocity, in the x-direction.
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A similar definition holds for V (and \overline{v}). The equations are solved by an explicit finite-difference technique on a uniform grid that is staggered both spatially and temporally (a Richardson lattice).

An additional and complicating factor in this region, however, is the necessity of formulating a suitable physical model of the GBR chain that can be incorporated within the numerical model. The reef would appear to play a number of roles, acting as a possible means for both large-scale tidal amplification plus considerable smaller-scale dissipation, a generator of extreme currents locally, and as possible offshore protection from even more extreme storm surge levels. In this and the works cited above, reefs and other low barriers (such as the extensive band of sandbanks at the mouth of Broad Sound) are modelled as weirs - after the approach of Reid and Bodine (11) and Sobey et. al. (12,13).

The model region has been shown already in Fig. 1. Both the actual coastline and its model approximation on the square grid of spatial resolution, $\Delta s = 5$ n miles are shown. This value allows considerable, although not complete resolution of individual reef elements. The figure also shows the region's bathymetry as well as the model's approximation of the reef structure and submerged barriers, which are represented by the dashed rectilinear elements. For the purposes of comparison of the various results that follow, particular attention will be paid to grid point (5,29) in the mouth of Broad Sound. This is the location of Flat Isles where, in fact, Flinders was moored for two weeks in 1814. This point is in the area of maximum tides as well as surge for the chosen model cyclone.

TIDAL MODEL

In the Mackay region, tides are predominantly semi-diurnal. In particular the M constituent accounts for roughly 50% of the total tidal range, as seen from Table I. As a result, M can be taken as representative of a mean tide over the spring-neap²cycle. It should be remembered, however, that total tidal water levels can be up to double these values. The tidal model is driven by imposing the M tide (amplitude and phase) along the three open boundaries. The tidal² amplitude is increased from zero to its full value over a build-up period of 6 hours in order to reduce the unwanted effects of initial transients (1,2).

TABLE I

RANGE OF PRINCIPAL TIDAL CONSTITUENTS (METRES) AT SELECTED LOCATIONS IN THE STUDY AREA, TOGETHER WITH THEIR SUM

Location	M2	5 ₂	N 2	ĸ	01	P ₁	Sum
Bowen	1.50	0.61	0,40	0.64	0.34	0.21	3.70
Hook Island	1.72	0.63	0.45	0.71	0.35	0.24	4.10
Mackay	3.36	1.20	0.80	0.76	0.40	0,23	6.75
Broad Sound	4.84	1.42	0.43	0.92	0.42	0,25	9.28
(McEwin Islet)							
Pt. Clinton	2.74	1.10	0.63	0.64	0.32	0.21	5.64
Bell Cay	2.26	1.20	0.42	0.46	0.32	0.21	4.87
Gladstone [(1,1) on Fig.1]	2.32	0.84	0.53	0.50	0.28	0.16	4.63

At present, there remains some uncertainty about this specification of the open boundary conditions, particularly along the edge of the continental shelf. Obtaining data along this stretch is made difficult by the fact that, apart from Hydrographer's Passage, no approach to the shelf edge can be made from the lagoon. Outside the reef, seas are generally too large for safe and recoverable deployment of instruments. Portunately, this situation is improving and proposed field experiments should help to remedy some of the inevitable uncertainties.

Tidal Results

Fig. 2 shows the results of a simulation of the M tide in this region. The notable feature is the effect of the 'reef': ²the relatively large gradients of surface elevation and the large phase change across the central (and densest) portion of the reef chain, indicate considerable flow retardation. The mechanism of tidal amplification can also be seen from this figure. The phases of the resultant tidal streams from the north and south are such that they tend to reinforce each other in the central part of the region. The resulting pattern is essentially a standing wave, with almost uniform phase over this large central portion. The tide subsequently progresses up Broad Sound with considerable further amplification.



<u>Fiq. 2.</u> Co-amplitude (m) and co-phase (g) contours for M tide. Grid size is 5 n miles; rectilinear elements depict reefs, etc.

M tidal ellipses, shown at every grid point in each coordinate direction, are presented in Fig. 3. They show the essential pattern of the tidal streams, while the indicated phase depicts the variation from an essentially progressive wave towards a standing wave pattern. The maximum amplitude of the tidal current is 1.8 ms⁻¹ (or roughly 3.5 knots) near grid point (25,32). However, personal observations indicate that for the area of the outer reef, tidal currents of order 6 knots are not uncommon between individual reefs.



Fig. 3 M, tidal ellipses for central 'window' of model region.

The effects of the reef on the propagation of the tides can be further demonstrated with a numerical model by the complete removal of the reef elements from the model. The results of this numerical experiment are shown in Fig. 4. The amplification of the tides is now much reduced. For example, at grid point (5,29), the M amplitude is reduced from 2.66 m in Fig. 2 to 2.01 m in Fig. 4. In addition, the tides are no longer so retarded at the edge of the shelf and phases and, as a result, are significantly earlier - by roughly 0.7 h - in the central coastal portion of the model region. The results of this simulation lend strong support to the original Flinders hypothesis of reef retardation leading to longshore lagoonal resonance - see also Ref. (9).



Fig. 4 As for Fig. 2 but without 'reef'.

STORM SURGE SIMULATION

In 1918 Mackay was hit by a tropical cyclone with an estimated central pressure of 940 mb. A significant component of the damage was due to the effects of storm surge (estimated at over 3.6 m at Mackay) and wave action, with the storm crossing the coast near the time of high tide. The combination of extreme winds and very high surge water levels devastated the town.

An engineering study of the effects of storm surges without tides at Mackay has been carried out previously - Ref. (5). In the present study, a simulated tropical cyclone of similar estimated magnitude to the 1918 storm is allowed to pass through the model region along the track indicated in Fig. 1. Altogether, a number of different simulations were effected, mainly to investigate the effect of the speed of forward movement and the phase of the storm relative to the tides, on the strength of the surge/tide interaction. The prototype storm, however, is identical to that used by Bode and Stark (3), although some recent modifications to the parameterisation of the wind stress field, suggested by Bode and Sobey (4) have been incorporated subsequently. The actual parameters governing the storm are detailed in Table II.

TABLE II

PHYSICAL PARAMETERS GOVERNING THE SIMULATED TROPICAL CYCLONE OF THIS STUDY

Return Period	500 years
Central Pressure	940 mb
Ambient Pressure	1013 mb
Radius of Max. Winds	30 km
Track (Bearing)	255°
Speed of forward movement	30 kph
Simulation Time	- 10 h to + 1 h
Initial Grid Position	(30.9, 46.1)
Final Grid Position	(0.2, 28.4)
Build-Up Time	4 hours

As with the tidal modelling, the storm is built up in magnitude over a number of hours, in order to minimise the unwanted effects of initial transients. The landfall position and path (Fig. 1) have been designed deliberately to cause maximum enhancement of the storm surge in the region of maximum tides (Fig. 2). According to Sobey *et al.* (11), the maximum surge for Southern Hemisphere cyclones should be situated a distance of order R, the radius of maximum winds, to the left of the eye at landfall, looking along the track of the storm. Thus both maximum tides and surge should occur around the mouth of Broad Sound, and it is hypothesised that this should result in a very considerable surge/tide interaction, to be discussed in the following section.

Figs. 5(a) and (b) show storm surge water levels for the standard run, at times of one hour before and after landfall (t = -l and +1) respectively. At the chosen point (5,29), the maximum surge is of order 4.3 m, although larger values are obtained farther up Broad Sound. Longshore currents are particularly intense and reach a maximum value roughly two hours prior to landfall (t = -2), as shown in Fig. 6. Maximum currents at this time are of order 1.7 ms⁻¹, or roughly 3.3 knots.



<u>Pig. 5</u> Sea surface elevation (m) above MSL for surge alone at times (a) t = -1 h and (b) +1 h with respect to landfall.

Fig. 7 shows the results of the standard surge simulation, but without reef elements at t = -1 - c.f. Fig. 4 for the corresponding tidal result. When compared with Fig. 5, it can be seen that, unlike the tides, storm surge water levels (and currents) are insensitive to the presence of even such dense reef structure as in the model region - see also Ref. (12). Apart from some minor differences, surge levels are almost unchanged by the absence of reef and peak levels are identical. Presumably, the transient nature of the forcing dictates such a response.





SURGE/TIDE INTERACTION

The calculations of the previous two sections have shown that both the storm surge and tidal phenomena have substantial magnitude, that are roughly of the same order. When this is considered along with the non-linearities of Eqs. (1)-(3), it would appear essential to consider the possible effects of surge/tide interactions. In other circumstances, this may not be necessary. For example, if the tide is the dominant effect, then it is possible to linearise the surge equation by appropriate techniques. Here, however, surge and tide are of the same order, but this presents no real difficulty with numerical modelling - boundary conditions and forcing terms from the individual simulations are added. The basic question is whether or not surge plus tide provided a sufficiently accurate estimate of the combined surge/tide simulation, and, if not, by how much does it under-estimate or possibly even over-estimate this?



Fig. 7 As for Fig. 5(a) but without reef.

In spite of the above, there has been scant attention given to hurricane surge/astronomical tide interactions, although there are some good reasons for this omission. Hurricanes in the US impact predominantly in the Gulf of Mexico where the astronomical tide is negligible, and hence total water loads are basically provided by the storm surge alone. In the UK and Europe tides are quite significant, particularly in the North Sea region, which has been subject to a number of devastating storm surges (10). However storms are of the mid-latitude variety: they are almost always less intense and slower moving than hurricanes and consequently differ considerably in their hydrodynamic response. The mid-latitude storm surge would appear also to be more amenable to analytical techniques. In this case, however, numerical modelling has demonstrated the importance of surge/tide interactions. Flather (5,8) has shown that surge hindcasts in the North Sea have been improved quite appreciably by joint consideration of the two effects.

Theoretical Considerations

The essential non-linearity of the problem has also made it difficult to assess analytically. One approach that has managed some progress is that of Prandle and Wolf (10), through a combination of statistical, analytical and numerical techniques, that concentrated mainly on the (one-dimensional) response of the Thames Estuary to a North Sea surge. Here it has been observed that the net surge tends to peak on the rising tide but not at high tide. In addition, it appears possible in some circumstances for there to be surge *amplification* as well as a change in the phase of the surge (10).

There are two main non-linear terms in the equations of motion. In Eq. (1), these are the pressure terms $(h+\eta)\partial\eta/\partial x$ and the quadratic bottom friction term. The first is affected by changes in the background water level and can be expected to change the propagation characteristics of a surface wave (its phase, principally), the second term is dissipative and is also affected by changes in water level - Eq. (1) - but the predominant effect is clearly due to the quadratic velocity term. Overall, the effect of a combined surge/tide might be expected to provide enhanced dissipation (by up to a factor of two!) if the surge and tide are of comparable magnitudes. An exception to this in one dimension is the case of opposing streams where the reduced dissipation may lead to possible surge amplification. An examination of the present two-dimensional case indicates that surge magnification would be most unlikely. In the case of a tropical cyclone storm surge, intense longshore currents (Fig. 6) are associated with the storm's passage across shallow continental shelf waters are . These provide a background against upon the quadratic friction term is applied, and the overwhelmingly likely result is a much higher dissipation rate with consequent damping in resultant elevation and current values. Prandle and Wolf (10) were able to show that the primary mechanism for surge dissipation was bottom friction; the pressure term had a negligible effect on surge levels, although, as noted above, the increase in background water level in the combined surge/tide case can result in higher wave celerities and consequent phase leads of peak surge levels. Both of these points are addressed below.

Results

Fig. 8 is a comparison of the sea surface elevations at 1 hour before landfall for the two cases: the sum of surge alone plus tide alone in (a) and the combined surge/tide simulation in (b). At the test position, grid point (5,29) the elevation at t = -1, which corresponds closely to the time of maximum surge, the elevations are 6.9 m and 6.1 m respectively. The marked reduction in total water levels for the combined simulation is apparent and is a most significant result.



<u>Piq. 8</u> Comparison of surface elevations (m) at t = -1 for (a) Surge + Tide, (b) combined Surge/Tide simulations.

The net surge at t = -1 is depicted in Fig. 9(a). This is obtained by subtracting the tidal elevation at t = -1 from the combined surge/tide elevation at the same time. The elevation at (5,29) is 3.5 m. This result can be compared with the case of surge alone in Fig. 5(a) for which the corresponding elevation is over 4.3 m. An alternative representation is shown in Fig. 9(b) which is a 'window' view of the central portion of the model region - reefs are omitted for clarity, although they were retained in the simulation. This figure gives the



<u>Fig. 9</u> (a) Net surge at t = -1 for combined surge/tide; (b) Excess elevation (m) of surge plus tide over surge/tide at t = -1.

excess elevation obtained from the addition of surge plus tide at t = -1 over the combined surge/tide elevations at the same time. This is obtained by subtracting the elevations of Fig. 9(a) from those of Fig. 5(a) and provides a measure of the extent to which the surge + tide result is conservative. Fig. 10 shows traces or time histories of the elevation and depth-averaged velocity components at (5,29). The chipping of the peaks is artificial and is due to the results of the numerical simulations being sampled much less frequently than the time step. Again, the reduction due to interaction, of both η and the velocity, particularly around the time of landfall, is clearly seen.



<u>Fig. 10</u> Traces of elevation and velocity components for surge plus tide and surge/tide simulations.

CONCLUSIONS

A number of important conclusions can be drawn from the present study. Firstly, the active role of the GBR chain in tidal amplification has been demonstrated. This is an unusual result, since elsewhere in the GBR Region, the reef appears to have a slightly dissipative effect on the tides, although in no way does it appear to act as a significant barrier. Here, by acting as a partial barrier to cross-shelf motion, longshore tidal streams are enhanced leading to an amplification, by the mechanism outlined. Storm surge levels, particularly for a track similar to that of the model storm of Fig. 1, would be very high in Broad Sound while longshore currents between there and Mackay would be of such magnitude as to cause significant changes to coastal morphology. The major result, however, is to show the significance of the surge/tide interaction. A reduction of total water levels of 1 metre is shown to be quite feasible and the corresponding economic and engineering implications warrant further attention in major coastal engineering studies.

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