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The Impact of Tropical Cyclone Olivia on Australia's Northwest Shelf

S J Buchan, WNI Science & Engineering
P.G. Black, NOAA Hurricane Research Div.
R.L. Cohen, WNI Oceanroutes

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Abstract
Tropical cyclone Olivia was the strongest storm of the 1995/96 season on Australia's Northwest Shelf. The storm caused significant damage to oil and gas facilities in the region. A broad spread of metocean measurements is available for this storm, enabling careful calibration of numerical simulations of associated winds, waves and currents. Together with tropical cyclone Orson (1989), this storm has led to a reassessment of metocean design criteria for the region.

Introduction
Tropical Cyclone Olivia was the most severe storm of the 1995/96 tropical cyclone season on Australia's Northwest Shelf. Wind gusts recorded on Barrow Island are believed to be the strongest ever measured anywhere in the world. Characteristics of the storm which contributed to its severity included:

- a central pressure as low as 925 hPa,
- a fast forward speed of up to 8 m s^{-1}, and
- the elliptical shape of the storm, contributing to elongated fetches.

The storm was monitored by remote wind and wave buoys in the deep water off the Northwest Shelf, and by a comprehensive real-time metocean monitoring system (REMS) on North Rankin (NRA) platform. Winds were also measured on Barrow and Thevenard Islands.

It is believed that waves generated by Olivia were responsible for damage incurred by the Campbell monopod in 40 m of water northeast of Barrow Island. Currents caused shifting of existing pipelines in the shallow water east of Barrow Island, and winds devastated facilities on Barrow and Varanus Islands.

Data from the deep water wave buoys provides important information on wave spreading under severe storms. Wave profile data from North Rankin demonstrates the variability of maximum single wave to significant wave height ratios. The wind data indicate that very extreme gust factors may apply in the eye wall of some severe tropical cyclones.

To provide answers to questions about actual storm loadings on various structures and pipelines, the winds, waves, currents and storm surge have been carefully modelled.

This paper describes some of the more important aspects of the measured data obtained under tropical cyclone Olivia, and illustrates the results of the numerical simulation of the storm.

Together with the recent occurrence of severe tropical cyclone Orson (April 1989), Olivia has caused a reassessment of design conditions on Australia's Northwest Shelf.

The wind measurements on Barrow Island are separately addressed in a companion paper (Black et al.)[1].

Geographic Setting
The southern portion of Australia's Northwest Shelf presently accommodates 24 marine oil and gas production facilities. The largest facility, North Rankin A platform, was also the first installed in 1984. It lies towards the northern periphery of the hydrocarbon domain, in 125 m of water.

Further developments lie shoreward of North Rankin, and along the shelf break extending from North Rankin southwest to the Griffin Venture FPSO, in about 130 m of water.

There are clusters of shallow water (40 m depth and less) developments to the northeast and south of Barrow Island.

Tropical Cyclone Olivia
In early April 1996, this region was bisected by tropical cyclone Olivia. It was the most intense storm of the season, with a minimum central pressure estimated to be 925 hPa within an ambient pressure of 1010 hPa. It had an eye diameter of the order of 75 km, and forward speed of 8 to 9 m s^{-1} through most of the domain of interest.

The storm track is illustrated in Figure 1, together with locations indicating the extent of the production region.

Historical Context
The Northwest Shelf region suffers from a relative paucity of tropical cyclone track data. Reasons contributing to this include the scarcity of coastal population centres, the

infrequency of merchant shipping, the lack of permanent offshore monitoring stations, and relatively poor coverage of coastal radar. No Northwest Shelf storms have ever been investigated by an instrumented aircraft. Consequently, great reliance is placed on satellite imagery and the application of the Dvorak technique, to provide storm location and central pressure estimates. Prior to satellite coverage, ship observations and coastal crossing information provided the only means of track estimation.

Satellite coverage of the Australian region commenced in 1959/60, and was not routinely operational until 1970. Therefore, it is very difficult to assess the overall severity of Olivia in an historical context. Figure 2, showing a time history of the lowest central pressures attained by all identified tropical cyclones approaching within 400 km of North Rankin location on Australia's Northwest Shelf, provides some measure of Olivia's relative severity. It also illustrates the inconsistency of pre-and post-satellite observations, via a 5 year running mean of lowest central pressures.

Storm Impact

The occurrence of Olivia caused the routine departure of FPSO's Cossack Pioneer and Griffin Venture from their moorings systems, and the early departure of an LNG vessel from Woodside's berthing facilities in Mermaid Sound.

All production facilities lying to the northeast of the track of tropical cyclone Olivia, were severely affected by the storm. Numerical modelling indicates significant wave heights exceeding 15 m at about 50 km to the west of North Rankin, and 10 minute mean wind speeds exceeding 56 m s^{-1} about 50 km to the east of Barrow Island. A peak 3 second gust speed of 113 m s^{-1} was recorded on Barrow Island. This is discussed in more detail in Black et al.[1].

Cyclone winds pushed over about 30 of the 400 beam pumps on Barrow Island, and caused substantial damage to buildings there and on neighbouring Varanus Island (off the northeast tip of Barrow Island).

Cyclone waves caused the collapse of the Campbell monopod, in 40 m of water about 40 km northeast of Barrow Island. According to Ronalds et al.[2], "it is believed to be the first platform designed since the 1980's to fail in this way around the world".

Waves in conjunction with very strong currents, caused the breaking of rock anchors on some sections of submarine pipelines, including the Barrow Island loadout line, and the Varanus Island Sales Gas line. Though the pipelines did move, they did not fail.

These impacts precipitated a detailed study of the influence of tropical cyclone Olivia, and a reassessment of design criteria at several Northwest Shelf production locations, including North Rankin and Stag facilities.

Most of the above locations of interest are illustrated in Figure 3.

Measurement Systems

WNI were in the fortunate position of being able to monitor tropical cyclone Olivia in real-time, via remote wind and wave buoys (installed for Woodside's Remote Offshore Warning System (ROWS)), a comprehensive metocean system (Rankin Environmental Monitoring System (REMS)) installed on Woodside's North Rankin platform, and by Woodside's Mooring and Environment Monitoring System (MEMS) installed at the LNG and LPG berths in Mermaid Sound. Winds were also measured on Barrow, Varanus and Thevenard Islands and waves were measured at Griffin location.

The locations of all abovementioned measurement sites are illustrated in Figure 3, which also shows the local cyclone track detail.

The ROWS comprises up to three Seatex (Wavescan) heave, pitch, roll (HPR) buoys, which monitor the directional spectral sea state and transmit the data via an Inmarsat C satellite link. The buoys also carry anemometers and atmospheric pressure sensors, which also assist in track definition. They are moored in water depths of 832, 366 and 86 m at HPR1, HPR2 and HPR3 locations, respectively. At the time of tropical cyclone Olivia, HPR3 buoy was not deployed.

The REMS comprises several components, including a Datawell Directional Waverider (with continuous HF telemetry to North Rankin 'A' platform), three anemometers (one at 100 m and two at 35 m above sea level), precision barometers, a downward-looking Acoustic Doppler Current Profiler, a downward-looking Marex radar air gap sensor, and other meteorological sensors. Supplementing REMS are five fixed, single-point current meters, a pressure activated tide gauge and Guyline Tension Monitoring System (GTMS) load cells. Data from the supplementary transducers are not available in real-time. However, data from all other sensors are updated on our Perth-based computer displays every 10 minutes, via Woodside's asynchronous network.

The MEMS is also linked into our Perth computers via the Woodside asynchronous network. Data displayed include directional wave spectra from two nearshore Datawell Directional Waverider buoys, berth-mounted wind data, tide data and hawser tensions for either LNG or LPG carriers.

Sample Data

At Varanus Island, a peak gust of 74 m s^{-1} was recorded, but on nearby Barrow Island, a much more remarkable wind record was obtained by WNI on behalf of West Australian Petroleum Pty Ltd (WAPET). This record has been released by WAPET, and is reproduced in Figure 4 for the 12 hours from 1200 (WST) on 10 April 1996.

The Barrow Island wind data show 5 minute mean wind speeds rising to 43.4 m s^{-1}, then falling to 34 m s^{-1} in the eye of the storm before rising again to a peak of 49.4 m s^{-1}. Of much greater significance though, are the 5 minute values of maximum 3 second gust. On the trailing eye wall of the storm, peak gusts rising to 113 m s^{-1} were recorded. These measurements are discussed in more detail in Black et al.[1].

North Rankin location reported a peak significant wave height of 12.6 m with 10 minute mean winds peaking at 27.1 m s^{-1}, and a peak gust of 37 m s^{-1}. The currents at the time of peak waves were unremarkable, being of similar magnitude to peak spring tidal currents. A time history plot of 10 minute mean winds (at 10 m above sea level), significant wave height and near-surface (12 m below MSL) current for the 12 hours from 1200 (WST) on 10 April 1996, is included in Figure 5. Note that the direction convention for currents is opposite to that for winds and waves.

The combined ROWS, REMS and MEMS wave data are illustrated in Figure 6, which presents a 12 hour time history of significant wave height (H_s), spectral peak direction (θ_p) and spectral peak spread ($\Delta\theta_p$), for HPR1, HPR2, North Rankin and Navaid 9 locations. The Navaid 9 waves are strongly constrained for a southerly direction by the physical sheltering and fetch limitation afforded by Mermaid Sound.

The frequency distribution of wave energy at the storm peak, is illustrated in Figure 7, taken from the results of directional spectral analysis of the North Rankin peak sea state. All spectral calculations were conducted at 10 minute intervals on a moving window of 1600 second wave profiles.

Numerical Simulation

Olivia was so severe, as to have substantial impact across the breadth of the southern Northwest Shelf. Accordingly, resort was made to numerical modelling, to extend our understanding of storm impacts well beyond the measurement locations.

Models adopted comprised a modified form of the Holland hurricane wind field[3], a refined form of the Young shallow water directional spectral wave model[4], and a substantially improved version of the Walker & Fandry fully 3D, baroclinic, z-coordinate wind and tide driven current model[5].

Calibration of these models against measured Barrow Island winds is illustrated in Figure 8, and against North Rankin waves, is illustrated in Figure 9.

The results of modelling storm peak significant waves across a 250 x 400 km domain (rotated at 30° anticlockwise from north to minimise land area), are illustrated in Figure 10. This figure is formed by contouring the largest H_s value which occurs at each of the 10 x 10 km grid points across the domain (i.e. it is not a snapshot in time, but a representation of the largest H_s attained at any time, at each grid point).

Specific Results from Measurements

Directional wave measurements at 4 locations across the shelf allows detailed investigation of the spread of high waves under tropical storm forcing.

Inspection of the spectral peak spread data from the three deepwater buoys (HPR1, HPR2 and NRA), presented in Figure 6, indicates that:

- spread from each buoy is similar, when they are measuring similar wave heights;
- spread is smallest for largest sea states; and
- there seems to be a tendency for the heave-pitch-roll (HPR) buoys to show slightly greater spread than the horizontal acceleration (NRA) buoy.

Whilst the spread values from the HPR buoys are consistent with the results presented by Forristall and Ewans[6], the values from the NRA buoy are significantly smaller than their recommended design spread of circa 34° for tropical cyclones. This will in some part be attributable to the fact that Figure 6 presents spectral peak spreads, rather than spectral mean spreads. However, inspection of Figure 7 shows that the lower values of spread extend across a substantial portion of the energetic part of the spectrum.

The consistently low values of spread obtained from Navaid 9 in Mermaid Sound, is contrary to the assertion of Khatri and Young[7], that spread increases in shallower water. However, in this instance, the influences of refraction, coastal shielding and fetch limitation combine to outweigh the influence of nonlinear wave-wave interaction.

As noted by Forristall and Ewans[6], correct specification of spreading can have important implications for design. Whilst their recommended value of spreading factor $\phi = 0.8666$ does represent (in their words) "a reasonably conservative reading of the data", it should be noted that values of ϕ as high as 0.95 are indicated for tropical cyclone Olivia, both for spectral peak energy, and for sites where physical sheltering constrains the available range of energetic wave directions.

Statistics on maximum single waves are also available from North Rankin. In particular, statistics associated with the peak maximum single wave height (H_{max}) and the peak significant wave height (H_s)) were as follows:

Date	Time (WST)	H_s (m)	H_{max} (m)	TH_{max} (s)	H_{max}/H_s	H_{max}/L_{max}
10/4/96	14:40	10.99	20.0	11.7	1.82	0.094
10/4/96	14:50	10.85	16.7	11.7	1.54	0.078
10/4/96	15:00	11.25	14.7	10.9	1.31	0.079
10/4/96	15:10	10.84	14.5	12.5	1.34	0.060
10/4/96	15:20	11.20	14.5	12.5	1.29	0.060
10/4/96	15:30	10.98	15.1	11.7	1.38	0.071
10/4/96	15:40	11.64	19.5	11.7	1.68	0.091
10/4/96	15:50	12.14	19.5	11.7	1.61	0.091
10/4/96	16:00	12.51	18.8	11.7	1.50	0.088
10/4/96	16:10	12.59	17.5	11.7	1.39	0.082

From the above, it is evident that there can be substantial variability in the H_{max}/H_s ratio, though the above H_{max}/H_s ratios do bracket the widely used value of 1.72 for cyclonic sea states.

The wave steepnesses (H_{max}/L_{max}) also span the range of 0.091 to 0.067, often used for cyclone sea states. It should be noted that these steepnesses accrue from a relatively well-behaved storm peak spectrum, such as that illustrated in Figure 7, which does not display any tendency to bimodality or non-linearity.

Also of potential significance to design of shore-based facilities, are the extremely high gust ratios recorded on Barrow Island. Whilst they followed the accepted mean of 1.3 (3 second gust to 10 minute mean) for most of the storm, Figure 4 shows gust ratios as high as 2.75 in the eye wall. This phenomenon is discussed in much more detail in our companion paper (Black et al.)[1].

Specific Results of Modelling

The most significant result of the modelling of tropical cyclone Olivia, is a reassessment of the storm impact on Campbell monopod.

As detailed by Ronalds et al.[2], the original Campbell design was to 50 year return period survival criteria, with a maximum single wave of 18.7 m and associated period of 14.5 seconds, with coexisting surface current of 1.84 m s^{-1}. The combination of the 50 year wave with an allowance for tide and storm surge, resulted in a design crest elevation of 55.3 m, and cellar deck elevation of 59.1 m, above an LAT of 38.2 m.

Careful modelling of Olivia now sets the peak H_s estimate at 11.7 m, with coincident tide and surge level of 3.3 m above LAT. Adopting standard values of $H_{max}/H_s \sim 1.72$ and crest elevation ratio of 0.68, yields an estimate of the peak crest elevation of 55.2 m, essentially the design condition. Increasing the H_{max}/H_s ratio to 1.9, would yield a crest elevation of 56.6 m, still 2.5 m below the cellar deck.

Modelled currents were about 10% less than the design condition, and peak 10 minute mean winds of 55.5 m s^{-1}, were 25% in excess of the original design condition. However, careful design calculations conducted by Kvaerner Oil and Gas Australia, suggest that this should not have contributed significantly to failure.

Whilst not attempting to identify the cause of the Campbell failure, the Ronalds et al.[2] paper does conclude that the innate reliability of monopod structures designed using working stress design, is less than other platforms configured for greater redundancy.

Implications for Northwest Shelf Developments

The recent occurrence of two extremely severe tropical cyclones (Orson and Olivia) on the Northwest Shelf, has led to queries about the adequacy of the tropical cyclone data base of the region. (Both storms generated peak waves in excess of the 100 year design condition for North Rankin, but fortunately, in conjunction with lesser currents).

Since there is very little shipping in the region, and the extensive coastline is sparsely populated, tropical cyclone data which predates satellite coverage (which commenced in 1959/60), are unreliable. This leaves us with a data base of perhaps 50 reliable storm tracks over the last 38 years, affecting some portion of the entire Northwest Shelf. Put simply, for some specific locations on the Northwest Shelf, it is now becoming apparent that there are insufficient reliable storms to provide a representative data base.

To overcome this deficiency, a practice of random shifting of storm tracks within certain prescribed distances has been adopted, to significantly increase the number of storms available for simulation (with commensurate increase in effective data base duration to ensure that statistics are not compromised). This practice has proved (at least partially) effective in ameliorating the 'outlier' effect of tropical cyclones Orson and Olivia, for locations sited in the most severe region of storm forcing. The practice is similar in effect to spatial averaging (adopted by Chouinard[8] in the Gulf of Mexico), but has the advantage of being able to accommodate varying shallow bathymetry.

Closure

Whilst tropical cyclone Olivia caused substantial heartache for the offshore oil and gas industry, the measurements and modelling conducted on behalf of Woodside and WAPET, have allowed significant improvement of our understanding of tropical cyclones, and have facilitated important improvements in Northwest Shelf design practice.

The data are extremely valuable and warrant further investigation.

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Acknowledgements

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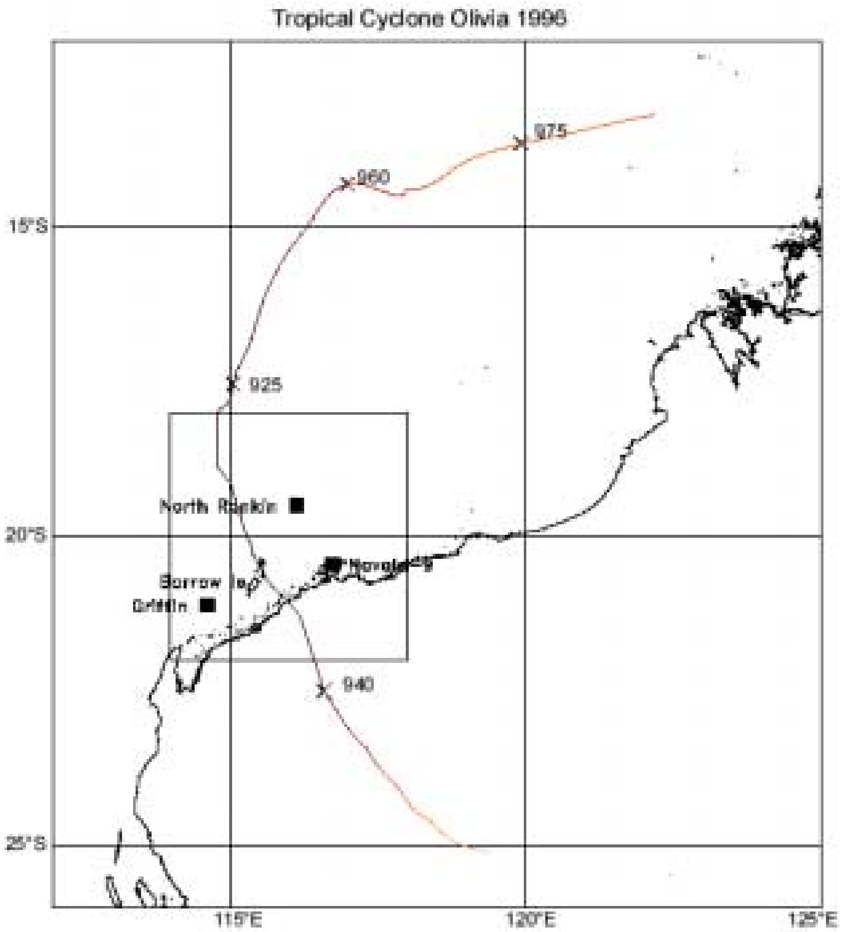

Figure 1 - Track plot of tropical cyclone Olivia, showing central pressures at 0000 hours, WST. The storm crossed the coast late on 10.4.96.

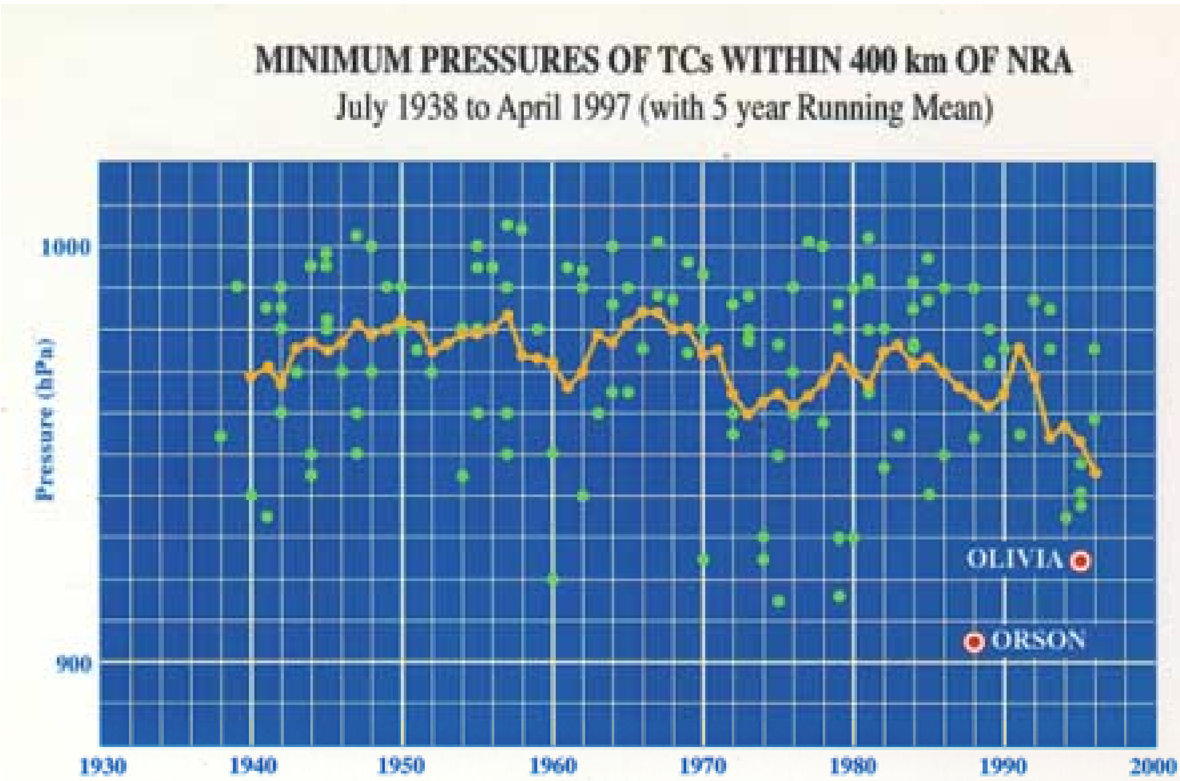

Figure 2 - Time history of lowest central pressures for storms passing within 400 km of North Rankin (including a 5 year running mean to show trend).

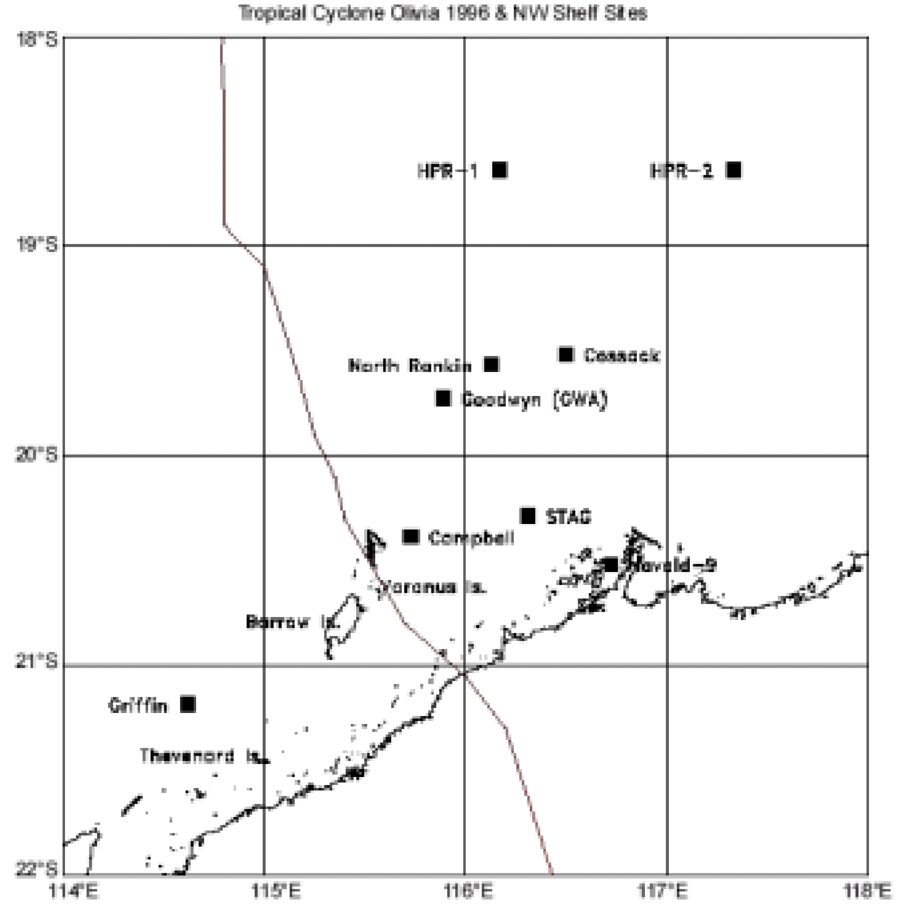

Figure 3 - Measurement and modelling sites, including the local track detail of tropical cyclone Olivia.

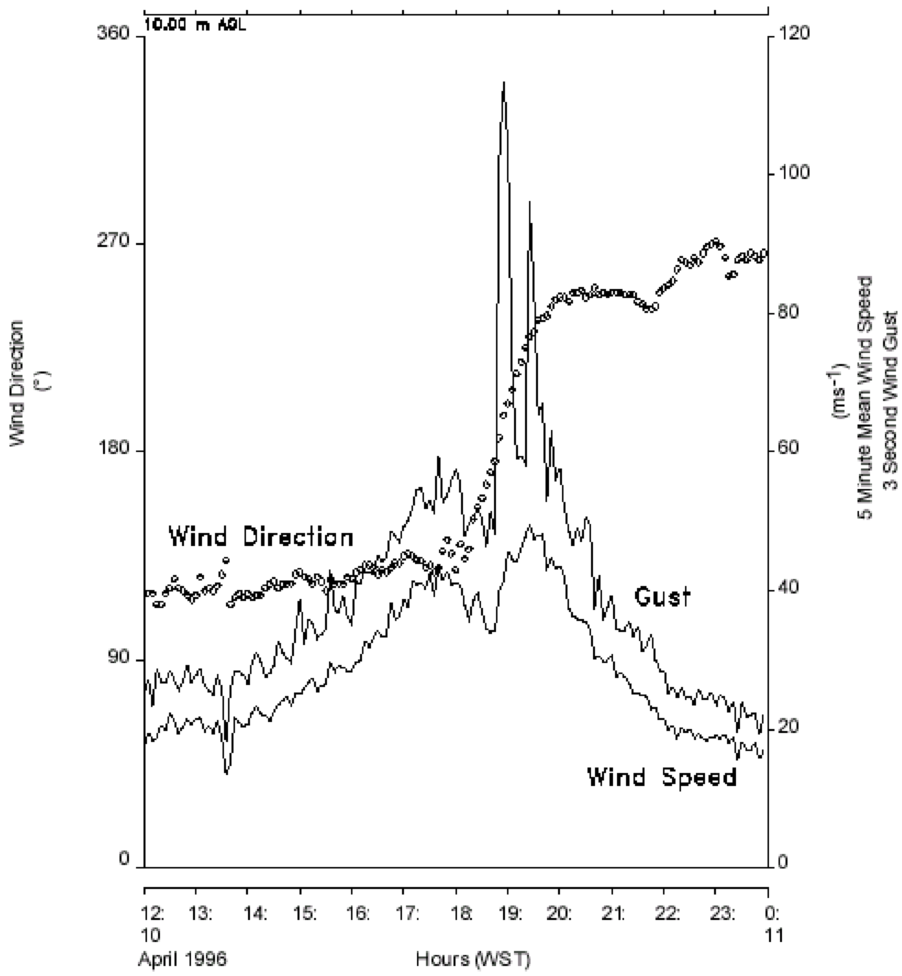

Figure 4 - Time history at measured winds at 10 m above ground level, from a location on Barrow Island at 74 m AHD.

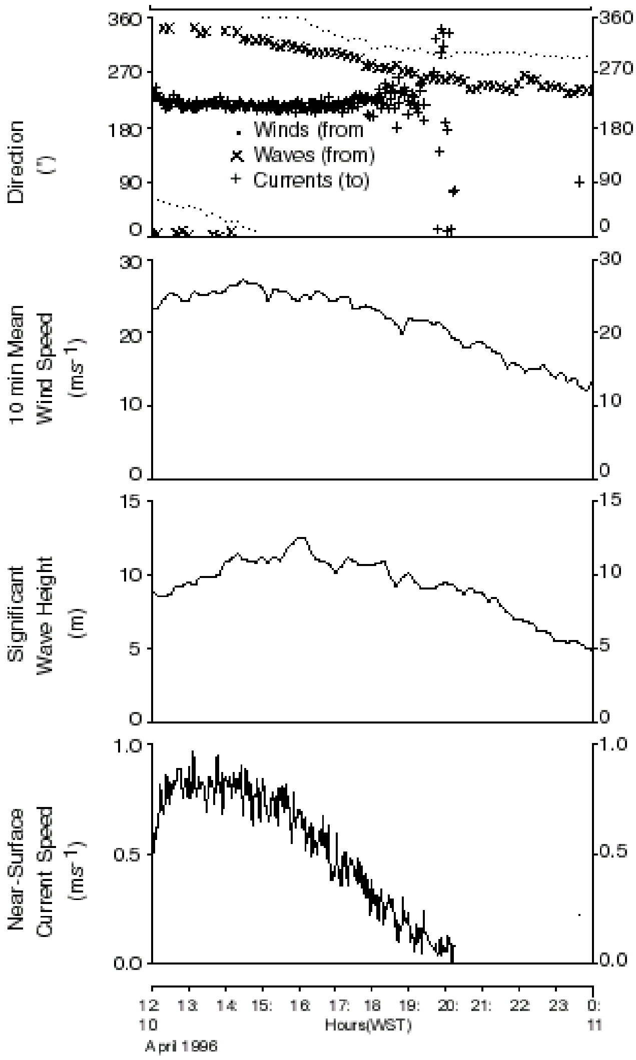

Figure 5 - Time history of measured winds, waves and near-surface (12 m below MSL) currents, at North Rankin location.

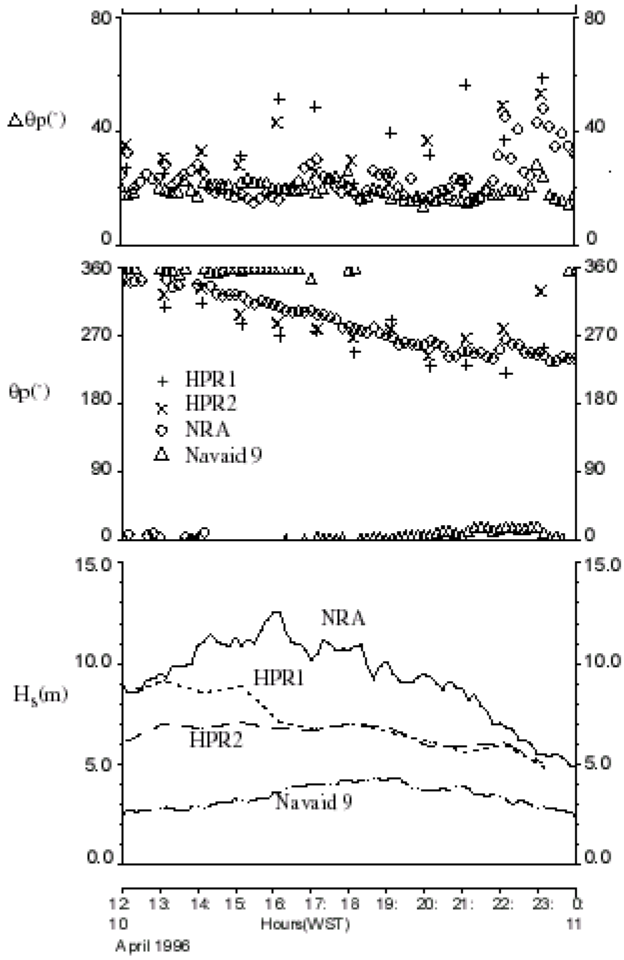

Figure 6 Time history of measured waves from HPR1, HPR2, NRA and Navaid 9 loctions, including significant wave height (H_s), spectral peak direction (θ_p) and spectral peak spread ($\Delta\theta_p$). (The same symbols are used for direction and spread).

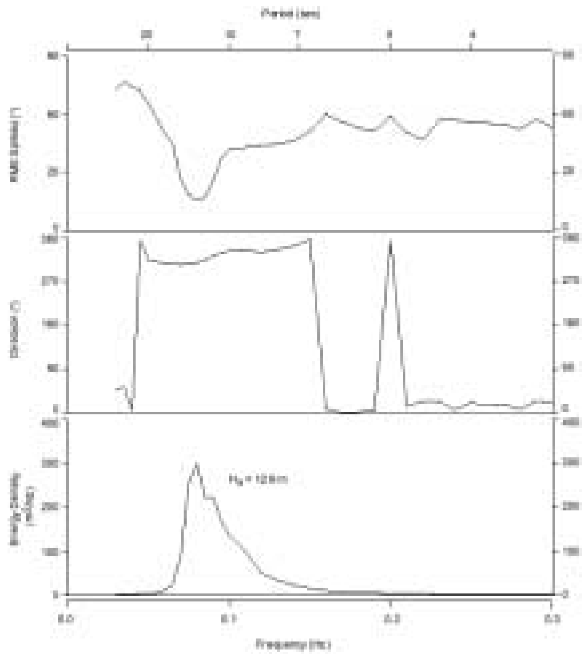

Figure 7 - Plots of the frequency spectra of energy density, direction and spread, for North Rankin waves at the time of the peak of tropical cyclone Olivia.

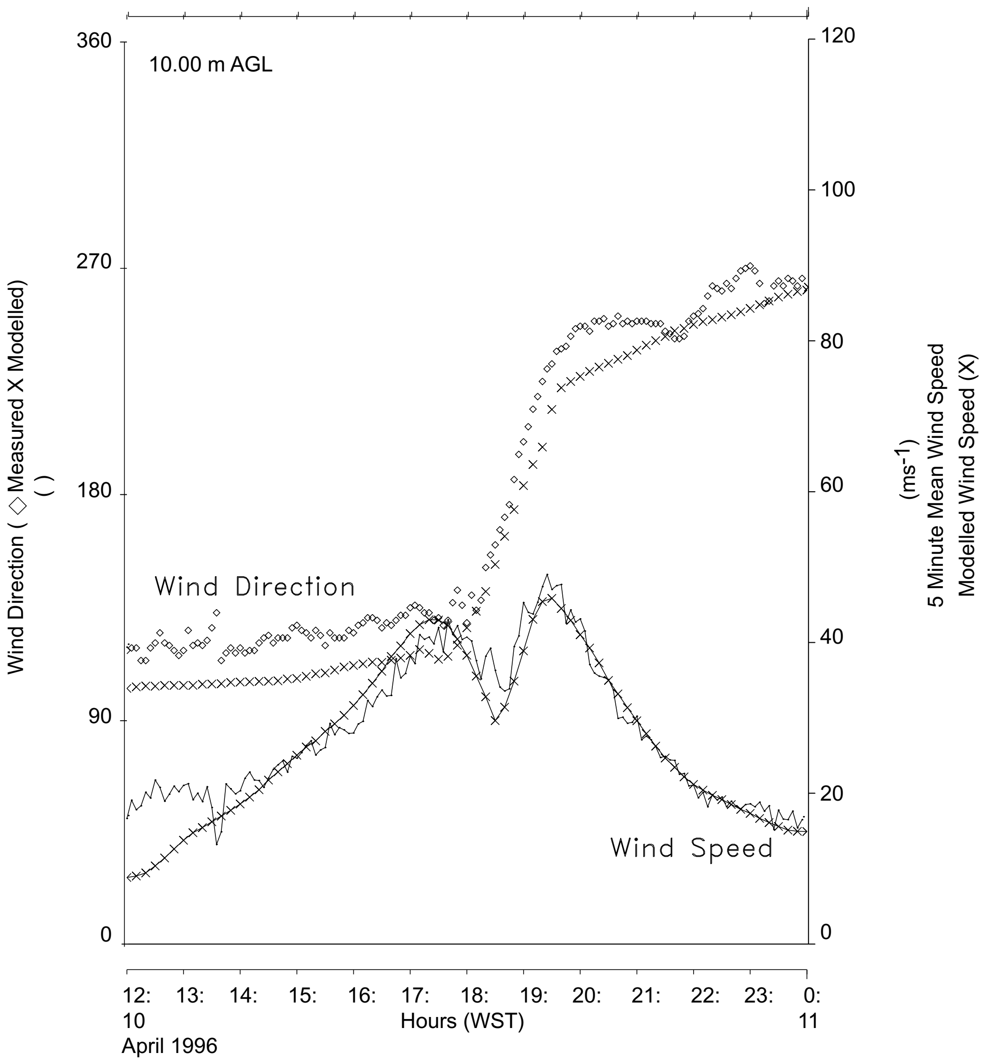

Figure 8 - Comparison of measured (5 min. mean) and modelled (10 min. mean) wind speeds at Barrow Island during tropical cyclone Olivia.

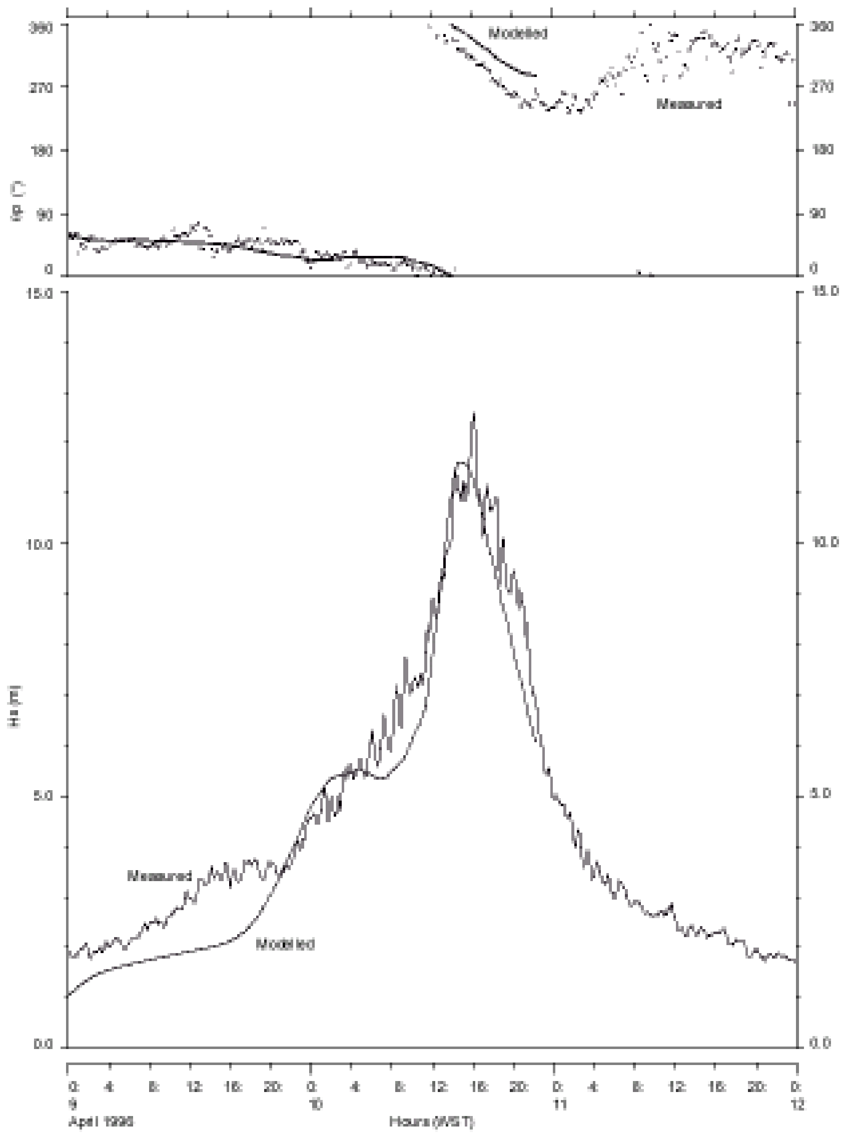

Figure 9 - Comparisons of measured and modelled waves at North Rankin during tropical cyclone Olivia.

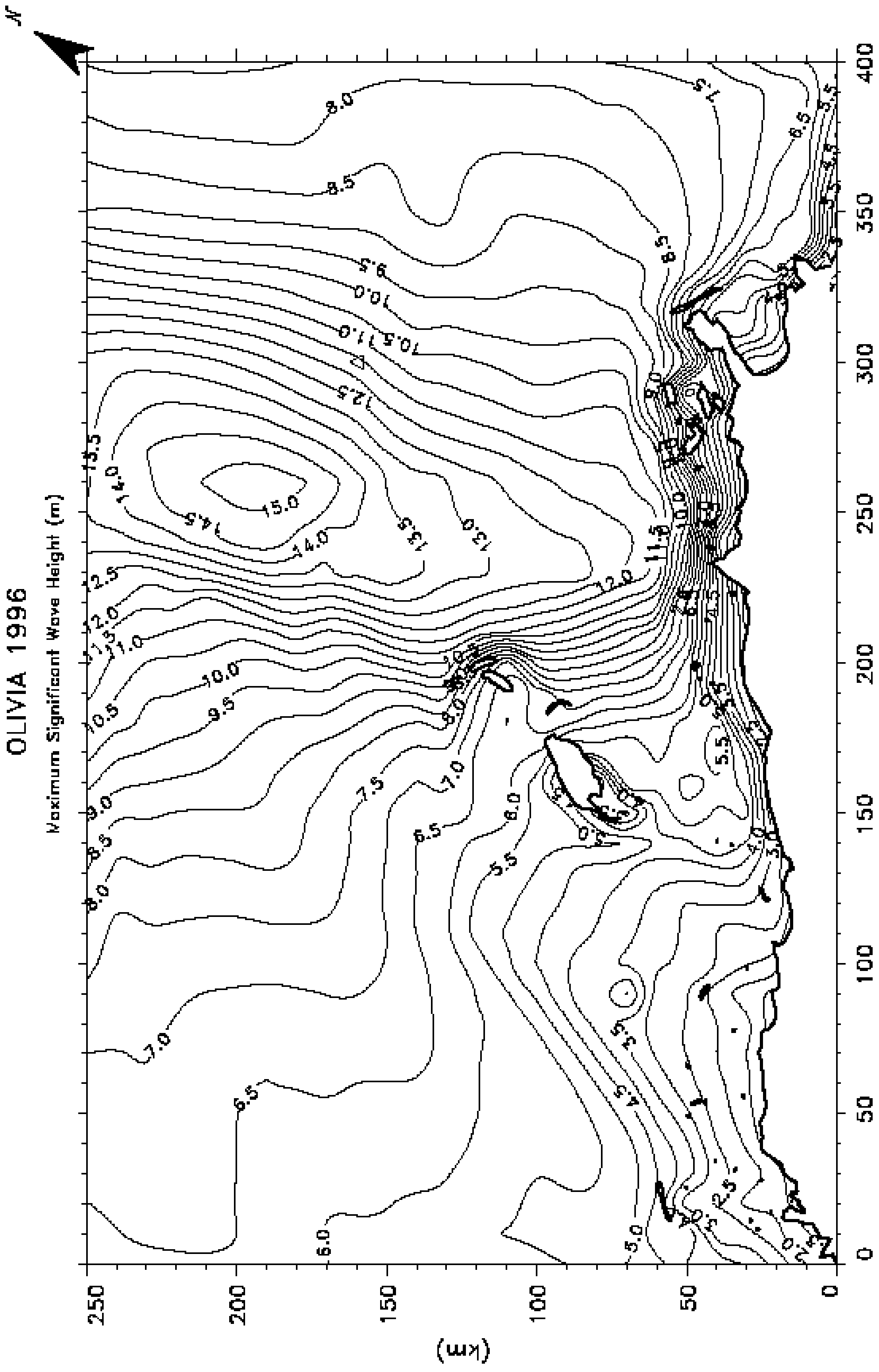

Figure 10 - Contours of peak values of H_S attained at each 10 km resolution grid point of the wave model, at any time during the passage of tropical cyclone Olivia. NRA is represented by the open triangle.