MEASURED TROPICAL CYCLONE SEAS

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1. INTRODUCTION

Wave forecasting and hindcasting usually entails spectral modelling, and therefore focuses on integral spectral parameters such as significant wave height, spectral mean period and spectral mean direction.

Many engineering applications require estimates of individual wave parameters, such as maximum single wave height, associated wave period and corresponding wave steepness. Other integral spectral parameters such as wave spreading may also be required, but are not well-represented by models. Previous studies have provided sound 'global' formulations for relationships between spectral and individual wave parameters and for wave spreading.

A comprehensive real-time directional wave monitoring system installed by Woodside Energy Ltd on their North Rankin 'A' platform, on the North West Shelf of Western Australia, allows for detailed examination of these relationships under severe tropical cyclone forcing.

This paper presents results from sea state measurements under 8 storms, with peak significant wave heights ranging from 4 to 12 m. Particular emphasis is placed on the variation of the spectral to individual wave relationships throughout each storm hydrograph.

Comparisons are made with 'global' formulations available from current literature, and implications are drawn for present metocean design practice.

2. TROPICAL CYCLONE CLIMATOLOGY

Australia's North West Shelf runs from Darwin in the north, to North West Cape, spanning latitudes 12° to 22°S.

The entire region is subject to tropical cyclone activity, which is most intense over the southern portion of the shelf (refer Figure 1). This region presently accommodates 28 marine oil and gas production facilities, the largest of which is North Rankin A platform.

The tropical cyclone season runs from November to April. Typically, between 2 and 7 tropical cyclones will pass within 400 km of North Rankin location within any tropical cyclone season. The most intense storm known to have affected the region is tropical cyclone Orson (April 1989), which had a reliably measured lowest central pressure of 904 hPa. The Maximum Potential Intensity attainable by tropical cyclones on the North West Shelf, is 880 hPa, (after Holland, 1997).

3. MEASURED DATA

Woodside Energy Limited (WEL), operator of the North Rankin A (NRA) platform, have installed a real-time environmental monitoring system, which includes a Datawell Directional Waverider and anemometers at 3 (now 5) heights above sea level. NRA is located in 125 m of water, about 130 km off the Port of Dampier.

The wave data are continuously telemetered at 1.28 Hz, and fed into two separate monitoring systems labelled REMS and ROWS. The REMS (Rankin Environmental Monitoring System) is used for operational decision making on NRA platform. The REMS operates on a sliding window of 2048 point (1600 second) profiles, updated every 10 minutes, from which integral parameters are calculated, displayed and archived. The ROWS (Remote Offshore Warning System) is used to generate a 4 hour forward prediction of tropical cyclone swell impinging on Mermaid Sound, to assist in management of LNG carrier transit. ROWS focuses only on hourly profiles of 2048 points, but differs from the REMS in that it archives the co and quad spectra, from which spread factor calculations can be made.

NRA wind data are logged as continuous 10 minute mean values. The data have been corrected to a nominal level of 10 m above MSL.

4. CALCULATED PARAMETERS

Integral wave parameters calculated from measured spectra include:

H_s significant wave height
T_p spectral peak period
T_m spectral mean period
T_z averaging zero-crossing period
θ_m spectral mean wave direction

$\Delta\theta_m$ spectral mean spread
$\Delta\theta_p$ spectral peak spread
ϕ_m mean spreading factor
ϕ_m peak spreading factor

Also available are individual wave parameters:

H_{max} maximum single wave height (in a profile)
TH_{max} period of the maximum wave
L_{max} length of the maximum wave
EH_{max} expected maximum single wave height

Given contemporaneous wind and wave data, also available are:

U_{60}/C_p hourly inverse wave age
Ψ-θ wind minus wave direction

In the above, spread is defined as the circular standard deviation of direction, and calculated (Kuik et al, …) as

$$\Delta\theta = \{2(1-m_1)\}^{1/2}$$

where $m_1 = \{a_1^2 + b_1^2\}^{1/2}$

and a_1 and b_1 are the first two terms of the Fourier Series expansion of the spreading function.

Spread factor ϕ is the in-line variance ratio defined as (after Forristall & Ewans, 1998):

$$\phi^2 = \alpha_{aa}^2/\alpha^2$$

$$= \frac{0.5\,(C_{uu} + C_{vv}) + \left\{0.25\,(C_{uu} - C_{vv})^2 + C_{uv}^{\ 2}\right\}^{1/2}}{C_{uu} + C_{vv}}$$

The expected maximum single wave height is calculated in accordance with the empirical relationship of Forristall (1978):

$$EH_{max} = m_0^{1/2} (\beta \ln N)^{1/\alpha} \{1 + \gamma (\alpha \ln N)^{-1}\}$$

where $m_0 =$ $H_s^2/16$ is the zeroth moment of the spectrum
$N =$ duration/T_z is the number of waves represented by m_0
$\alpha =$ 2.125
$\beta =$ 8.42
and $\gamma =$ 0.5772 (Euler's Constant)

In calculating EH_{max}, a subjective judgement must be made as to the duration for which H_s is representative. This becomes a problem for rapidly varying storms like tropical cyclones, where small timesteps are required to accurately resolve peaks. EH_{max} calculated for a 30 minute mean H_s at the peak of a storm, may be less than that calculated from a 3 hour mean H_s for the same storm.

WNI have resolved this issue by calculating EH_{max} on a widening window of storm duration centred on the storm peak. For a range of durations from 10 minutes to 12 hours, storm mean H_s and T_z (and hence N) values are calculated, and corresponding EH_{max} values determined. The duration yielding the largest EH_{max} value is selected, providing a conservative estimate of EH_{max}.

The period associated with EH_{max} (ETH_{max}) has no rigorous derivation, but has been empirically related to T_m by Goda (1985).

$$ETH_{max} \sim 1.15\ T_m.$$

5. TROPICAL CYCLONE OLIVIA AT NRA

In April 1996, the NRA REMS and ROWS recorded the impact of severe tropical cyclone Olivia (Buchan et al, 1999).

Because of the high level of damage caused by TC Olivia (at locations other than North Rankin), data recorded by the REMS and ROWS, were subject to detailed examination.

Figure 2 shows a composite of directional spectra calculated at 2 hour intervals either side of the storm peak (at about 1600 on 10/4/96). The RMS spread values calculated at the spectral peak are lower than anticipated.

Figures 3 to 5 show 24 hour time histories of individual wave heights (H), ratio of maximum single to significant wave height (H_{max}/H_s) and maximum single wave steepness (H_{max}/L_{max}). For reference purposes, in each figure, the H_s time history is also plotted. Each time history illustrates the unexpectedly large variability of the single wave parameters, and also emphasises the fact that the biggest single waves in a storm may not coincide with the storm peak H_s.

Figure 6 provides a further illustration of the steepness of individual waves, showing slopes of large waves ranging from 1:8 to 1:17, with 1:10 to 1:11 providing a good representation of largest waves.

Figure 7 presents a time history of measured H_s and H_{max} (from 1600 second profiles), compared with calculated EH_{max} for an assumed 1600 second H_s duration. The agreement between H_{max} and EH_{max} is generally very good, though again there is much greater variability in the measured H_{max} values. The peak value of EH_{max} is 1.1 m less than the measured peak H_{max} of 20.0 m, and it occurs 2 hours later.

A similar confirmation of the ETH_{max} versus TH_{max} time history is provided in Figure 8. Again, the agreement is very good in the mean, but actual measured values show much greater variability.

6. EXTENSION TO ADDITIONAL STORMS

In addition to TC Olivia, seastate measurements under seven other tropical cyclones were available for analysis. Tracks of all eight storms are illustrated in Figure 9.

Since space precludes the inclusion of equivalent plots to those prepared for TC Olivia, summary tabulations have been prepared instead.

6.1 Winds and Waves

Table 1 provides general information on the winds and waves measured at NRA (at time of peak H_s).

These data are provided to assist in evaluation of later tables, and no specific inferences are drawn, other than to note that no storms approached within the radius to maximum wind. Even so, there were still significant divergences between wind and wave directions at the storm peak.

The inverse wave age ranged from 1.05 to 1.47, implying relatively mature seas. Young (1998) observes that such seas are well-represented by JONSWAP parameterisation.

6.2 Directional Spread

Table 2 summarises storm peak spread ($\Delta\theta$) and spread factor (ϕ).

Typically, $\phi_p > \phi_m$, as expected, with mean values of 0.95 and 0.90, respectively. These compare with the American Petroleum Institute (API, 1993) recommended range of 0.85 to 0.95, and the value of 0.867 recommended by Forristall & Ewans (1998) for tropical storms.

Spread factor ϕ is usually higher prior to the storm peak, and lower after. This is weakly correlated with the difference in wind and wave direction.

The trends in spread ($\Delta\theta$) are opposite to those of spread factor (ϕ).

6.3 Maximum Single Waves

Table 3 presents three estimates of the storm peak H_{max}/H_s ratio.

The 'Forristall' estimate is derived from the measured H_s and N values for the storm peak 1600 second profile. The 'Coincident' estimate is the ratio of the directly measured H_{max} and H_s values from this profile, and the 'Storm' estimate is derived via the 'widening window' method described in Section 4.

The slight disparity between the 'Forristall' and 'Coincident' results, suggests that the Forristall (1978) distribution might slightly overestimate heights of maximum single waves in tropical cyclones (by perhaps 7%).

It is noted that the 'Storm' mean estimate of 1.73 closely matches the API recommendation of 1.72 for Gulf of Mexico hurricanes.

Also included in Table 3, are measurements of the storm peak maximum single wave steepness. These range between 1:15.6 to 1:9.7, with a mean of 1:12.5. This compares with API code recommended range of 1:11 to 1:15.

From inspection of steepness hydrographs, it was noticed that highest steepnesses usually occurred an hour or two prior to the storm peak H_s. This often corresponded with the largest H_{max}.

Storm peak values of H_{max} and H_s did not often coincide.

6.4 Expected Maximum Single Waves

Table 4 compares results of storm peak EH_{max} calculations performed using the 'widening window' technique of Section 4, with measured storm peak H_{max} values.

Whilst there is significant variability in H_{max} (as indicated in Figure 7), the storm peak EH_{max} estimates are relatively consistent, and in the mean, in very good agreement with measurement.

No tabular summary of the ETH_{max} calculations has been presented, due principally to the large variability of the TH_{max} measurements against which ETH_{max} might be compared.

Inspection of time history overlays of TH_{max} and ETH_{max} for all storms (such as that illustrated in Figure 8), shows that $ETH_{max} = 1.15\ T_m$ provides a very good representation of typical values of TH_{max} in tropical cyclone seastates.

7. CONCLUSIONS

The real-time monitoring systems operating on North Rankin A platform have provided an excellent suite of contemporaneous marine wind and directional wave data through eight relatively severe recent tropical cyclones.

These data provide a sound basis for the estimation of directional spread and individual wave parameters from modelled tropical cyclone seastates.

In particular, individual wave parameters (H_{max} and TH_{max}) are seen to fluctuate widely throughout each storm, but accepted storm mean parameterisations appear to work well.

Measurements of directional spread suggest that values recommended in recent literature may be nonconservative (spread factor too low) for severe tropical cyclones.

A 'widening window' method for calculation of EH_{max} has been tested against measured data, and shown to produce reliable results.

8. REFERENCES

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9. ACKNOWLEDGEMENTS

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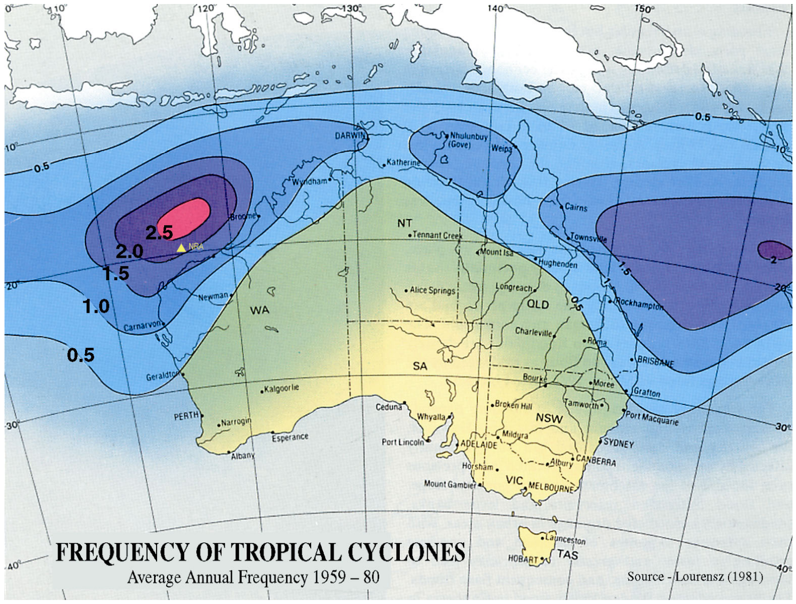

Figure 1 Tropical cyclone frequency.

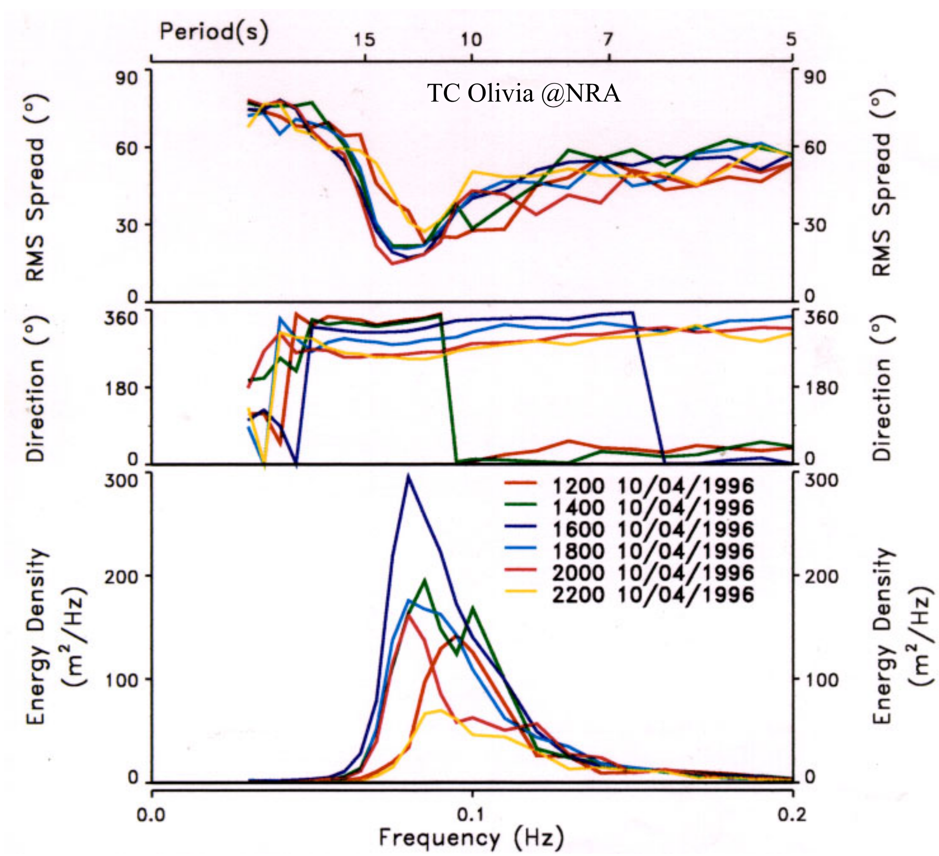

Figure 2 Directional wave spectra under TC Olivia at NRA.

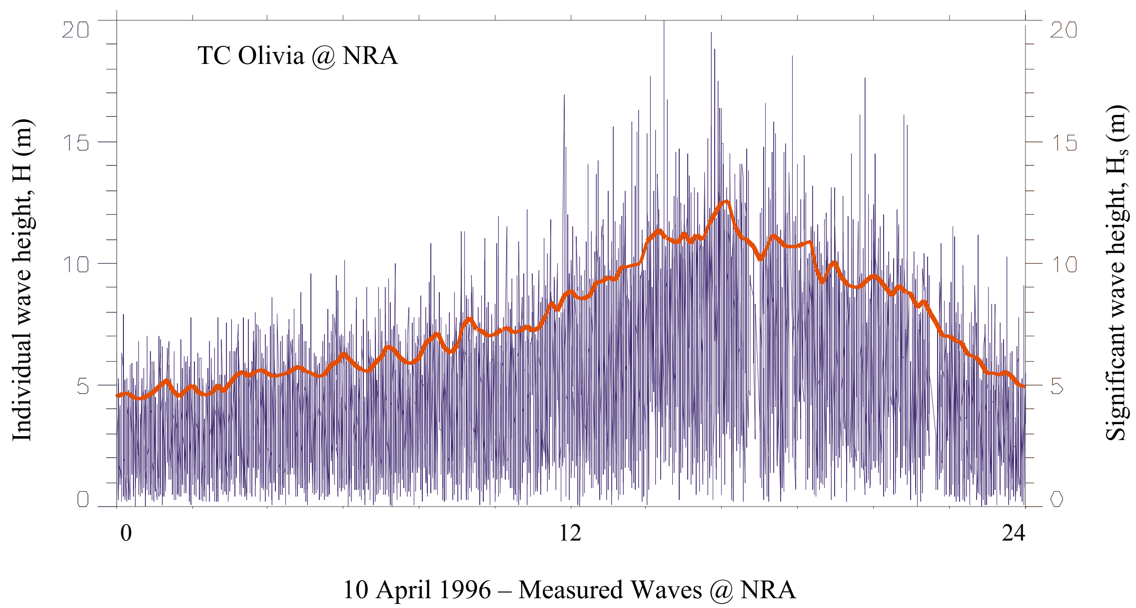

Figure 3 Individual waves under TC Olivia at NRA.

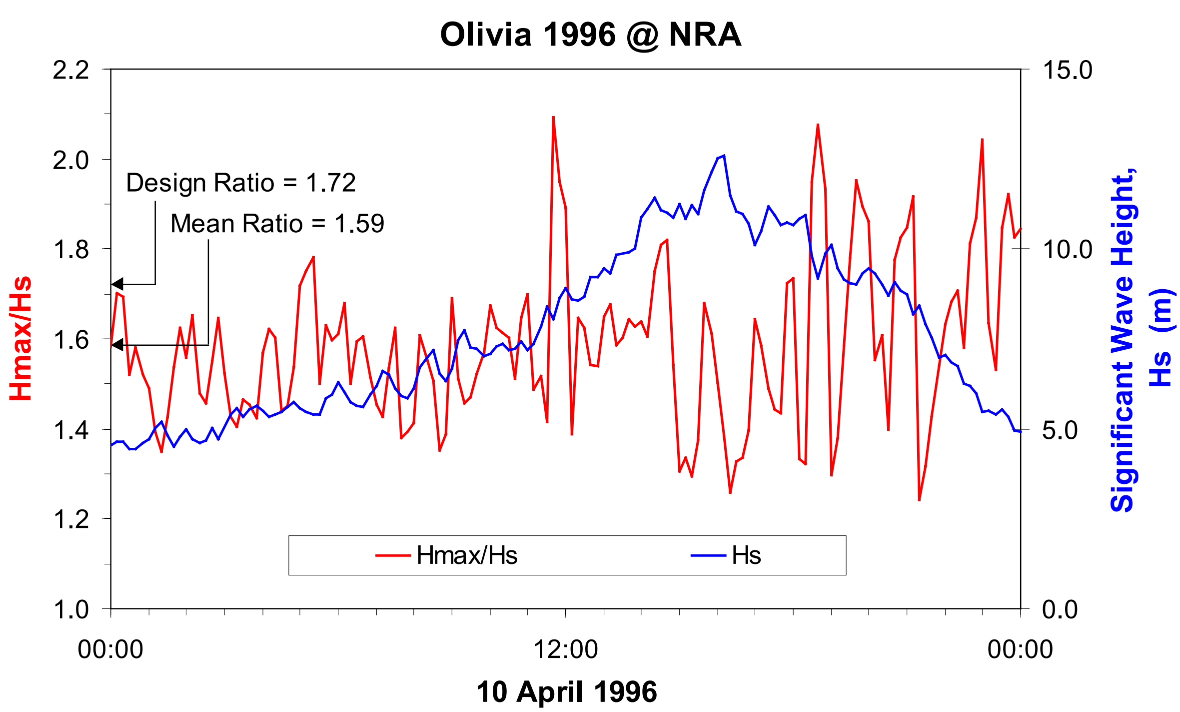

Figure 4 Ratio of H_{max}/H_s under TC Olivia at NRA

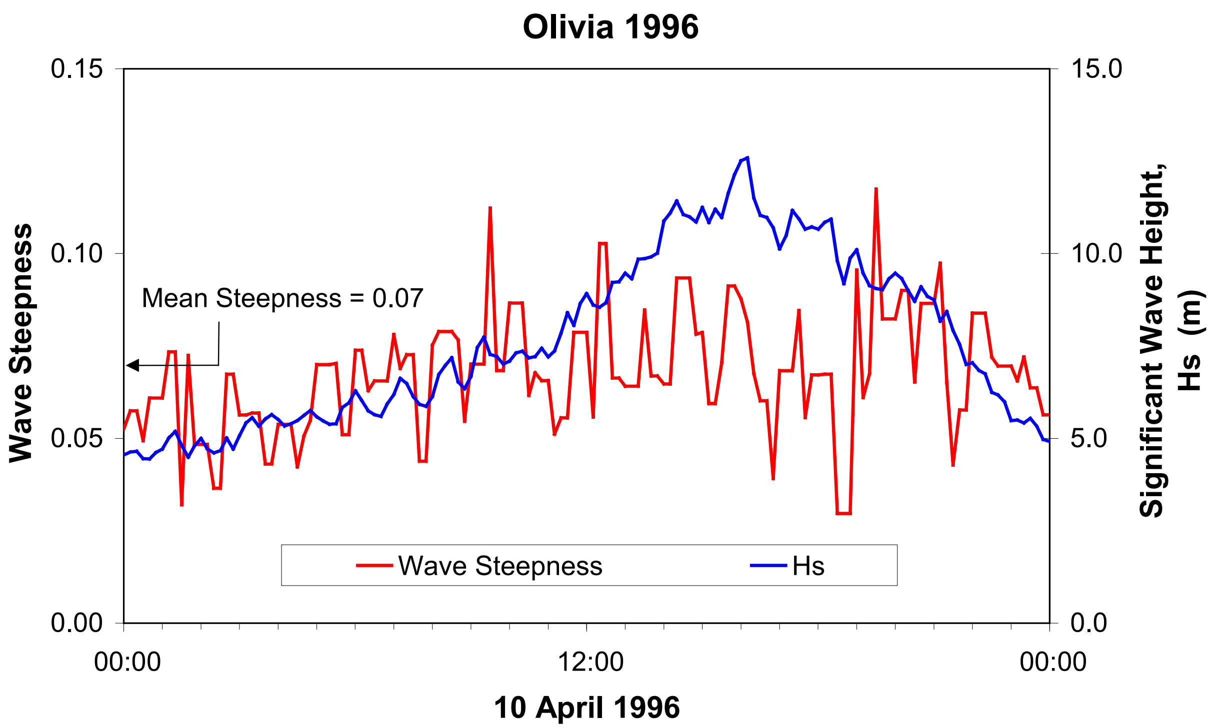

Figure 5 Wave steepness under TC Olivia at NRA.

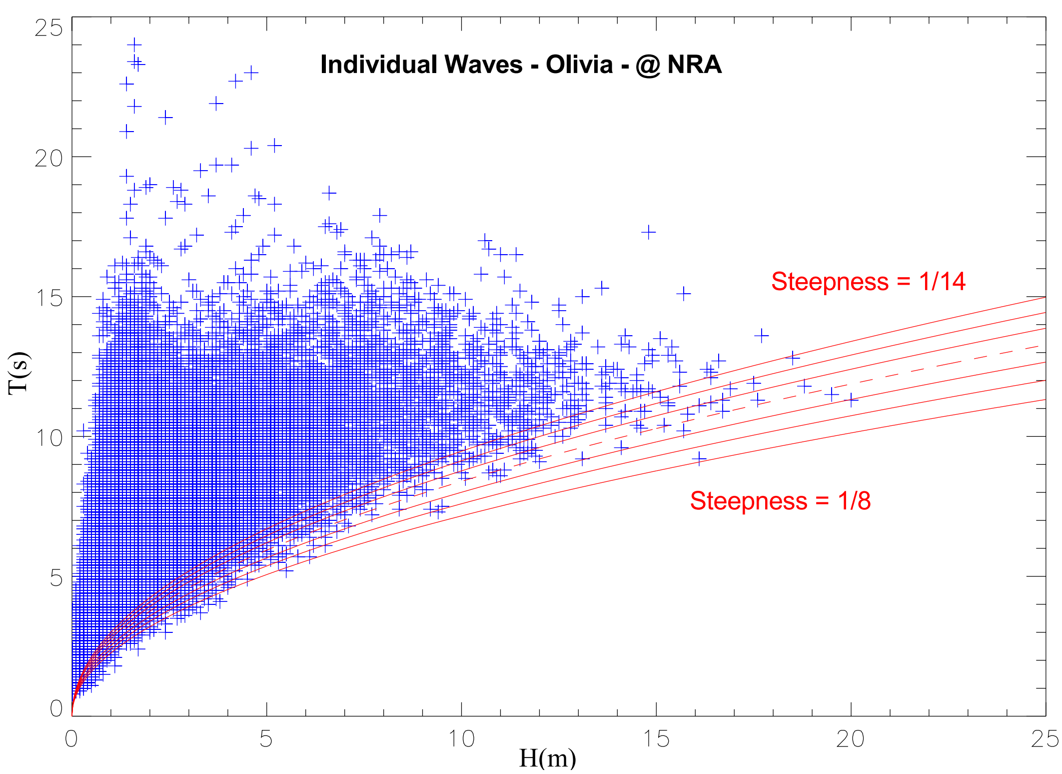

Figure 6 Individual wave heights and periods under TC Olivia at NRA.

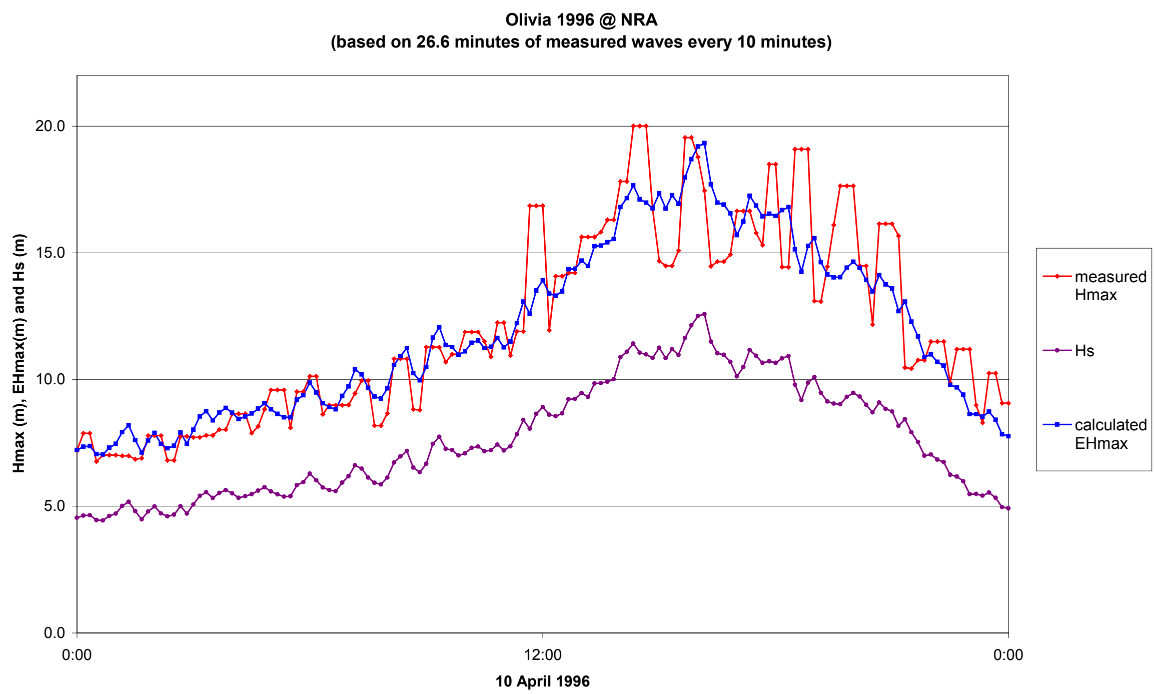

Figure 7 EH_{max}, H_{max} and H_s under TC Olivia at NRA.

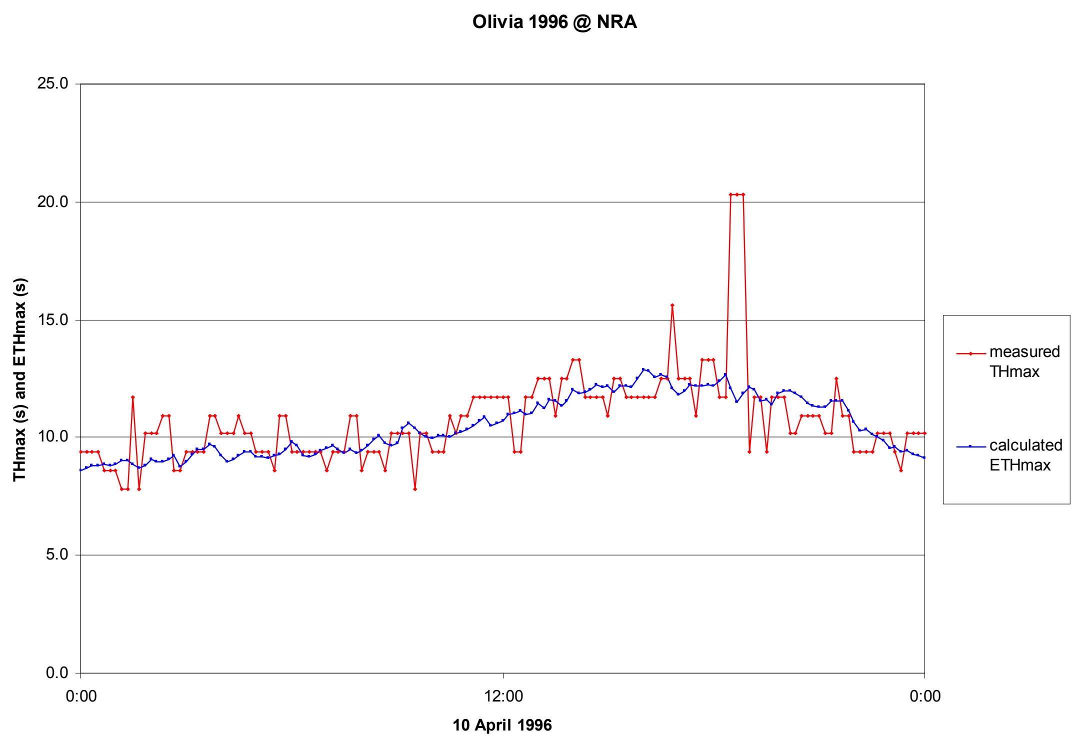

Figure 8 ETH_{max} and TH_{max} under TC Olivia at NRA.

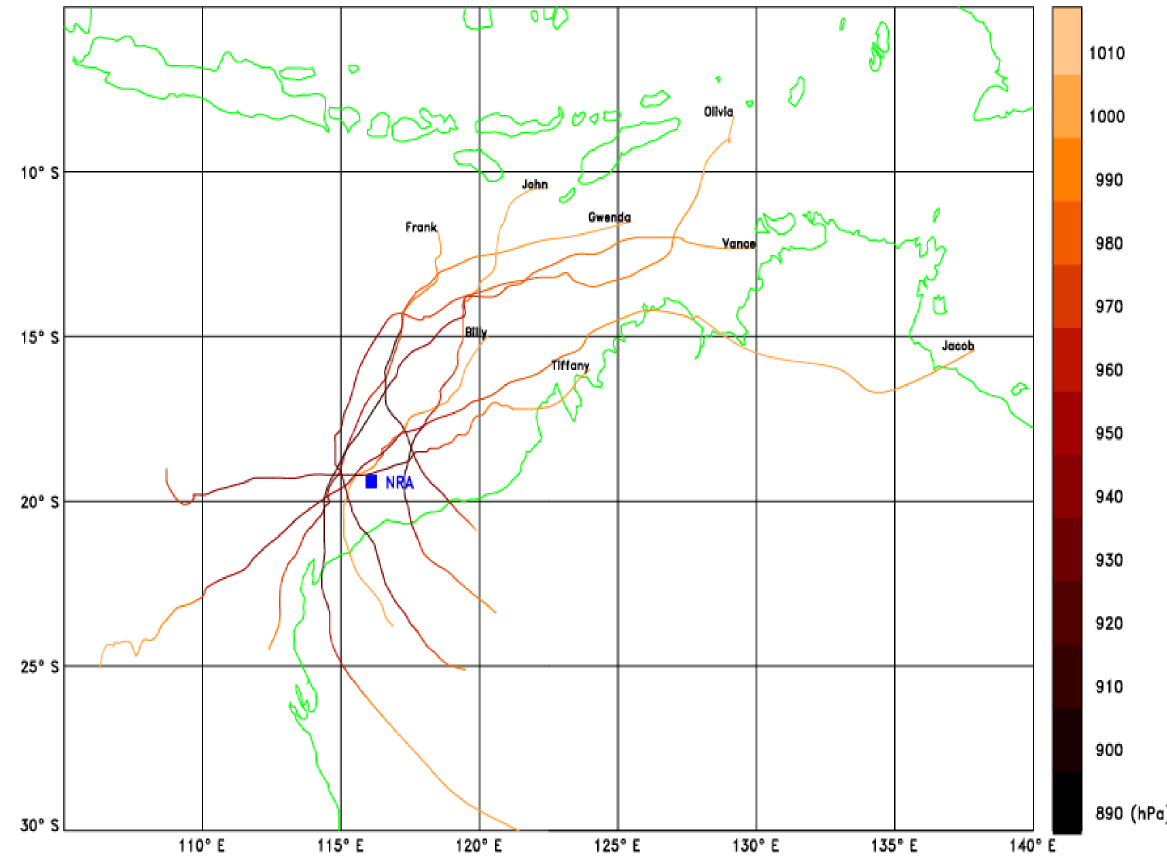

Figure 9 Tracks of 8 tropical cyclones measured NRA.

Storm	H_s (m)	Closest Approach*(km)	U_{60}/Cp	ψ-θ_m (deg)
Frank	7.34	140	1.09	75
Jacob	7.28	80	1.47	26
Olivia	11.94	100	1.17	30
Tiffany	7.95	50	1.44	-11
Billy	4.84	65	1.05	66
Vance	8.90	150	1.40	57
Gwenda	4.62	-200	1.10	64
John	6.94	-130	1.37	114
Mean	-	114	1.26	53

TABLE 1 Measured storm peak wind and wave parameters at NRA.

Storm	H_s(m)	ϕ_p	ϕ_m	$\Delta\theta_p$ (deg)	$\Delta\theta_m$ (deg)
Frank	7.34	0.97	0.90	18	30
Jacob	7.28	0.93	0.91	24	31
Olivia	11.94	0.97	0.91	19	30
Tiffany	7.95	0.98	0.93	14	25
Billy	4.84	0.95	0.91	29	38
Vance	8.90	0.93	0.89	26	31
Gwenda	4.62	0.92	0.88	24	37
John	6.94	0.95	0.88	30	42
Mean	-	0.95	0.90	23	33

TABLE 2 Measured storm peak wave spread parameters at NRA

Storm	Peak H_s(m)	Forristall H_{max}/H_s	Coincident H_{max}/H_s	Storm H_{max}/H_s	Steepness H_{max}/L_{max}
Frank	7.34	1.56	1.41	1.92	0.064
Jacob	7.28	1.56	1.36	1.78	0.072
Olivia	11.94	1.51	1.46	1.68	0.082
Tiffany	7.95	1.56	1.46	1.56	0.085
Billy	4.84	1.58	2.04	2.04	0.103
Vance	8.90	1.56	1.44	1.53	0.080
Gwenda	4.62	1.59	1.44	1.59	0.070
John	6.94	1.57	1.58	1.73	0.080
Mean	-	1.56	1.52	1.73	0.080

TABLE 3 Measured maximum single wave parameters at NRA.

Storm	H_s(m)	Duration (hrs)	Peak H_{max} (m)	Peak EH_{max}(m)	EH_{max}/H_{max}
Frank	7.34	6	14.1	13.3	0.94
Jacob	7.28	-	13.0	data gaps	-
Olivia	11.94	3	20.0	19.8	0.99
Tiffany	7.95	3	12.4	13.1	1.06
Billy	4.84	-	9.9	data gaps	-
Vance	8.90	4.5	15.8	14.4	0.91
Gwenda	4.62	6	7.8	8.2	1.05
John	6.94	-	12.0	data gaps	-
Mean	-	4.5	-	-	0.99

TABLE 4 EH_{max} calculations for storms at NRA.