

MARDIE SALT PROJECT, PRELIMINARY STORM SURGE STUDY

Prepared for **BC Iron Limited**

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Executive Summary

BC Iron Limited are proposing the development of a new solar salt evaporation project near Mardie in the Pilbara region of Western Australia.

A key cost component of the development would be the construction of a bund wall on the seaward side of the crystallizer ponds, along the inside line of the mangrove trees. The height of this wall would be determined by storm surge associated with tropical cyclones, and the level of risk of overtopping which the proponent might want to accept for the varying stages of the evaporation process.

Since this project is presently only at the pre-feasibility stage, RPS MetOcean (a Division of RPS Australia West Pty Ltd) were engaged to access pre-existing modelled data to allow tropical cyclone wind, wave and storm surge assessment for return periods of 10, 25, 100 and 500 years.

A location map of the proposed development is included below. Due to the extent of the proposed development, analysis was conducted at two locations, representing the northern and southern extremes.

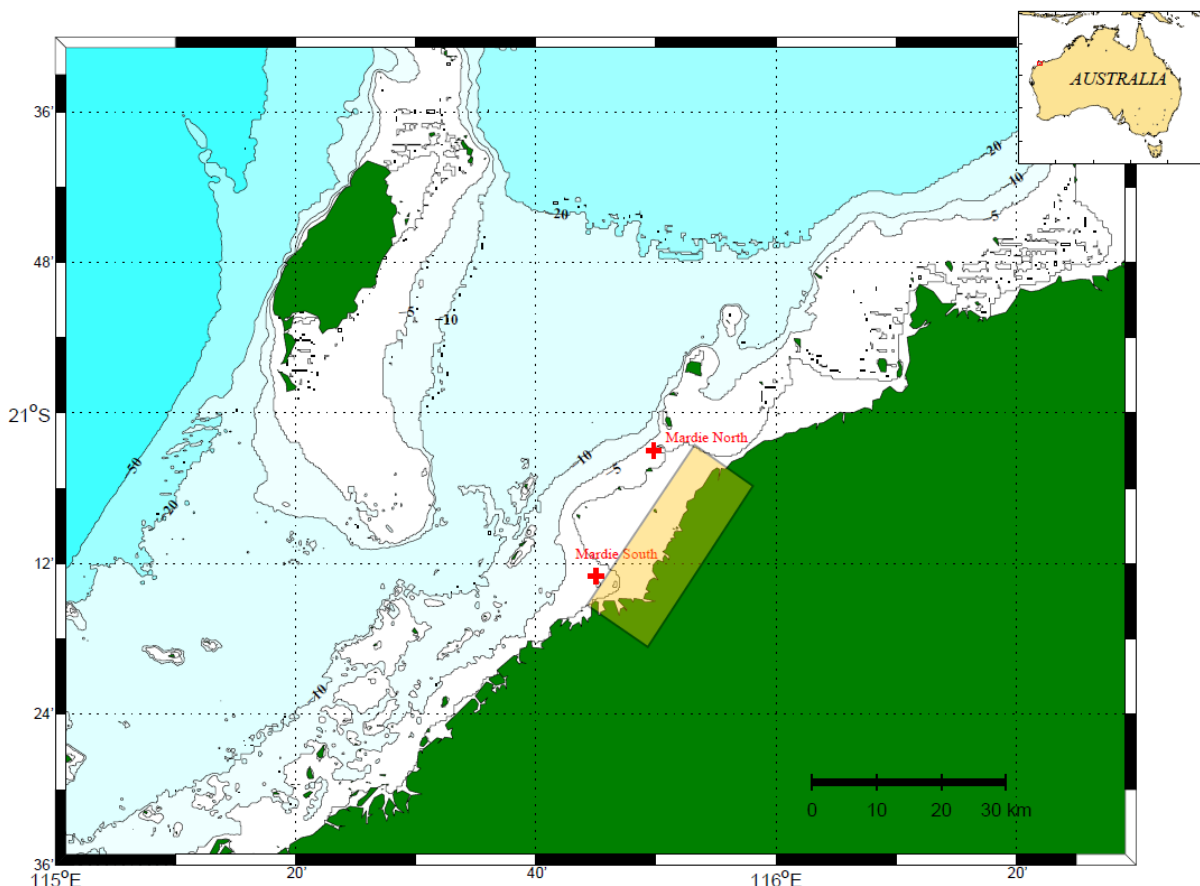


Figure 1.1 Location map and regional bathymetry of the proposed development near Mardie.

Since surge will be the prime determinant of inundation level, extreme waves (for set-up calculations) were analysed at the time of peak surge. Preliminary design criteria for the North and South locations are

included in Table 4.11 (reproduced below). These estimates are for combined Total Still Water Level (tide + surge + setup + sea level rise) above Australian Height Datum (AHD). It is assumed that AHD ~ MSL. These estimates take no account of subsequent flooding from delayed river runoff, which we understand will be the subject of another study.

Location	Return Period (Years)	Tide + Surge (m)	Hs (m)	Wave Setup (m)	Sea Level Rise (m)	Total SWL (m AHD)
North	10	2.79	2.83	0.71	0.20	3.70
	25	2.94	3.22	0.81	0.20	3.95
	100	3.15	3.39	0.85	0.20	4.20
	500	3.39	3.48	0.87	0.20	4.46
South	10	2.73	2.25	0.56	0.20	3.49
	25	3.00	2.52	0.63	0.20	3.83
	100	3.38	2.69	0.67	0.20	4.25
	500	3.77	2.75	0.69	0.20	4.66

Table 4.11 Estimates of Total Still Water Level above AHD (combined tide, surge, wave setup and sea level rise) for 10, 25, 100 and 500 years return period at Mardie North and Mardie South locations.

Recommendation for Future Work

To generate design criteria suitable for final design, the over-riding requirement is for detailed accurate bathymetry surrounding the proposed facility. RPS have previously worked with LADs bathymetry data supplied by a third party for both the Barrow Shoals region, and for Regnard Bay (immediately to the NE of Cape Preston), and found it to be well-suited to near-coastal modelling.

Once accurate bathymetry is available – tropical cyclone wave and circulation modelling can be conducted at grid scales relevant to the development, and to the offshore islets and reefs.

To properly address the issues of wave breaking and setup on this very complex coastline, it is likely to be necessary to invoke a surf zone model such as 2DBeach or XBeach.

The SHOC 3D hydrodynamic model would be used to simulate contributions from currents and tide + surge water levels.

Note that this additional modelling is not warranted without the inclusion of accurate bathymetry.

The resulting winds should be sufficient for conducting simplistic fetch-limited wind wave calculations for the ponds. There will probably also be a small wind setup on each pond – again amenable to cursory calculation.

Contents

1.0	INTRODUCTION	1
1.1	Background	1
1.2	Study Objectives	1
1.3	Salient Oceanographic Features	2
1.4	Study Approach	2
1.5	Recommendations for Further Work	3
2.0	AVAILABLE MODELLED DATA.....	4
2.1	Winds.....	4
2.1.1	Model Forcing	4
2.1.2	Model Calibration	5
2.1.3	Cyclone Tracks	5
2.1.4	Vortex Blending.....	6
2.1.5	Model Domains	6
2.1.6	Temporal Extents.....	7
2.1.7	Verification	7
2.2	Waves.....	7
2.2.1	Model Forcing and Configuration.....	7
2.2.2	Verification	8
2.3	Currents and Water Levels.....	8
2.3.1	Model Forcing and Configuration.....	8
2.3.2	Verification	9
3.0	ANALYSIS METHODOLOGIES	11
3.1	Extreme Analyses	11
3.2	Spectral Shape Fitting	11
3.3	Tropical Cyclone Individual Wave, Crest Elevation and Period.....	13
3.4	Tropical Cyclone Gust Factors	15
3.5	Kernel Density Estimator (KDE) Contour Plots	16
4.0	EXTREME CYCLONIC CONDITIONS	18
4.1	Introduction	18
4.2	Storm Selection	18
4.3	Track Parameters	19
4.4	Track Shifting	19
4.5	Resulting Extremes.....	20
4.6	Treatment of Wave Setup.....	21
4.7	Sea Level Rise	22
4.8	Final Estimates of Surge Extremes.....	22



5.0 RECOMMENDATIONS FOR FURTHER WORK24

6.0 REFERENCES25

List of Tables

(compiled at rear of report)

Table 4.1	Tropical cyclone occurrence and intensity statistics for the Mardie study site.
Table 4.2	List of tropical cyclones selected for numerical simulation.
Table 4.3	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 10 year return period at Mardie North location.
Table 4.4	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 25 year return period at Mardie North location.
Table 4.5	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 100 year return period at Mardie North location.
Table 4.6	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 500 year return period at Mardie North location.
Table 4.7	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 10 year return period at Mardie South location.
Table 4.8	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 25 year return period at Mardie South location.
Table 4.9	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 100 year return period at Mardie South location.
Table 4.10	Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 500 year return period at Mardie South location.
Table 4.11	Estimates of Total Still Water Level above AHD (combined tide, surge, wave setup and sea level rise) for 10, 25, 100 and 500 years return period at Mardie North and Mardie South locations.

List of Figures

(compiled at rear of report)

Figure 1.1 Location map and regional bathymetry of the proposed development near Mardie.

Figure 2.1 Extent of tropical cyclone wind, wave and current modelling grids.

Figure 2.2 Tide height constituent amplitude and phase calibrations.

Figure 4.1 Model output locations.

Figure 5.1a Extent of proposed WW3 B & C grids for recommended further modelling.

Figure 5.1b Extent of proposed WW3 C & D grids for recommended further modelling.

Figure 5.1c Extent of proposed WW3 D & E grids for recommended further modelling.

Figure 5.1d Extent of proposed WW3 E grid for recommended further modelling.



List of Appendices

Appendix A Tropical Cyclone Monthly Track Plots

Appendix B Wave and Surge Extremes, Supporting Documentation

I.0 INTRODUCTION

I.1 Background

BC Iron Limited are proposing the development of a new solar salt evaporation project near Mardie in the Pilbara region of Western Australia. A location map of the proposed development is included in Figure 1.1.

A key cost component of the development would be the construction of a bund wall on the seaward side of the crystallizer ponds, along the inside line of the mangrove trees. The height of this wall would be determined by storm surge associated with tropical cyclones, and the level of risk of overtopping which the proponent might want to accept for the varying stages of the evaporation process.

Since this project is presently only at the pre-feasibility stage, RPS MetOcean (a Division of RPS Australia West Pty Ltd) has been engaged to access pre-existing modelled data to allow tropical cyclone wind, wave and storm surge assessment for return periods of 10, 25, 100 and 500 years.

Though the pre-existing modelled data (waves in particular) are at relatively coarse resolution, without access to substantially improved bathymetry offshore from the project development, there is little merit in refined modelling.

I.2 Study Objectives

Modelled tropical cyclone time series data (winds, wave and water level) from each of the ~100 modelled storms will be extracted for a grid point considered most representative of metocean conditions at a nearshore site in ~5 m water depth. Analysis will be conducted at two locations, representing the northern and southern extremes of the proposed development.

The modelled TC data will be subjected to an extreme analyses (to calculate return period values) using the Conditional Weibull method. Data input to the Conditional Weibull method is selected by the 'peak-over-threshold' method, where typically, at least 20 values are required to ensure that asymptotic assumptions regarding the plotting position formula are satisfied. Resulting extremes will be calculated at return periods of 10, 25, 100 and 500 years.

Since surge will be the prime determinant of inundation level, extreme waves (for set-up calculations) will be analysed at the time of peak surge.

To calculate the corresponding wave periods associated with the return period wave heights, contours of H_s and T_p pairs will be derived using a Kernel Density Estimator (KDE). These data will be used in the manual wave set-up calculation.

1.3 Salient Oceanographic Features

The study region is subject to severe tropical cyclone activity (in terms of both strength and frequency of occurrence) in the predominant summer months of December to April, with extremely rare occurrences also possible in November and May. Tropical cyclones tend to be most severe in late March and April, when sea surface temperatures typically reach a peak, and they are most frequent in the months of January to March. Tropical cyclones, and their associated wind, wave and current/surge fields, will provide the limiting environmental conditions on engineering design criteria for the region.

The moderate semi-diurnal tide range (~4.0 m at springs) of this region makes a significant contribution to currents at all levels, and an equivalent contribution to extreme water levels as tropical cyclone surge.

The Mardie coastline is protected from strong tropical cyclone swell by the Monte Bello Islands to the north, Barrow Island to the northwest, and the very extensive Barrow Shoals to the west and southwest. The only tropical cyclone swell of significance which will influence the Mardie coastline, will arrive from the north-northeast after having refracted past the Dampier Archipelago and Cape Preston.

Just off the Mardie coast, there are several islets and reefs which offer further protection from wave attack, and mitigation of storm surge.

Bathymetry in the nearshore zone is very poorly known, and likely to vary under the occasional influence of strong tropical cyclone forcing.

1.4 Study Approach

Since this project is presently only at the pre-feasibility stage, RPS have elected at this stage to access pre-existing modelled data to allow tropical cyclone wind, wave and storm surge assessment. Though the pre-existing modelled data (waves in particular) are at relatively coarse resolution, without access to substantially improved bathymetry offshore from the project development, there is little merit in refined modelling.

Due to the extent of the proposed development, analysis has been conducted at two locations, representing the northern and southern extremes. The modelled tropical cyclone time series data (winds, wave and water level) from each of the modelled storms has been extracted for the grid points considered representative of metocean conditions at a nearshore site in ~5 m water depth at the two analysis points. The approximate location details of the two analysis points are outlined in the table below.

Location	Model	Latitude	Longitude	Water Depth
Mardie North	Waves	21° 3' S	115° 45' E	~ 9 m MSL
	Surge	21° 3' S	115° 54' E	~ 4 m MSL
Mardie South	Waves	21° 13' S	115° 42' E	~ 7 m MSL
	Surge	21° 13' S	115° 47' E	~ 4 m MSL

Locations vary for the wave and surge models. The surge output points are in shallower water where the surge values will be more representative of the coastal surge levels (without the model being compromised by the presence of the digitized coastline). The wave output points are deeper, to avoid sub-gridscale effects of the several nearshore islets, and to avoid the limitations of excessive depth-limited wave breaking.

The lengthscale of the surge response to tropical cyclones is such that the outputs from the wave and surge models can still be regarded as 'synchronous'.

The modelled TC data would be subjected to an extreme analyses (to calculate return period values) using the Conditional Weibull method. Data input to the Conditional Weibull method was selected by the 'peak-over-threshold' method, where typically, at least 20 values are required to ensure that asymptotic assumptions regarding the plotting position formula are satisfied. Resulting extremes will be calculated at return periods of 10, 25, 100 and 500 years.

Since surge will be the prime determinant of inundation level, extreme waves (for set-up calculations) have been analysed at the time of peak surge.

To calculate the corresponding wave periods associated with the return period wave heights, contours of H_s and T_p pairs were derived using a Kernel Density Estimator (KDE). These data have been used in the manual wave set-up calculation.

In addition to the 10, 25, 100 and 500 year return period tropical cyclone data, Tropical Cyclone activity (occurrence/frequency) and intensity (TC Category) statistics by month for various radii (100, 200, 300, 400, 500 and 600 km) around the Mardie study site are also included in this report.

1.5 Recommendations for Further Work

Final Chapter 5 presents recommendations for further work to refine the estimates of storm surge, and to provide input to internal crystallizer pond wave and water level calculations.

2.0 AVAILABLE MODELLED DATA

The best modelled tropical cyclone wind, wave and surge data available for the region is that completed by RPS for the recent Equus Development. The commercial arrangements under which that study was conducted, means that the archived modelled data may be accessed by RPS for application to other projects.

The available data are described in the following sections.

2.1 Winds

The RPS in-house ambient global gridded wind database (originally from NCEP) was enhanced for cyclonic conditions using a high-resolution parameterized vortex model. The tropical cyclone vortices were modelled by applying a parameterized method to our in-house TC track database. The model is based on the work of Holland (1980) with the addition of the latest scientific methods for parameters such as the pressure-wind relationship, the atmospheric profile and the gust factor.

A vortex was generated for each cyclone that came within 400 km of the North Rankin location during the post-satellite era of 1968/1969 to 2013/2014. The resulting vortices were blended into the latest NCEP global gridded wind database (CFSR & CFSv2) to account for ambient winds outside the vortex, generating a gridded TC wind field that is as realistic as possible. This blending method was developed in-house based on rigorous testing, and its previous version has been used extensively in developing reliable metocean design criteria for the North West Shelf for the last five years.

2.1.1 Model Forcing

The global gridded wind database was collated from NRAW (NCEP Reanalysis), CFSR (Climate Forecast System Reanalysis) and CFSv2 (Climate Forecast System Version 2) data which originally came from the National Centers for Environmental Prediction (NCEP).

The NRAW model is a 40-year reanalysis product that was produced in response to the global warming climate debate of the early 1990's. It spans 1948 to present, and has a coarse spatial resolution of 2.5° x 2.5° and temporal resolution of 6 hours. The analysis and forecast model for all years are based on the 1995 version of NCEP's Medium Range Forecast (MRF) model.

The Climate Forecast System ambient gridded global wind database is retained in-house at RPS. The product is available in two parts. The reanalysis product (CFSR) spans 1979 to 2010 and consists of a multiyear global state-of-the-art representation of atmospheric states derived from a constant model and data assimilation system. Assimilated data includes surface meteorological observations, geostationary satellite estimates of atmospheric motion, microwave image data of cloud temperatures, scatterometer measures of ocean wind speed, several sources of cloud irradiance data and radio occultation data. In other

words, the CFSR is a standardised dataset that incorporates the best known atmospheric observations and modelling physics over a period of more than 30 years. The CFSR has a horizontal resolution of approximately 38 km (0.3°), with 64 vertical levels through the atmosphere, and a temporal resolution of 1 hour.

The Climate Forecast Systems Version 2 (CFSv2) is operational forecast data at NCEP from January 2011 that uses the upgraded model physics and data assimilation developed through the CFSR. It is a fully-coupled atmosphere-ocean-land model. The horizontal resolution is very high for a global dataset at approximately 27 km grid spacing (0.2°), with 64 vertical levels in the atmosphere and 40 vertical levels in the ocean. The temporal resolution is one hour and over 800 parameters are calculated. The CFSv2 is run by NCEP every six hours and RPS uses the best data for each time step (the analysis products at 0 hours out to the 6-hour forecast).

The combination of the CFSR (1979-2010) and CFSv2 (2011 to present) ensures continuity and quality in atmospheric analysis for a period of more than 35 years anywhere on the globe. It is widely known as the best available dataset. NRAW is used for the earlier storms (prior to 1979) and is regarded as a reliable representation of the greater global circulation over this period.

2.1.2 Model Calibration

The ambient global gridded wind database had the following calibration factors applied to the wind speed:

Data Set	Period	Data Interval	Calibration Factor
NRAW	June 1967 – June 1978	6 hour	1.02
NRAW2	July 1978 – December 1979	6 hour	0.88
CFSR	June 1979 – December 2010	1 hour	1.05
CFSv2	January 2011-present	1 hour	1.05

The calibration factors were calculated by comparison of the modelled data with all available measured wind speed data by our in-house meteorologist. Note that a larger wind calibration standard deviation for NRAW was expected as these modelled data are of coarser resolution.

2.1.3 Cyclone Tracks

The RPS cyclone track database is based on the Bureau of Meteorology's best track archive. It has been augmented and amended by verification against propriety third party data from the North West Shelf. In addition, some critical modelling parameters such as Radius to Maximum Wind are calculated using empirical formulae developed in-house for cyclones in this particular region.

2.1.4 Vortex Blending

Parameterised models of cyclone vortices have long been used to model the extreme winds of tropical storms. However, to best capture the outer circulation and the resultant waves and currents for the greater region, we choose to use the global modelled winds of the datasets described above, rather than attempt (as some do) to try to fit a double vortex model. On the NWS, there are far too little data to be able to do this reliably. Instead, we choose to blend the single vortex of the parametric Holland wind field model into the global modelled wind field.

When the location of the tropical cyclone vortex in the global gridded winds coincides with the "best track" tropical cyclone, blending is a simple position-dependent combination of the parametric winds with the global modelled winds. This results in a smooth transition between the parametric winds near the storm centre, and the global modelled winds further from the storm. Specifically, within the Radius to Maximum Winds (R_{max}), the parametric wind speeds are used. Between R_{max} and 3 times R_{max} , the parametric wind speeds and directions are linearly blending with the global modelled winds. Outside 3 times R_{max} the global modelled winds are used.

In instances where the modelled vortex and the "best-track" diverge, the following process is adopted, in order to "correct" the modelled wind field effectively. At each required time, the centre of the modelled vortex and the coincident point on the "best track" are located. An ellipse is formed with these two points as the foci. The global modelled grid is then "warped", or distorted, shifting points inside the ellipse smoothly, such that the centre of the modelled vortex is moved to the "best track", while points on the periphery of the ellipse are not moved at all. This warped grid is then interpolated back onto the original modelled grid, resulting in global gridded winds that better represent the outer reaches of the storm. This process is described more fully in a paper by Foster et al (2009).

The CFSR database resolves the outer vortex winds quite well, and the position is mostly good too, but still requires vortex re-location. The NRAW database generally always required vortex re-location.

2.1.5 Model Domains

For each cyclone event, the gridded winds were interpolated to an "A" grid of $0.25^\circ \times 0.25^\circ$ resolution, which spans the North West Shelf and the Timor and Arafura Seas. The "A" grid comprised of 141×102 cells, spanning $104^\circ 00' 00''\text{E}$ to $139^\circ 00' 00''\text{E}$ and $27^\circ 15' 00''\text{S}$ to $2^\circ 00' 00''\text{S}$. The tropical cyclone vortices that affected the study site during this period were generated using the modified Holland (1980) wind field model and blended into the ambient "A" grid wind fields.

The gridded winds were also interpolated to the finer resolution "B" grid. The tropical cyclone vortices that affected the study site during this period were generated at this resolution using the modified Holland (1980) wind field model and blended into these "B" grid wind fields. The "B" grid cell resolution is $0.05^\circ \times 0.05^\circ$, comprised of 296×221 cells spanning $108^\circ 00' 00''\text{E}$ to $122^\circ 45' 00''\text{E}$ and $25^\circ 45' 00''\text{S}$ to $14^\circ 45' 00''\text{S}$. The extents of the "B" and "C" wind modelling grids compared to the "B" and "C" wave modelling grids, are illustrated in Figure 2.1.

2.1.6 Temporal Extents

The cyclonic wind fields included five days of ambient winds prior to the start of the storm to facilitate proper boundary forcing of the wave model, and two days after the final record of the track to facilitate modelling of possible inertial current oscillations after the storm had passed the site.

2.1.7 Verification

The modelled cyclonic winds were compared against winds measured at various locations around the North West Shelf such as Browse Island, Adele Island, Onslow and Rowley Shoals.

From reliable measurements with good exposure, sample frequency and robustness, comparison to modelled storm peak data was very good. The fitted slope on the comparison plot was 0.99, with a correlation coefficient of 0.83. Modelled data were also compared to a broad selection of propriety third party data with similar results. Overall, the modelled versus measured wind comparisons were excellent, and demonstrated that no calibration correction was required.

2.2 Waves

A third generation directional spectral wave model, WAVEWATCH-III (Tolman 2003, 2003a, 2009), was used to simulate wave parameters for both ambient and tropical cyclone conditions for the locations of interest.

WAVEWATCH-III (WW3) solves the spectral action density balance equation for wavenumber-direction spectra. The governing equations include refraction and straining of the wave field due to temporal and spatial variations of the mean water depth and wave growth and decay due to the actions of wind, nonlinear resonant interactions, dissipation ("whitecapping") and bottom friction.

2.2.1 Model Forcing and Configuration

Four model grid domains were set-up with a one-way nesting scheme. See Figure 2.1 for illustration of all nested grid domains discussed below.

The coarse resolution "Global" grid of $1.00^\circ \times 1.25^\circ$ resolution accessed the in-house gridded database of ice conditions and was forced using the ambient global gridded winds. This grid was used to model ambient wave conditions to provide nested boundary data for each of the cyclones modelled over the 45 year period.

Together with the modelled tropical cyclone winds, these data were used to force a $0.25^\circ \times 0.25^\circ$ resolution "B" grid, spanning 110° E to 125° E and 24° S to 12° S. This grid was used to generate nested boundary forcing conditions for the finer $0.05^\circ \times 0.05^\circ$ resolution "C" grid spanning 112° to 118.75° E and 22.5° S to 18° S.

An even finer $0.02^\circ \times 0.02^\circ$ resolution “D” grid did not extend to the Mardie region, and so was not available to this study.

2.2.2 Verification

The modelled cyclonic waves were compared against waves measured at various locations around the North West Shelf.

Comparison to modelled storm peak data was very good. The fitted slope on the comparison plot was 1.04, with a correlation coefficient of 0.80. Overall, we have chosen to accept the slight conservatism indicated by this peak-to-peak comparison, and no calibration correction has been applied.

2.3 Currents and Water Levels

The Sparse Hydrodynamic Ocean Code (SHOC), developed by CSIRO Marine and Atmospheric Research (Herzfeld et al. 2010), is used to model ambient and cyclone-induced currents, sea levels and internal tides (although only water level data has been used in this study). SHOC is a general purpose circulation model, which is applicable on all spatial scales from estuary and coastal to the regional oceans. It is a fully nonlinear, 3D, baroclinic hydrodynamic model with hydrostatic and Boussinesq approximations. High-order advection schemes (e.g., second order upwind and ULTIMATE-QUICKEST) and a variety of two-equation turbulence closure schemes (e.g., Mellor-Yamada 2.0, Mellor-Yamada 2.5, $k-\omega$, and $k-\epsilon$) for vertical mixing are available. It includes parameterisations of wave enhanced bottom friction and wave effects on surface roughness. It has both one-and two-way nesting and parallel processing capabilities.

SHOC has been extensively calibrated and validated against in-house field data that have been collected over the last ~30 years on the North West Shelf and other regions, and routinely applied to current, sea-level and internal tidal modelling for many major projects. These calibrations involved running the model with different configurations of mixing schemes, surface and bottom roughness lengths, surface wave effects and wind stress drag formulations, and selecting the configuration that was the best overall match to selected measured data appropriate to the specific application.

2.3.1 Model Forcing and Configuration

A 2-level nested grid system is used, with a $0.1^\circ \times 0.1^\circ$ (approx. 10 km x 10 km) resolution “A” grid, covering the North West Shelf, which forced one-way to a $0.02^\circ \times 0.02^\circ$ (approx. 2 km x 2 km) resolution “B” grid that covers the region of interest (see Figure 2.1).

The “A” grid is forced at the boundaries with tidal elevations predicted from the fourth generation Centre for Space Research ocean tide model, CSR 4.0 (Eanes and Bettadpur 1996, Eanes 1999). In-house tests and calibrations have shown the database to be quite accurate on the North West Shelf.

To incorporate the important effects of stratification (internal tides), the “A” grid model is initialised and forced at the open boundaries with temperature and salinity fields obtained from the BLUElink project (Schiller et al. 2008). Daily averaged hindcast BLUElink data are used when the model runs are within the BLUElink project years (1998 to 2014). Otherwise, the climatological monthly averaged temperature and salinity fields are used because BLUElink does not span the entire period of the production model runs.

The nested “B” grid is forced along the open boundary by currents as described in Herzfeld (2009), and 3D temperature and salinity data from the “A” grid. These so-called “velocity open boundary conditions” use the “A” grid results to specify both normal and tangential velocity components along the open “B” grid boundaries.

The model has 33 vertical levels with a resolution varying from 2.5 m near the surface to about 15 m in water depths of around 100 m and coarser in deeper water.

A large number of alternative physical parameterizations and numerical schemes are available in SHOC, which can have varying effects on model stability and skill. Over the past 10 years RPS has gained very extensive experience in the use of SHOC and its forerunner models. Based on this past experience and experimentation, the configuration of SHOC used has the following main features:

- a modified Large & Pond (1981) style wind drag scheme, with the drag coefficient capped to 0.00218 at wind speeds greater than 26 m s^{-1} ;
- bottom roughness length scale equal to 0.0002 m. Note that this default value is usually overridden by wave-enhanced bottom friction in continental shelf waters;
- vertical eddy viscosity and diffusivity calculated using the k- ϵ mixing scheme;
- horizontal viscosity and diffusivity, calculated using the Smagorinsky (1963) scheme, which is based on horizontal current shear;
- velocity open boundary conditions along the B grid open boundaries;
- a 2nd order momentum advection scheme and the QUICKEST tracer (salinity, temperature) advection scheme;
- wave-enhanced bottom friction based on the formulation of Madsen (1994);
- wave-enhanced turbulent mixing at the surface based on the formulation of Craig and Banner (1984).

2.3.2 Verification

The modelled near-surface currents were compared against measurements at various locations around the North West Shelf. Comparison to modelled storm peak data was very good. The fitted slope on the comparison plot was 0.92, with a correlation coefficient of 0.74.

Verification of storm surge values is more difficult, due to the relative scarcity of reliable data, and the complications arising from the fact that tides usually make the dominant contribution to still water level, but wave setup can also be of significance (not simulated by the SHOC model).

Instead, surface elevation constituents output from the model were compared against measured tidal constituents within the model domain. A number of publicly available constituents were taken from the Australian National Tide Tables (Australian Hydrographic Service 2008). Additionally, a number of stations where RPS holds measured data were harmonically analysed. The SHOC "A" grid was run for a period of 2 months, and surface elevations at locations corresponding to the measurement sites were harmonically analysed, and the tidal constituents compared. Initial analysis showed that the tides were consistently too high. Multiplying the constituent magnitudes from CSR4.0 by a factor of 0.7 gave much better results

The tides were then run through the SHOC "B" grid. A scatterplot of the 4 main tidal constituent amplitudes and phases is displayed in Figure 2.2. This scatterplot shows a good agreement with tidal amplitudes, with some mismatches in phase at some stations. The discrepancies would be due to the relatively coarse model resolution and differences between cell depth and the depth of the stations. Overall, the model matches tides very well.

The fact that both tides and currents are well-simulated by SHOC, gives confidence that it will also generate reliable estimates of storm surge.

3.0 ANALYSIS METHODOLOGIES

3.1 Extreme Analyses

Throughout this study, the Conditional Weibull method of extreme analysis has been adopted.

Data input to the Conditional Weibull method is selected by the 'peak-over-threshold' method. Typically, at least 20 values are required to ensure that asymptotic assumptions regarding the plotting position formula are satisfied.

This method fixes the location parameter of the 3 parameter Weibull distribution to the threshold value (used in data selection) and then fits the scale and index parameters using a maximum likelihood technique.

Some judgment is required in the setting of an appropriate threshold. Usually a balance must be struck between retaining enough events to ensure acceptable behaviour of asymptotes, whilst avoiding inclusion of too many 'non extreme' values. In most instances the methodology is well-behaved, showing only slight sensitivity to threshold selection.

Since surge will be the prime determinant of inundation level, extreme waves (for set-up calculations) have been analysed at the time of peak surge in addition to at time of peak waves. Design tables for at time of peak winds have also been included for completeness.

3.2 Spectral Shape Fitting

Though developed specifically for the description of a "young" or "rising" sea (one in which active wind input is still occurring due to wind speed increase or fetch limitation), the JONSWAP formulation has sufficient free parameters to describe most unimodal spectra (a unimodal spectrum has only one major energy peak).

The JONSWAP spectrum is given by:

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp \left\{ -5/4 \left(\frac{f}{f_p} \right)^{-4} \right\} \gamma^{\exp \left\{ -\frac{(f-f_p)^2}{2\sigma^2 f_p^2} \right\}}$$

where $\sigma = \sigma_A$ for $f \leq f_p$

σ_B for $f > f_p$,

and $E(f)$ is the energy spectrum over frequency f .

The formulation has five free parameters, being

- peak frequency f_p
- Phillips parameter α
- Peakedness parameter γ
- low frequency spectral width parameter σ_A
- high frequency spectral width parameter σ_B

The Pierson-Moskowitz spectrum is a special case of the JONSWAP spectrum, for which $\gamma = 1$ (thereby eliminating the effect of σ_A and σ_B) and $\alpha = 0.0081$, reducing it to a single parameter (f_p) distribution. The Pierson-Moskowitz spectrum is theoretically only applicable to a "fully arisen" sea (one in which energy input from the wind is balanced by dissipation processes - principally wave breaking).

JONSWAP Parameterisation

Lewis & Allos (1990) have demonstrated inconsistencies in the original JONSWAP analyses of Hasselman et al. (1976). They instead formulated a self-consistent suite of JONSWAP spectral parameterisation equations, as follows:

Phillips parameter	α	$= 103.39 m_0^{0.0687} g^{-1.375} T_p^{-2.750}$
Peakedness parameter	γ	$= 2.214 \times 10^5 m_0^{0.887} g^{-1.774} T_p^{-3.550}$
low frequency width	σ_A	$= 1.071 \times 10^{-3} m_0^{-0.331} g^{0.662} T_p^{1.325}$
high frequency width	σ_B	$= 1.104 \times 10^{-2} m_0^{-0.165} g^{0.330} T_p^{0.660}$

where m_0 is the zeroth moment of the spectrum given by $m_0 = H_s^2/16$, $T_p = 1/f_p$ is the spectral peak period and g is gravitational acceleration.

The Lewis & Allos JONSWAP spectral parameterisation equations have been used in describing the tropical cyclone wave spectra in this study.

It is noted that this may not be appropriate for strongly breaking seastates such as will occur in shallow water under strong tropical cyclone forcing, but at this stage, the whole precept of a 'spectral' description of a seastate comes into question, and there are presently no obviously better alternatives.

3.3 Tropical Cyclone Individual Wave, Crest Elevation and Period

Maximum Single Wave Height

Maximum single wave heights are usually determined from significant wave heights by a simple multiplier, which is related to the number of waves which occur over the period for which the significant wave height is representative. For ambient seastates, this is usually of the order of three to six hours, and the Rayleigh distribution is appropriate.

Under storm conditions, it is widely accepted that the Rayleigh distribution overestimates the largest wave heights. Forristall (1978) has presented a detailed study of the statistics of wave heights in a storm. In particular, he provides an empirical determination of the relationship between expected maximum single wave height (EH_{max}) and the zeroth moment of the spectrum (m_0) as follows:

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

where $\alpha = 2.125$

$\beta = 8.42$

$\gamma = 0.5772$ (Euler's Constant)

and N = the number of waves represented by the modelled spectrum.

For modelled spectra, it is generally accepted that the significant wave height (H_s) is given by $H_s = 4 (m_0)^{1/2}$.

The above formulation cannot be directly applied to the output of the spectral wave model, because while the resultant H_s values are intended to represent a “quasi-stationary” wave field (i.e. slowly varying over a time span of a few hours), fine grid model output is available every 30 minutes. A problem arises in that the multiplier appropriate to 30 minutes, when applied to the maximum hindcast H_s value, results in lower estimates of EH_{max} than a multiplier appropriate to 6 hours when applied to a 6 hourly mean of H_s .

Tucker & Pitt (2004) resolve this difficulty by invoking the Borgman convolution of the short term (Forristall) individual wave height distribution, with the longer term storm hydrograph. To avoid the ‘parabolic hydrograph’ assumption implicit in this method, RPS MetOcean have derived a robust inverse FFT technique which achieves equivalent results, as follows:

- For each analysis location (north and south), for each storm, all surface wave spectra $S_{\eta\eta}$ were selected for which $H_s > 0.5 H_{Smax}$ for that storm.
- For each surface spectrum, an inverse FFT is performed (using random phase), to obtain a synthetic wave profile which spans the duration of the model output interval.
- For the duration of the storm ($H_s > 0.5 H_{Smax}$), all profiles were scanned to find the peak value of maximum single wave height, H_{max} .

- The entire exercise is then repeated for a different random phase, and a running mean of H_{\max} accumulated until the mean stabilises to EH_{\max} . For this storm we then obtain a ratio of EH_{\max} to storm peak H_s (or $H_{S\max}$).
- This exercise is then repeated for the top 10 storms which were selected for extreme analysis for each location, and a mean $EH_{\max}/H_{S\max}$ ratio calculated. This ratio is then used to determine EH_{\max} from extrapolated values of H_s .

In this instance the calculated $EH_{\max}/H_s = 1.91$ for both the northern location and the southern location.

Period of Maximum Single Wave

The period of the maximum single wave for tropical cyclone sea states, TH_{\max} , was set using the empirical relationship of Goda (1985):

$$TH_{\max} = 1.15 T_m.$$

The applicability of this formula to tropical cyclone seastates is corroborated by Tron et al (2002).

Crest Elevation

The most applicable work on crest elevations (h_c) is that published by Forristall (2000). He shows that second order simulations of wave crests agree well with measurements, and has developed parametric crest distributions that are "accurate enough for engineering use". Forristall's crest height calculation comes directly from the WW3 modelled estimates of H_s and the spectral mean wave period, T_m .

The parameterisation of the simulated waves involved two steps of fitting. First, each case was fitted to a Weibull distribution of the form:

$$P(\eta_c > \eta) = \exp \left[- \left(\frac{\eta}{\alpha H_s} \right)^\beta \right] \quad (\text{Forristall, 2000})$$

where H_s is the significant wave height:

η is the crest height;

and Weibull parameters α and β are simple expressions found as functions of the water depth and wave steepness.

A fit to two-dimensional wave data uses the following Weibull parameters:

$$\begin{aligned} \alpha_2 &= 0.3536 + 0.2892S_1 + 0.1060U_r, \\ \beta_2 &= 2 - 2.1597S_1 + 0.0968U_r^2 \end{aligned}$$

A fit to three dimensional wave data uses the following Weibull parameters:

$$\alpha_3 = 0.3536 + 0.2568S_1 + 0.08000U_r,$$

$$\beta_3 = 2 - 1.7912S_1 + 0.5302U_r + 0.248U_r^2$$

In both cases, S_1 is the steepness parameter $S_1 = \frac{2\pi}{g} \frac{H_s}{T_m^2}$

U_r is the Ursell number $U_r = \frac{H_s}{k_m^2 d^3}$

and k_m is the wavenumber for a frequency of $1/T_m$.

This method was used to calculate crest elevation ratios for each analysis location based on the top 10 tropical cyclone events.

3.4 Tropical Cyclone Gust Factors

Vertical Profile of Tropical Cyclone Winds

As recommended by ISO 19901-1 (2005), and as represented by measurements of offshore conditions in strong, nearly neutrally stable atmospheric wind conditions, the mean wind speed profile $U_w(z)$ in storm conditions can be more accurately described by the following logarithmic profile than by the power law profile traditionally used:

$$U_{w,1h}(z) = U_{w0} \left[1 + C \ln \left(\frac{z}{z_r} \right) \right] \quad (3.1)$$

where $U_{w,1h}(z)$ is the 1 hour sustained wind speed at a height z above mean sea level;

U_{w0} is the 1 hour sustained wind speed at the reference elevation z_r and is the standard reference speed for sustained winds;

C is a dimensionally dependent coefficient, the value of which is dependent on the reference elevation and the wind speed, U_{w0} .

For $z_r = 10$ m,

$C = (0.0573)(1 + 0.15U_{w0})^{1/2}$ where U_{w0} is in units of metres per second ($m s^{-1}$);

z is the height above mean sea level;

z_r is the reference elevation above mean sea level ($z_r = 10$ m).

For the same storm conditions, the mean wind speed for averaging times shorter than 1 h may be expressed by the following equation using the 1 h sustained wind speed $U_{w,1h}(z)$ of Equation 3.1:

$$U_{w,T}(z) = U_{w,1h}(z) \left[1 - 0.41 I_u(z) \ln\left(\frac{T}{T_0}\right) \right]$$

where $U_{w,T}(z)$ is the sustained wind speed at height z above mean sea level, averaged over a time interval $T < 3600s$;

$U_{w,1h}(z)$ is the 1 h sustained wind speed at height z above mean sea level, see Equation 6.1;

T is the time averaging interval with $T < T_0 = 3600s$;

T_0 is the standard reference time averaging interval for wind speed of 1 h = 3600s;

$I_u(z)$ is the dimensionally dependent wind turbulence intensity at a height z above mean sea level, given below, where U_{w0} is in units of metres per second ($m s^{-1}$)

$$I_u(z) = (0.06) [1 + 0.043 U_{w0}] \left(\frac{z}{z_r} \right)^{-0.22}$$

3.5 Kernel Density Estimator (KDE) Contour Plots

To provide an understanding of the bounds of H_s and T_p , T_m or T_z for a given return period, contours of H_s and T_p , T_m or T_z pairs may be derived using a Kernel Density Estimator (KDE).

The KDE is a natural extension of the Histogram. From the scatter plot of H_s and T_p we apply a “kernel function” (a probability density function) to each data point, and add up their contributions to determine an overall density at any point of interest. The KDE can be defined as:

$$\text{Prob}(H, T) = \frac{1}{N} \sum_{i=1}^N \text{kernel}(H, T, H[i], T[i], B_H, B_T)$$

where $H[i]$ & $T[i]$ are the i^{th} values of the sample data,

H & T are our points of interest and

B_H and B_T are the “Bandwidths” of the kernel function.

The bandwidths determine the overall “smoothness” of the density function. While subjective, there are “rules-of-thumb” available to optimise the bandwidths, providing a balance between smoothness and “data-following”. A common rule is by Scott (1992).

$$B_i = N^{-1/6} \cdot \sigma_i$$

where N is the number of points, and σ is the standard deviation of the data in the i^{th} dimension.

Our KDE method multiplies these bandwidths by a “smoothing” factor between 2 and 4 (typically) in order to obtain a better looking curve.

The contour (or probability) level is the maximum value of the KDE at the specified design height. For example, the 10 year contour is formed by finding the probability of the 10 year peak

$$P_{10} = \max\{KDE(H_{10}, T)\} , \text{ where } H_{10} = 10 \text{ year return period wave height}$$

and then contouring at that probability level.

To preserve the natural steepness limitation of short period waves, a steepness transformation is applied to the H and T data prior to the KDE contouring process. The contoured H and T distribution is then re-transformed. Empirical corrections can be made for maximum wave steepness, and overall contour smoothness.

The corresponding wave periods associated with the return period wave heights have been used in manual wave set-up calculations.

4.0 EXTREME CYCLONIC CONDITIONS

4.1 Introduction

Tropical cyclones are the controlling storm type for return periods of a few years and longer in the study region.

Statistical information qualifying tropical cyclones affecting the study location is presented in Table 4.1. The table presents data on tropical cyclone occurrence and intensity within selected radii of the study location. The statistics in this table are derived from all tropical cyclones occurring off Australia's North West Shelf between the 1969/1970 to 2015/2016 cyclone seasons.

For this study, the highly-tuned, coupled wind, wave and current models (water levels) discussed in Chapter 2, have been used to simulate the influence of tropical cyclones on the Mardie coastline.

For tropical cyclones, each storm may be characterised by selected parameters (identified from historical meteorological records) which are allowed to vary along the path of the storm. These storms may then be numerically modelled to compute temporally and spatially varying wind and barometric pressure fields throughout the life of the storm. These fields can in turn be used to numerically simulate wave, current and storm surge fields under the tropical cyclone.

4.2 Storm Selection

Evaluation of tropical cyclones includes the construction of a storm database and the selection of appropriate wind, wave, storm current and storm tide models. Each model requires the path of the tropical cyclone of interest to be defined, together with other storm track parameters such as forward speed, central pressure and radius of maximum wind.

Early years — Pre 1968

Little cyclone information of any quality is available over the North West Shelf prior to satellite coverage. Also there was little in the way of population to report tropical cyclones in the region.

The first meteorological satellites were launched in 1960 but storm data prior to routine coverage from 1968, should be used with caution. Central pressure data estimated prior to implementation of the Dvorak (1975) technique should also be used with caution, however sufficient information was available to apply the method retrospectively for this study. In this study modelling was limited to post 1968 storms.

1969/1970 – 2014

Tropical cyclones were extracted from RPS' quality controlled tropical cyclone database from 1969 to 2014 over the area. Storms were selected based on proximity to the study location. This resulted in a total of 117 storms that originally passed within a 400 km radius of either Equus field or NRA. The wind fields associated with these original storm tracks were then modelled by blending the cyclone vortex generated by the Holland wind field model into the ambient gridded winds.

Most of these storms are relevant to the Mardie coastline, and it is unlikely that any storms of significance have been 'missed'. Track plots for each calendar month are presented in Appendix A.

4.3 Track Parameters

Storm position and forward speed are largely determined from satellite imagery, supplemented by some site observations and coastal radar data for more recent storms.

Storm Central Pressure

The central pressure data are those determined by the Bureau of Meteorology. Prior to 1970, central pressures were determined generally from the synoptic charts and have estimated accuracies of ± 20 mb. The improved satellite coverage subsequent to 1970, has allowed central pressures to be estimated by Dvorak's method (Dvorak, 1975) with probable accuracies of ± 10 mb. This method relies on estimating the central pressure from the type of clouds and rainbands present.

Radius of Maximum Winds

All tropical cyclone wind field models require the radius of maximum wind (distance from the storm centre to the maximum wind band) for each time step. A detailed description of the method is presented in RPS MetOcean Tech. Note TN370 (RPS MetOcean, 2004). The method used all measured and observed (radar and satellite) information available.

4.4 Track Shifting

To lengthen the 47 year (1969 to 2014) tropical cyclones database, and thereby improve confidence in long return period estimates, a 'track shifting' approach was adopted. Track shifting relies on the premise that tropical cyclone tracks are essentially random, such that the relative proximity of the point of closest approach to a particular site is also random.

To artificially increase the storm population, the gridded winds resulting from these blended storm tracks were shifted four times to yield a 585 storms and an effective data base duration of 225 years. Track shifting

was accommodated by a random displacement of the track origin, in both the north-south and east-west direction. Statistics were derived on the distance of closest approach of the original 117 storms that passed within 400 km of the Equus and NRA fields. The standard deviation of this distance was 153 km in a north-south direction, and 200 km in an east-west direction.

The tracks were randomly shifted by 1.5 standard deviations of the distance of closest approach. The value of 1.5 standard deviations was selected by subjective assessment of track distributions and resulting analysis of extrapolated wind speeds. Once the randomly shifted origin was located, the shifted tracks paralleled the original tracks.

The intensity of the storms was unchanged as variability in intensity is accommodated via the extrapolation process. That is why the “track shifting” process was not carried further than four shifts of the original tracks (representative of a 225 year database).

To this end, a limited set of severe storms derived from a limited duration database, may be extended by random relocation of the storm paths, and corresponding increase in the “effective” storm data base duration.

Gridded winds associated with the original 117 storms were initially modelled and blended into the ambient wind fields on a parent grid of $0.25^\circ \times 0.25^\circ$ resolution. These gridded winds were then replicated and shifted for each of the four randomly shifted tracks described above. To refine the number of storms, the shifted storms were again selected on whether they came within 400 km of Equus or NRA, resulting in 533 storms.

These 533 storms were then modelled on the WW3 B grid and SHOC A grid and point output at select locations were generated. A list of peak Hs at each location for each storm was then generated, ordered from largest to smallest, and limited to storms with peak Hs larger than 5 m (an estimate of the 100 year return period non-cyclonic Hs). The three lists were then collated. A list of peak surface current speed at each location for each storm was then generated, ordered from largest to smallest, limited to the top 130 storms then collated. The peak Hs and peak surface current lists were then collated, resulting in 333 cyclones to be modelled on the remaining WW3 and SHOC grids. Once the modelling was finalised this method was repeated to generate a list of 269 storms to be analysed.

A list of the tropical cyclones selected for analysis is detailed in Table 4.2.

4.5 Resulting Extremes

The tropical cyclone wind, wave and circulation models detailed in Chapter 2, were applied to the storm tracks listed in Table 4.2, to generate an effective 225 year database of winds, waves and storm surge off the Mardie coast.

Due to the significant north-south extent of the prospective Mardie Salt development of tropical cyclone extremes at two locations was warranted, representing the northern and southern extremes of the development. While the wave and circulation model grids overlapped – they were at differing spatial

resolutions, and represented differing exposure to tropical cyclones. The presence of near-shore islets and reefs meant that the coastline was afforded sub-gridscale protection from waves, but not from surge. Consequently, locations chosen for wave and circulation model output – though representative of the northern and southern extents of the development, were at differing locations. Selected location details are repeated in the table below, and illustrated in Figure 4.1.

Location	Model	Latitude	Longitude	Water Depth
Mardie North	Waves	21° 3' S	115° 45' E	~ 9 m MSL
	Surge	21° 3' S	115° 54' E	~ 4 m MSL
Mardie South	Waves	21° 13' S	115° 42' E	~ 7 m MSL
	Surge	21° 13' S	115° 47' E	~ 4 m MSL

Time histories of modelled wave parameters and water levels (tide plus surge above MSL) for each storm were output for analysis at each location. Since the ultimate requirement from this pre-feasibility study was estimates of storm surge, the directionality of wave forcing was not considered in the analysis. The offshore wave extremes were only used to assess the potential effect on wave setup, which is not simulated by the SHOC circulation model.

While directionality was not of significance (particularly given the unknown impact of complex near-shore bathymetry), joint occurrence of waves and surge is important. Consequently, extreme analysis of simultaneous wind, wave and surge levels has been conducted at the time of peak winds, at the time of peak waves, and at the time of peak surge, at both the northern and southern locations. Results are tabulated as follows:

- Mardie North
 - Table 4.3 – 10 years return period
 - Table 4.4 – 25 years return period
 - Table 4.5 – 100 years return period
 - Table 4.6 – 500 years return period
- Mardie South
 - Table 4.7 – 10 years return period
 - Table 4.8 – 25 years return period
 - Table 4.9 – 100 years return period
 - Table 4.10 – 500 years return period

All associated supporting information (extreme analyses, KDEs) are presented in Appendix B.

4.6 Treatment of Wave Setup

Since the nature of the near-shore bathymetry off the Mardie coast is unknown, detailed computation of wave setup (the added surge effect resulting from excess momentum arising from wave breaking in the surf zone), cannot be conducted.

The best available guidance on the manual computation of wave setup is provided by the US Army CERC Coastal Engineering Manual (CEM) (EM 1110-2-1100 June 2006), which has replaced the Shore Protection Manual.

Given that the WaveWatchIII wave model already has within it treatment of depth-limited wave breaking (at a spectral level), the application of modified Miche criteria as advocated by the CEM, becomes a circular argument over where breaking initiates and the resulting wave setup. The published setup curves result in no nett increase in elevation.

Instead, to provide a conservative estimate of the wave setup, the CEM-suggested 'rule-of-thumb' is adopted whereby wave setup, η , is given roughly by

$$\eta = 0.15 d_b$$

where d_b is the depth of breaking.

Again, this becomes a somewhat circular argument, because the depth of wave breaking has to be established, and our spectral wave model has already initiated spectral depth-limited breaking. Recent offshore engineering practice has adopted a Breaker Index of 0.6 for significant wave height. Accordingly $d_b = H_s/0.6$, and the allowance for wave setup becomes $\eta = 0.25 H_s$.

4.7 Sea Level Rise

It would be imprudent to not make some allowance for Sea Level Rise. Current IPCC estimates for sea level rise to 2050 are about 0.2 m. This should be adopted for pre-feasibility purposes.

Sea level off WA's coast has risen by about 3.2 mm/year over the last 20 years. From the BoM's latest "State of the Climate, 2014" report, 0.2 m is the best estimate for expected Sea Level Rise from between now and 2050. If this project's time horizons go beyond this, then higher numbers will accrue (at an increasing rate).

Given present uncertainties, we believe 0.2 m is a reasonable allowance. If the time horizon is longer – the Sea Level Rise effect will be simply additive. There are too many other uncertainties to assess whether storms will be stronger or waves will be bigger.

4.8 Final Estimates of Surge Extremes

Final estimates of tropical cyclone induced storm surge levels at the northern and southern extremities of the proposed Mardie Salt project are presented in Table 4.11. These estimates are for combined Total Still Water Level (tide + surge + setup + sea level rise) above Australian Height Datum (AHD). It is assumed that AHD ~ MSL.

These estimates take no account of subsequent flooding from delayed river runoff, which we understand will be the subject of another study.

We note that the North and South peak total seawater levels swap at 100 year return period (i.e. return period is always higher at North except at 100 years). This occurs because of the shift in the balance between surge contribution and wave setup contribution. At the northern location, the contribution of wave setup is always higher, but the contribution of surge (tide + surge) increases more steeply with return period at the southern location (unsurprising as the resistance to the southward generated current surge increases).

5.0 RECOMMENDATIONS FOR FURTHER WORK

BC Iron requested RPS to make a recommendation for further work needed for final design, and specifically to confirm:

1. a 100 year return basis of design,
2. the effect of wind waves within the pond.

The over-riding requirement is for detailed accurate bathymetry surrounding the proposed facility. RPS have previously worked with LADs bathymetry data supplied by a third party for both the Barrow Shoals region, and for Regnard Bay (immediately to the NE of Cape Preston), and found it to be well-suited to near-coastal modelling.

Once accurate bathymetry is available – tropical cyclone modelling can be conducted at grid scales relevant to the development, and to the offshore islets and reefs.

We would propose to run the WW3 wave model through a series of 5 nested grids as follows:

- A grid – $1^{\circ} \times 1.25^{\circ}$
- B grid – $0.25^{\circ} \times 0.25^{\circ}$
- C grid – $0.05^{\circ} \times 0.05^{\circ}$
- D grid – $0.02^{\circ} \times 0.02^{\circ}$
- E grid – $0.004^{\circ} \times 0.004^{\circ}$

See figures 5.1 a, b, c & d for grid extents.

To properly address the issues of wave breaking and setup on this very complex coastline, it is likely to be necessary to invoke a surf zone model such as 2DBeach or XBeach.

The SHOC 3D hydrodynamic model would also be used to simulate contributions from currents and tide + surge water levels.

Note that this additional modelling is not warranted without the inclusion of accurate bathymetry.

The resulting winds should be sufficient for conducting simplistic fetch-limited wind wave calculations for the ponds. There will probably also be a small wind setup on each pond – again amenable to cursory calculation.

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TABLES

Cyclone occurrence rates by month and intensity (cycmonth)

Position: 115.83000 degrees East, 21.12000 degrees South

Exposure period: 48 years from 1969/1970 season to 2016/2017 season

Storm tracks analysed: 142

r (km)		Nov	Dec	Jan	Feb	Mar	Apr	May	Annual
600	N	1	19	43	36	36	12	2	133
600	f	0.021	0.396	0.896	0.750	0.750	0.250	0.042	2.771
600	N1	0	3	14	12	3	3	0	27
600	N2	0	4	11	10	8	3	2	32
600	N3	0	4	9	1	7	2	0	23
600	N4	1	4	5	8	11	1	0	29
600	N5	0	4	4	5	7	3	0	22
500	N	0	13	34	29	31	9	1	105
500	f	0.000	0.271	0.708	0.604	0.646	0.188	0.021	2.188
500	N1	0	0	8	9	4	1	0	16
500	N2	0	4	10	7	9	4	1	31
500	N3	0	3	7	1	3	1	0	15
500	N4	0	4	5	8	9	0	0	25
500	N5	0	2	4	4	6	3	0	18
400	N	0	12	23	21	24	8	1	80
400	f	0.000	0.250	0.479	0.438	0.500	0.167	0.021	1.667
400	N1	0	2	5	6	2	1	0	13
400	N2	0	2	6	6	6	4	1	21
400	N3	0	4	5	1	5	0	0	15
400	N4	0	2	5	5	8	1	0	20
400	N5	0	2	2	3	3	2	0	11
300	N	0	10	19	15	19	5	1	64
300	f	0.000	0.208	0.396	0.312	0.396	0.104	0.021	1.333
300	N1	0	1	3	4	4	1	0	11
300	N2	0	2	9	5	4	2	1	21
300	N3	0	3	4	0	6	0	0	13
300	N4	0	2	2	4	3	0	0	10
300	N5	0	2	1	2	2	2	0	9
200	N	0	7	9	10	12	4	1	41
200	f	0.000	0.146	0.188	0.208	0.250	0.083	0.021	0.854
200	N1	0	1	1	3	2	1	1	9
200	N2	0	2	5	2	3	1	0	12
200	N3	0	1	3	1	4	0	0	9
200	N4	0	2	0	2	1	0	0	4
200	N5	0	1	0	2	2	2	0	7
100	N	0	4	3	5	6	4	0	21
100	f	0.000	0.083	0.062	0.104	0.125	0.083	0.000	0.438
100	N1	0	2	0	1	0	1	0	4
100	N2	0	1	2	1	2	1	0	6
100	N3	0	1	1	1	2	0	0	5
100	N4	0	0	0	0	2	0	0	2
100	N5	0	0	0	2	0	2	0	4

r: radius about position (km)

N: total number of storms entering radius

f: average frequency (storms per year)

Intensity classification scheme: australia (Pc)

N1: number of storms with minimum central pressure $P_c > 985$ hPa

N2: number of storms with minimum central pressure $970 < P_c \leq 985$ hPa

N3: number of storms with minimum central pressure $955 < P_c \leq 970$ hPa

N4: number of storms with minimum central pressure $930 < P_c \leq 955$ hPa

N5: number of storms with minimum central pressure $P_c \leq 930$ hPa

Note that a single storm may be counted in more than one month.

Table 4.1 Tropical cyclone occurrence and intensity statistics for the Mardie study site.

Beverley.1975.s000	Fiona-gwenda.1974.s003	Kirrily.2000.s003	Rachel.1997.s002
Beverley.1975.s001	Floyd.2006.s000.nc	Lena.1983.s002	Rachel.1997.s004
Beverley.1975.s002	Floyd.2006.s001.nc	Lena.1983.s004	Rhonda.1986.s000
Beverley.1975.s003	Floyd.2006.s002.nc	Lena.1993.s000	Rhonda.1986.s002
Beverley.1975.s004	Floyd.2006.s004.nc	Lena.1993.s001	Rhonda.1986.s003
Bianca.2011.s000	Frank.1984.s003	Lena.1993.s002	Rita.1971.s000
Bianca.2011.s003	Frank.1995.s000	Lena.1993.s003	Rita.1971.s001
Bianca.2011.s004	Frank.1995.s001	Leo.1977.s002	Rita.1971.s002
Billy.1998.s000	Frank.1995.s003	Lua.2012.s001	Rita.1971.s004
Billy.1998.s001	Frank.1995.s004	Lua.2012.s002	Rusty.2013.s001
Billy.1998.s002	Gertie.1985.s001	Lua.2012.s003	Rusty.2013.s002
Bobby.1984.s000	Glenda.2006.s000	Mabel.1981.s000	Rusty.2013.s003
Bobby.1984.s001	Glenda.2006.s001	Mabel.1981.s001	Rusty.2013.s004
Bobby.1984.s002	Glenda.2006.s002	Mabel.1981.s002	Sharon.1994.s000
Bobby.1984.s003	Glenda.2006.s003	Mabel.1981.s004	Sharon.1994.s003
Bobby.1984.s004	Glenda.2006.s004	Madge.1973.s000	Sharon.1994.s004
Bobby.1995.s000	Glynis.1970.s000	Madge.1973.s001	Sheila.1971.s000
Bobby.1995.s003	Glynis.1970.s001	Madge.1973.s002	Sheila.1971.s001
Bobby.1995.s004	Glynis.1970.s002	Margot.1985.s001	Sheila.1971.s003
Bruno.1982.s001	Glynis.1970.s004	Margot.1985.s002	Sheila.1971.s004
Carlos.2011.s001	Gwenda.1999.s001	Mavis.1971.s000	Steve.2000.s003
Carlos.2011.s002	Gwenda.1999.s004	Mavis.1971.s001	Steve.2000.s004
Chloe.1984.s004	Hazel.1979.s000	Mavis.1971.s003	Tiffany.1998.s000
Clara.1980.s000	Hazel.1979.s001	Mavis.1971.s004	Tiffany.1998.s001
Clara.1980.s001	Hazel.1979.s002	Melanie.2007.s000	Tiffany.1998.s002
Clara.1980.s002	Hazel.1979.s003	Melanie.2007.s001	Tiffany.1998.s003
Clara.1980.s003	Hazel.1979.s004	Melanie.2007.s002	Tiffany.1998.s004
Clare.2006.s003	Helen.1974.s001	Melanie.2007.s004	Tina.1990.s000
Connie.1987.s002	Helen.1974.s002	Mitchell.2012.s004	Tina.1990.s001
Connie.1987.s003	Helen.1974.s004	Monty.2004.s000	Tina.1990.s002
Damien.1987.s001	Hubert.2006.s000	Monty.2004.s001	Tina.1990.s003
Damien.1987.s003	Hubert.2006.s001	Monty.2004.s002	Tina.1990.s004
Daphne.1991.s000	Hubert.2006.s002	Monty.2004.s003	Trixie.1975.s000
Daphne.1991.s001	Hubert.2006.s004	Monty.2004.s004	Trixie.1975.s001
Daphne.1991.s002	Ian.1982.s000	Narelle.2013.s000	Trixie.1975.s002
Daphne.1991.s003	Ian.1982.s004	Narelle.2013.s001	Trixie.1975.s003
Daphne.1991.s004	Ian.1992.s000	Narelle.2013.s002	Trixie.1975.s004
Daphne-fifi.1982.s000	Ian.1992.s003	Narelle.2013.s003	Vance.1999.s000
Daryl.2006.s000	Ian.1992.s004	Narelle.2013.s004	Vance.1999.s001
Daryl.2006.s001	Ilona.1988.s000	Ned.1989.s004	Vance.1999.s002
Daryl.2006.s002	Ilona.1988.s001	Neil.1981.s001	Vance.1999.s003
Daryl.2006.s003	Ilona.1988.s004	Neil.1981.s003	Vance.1999.s004
Daryl.2006.s004	Ilsa.1999.s000	Neil.1981.s004	Vanessa.1976.s000
Dianne.2011.s000	Ilsa.1999.s004	Nicholas.2008.s000	Vanessa.1976.s001
Dianne.2011.s001	Ingrid.1970.s000	Nicholas.2008.s001	Vanessa.1976.s002
Dianne.2011.s002	Ingrid.1970.s001	Nicholas.2008.s002	Vanessa.1976.s003
Dianne.2011.s003	Ingrid.1970.s002	Nicholas.2008.s003	Vanessa.1976.s004
Dianne.2011.s004	Ingrid.1970.s003	Nicholas.2008.s004	Victor.1986.s000
Dominic.2009.s004	Inigo.2003.s001	Norman.2000.s000	Victor.1986.s001
Doris-gloria.1980.s001	Jacob.1996.s000	Norman.2000.s001	Victor.1986.s002
Doris-gloria.1980.s002	Jacob.1996.s003	Norman.2000.s002	Victor.1986.s003
Doris-gloria.1980.s003	Jacob.1996.s004	Norman.2000.s003	Victor.1986.s004
Doris-gloria.1980.s004	Jacob.2007.s001	Norman.2000.s004	Vincent.1990.s000
Elaine.1999.s000.nc	Jacob.2007.s003	Olga.2000.s000	Vincent.1990.s001
Elaine.1999.s001.nc	Jacob.2007.s004	Olga.2000.s003	Vincent.1990.s002
Elaine.1999.s002.nc	Jane.1983.s001	Olga.2000.s004	Vincent.1990.s003
Elaine.1999.s003.nc	Jean.1973.s001	Olivia.1996.s000	Vincent.1990.s004
Elaine.1999.s004.nc	Jean.1973.s003	Olivia.1996.s001	Wally.1976.s000
Emma.2006.s000	Joan.1975.s002	Olivia.1996.s002	Wally.1976.s001
Emma.2006.s001	John.1999.s000	Olivia.1996.s003	Wally.1976.s003
Emma.2006.s002	John.1999.s001	Orson.1989.s000	Wally.1976.s004
Emma.2006.s003	John.1999.s004	Orson.1989.s001	Willy.2005.s002
Erica.1973.s002	Kara.2007.s002	Orson.1989.s002	Willy.2005.s004
Erica.1973.s003	Karen.1977.s003	Orson.1989.s003	
Errol.1982.s000	Kerry.1973.s000	Phil.1996.s000	
Errol.1982.s003	Kerry.1973.s001	Phil.1996.s001	
Fiona-gwenda.1974.s000	Kerry.1973.s004	Phil.1996.s002	
Fiona-gwenda.1974.s001	Kirrily.2000.s000	Rachel.1997.s001	

Table 4.2 List of tropical cyclones selected for numerical simulation.

Cyclonic Conditions

10 Year Return Period

J3312 - Mardie_North

			Omni at Time of:		
Parameter	Symbol	Units	Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U_g	$m\ s^{-1}$	39.49	37.78	21.08
Mean (1 minute)	U_1	$m\ s^{-1}$	34.83	33.39	19.04
Mean (10 minute)	U_{10}	$m\ s^{-1}$	31.24	30.01	17.48
Mean (1 hour)	U_{60}	$m\ s^{-1}$	28.45	27.38	16.26
Waves					
Significant Wave Height	H_s	m	3.32	3.33	2.83
Spectral Peak Period [2]	T_p	s	10.77	10.81	9.58
Spectral Mean Period [3]	T_m	s	7.78	7.81	6.90
Zero Crossing Period [4]	T_z	s	6.67	6.70	5.99
Maximum Single Wave Height	EH_{max}	m	6.33	6.36	5.40
Period of Maximum Single Wave	TH_{max}	s	8.94	8.98	7.94
Steepness of Maximum Single Wave	L/EH_{max}		13.26	13.25	13.82
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0050	0.0050	0.0056
Peakedness Parameter	γ		0.60	0.60	0.69
Sigma A	σ_A		0.128	0.128	0.122
Sigma B	σ_B		0.120	0.120	0.117
Water Levels					
Chart Depth (LAT)	h	m	6.60	6.60	6.60
Tidal MSL (above LAT)	h_{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h_s	m	1.88	1.86	2.79
Maximum Still Water Level (ASB)	h_{max}	m	10.88	10.86	11.79
Wave Crest Elevation [6]	h_c	m	4.53	4.56	3.87
Maximum Instantaneous Water Level (ASB) [7]	$h_{inst,max}$	m	15.41	15.41	15.66
Independent Water Levels [8]					
Most Probable Maximum Single Wave Height	H_{mp}	m	-	6.51 [9]	-
Wave Crest Elevation [6]	$h_{c,ind}$	m	-	4.56	-
Maximum Instantaneous Water Level (ASB) [7]	$h_{inst\ max\ ind}$	m	-	15.41	-

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Short-term plus long-term convolution
 9. Surface waves may be breaking

Table 4.3 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 10 year return period at Mardie North location.

Cyclonic Conditions

25 Year Return Period

J3312 - Mardie_North

			Omni at Time of:		
Parameter	Symbol	Units	Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	52.20	49.49	30.26
Mean (1 minute)	U ₁	m s ⁻¹	45.40	43.17	26.99
Mean (10 minute)	U ₁₀	m s ⁻¹	40.18	38.31	24.48
Mean (1 hour)	U ₆₀	m s ⁻¹	36.12	34.53	22.52
Waves					
Significant Wave Height	H _s	m	3.39	3.42	3.22
Spectral Peak Period [2]	T _p	s	10.93	11.01	10.53
Spectral Mean Period [3]	T _m	s	7.90	7.96	7.60
Zero Crossing Period [4]	T _z	s	6.77	6.81	6.54
Maximum Single Wave Height	EH _{max}	m	6.46	6.52	6.15
Period of Maximum Single Wave	TH _{max}	s	9.09	9.15	8.74
Steepness of Maximum Single Wave	L/EH _{max}		13.43	13.40	13.78
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0050	0.0049	0.0051
Peakedness Parameter	γ		0.59	0.58	0.62
Sigma A	σ _A		0.129	0.129	0.127
Sigma B	σ _B		0.120	0.120	0.119
Water Levels					
Chart Depth (LAT)	h	m	6.60	6.60	6.60
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	2.28	2.23	2.94
Maximum Still Water Level (ASB)	h _{max}	m	11.28	11.23	11.94
Wave Crest Elevation [6]	h _c	m	4.63	4.67	4.40
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	15.91	15.89	16.34
Independent Water Levels [8]					
Most Probable Maximum Single Wave Height	H _{mp}	m	-	6.73 [9]	-
Wave Crest Elevation [6]	h _{c,ind}	m	-	4.70	-
Maximum Instantaneous Water Level (ASB) [7]	h _{inst max ind}	m	-	15.93	-

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Short-term plus long-term convolution
 9. Surface waves may be breaking

Table 4.4 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 25 year return period at Mardie North location.

Cyclonic Conditions

100 Year Return Period

J3312 - Mardie_North

Parameter			Symbol	Units
Wind [1]				
Gust (3 second)	U _g	m s ⁻¹		
Mean (1 minute)	U ₁	m s ⁻¹		
Mean (10 minute)	U ₁₀	m s ⁻¹		
Mean (1 hour)	U ₆₀	m s ⁻¹		
Waves				
Significant Wave Height	H _s	m		
Spectral Peak Period [2]	T _p	s		
Spectral Mean Period [3]	T _m	s		
Zero Crossing Period [4]	T _z	s		
Maximum Single Wave Height	EH _{max}	m		
Period of Maximum Single Wave	TH _{max}	s		
Steepness of Maximum Single Wave	L/EH _{max}			
JONSWAP Parameters [5]				
Phillips Parameter	α			
Peakedness Parameter	γ			
Sigma A	σ _A			
Sigma B	σ _B			
Water Levels				
Chart Depth (LAT)	h	m		
Tidal MSL (above LAT)	h _{msl}	m		
Tide + Surge (AMSL)	h _s	m		
Maximum Still Water Level (ASB)	h _{max}	m		
Wave Crest Elevation [6]	h _c	m		
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m		
Independent Water Levels [8]				
Most Probable Maximum Single Wave Height	H _{mp}	m		
Wave Crest Elevation [6]	h _{c,ind}	m		
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max,ind}	m		

Omni at Time of:		
Winds	Waves	Tide+Surge
67.34	62.98	42.88
57.74	54.22	37.67
50.36	47.48	33.66
44.62	42.24	30.55
3.43	3.46	3.39
11.05	11.11	10.94
7.99	8.03	7.91
6.84	6.87	6.77
6.55	6.59	6.46
9.18	9.23	9.09
13.64	13.59	13.83
0.0049	0.0049	0.0050
0.58	0.58	0.59
0.130	0.130	0.129
0.120	0.121	0.120
6.60	6.60	6.60
2.40	2.40	2.40
2.75	2.64	3.15
11.75	11.64	12.15
4.69	4.72	4.63
16.44	16.37	16.78
-	6.96 [9]	-
-	4.88	-
-	16.52	-

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Short-term plus long-term convolution
 9. Surface waves may be breaking

Table 4.5 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 100 year return period at Mardie North location.

Cyclonic Conditions

500 Year Return Period

J3312 - Mardie_North

			Omni at Time of:		
Parameter	Symbol	Units	Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	81.82	75.58	56.49
Mean (1 minute)	U ₁	m s ⁻¹	69.32	64.35	48.92
Mean (10 minute)	U ₁₀	m s ⁻¹	59.72	55.73	43.11
Mean (1 hour)	U ₆₀	m s ⁻¹	52.24	49.01	38.59
Waves					
Significant Wave Height	H _s	m	3.47	3.48	3.48 [9]
Spectral Peak Period [2]	T _p	s	11.13	11.17	11.17
Spectral Mean Period [3]	T _m	s	8.05	8.07	8.07
Zero Crossing Period [4]	T _z	s	6.88	6.90	6.90
Maximum Single Wave Height	EH _{max}	m	6.61	6.64	6.64
Period of Maximum Single Wave	TH _{max}	s	9.25	9.29	9.29
Steepness of Maximum Single Wave	L/EH _{max}		13.83	13.76	13.92
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0049	0.0049	0.0049
Peakedness Parameter	γ		0.58	0.57	0.57
Sigma A	σ _A		0.130	0.130	0.130
Sigma B	σ _B		0.121	0.121	0.121
Water Levels					
Chart Depth (LAT)	h	m	6.60	6.60	6.60
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	3.19	3.02	3.39
Maximum Still Water Level (ASB)	h _{max}	m	12.19	12.02	12.39
Wave Crest Elevation [6]	h _c	m	4.74	4.76	4.76
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	16.93	16.78	17.15
Independent Water Levels [8]					
Most Probable Maximum Single Wave Height	H _{mp}	m	-	7.16 [10]	-
Wave Crest Elevation [6]	h _{c,ind}	m	-	5.04	-
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max,ind}	m	-	17.06	-

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Short-term plus long-term convolution
 9. Value replaced with independent omnidirectional value
 10. Surface waves may be breaking

Table 4.6 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 500 year return period at Mardie North location.

**Cyclonic Conditions
10 Year Return Period
J3312 - Mardie_South**

Parameter	Symbol	Units	Omni at Time of:		
			Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	38.32	35.18	22.08
Mean (1 minute)	U ₁	m s ⁻¹	33.84	31.19	19.92
Mean (10 minute)	U ₁₀	m s ⁻¹	30.40	28.12	18.25
Mean (1 hour)	U ₆₀	m s ⁻¹	27.72	25.73	16.96
Waves					
Significant Wave Height	H _s	m	2.57	2.63	2.25
Spectral Peak Period [2]	T _p	s	7.90	8.05	7.16
Spectral Mean Period [3]	T _m	s	5.79	5.89	5.32
Zero Crossing Period [4]	T _z	s	5.15	5.22	4.77
Maximum Single Wave Height	EH _{max}	m	4.87 [8]	4.95 [8]	4.28
Period of Maximum Single Wave	TH _{max}	s	6.66	6.77	6.12
Steepness of Maximum Single Wave	L/EH _{max}		11.02	11.12	11.55
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0083	0.0081	0.0090
Peakedness Parameter	γ		1.14	1.11	1.28
Sigma A	σ _A		0.101	0.102	0.097
Sigma B	σ _B		0.106	0.107	0.104
Water Levels					
Chart Depth (LAT)	h	m	4.59	4.59	4.59
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	1.83	1.92	2.73
Maximum Still Water Level (ASB)	h _{max}	m	8.82	8.91	9.72
Wave Crest Elevation [6]	h _c	m	3.43	3.48	3.01
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	12.24	12.39	12.74

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Surface waves may be breaking

Table 4.7 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 10 year return period at Mardie South location.

Cyclonic Conditions 25 Year Return Period J3312 - Mardie_South

Parameter	Symbol	Units	Omni at Time of:		
			Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	50.62	44.05	32.51
Mean (1 minute)	U ₁	m s ⁻¹	44.10	38.65	28.92
Mean (10 minute)	U ₁₀	m s ⁻¹	39.09	34.50	26.15
Mean (1 hour)	U ₆₀	m s ⁻¹	35.19	31.27	24.00
Waves					
Significant Wave Height	H _s	m	2.64	2.66	2.52
Spectral Peak Period [2]	T _p	s	8.06	8.11	7.80
Spectral Mean Period [3]	T _m	s	5.90	5.92	5.73
Zero Crossing Period [4]	T _z	s	5.23	5.25	5.09
Maximum Single Wave Height	EH _{max}	m	5.02	5.06	4.81
Period of Maximum Single Wave	TH _{max}	s	6.78	6.81	6.59
Steepness of Maximum Single Wave	L/EH _{max}		11.16	11.14	11.47
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0081	0.0081	0.0084
Peakedness Parameter	γ		1.11	1.10	1.16
Sigma A	σ _A		0.102	0.102	0.100
Sigma B	σ _B		0.107	0.107	0.106
Water Levels					
Chart Depth (LAT)	h	m	4.59	4.59	4.59
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	2.39	2.37	3.00
Maximum Still Water Level (ASB)	h _{max}	m	9.38	9.36	9.99
Wave Crest Elevation [6]	h _c	m	3.54	3.56	3.38
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	12.91	12.92	13.37

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation

Table 4.8 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 25 year return period at Mardie South location.

Cyclonic Conditions
100 Year Return Period
J3312 - Mardie_South

Parameter	Symbol	Units	Omni at Time of:		
			Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	65.62	57.32	50.52
Mean (1 minute)	U ₁	m s ⁻¹	56.35	49.61	44.02
Mean (10 minute)	U ₁₀	m s ⁻¹	49.23	43.68	39.02
Mean (1 hour)	U ₆₀	m s ⁻¹	43.68	39.06	35.13
Waves					
Significant Wave Height	H _s	m	2.66	2.69	2.69 [8]
Spectral Peak Period [2]	T _p	s	8.13	8.05	8.05
Spectral Mean Period [3]	T _m	s	5.94	5.98	5.98
Zero Crossing Period [4]	T _z	s	5.26	5.29	5.29
Maximum Single Wave Height	EH _{max}	m	5.08	5.13	5.13
Period of Maximum Single Wave	TH _{max}	s	6.83	6.87	6.87
Steepness of Maximum Single Wave	L/EH _{max}		11.44	11.34	11.52
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0080	0.0084	0.0084
Peakedness Parameter	γ		1.10	1.16	1.16
Sigma A	σ _A		0.102	0.100	0.100
Sigma B	σ _B		0.107	0.106	0.106
Water Levels					
Chart Depth (LAT)	h	m	4.59	4.59	4.59
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	3.13	2.91	3.38
Maximum Still Water Level (ASB)	h _{max}	m	10.12	9.90	10.37
Wave Crest Elevation [6]	h _c	m	3.57	3.61	3.61
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	13.69	13.51	13.97

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Value replaced with independent omnidirectional value

Table 4.9 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 100 year return period at Mardie South location.

Cyclonic Conditions
500 Year Return Period
J3312 - Mardie_South

Parameter	Symbol	Units	Omni at Time of:		
			Winds	Waves	Tide+Surge
Wind [1]					
Gust (3 second)	U _g	m s ⁻¹	80.22	72.62	74.55
Mean (1 minute)	U ₁	m s ⁻¹	68.05	61.98	63.53
Mean (10 minute)	U ₁₀	m s ⁻¹	58.70	53.81	55.06
Mean (1 hour)	U ₆₀	m s ⁻¹	51.42	47.45	48.47
Waves					
Significant Wave Height	H _s	m	2.68	2.73	2.73 [8]
Spectral Peak Period [2]	T _p	s	8.16	8.14	8.14
Spectral Mean Period [3]	T _m	s	5.96	6.03	6.03
Zero Crossing Period [4]	T _z	s	5.28	5.34	5.34
Maximum Single Wave Height	EH _{max}	m	5.11	5.20	5.20
Period of Maximum Single Wave	TH _{max}	s	6.85	6.94	6.94
Steepness of Maximum Single Wave	L/EH _{max}		11.67	11.52	11.64
JONSWAP Parameters [5]					
Phillips Parameter	α		0.0080	0.0083	0.0083
Peakedness Parameter	γ		1.10	1.14	1.14
Sigma A	σ _A		0.102	0.101	0.101
Sigma B	σ _B		0.107	0.106	0.106
Water Levels					
Chart Depth (LAT)	h	m	4.59	4.59	4.59
Tidal MSL (above LAT)	h _{msl}	m	2.40	2.40	2.40
Tide + Surge (AMSL)	h _s	m	3.77 [8]	3.43	3.77
Maximum Still Water Level (ASB)	h _{max}	m	10.76	10.42	10.76
Wave Crest Elevation [6]	h _c	m	3.59	3.66	3.66
Maximum Instantaneous Water Level (ASB) [7]	h _{inst,max}	m	14.36	14.08	14.42

- Note :**
1. Wind speeds determined from U10 as per ISO Profile
 2. T_p calculated from wave climate KDE
 3. T_m calculated from wave climate KDE
 4. T_z calculated from wave climate KDE
 5. JONSWAP parameters as per Lewis & Allos formulations
 6. Datum is Maximum Still Water Level
 7. Maximum Instantaneous Water Level = Maximum Still Water Level + Wave Crest Elevation
 8. Value replaced with independent omnidirectional value

Table 4.10 Summary omnidirectional joint occurrent tropical cyclone winds, waves, tide and surge for 500 year return period at Mardie South location.

Location	Return Period (Years)	Tide + Surge (m)	Hs (m)	Wave Setup (m)	Sea Level Rise (m)	Total SWL (m AHD)
North	10	2.79	2.83	0.71	0.20	3.70
	25	2.94	3.22	0.81	0.20	3.95
	100	3.15	3.39	0.85	0.20	4.20
	500	3.39	3.48	0.87	0.20	4.46
South	10	2.73	2.25	0.56	0.20	3.49
	25	3.00	2.52	0.63	0.20	3.83
	100	3.38	2.69	0.67	0.20	4.25
	500	3.77	2.75	0.69	0.20	4.66

Table 4.11 Estimates of Total Still Water Level above AHD (combined tide, surge, wave setup and sea level rise) for 10, 25, 100 and 500 years return period at Mardie North and Mardie South locations.



FIGURES

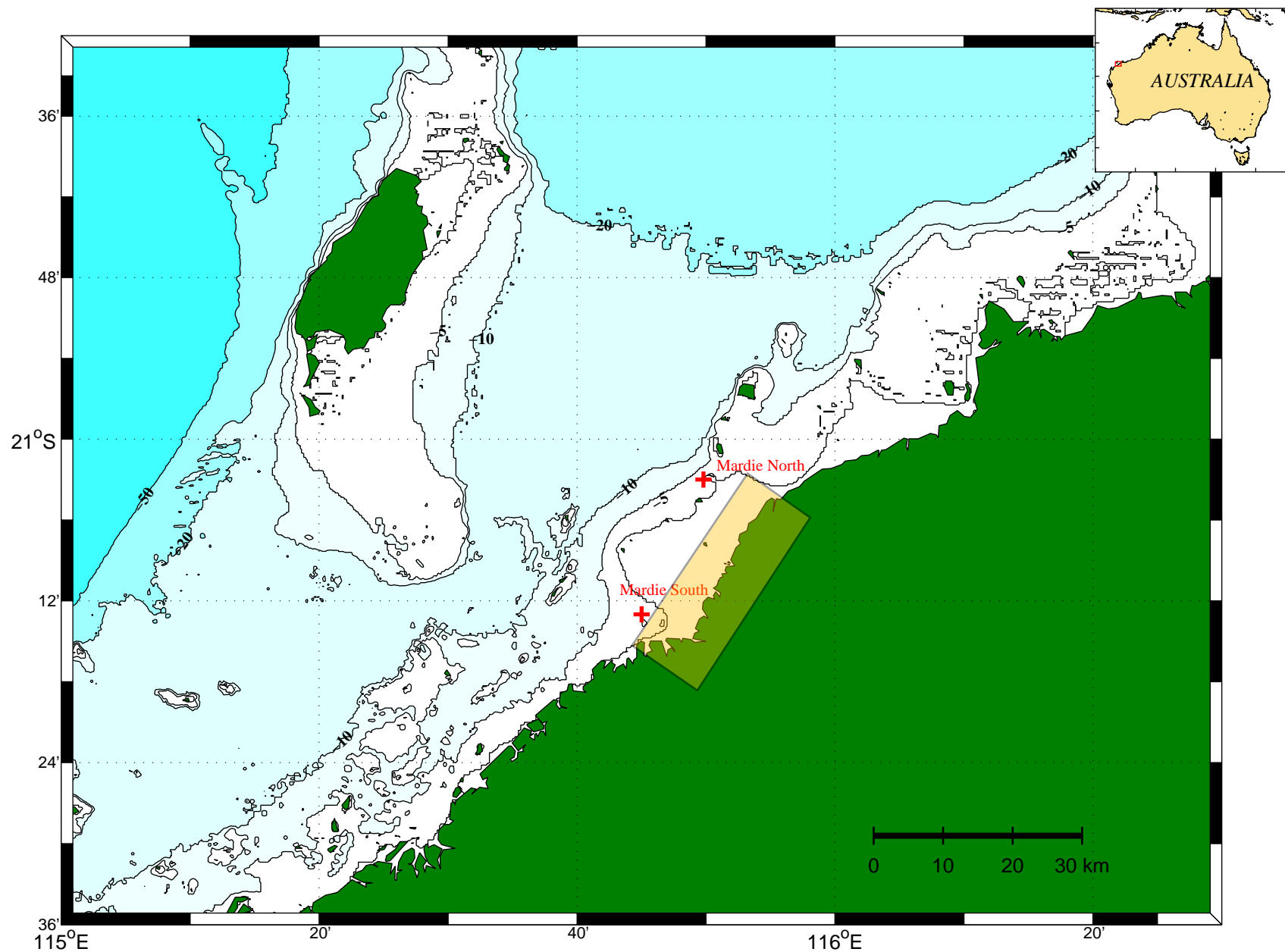


Figure 1.1 Location map and regional bathymetry of the proposed development near Mardie.

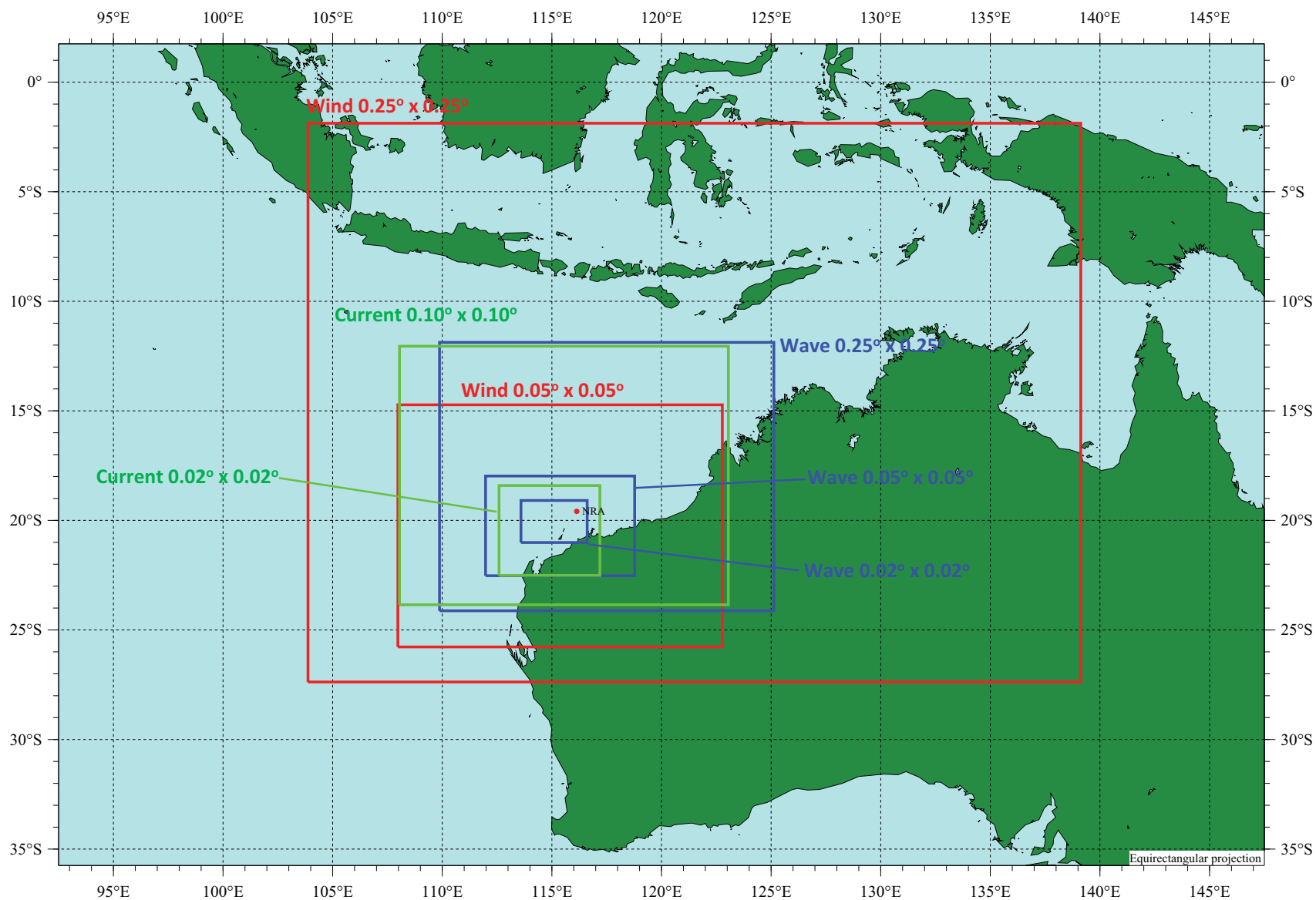


Figure 2.1 Extent of tropical cyclone wind, wave and current modelling grids

Measured vs Modelled tidal elevation constituents from
29 locations within the $0.02^\circ \times 0.02^\circ$ "B" grid

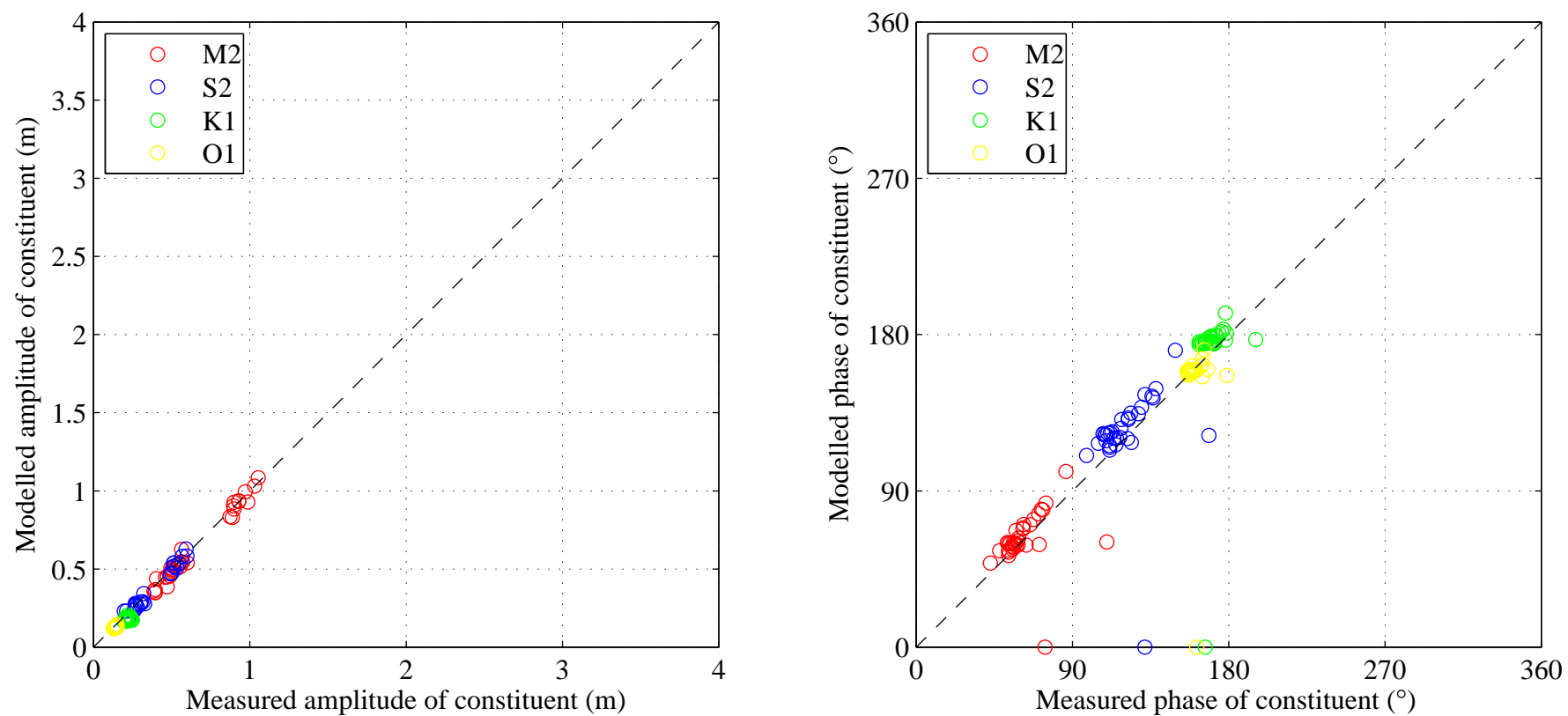


Figure 2.2 Tide height constituent amplitudes and phase calibrations.



Figure 4.1 Model output locations.

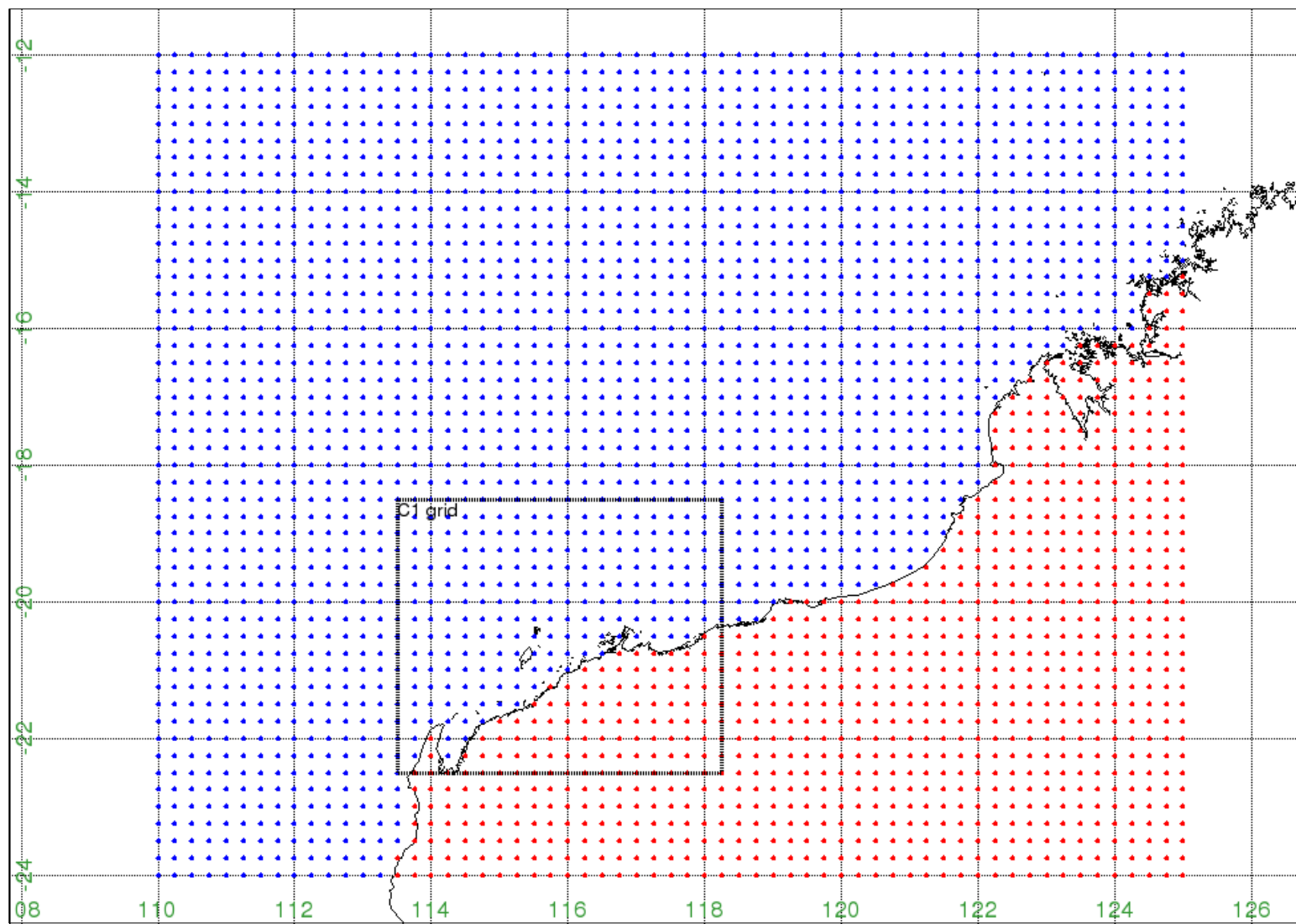


Figure 5.1a Extent of proposed WW3 B & C grids for recommended further modelling.

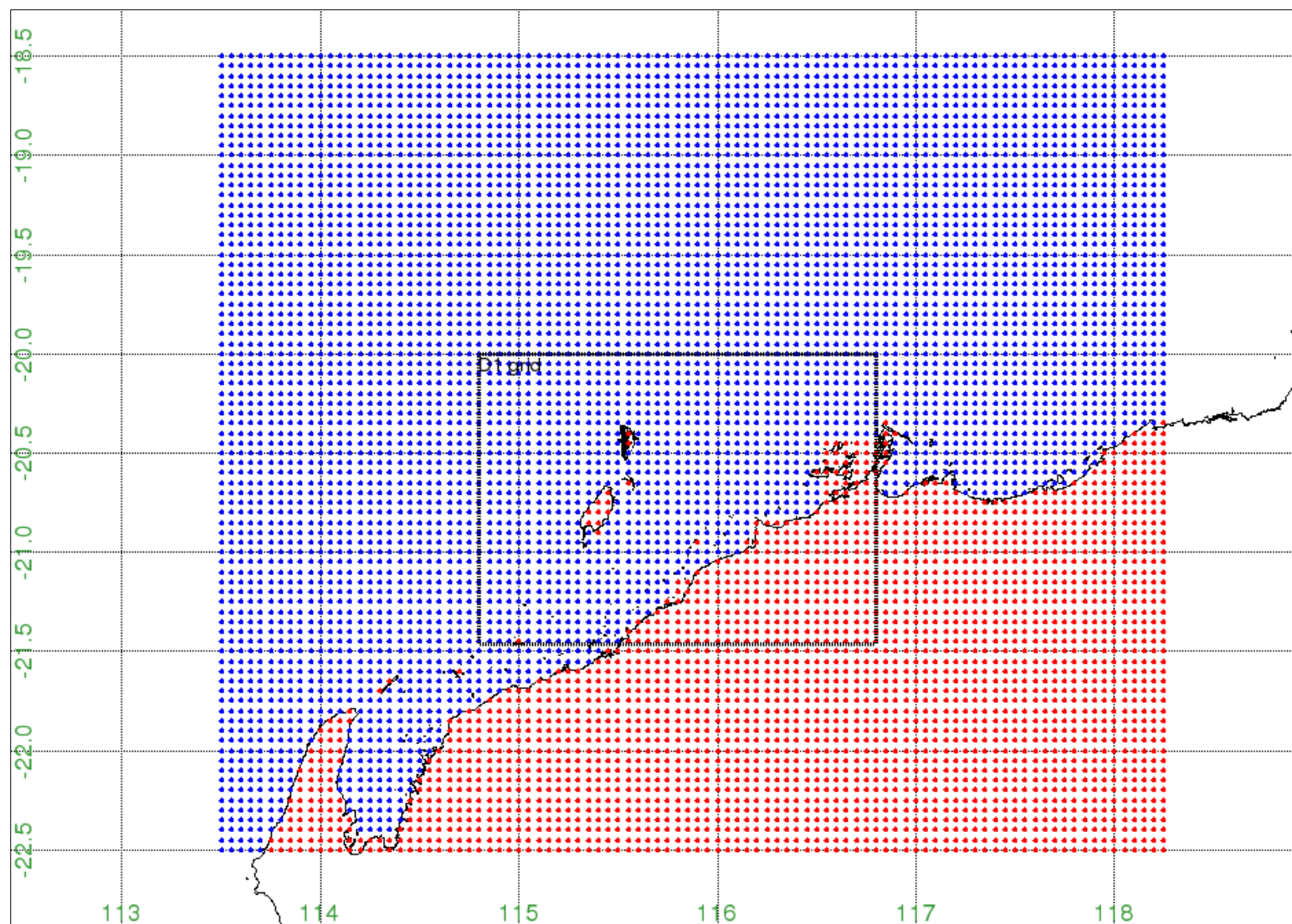


Figure 5.1b Extent of proposed WW3 C & D grids for recommended further modelling.

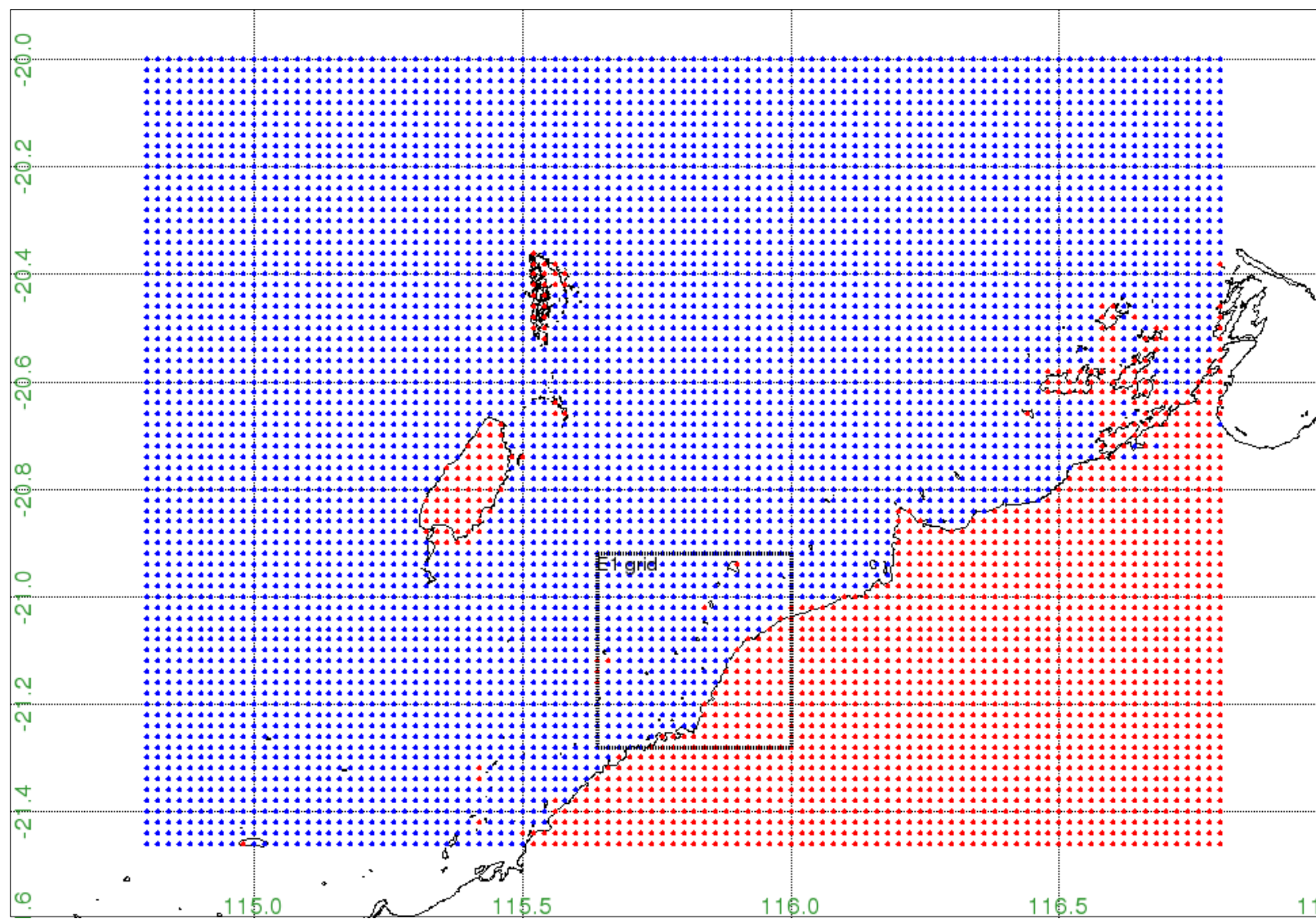


Figure 5.1c Extent of proposed WW3 D & E grids for recommended further modelling.

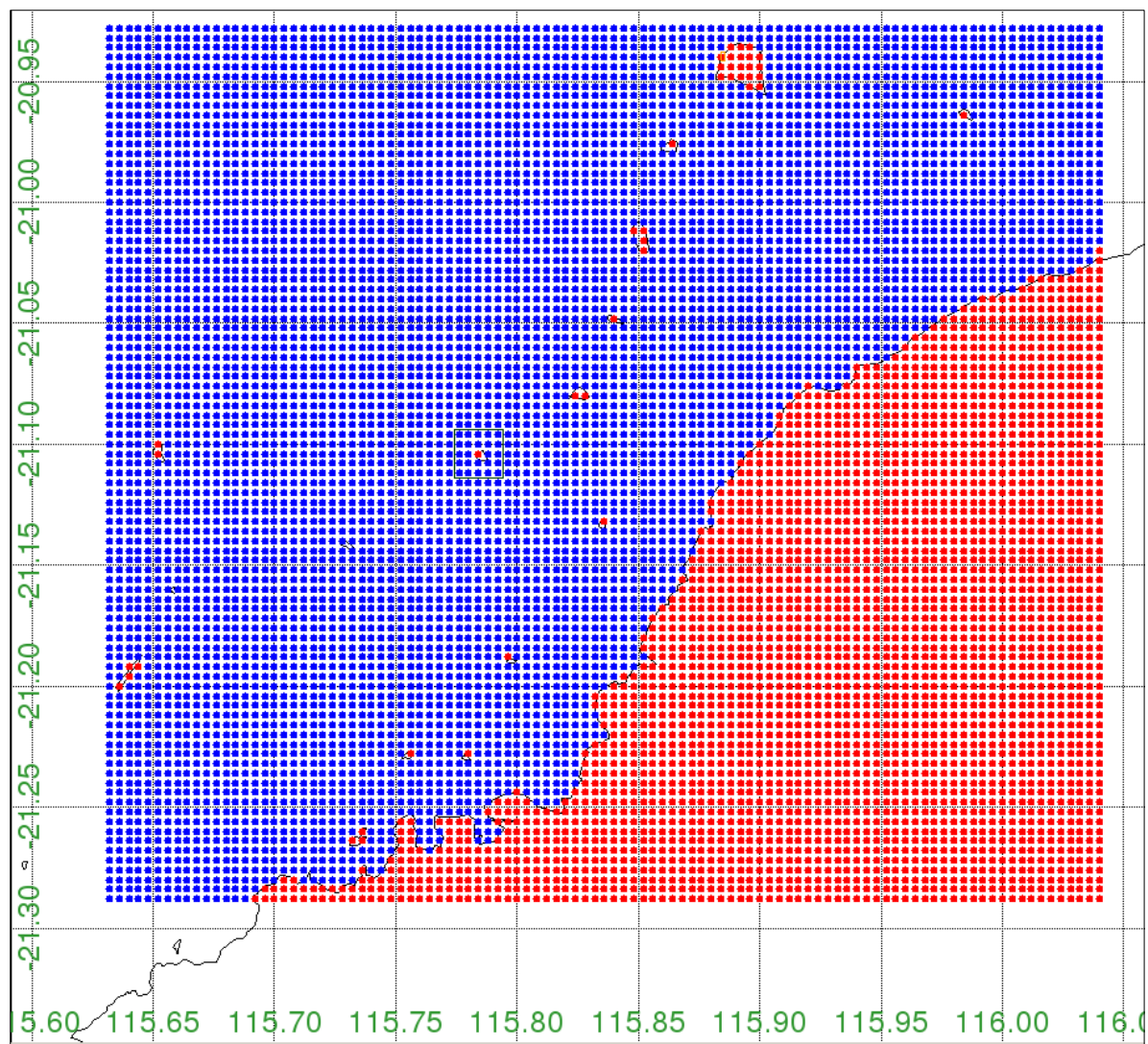
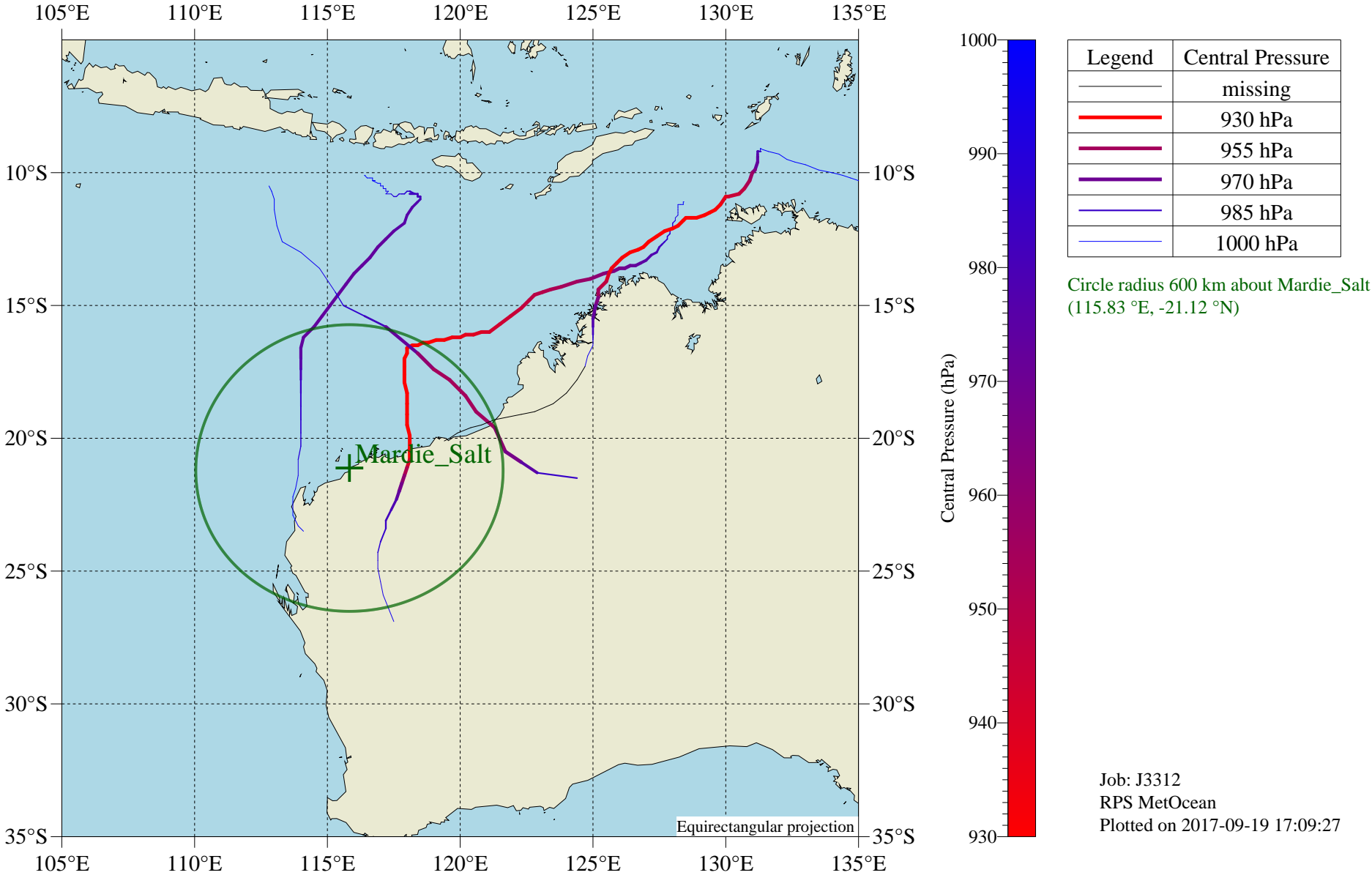


Figure 5.1d Extent of proposed WW3 E grid for recommended further modelling.

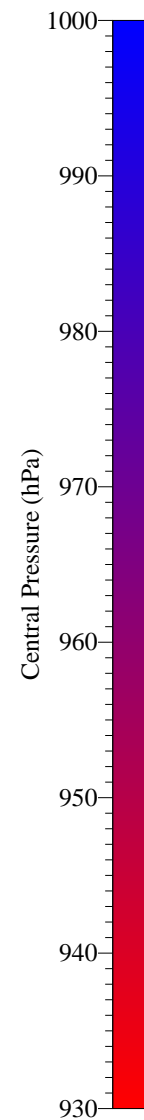
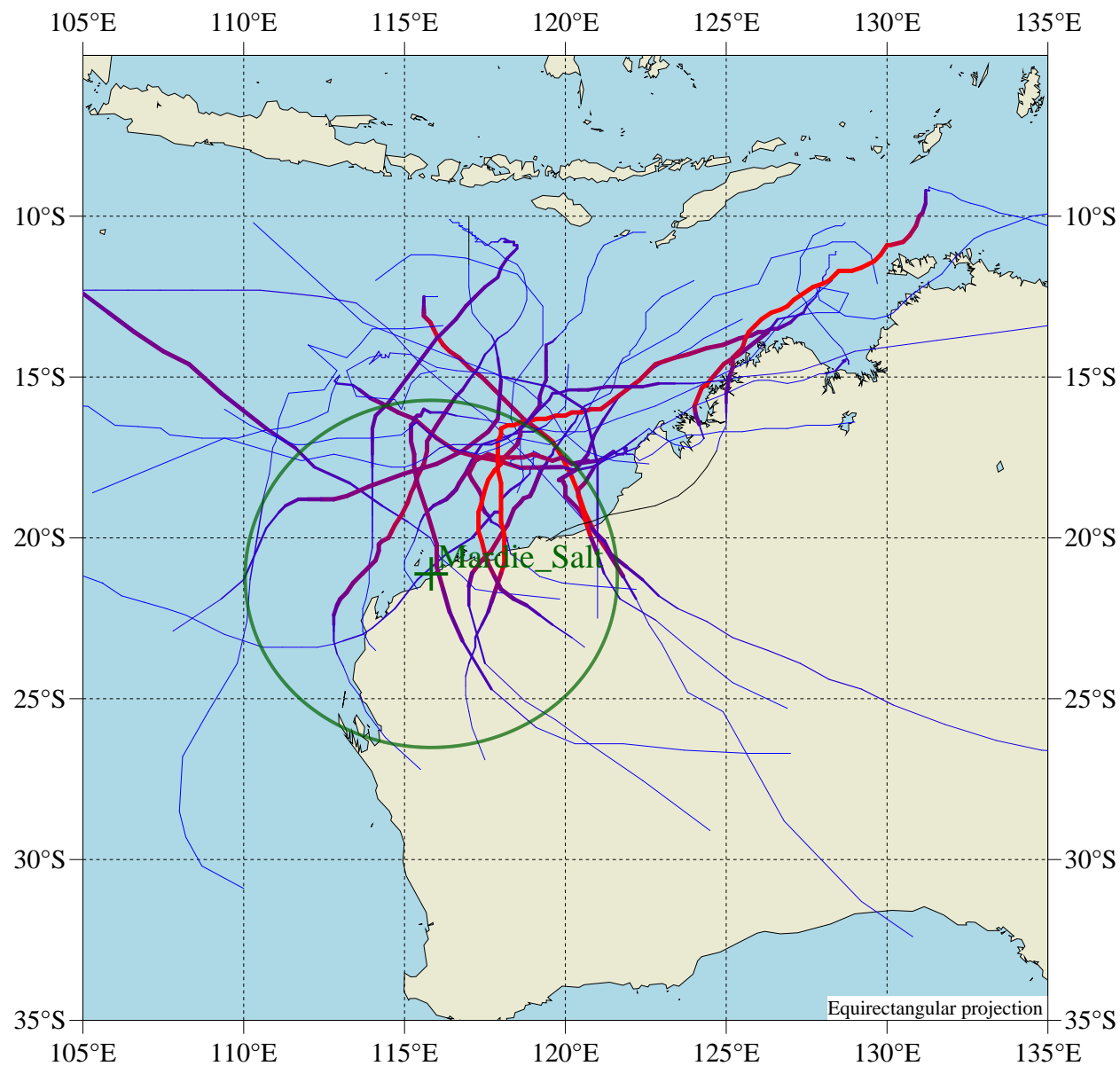
Appendix A

Tropical Cyclone Monthly Track Plots

Monthly TC Track Plots - November



Monthly TC Track Plots - December

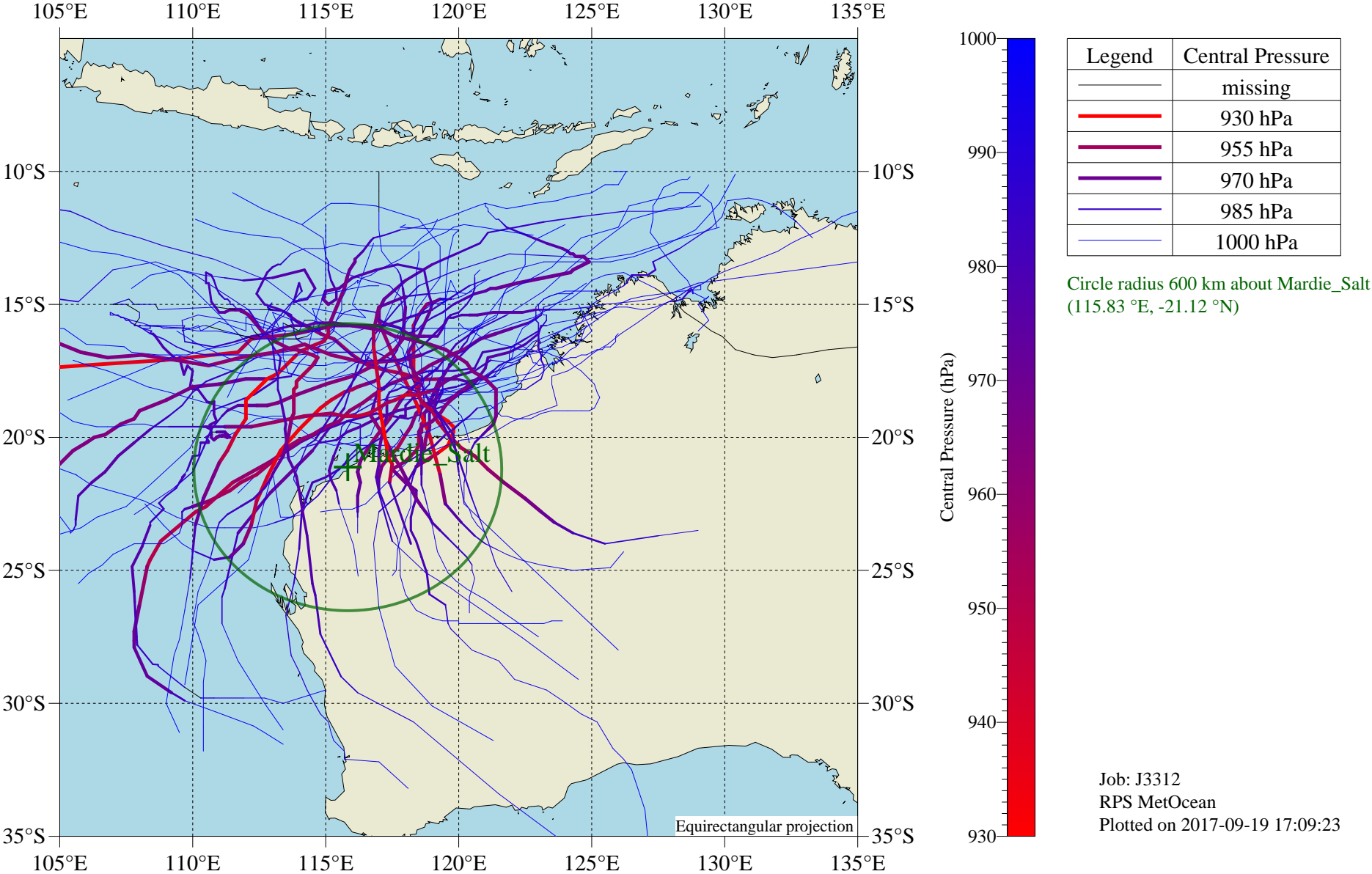


Legend	Central Pressure
—	missing
—	930 hPa
—	955 hPa
—	970 hPa
—	985 hPa
—	1000 hPa

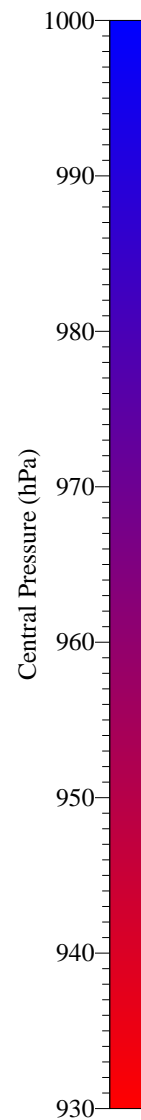
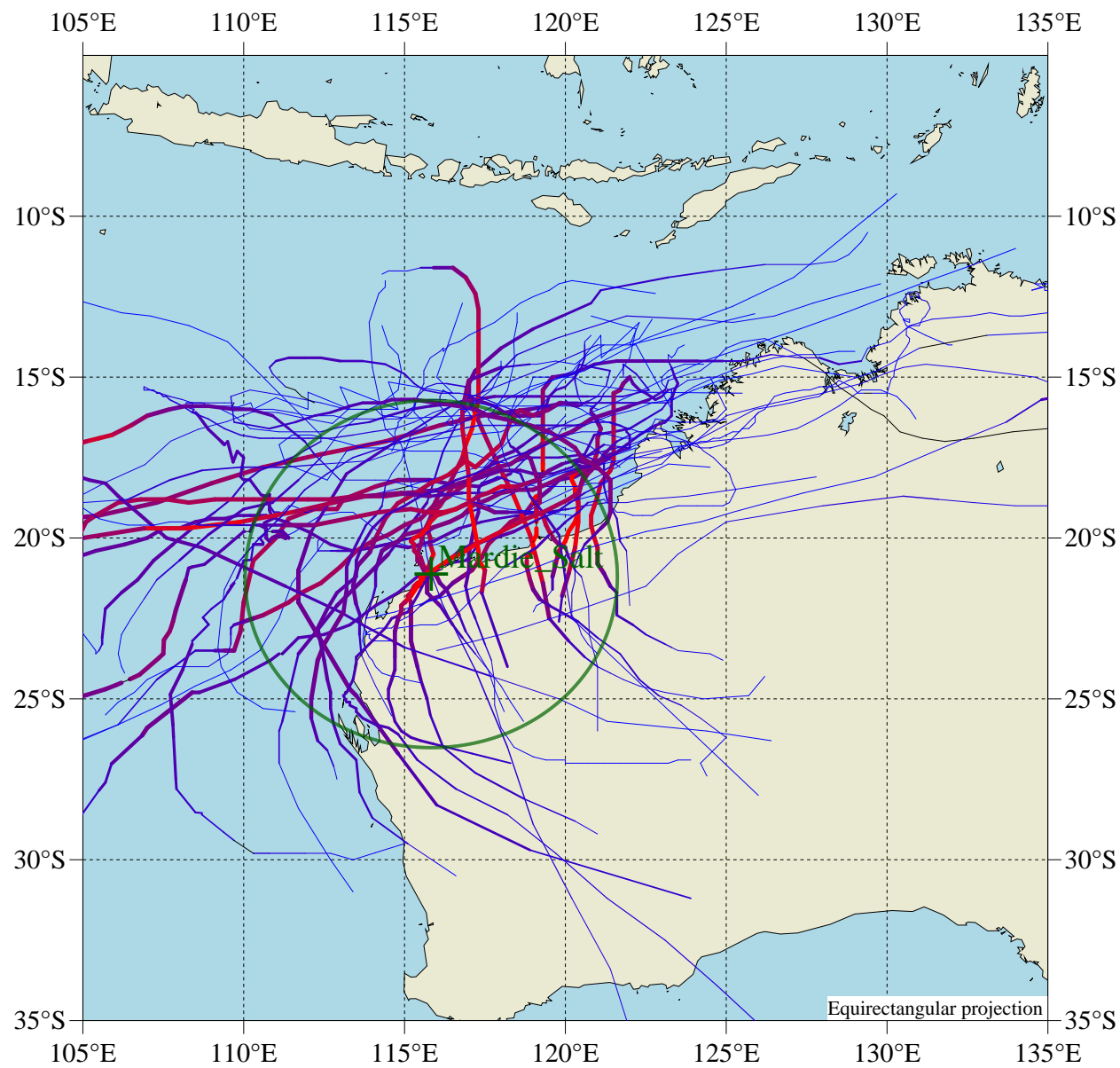
Circle radius 600 km about Mardie_Salt
(115.83 °E, -21.12 °N)

Job: J3312
RPS MetOcean
Plotted on 2017-09-19 17:09:27

Monthly TC Track Plots - January



Monthly TC Track Plots - February

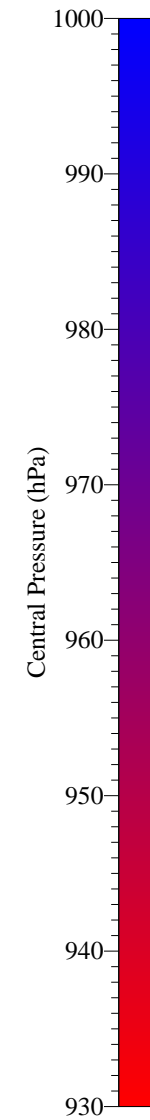
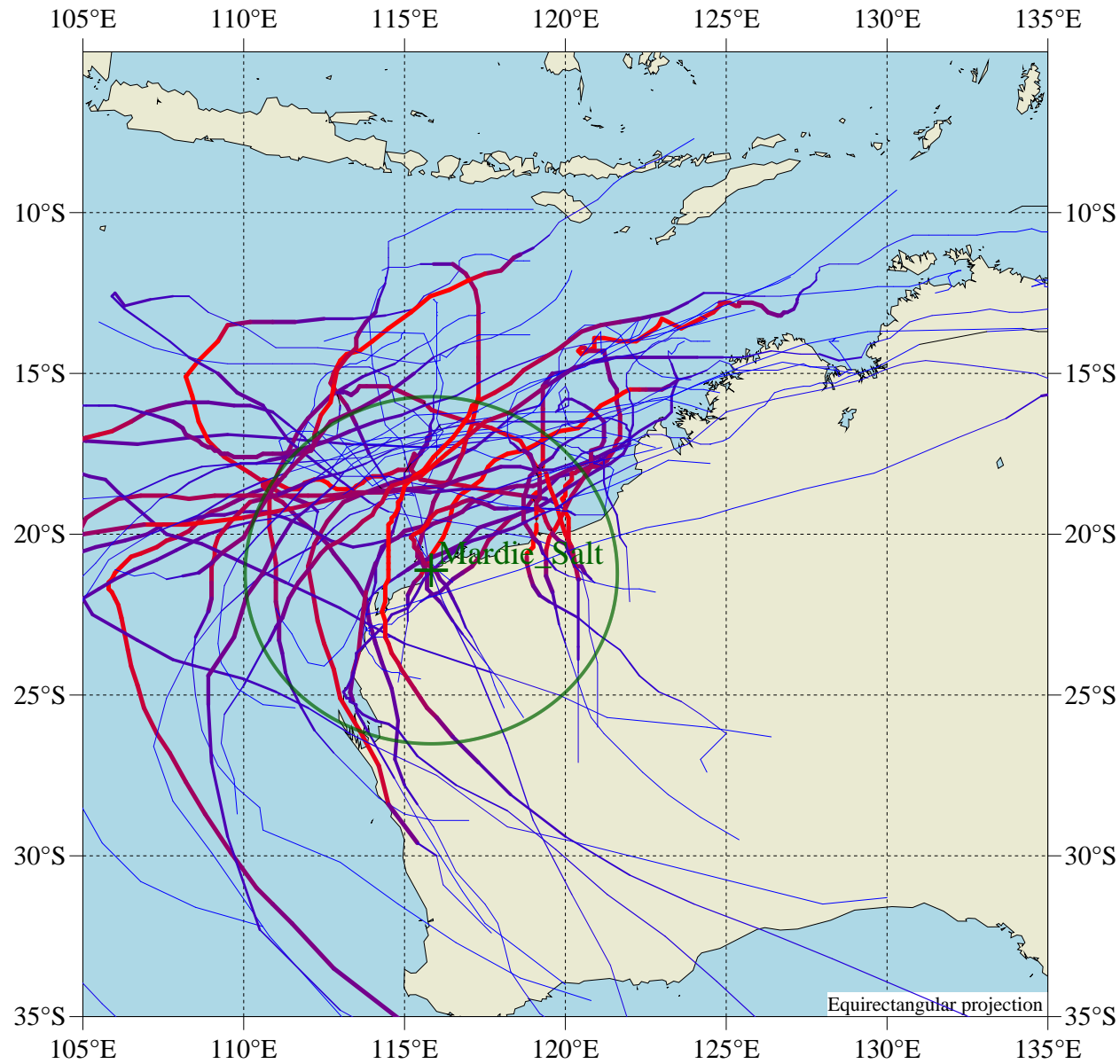


Legend	Central Pressure
	missing
	930 hPa
	955 hPa
	970 hPa
	985 hPa
	1000 hPa

Circle radius 600 km about Mardie_Salt
(115.83 °E, -21.12 °N)

Job: J3312
RPS MetOcean
Plotted on 2017-09-19 17:09:24

Monthly TC Track Plots - March

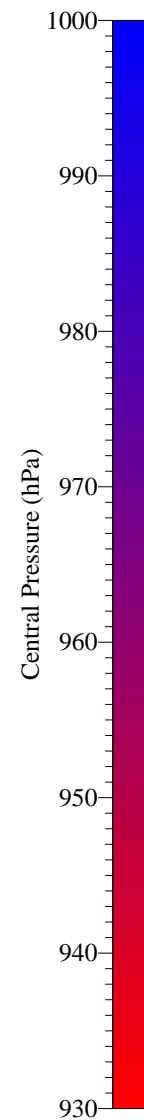
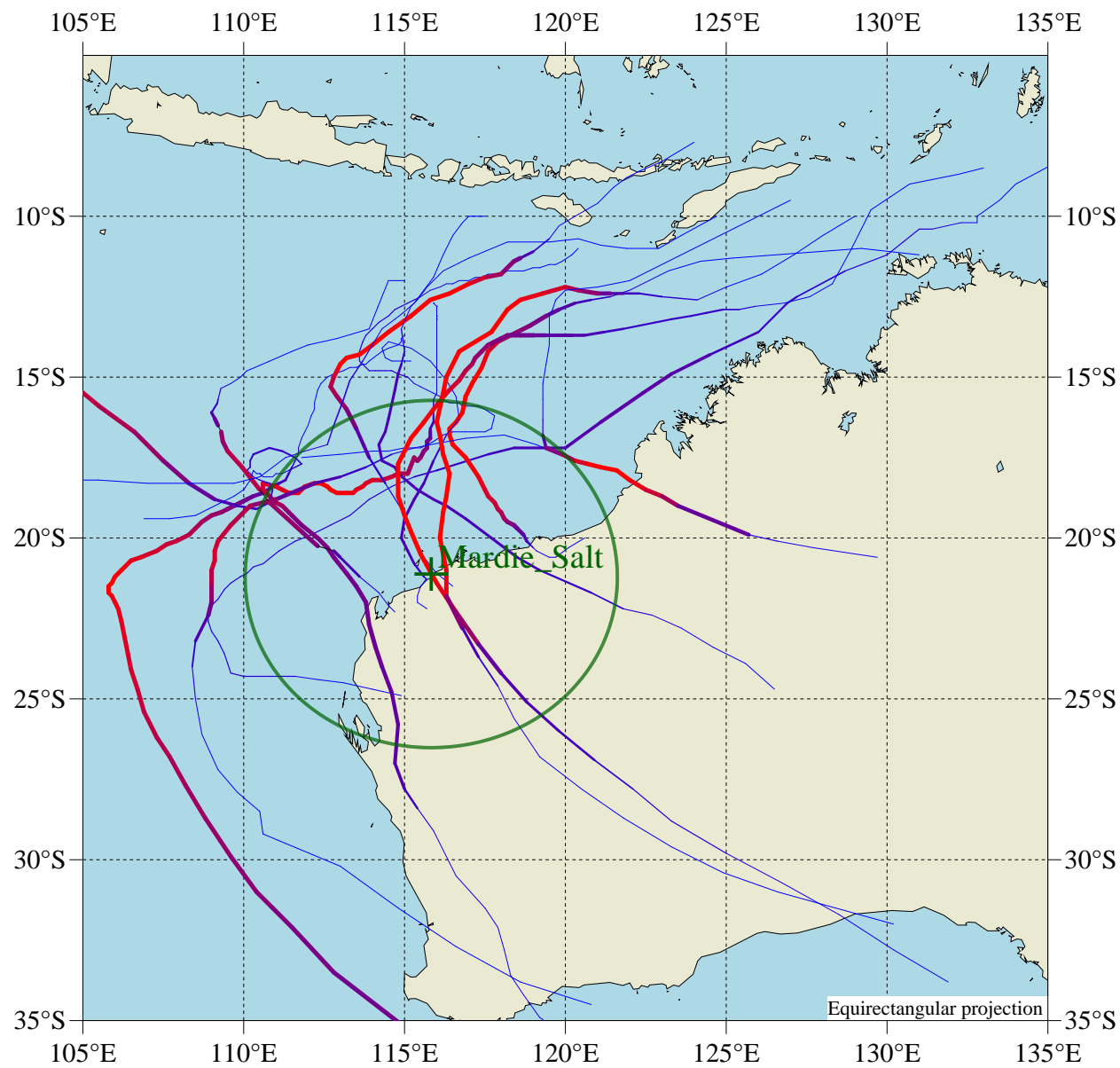


Legend	Central Pressure
	missing
	930 hPa
	955 hPa
	970 hPa
	985 hPa
	1000 hPa

Circle radius 600 km about Mardie_Salt
(115.83°E, -21.12°N)

Job: J3312
RPS MetOcean
Plotted on 2017-09-19 17:09:24

Monthly TC Track Plots - April

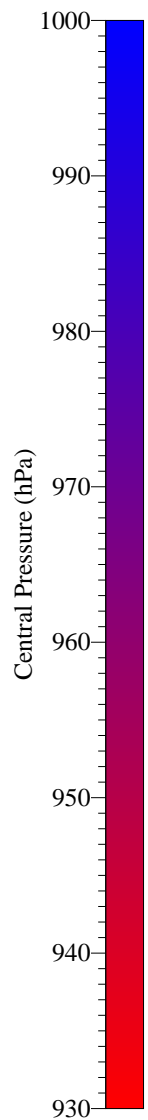
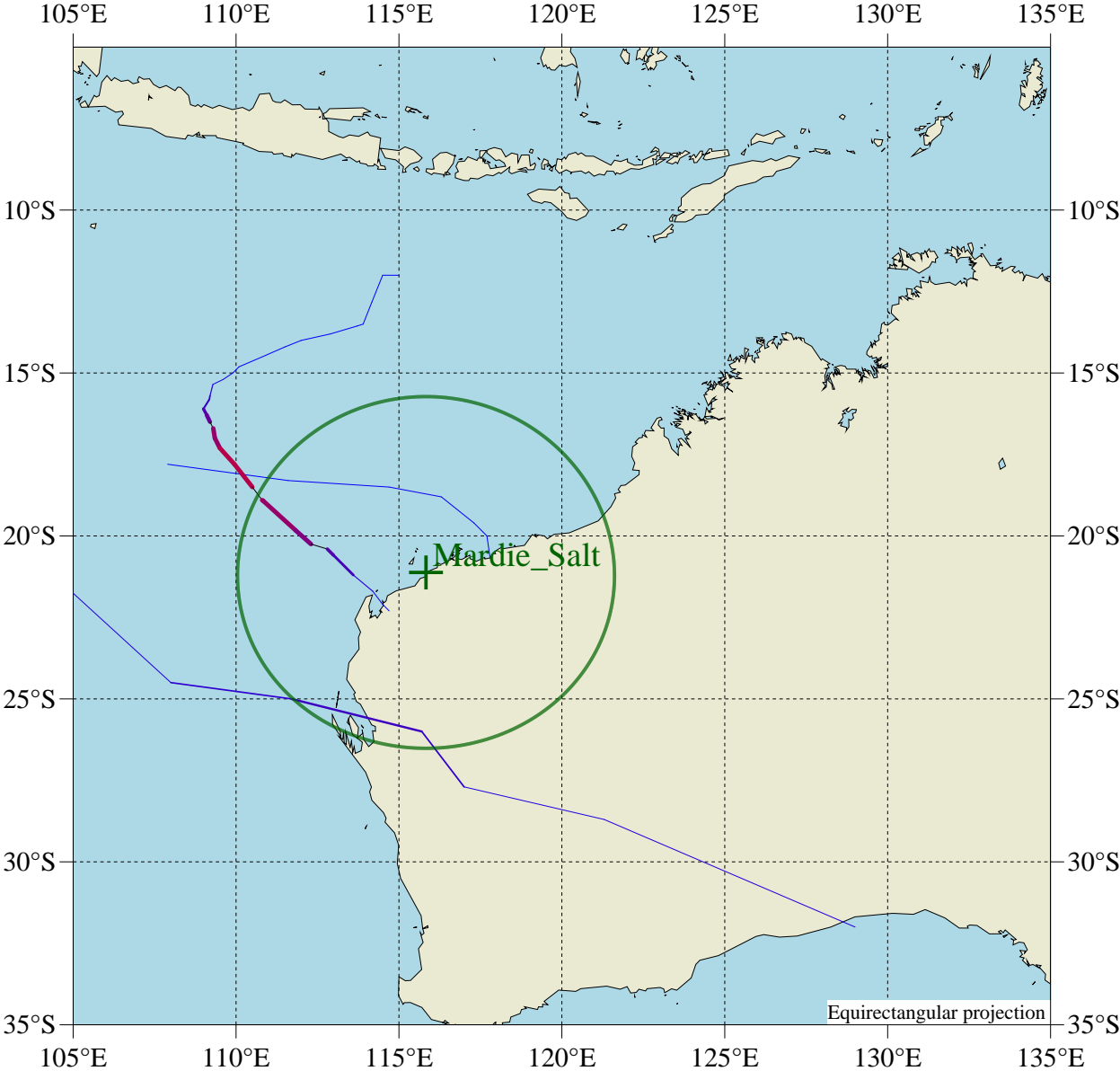


Legend	Central Pressure
	missing
	930 hPa
	955 hPa
	970 hPa
	985 hPa
	1000 hPa

Circle radius 600 km about Mardie_Salt
(115.83 °E, -21.12 °N)

Job: J3312
RPS MetOcean
Plotted on 2017-09-19 17:09:24

Monthly TC Track Plots - May



Legend	Central Pressure
	missing
	930 hPa
	955 hPa
	970 hPa
	985 hPa
	1000 hPa

Circle radius 600 km about Mardie_Salt
(115.83 °E, -21.12 °N)

Job: J3312
RPS MetOcean
Plotted on 2017-09-19 17:09:25

Appendix B

Wave and Surge Extremes, Supporting Documentation

Mardie North

Design Criteria Supporting Documentation

Source File: weibull/weibull.WindSpd.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: WindSpd
Number of Events: 30
Observation Period: 225 years
Event Frequency: 0.133333
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.19718
Scale,a: 28.3142 m s-1
Location,b: 0 m s-1
Threshold,c: 27.7108 m s-1
RMS Error: 0.02778

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	30.091516	30.449913	31.243158	32.285122	33.010799
25	37.222504	38.253197	40.180679	42.343796	43.785141
50	41.948883	43.212265	45.611992	48.615593	50.911003
100	45.939281	47.384628	50.361286	54.590931	58.080067
500	52.832405	54.862827	59.717499	67.796600	74.931000

Source File: weibull/weibull.Hs.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: Hs
Number of Events: 35
Observation Period: 225 years
Event Frequency: 0.155556
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 47.5609
Scale,a: 3.3587 m
Location,b: 0 m
Threshold,c: 3.21207 m
RMS Error: 0.0252153

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	3.295413	3.303906	3.318186	3.331845	3.339499
25	3.367954	3.374851	3.386390	3.398305	3.405900
50	3.396050	3.402374	3.413886	3.427344	3.436858
100	3.414959	3.421365	3.433833	3.449585	3.461346
500	3.443277	3.450690	3.466179	3.487299	3.503930

Source File: weibull/weibull.TideHeight.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: TideHeight
Number of Events: 71
Observation Period: 225 years
Event Frequency: 0.315556
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.33127
Scale,a: 1.5349 m
Location,b: 0 m
Threshold,c: 1.08917 m
RMS Error: 0.0192992

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	1.761850	1.803500	1.877049	1.954707	2.002955
25	2.135338	2.185766	2.279733	2.389463	2.465242
50	2.356103	2.414995	2.530654	2.676024	2.782754
100	2.541569	2.610760	2.752169	2.939221	3.082268
500	2.888234	2.984337	3.191680	3.485691	3.724021

Source File: weibull/weibull.WindSpd.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: WindSpd
Number of Events: 30
Observation Period: 225 years
Event Frequency: 0.133333
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.38301
Scale,a: 28.19 m s-1
Location,b: 0 m s-1
Threshold,c: 26.6327 m s-1
RMS Error: 0.0338371

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	28.889051	29.237974	30.012789	31.025637	31.725100
25	35.573307	36.534794	38.311718	40.279522	41.584026
50	39.922245	41.068558	43.232166	45.944569	48.032185
100	43.518520	44.809921	47.479034	51.310547	54.501282
500	49.570972	51.377216	55.725292	63.047344	69.585770

Source File: weibull/weibull.Hs.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: Hs
Number of Events: 23
Observation Period: 225 years
Event Frequency: 0.102222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 69.2991
Scale,a: 3.41147 m
Location,b: 0 m
Threshold,c: 3.32881 m
RMS Error: 0.0327446

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	3.331486	3.332276	3.334268	3.337502	3.340224
25	3.400401	3.406809	3.417099	3.426901	3.432737
50	3.426123	3.431575	3.440919	3.451425	3.459009
100	3.442212	3.447308	3.457025	3.469758	3.480128
500	3.463946	3.469558	3.481850	3.500589	3.517712

Source File: weibull/weibull.TideHeight.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: TideHeight
Number of Events: 53
Observation Period: 225 years
Event Frequency: 0.235556
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.61256
Scale,a: 1.58176 m
Location,b: 0 m
Threshold,c: 1.35397 m
RMS Error: 0.0170712

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	1.758314	1.793872	1.858074	1.926262	1.968178
25	2.096348	2.141894	2.225187	2.320827	2.386808
50	2.295305	2.347214	2.448745	2.578349	2.676305
100	2.457773	2.518141	2.643470	2.816262	2.954598
500	2.748801	2.833449	3.023769	3.313758	3.564960

Source File: weibull/weibull.WindSpd.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: WindSpd
Number of Events: 41
Observation Period: 225 years
Event Frequency: 0.182222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 1.43478
Scale,a: 13.3313 m s-1
Location,b: 0 m s-1
Threshold,c: 12.1448 m s-1
RMS Error: 0.0219568

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	16.082817	16.549856	17.477987	18.565451	19.272802
25	21.939575	22.822245	24.476786	26.402521	27.738047
50	25.960167	27.060802	29.228321	32.033253	34.181843
100	29.506107	30.842690	33.664055	37.668785	40.926903
500	36.237530	38.287075	43.111889	50.869518	57.691601

Source File: weibull/weibull.Hs.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: Hs
Number of Events: 24
Observation Period: 225 years
Event Frequency: 0.106667
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 16.896
Scale,a: 3.21628 m
Location,b: 0 m
Threshold,c: 2.69631 m
RMS Error: 0.0501686

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.768621	2.788084	2.830356	2.881864	2.914293
25	3.152509	3.179479	3.222221	3.263254	3.288087
50	3.260570	3.282880	3.321742	3.365748	3.396746
100	3.326813	3.348109	3.388823	3.440432	3.479680
500	3.418597	3.442363	3.492714	3.563402	3.620819

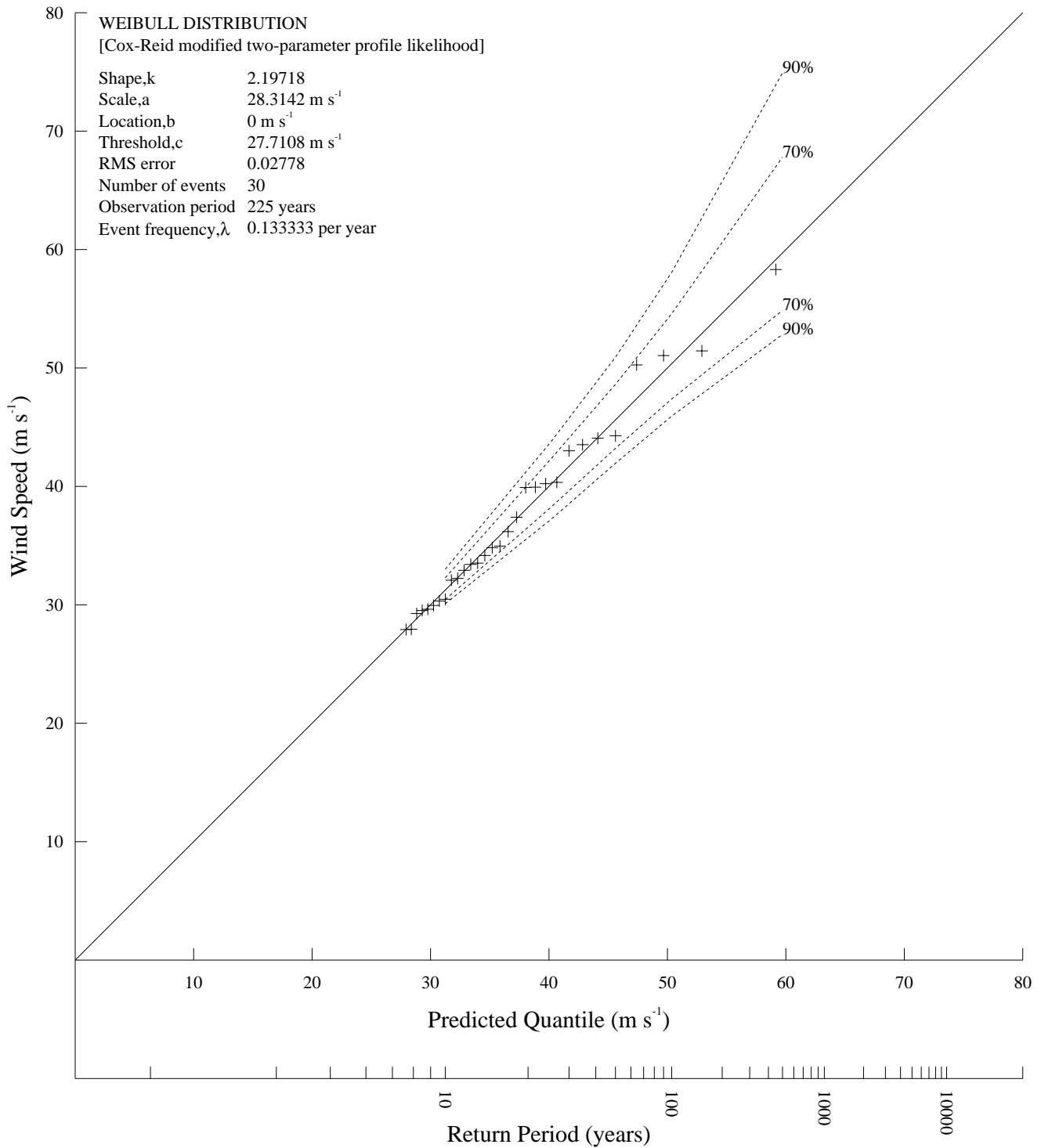
Source File: weibull/weibull.TideHeight.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_North
Latitude: -21.05
Longitude: 115.91
Data Variable: TideHeight
Number of Events: 64
Observation Period: 225 years
Event Frequency: 0.284444
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 1.48957
Scale,a: 0.537754 m
Location,b: 0 m
Threshold,c: 2.62297 m
RMS Error: 0.0766062

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.762834	2.773437	2.793999	2.818248	2.834487
25	2.883580	2.902773	2.939792	2.983300	3.012504
50	2.973371	2.998742	3.047764	3.105761	3.144991
100	3.061466	3.092864	3.153895	3.226800	3.276492
500	3.257481	3.303216	3.393869	3.504259	3.580318

EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

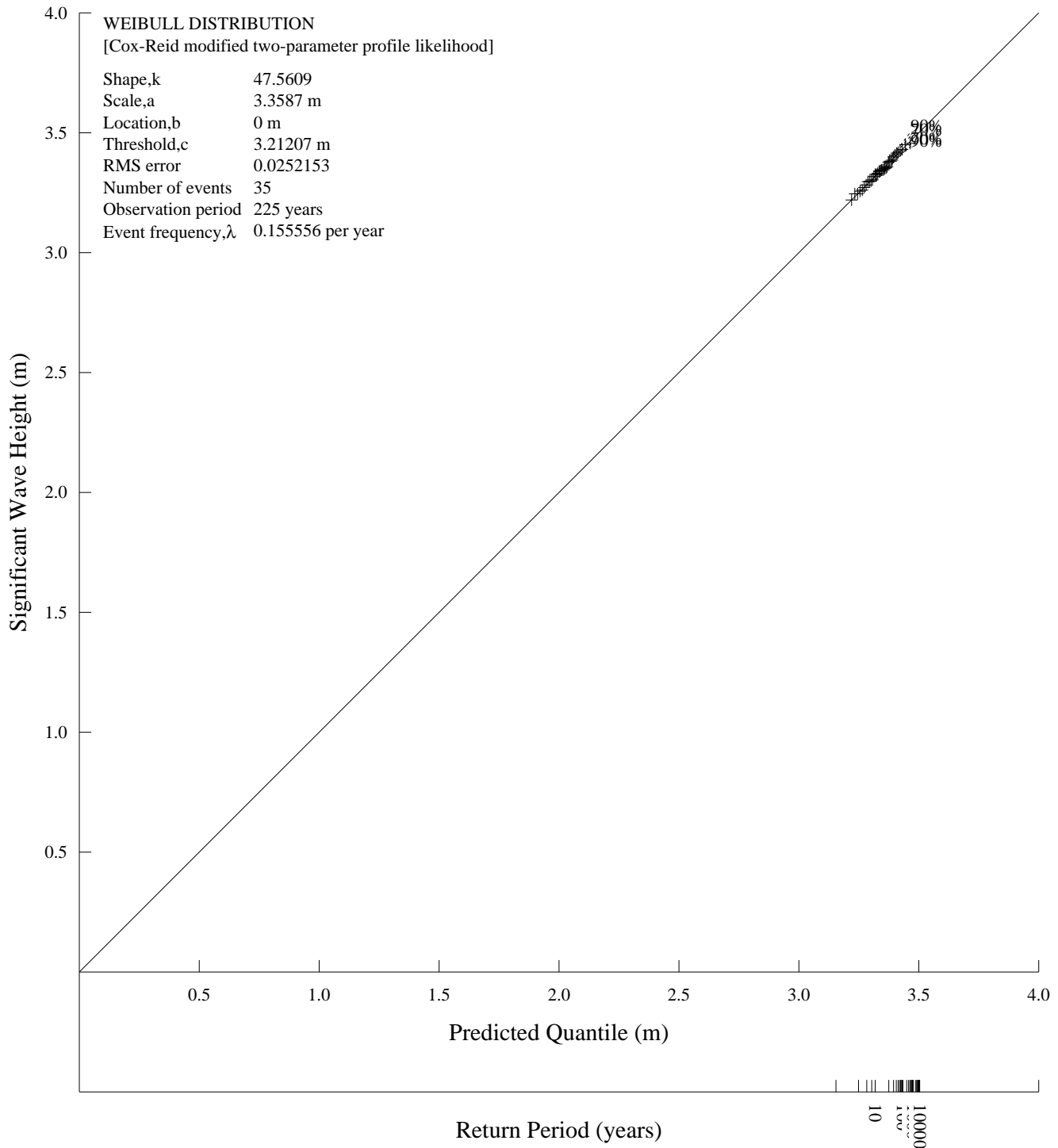
Mardie_North - WindSpd at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

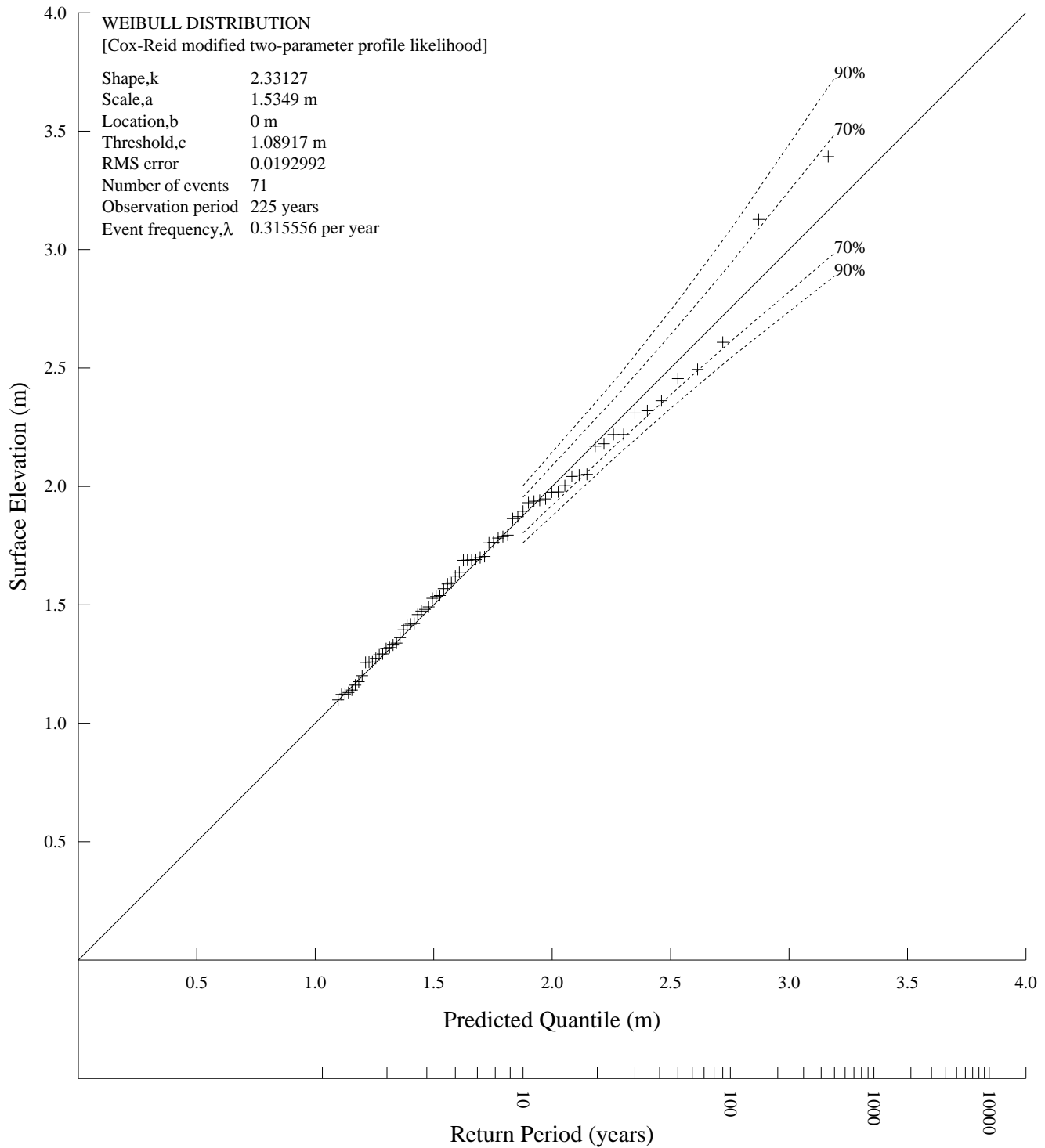
Mardie_North - Hs at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

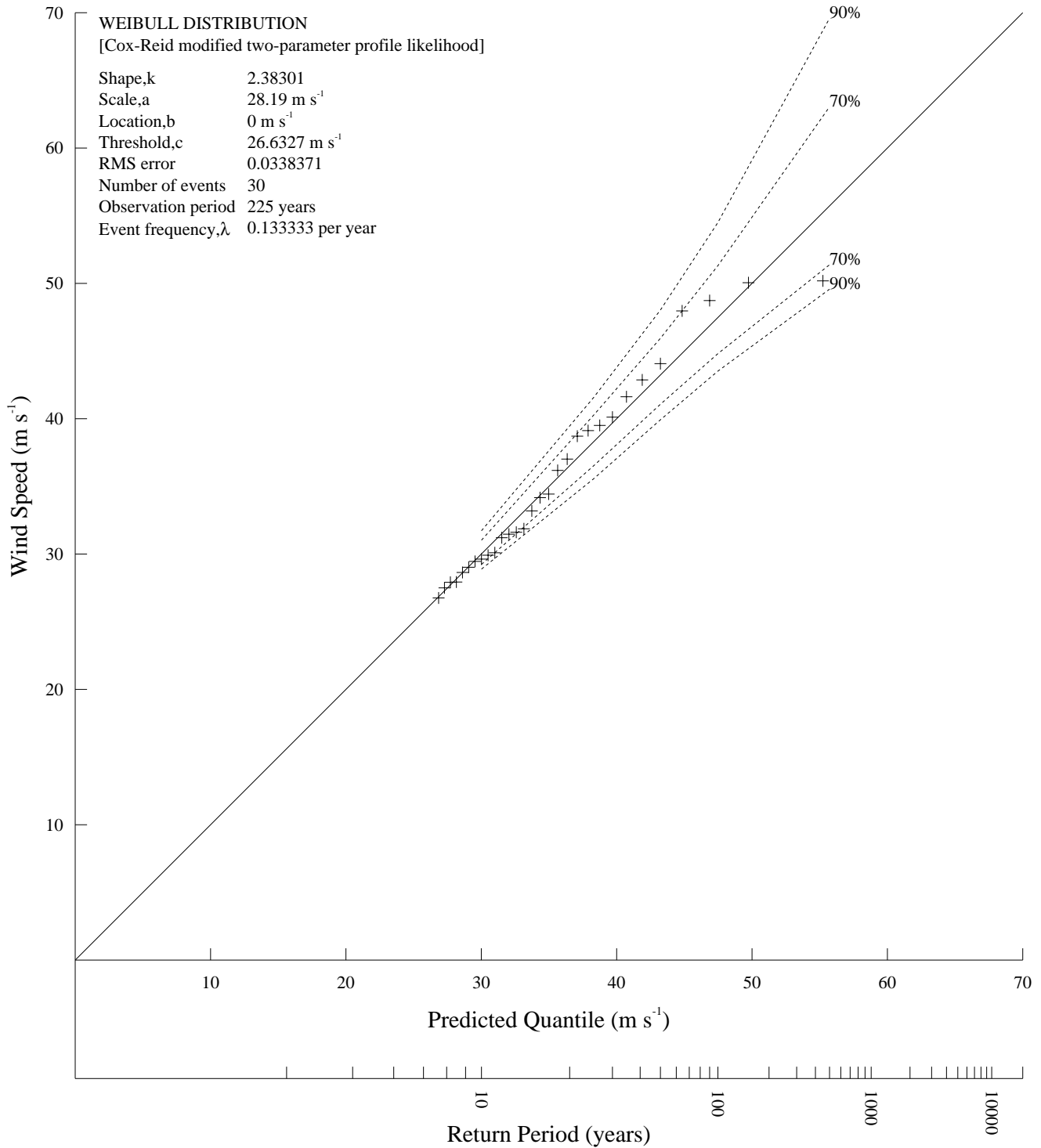
Mardie_North - TideHeight at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

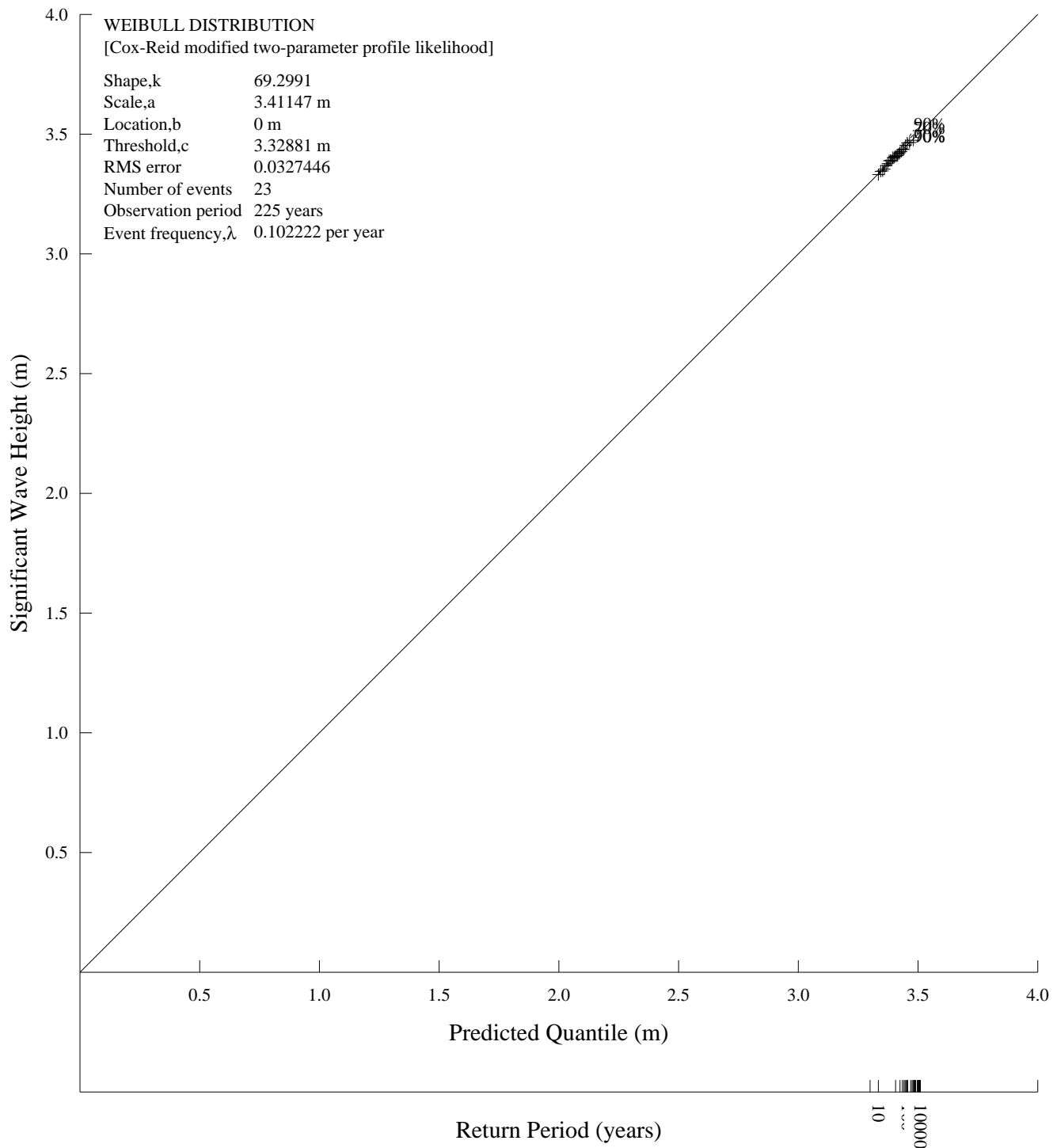
Mardie_North - WindSpd at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

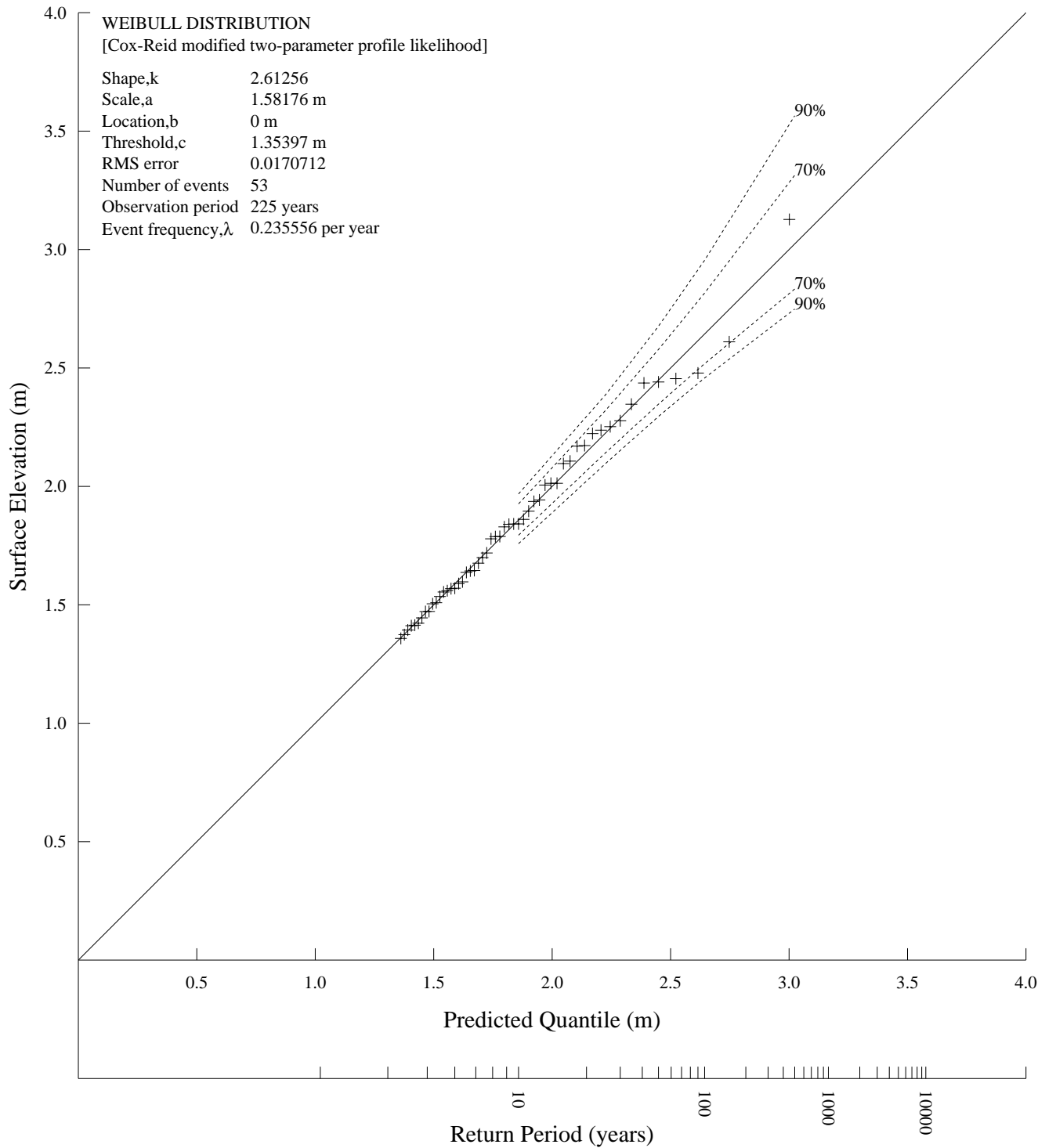
Mardie_North - Hs at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

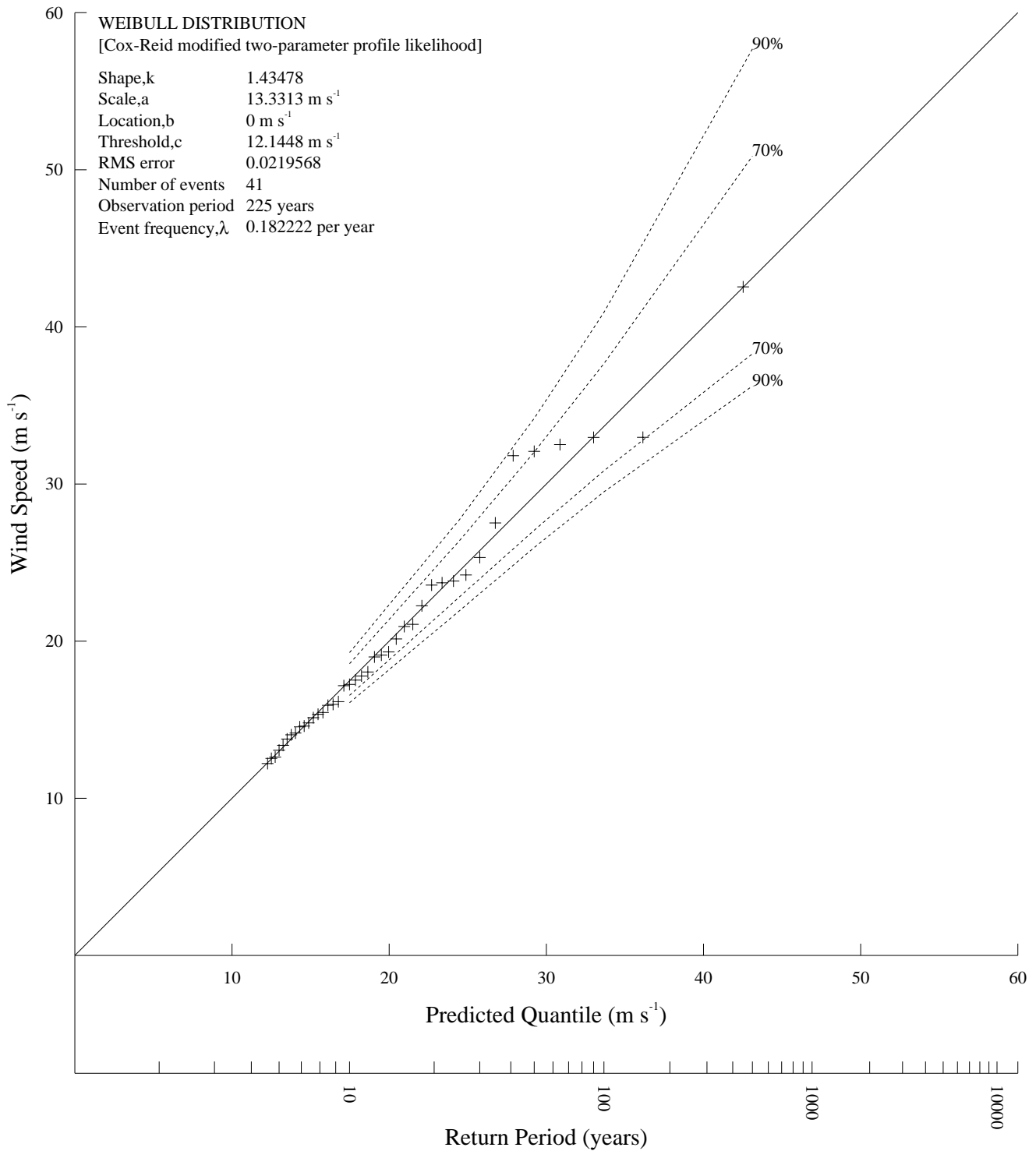
Mardie_North - TideHeight at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

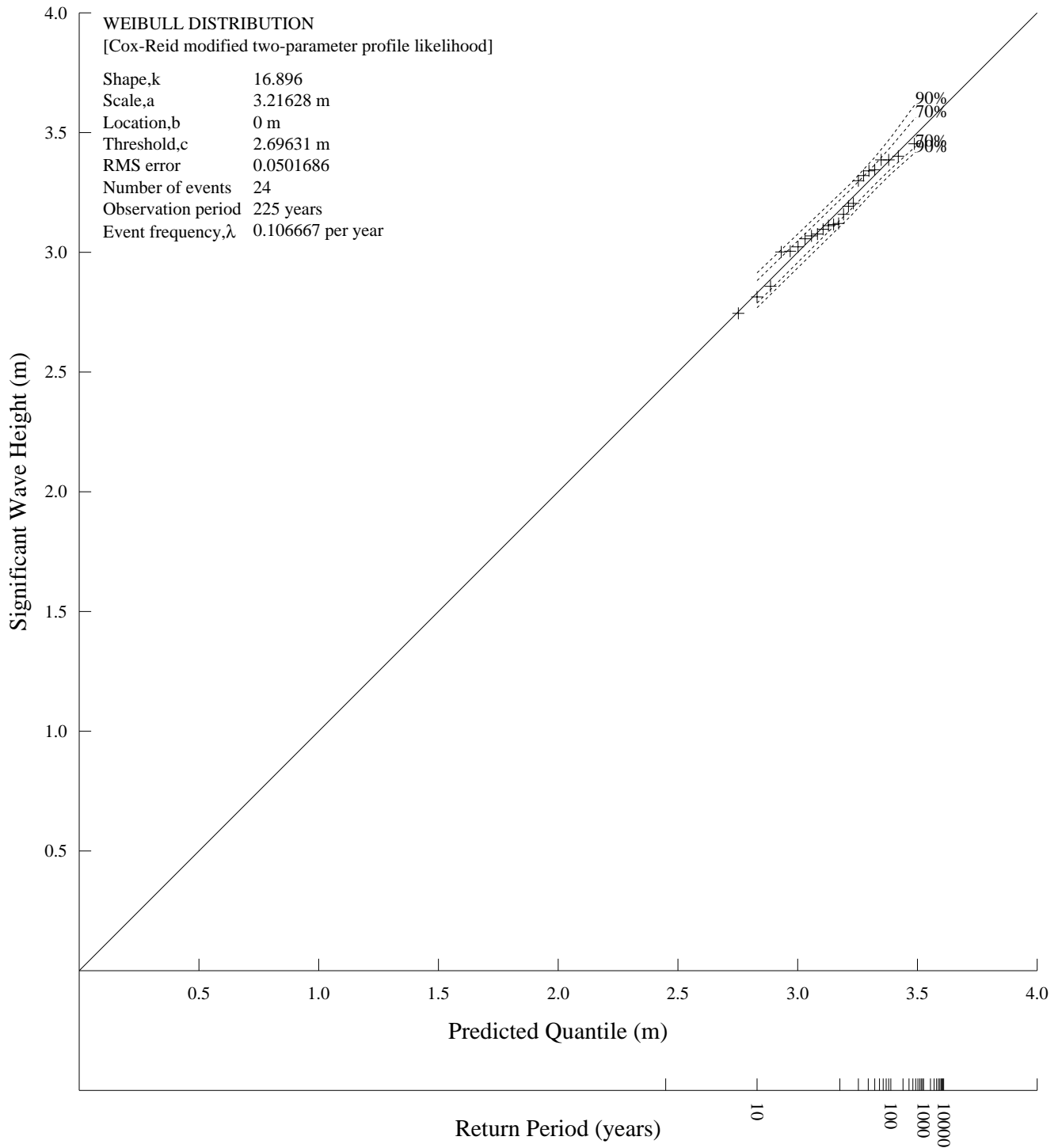
Mardie_North - WindSpd at peak TideHeight



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

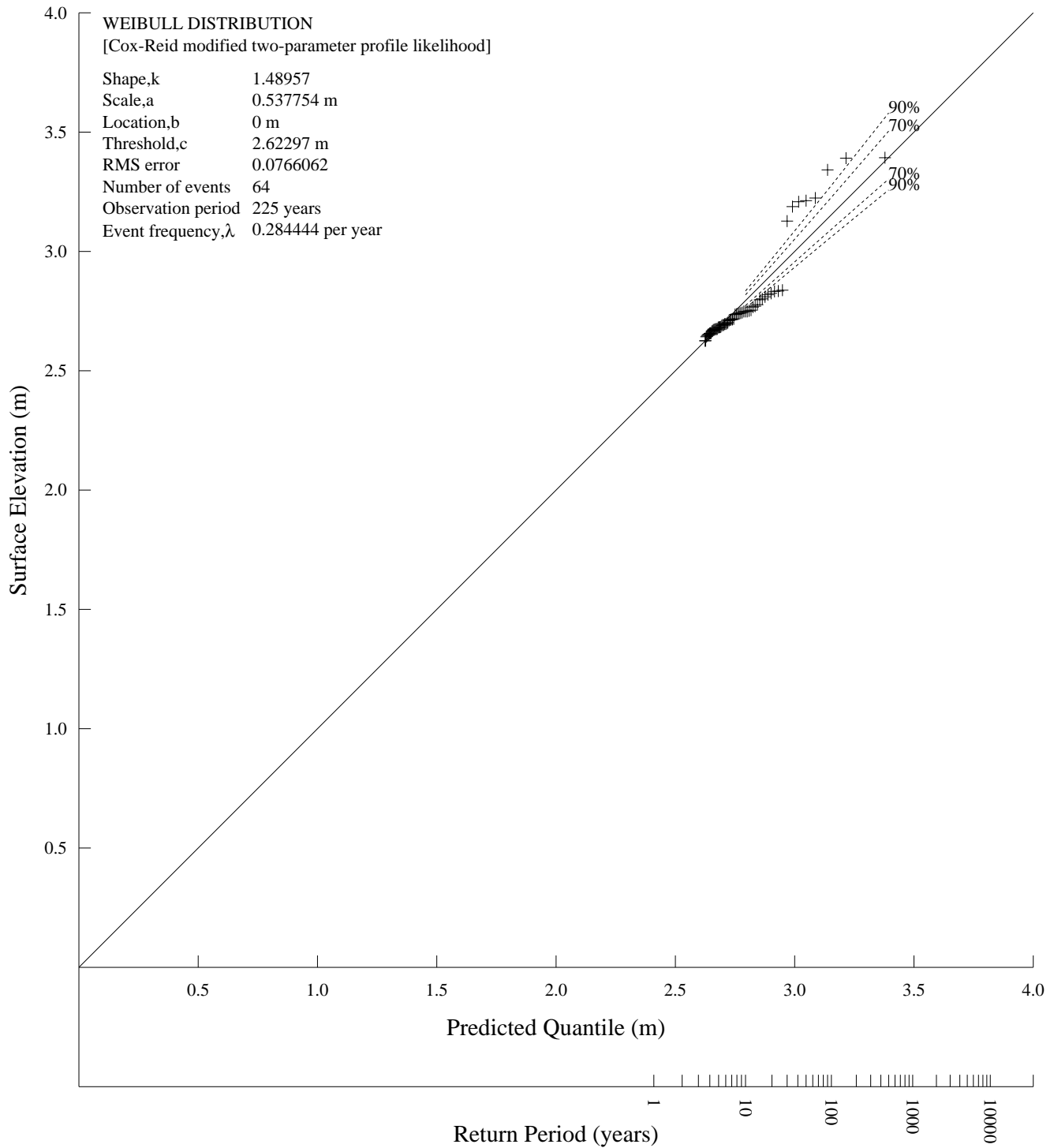
Mardie_North - Hs at peak TideHeight



EXTREME ANALYSIS

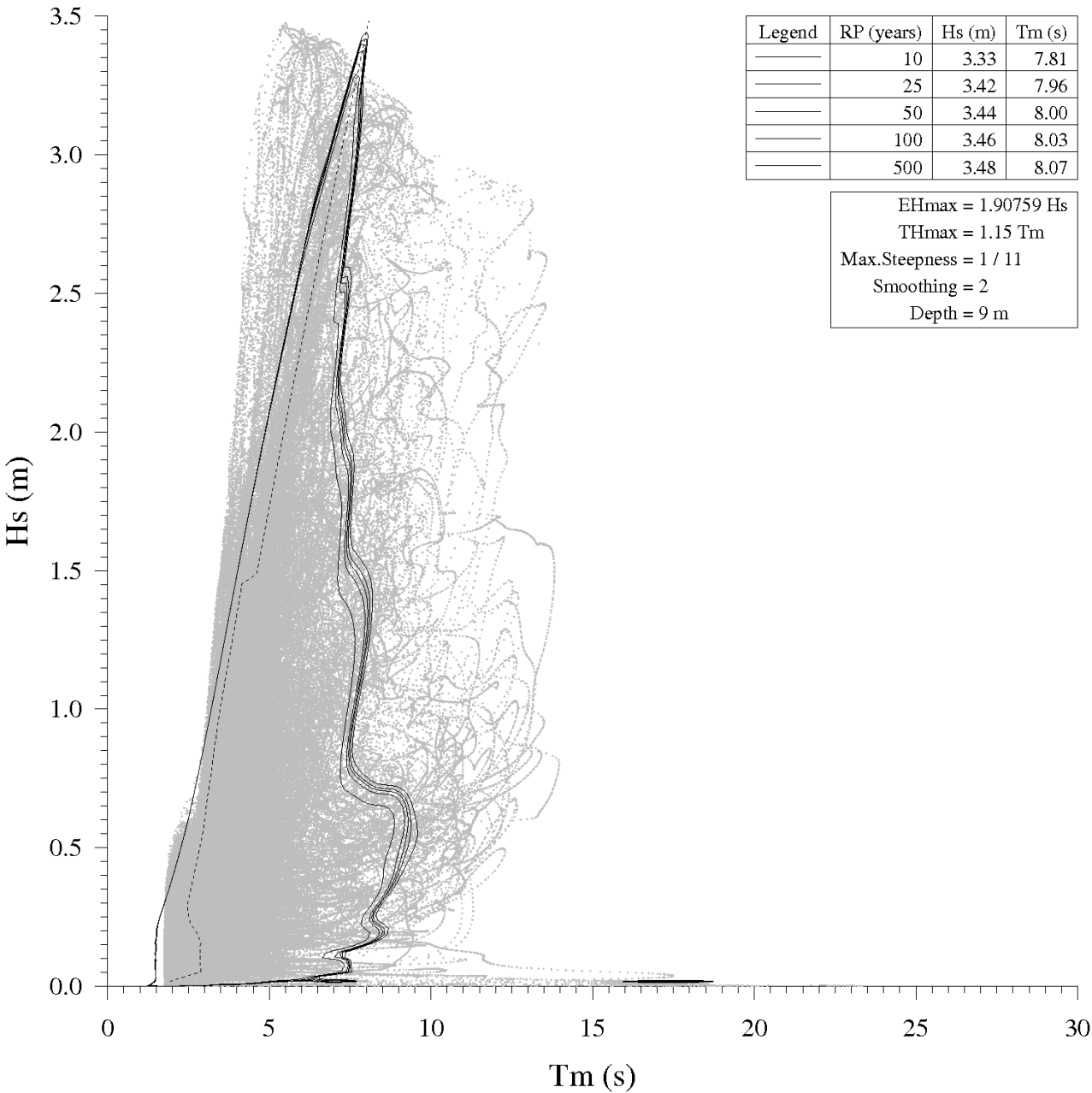
CONDITIONAL WEIBULL METHOD

Mardie_North - TideHeight at peak TideHeight



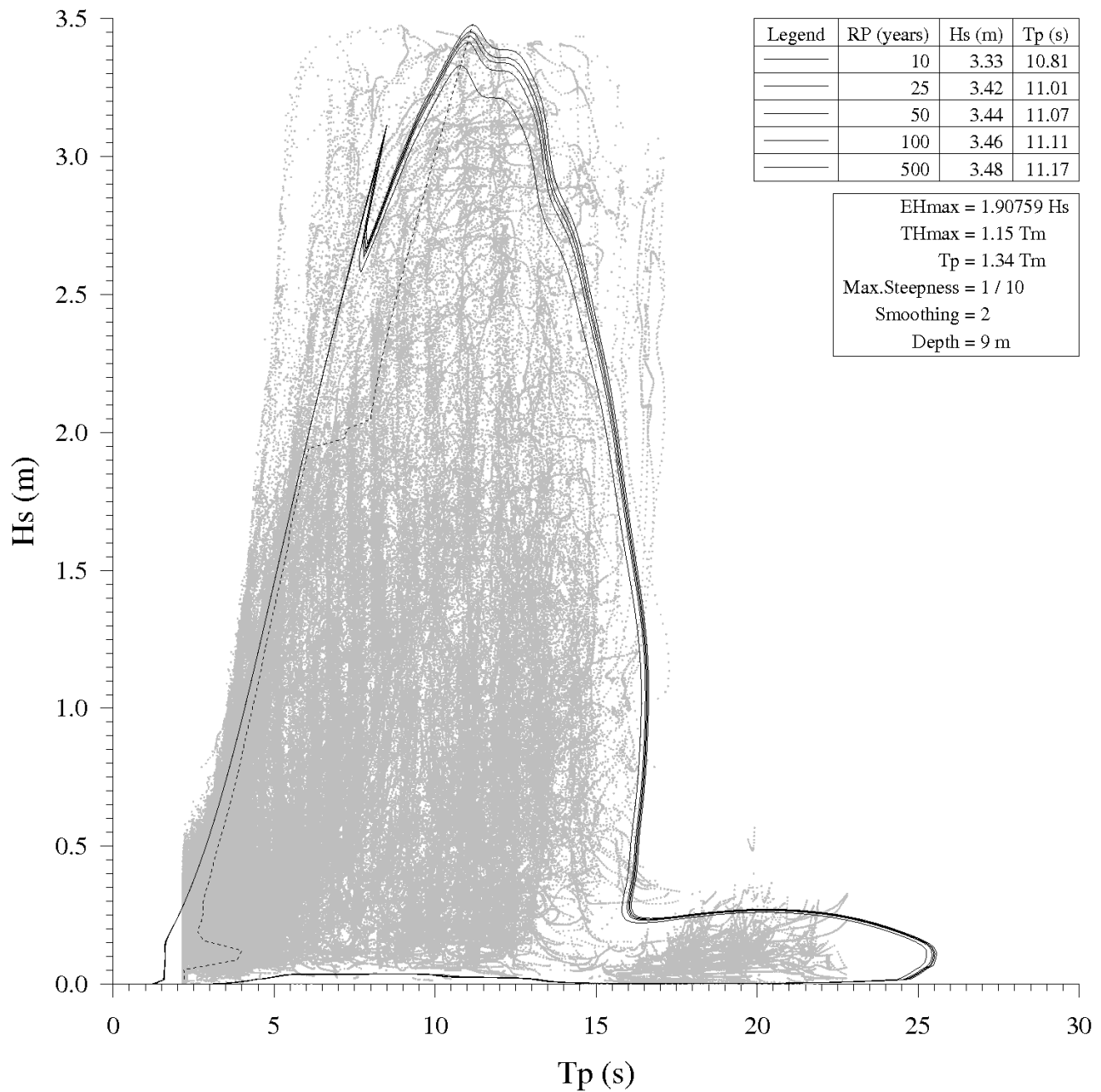
J3312 - Mardie_North - Hs vs Tm

Mardie_North



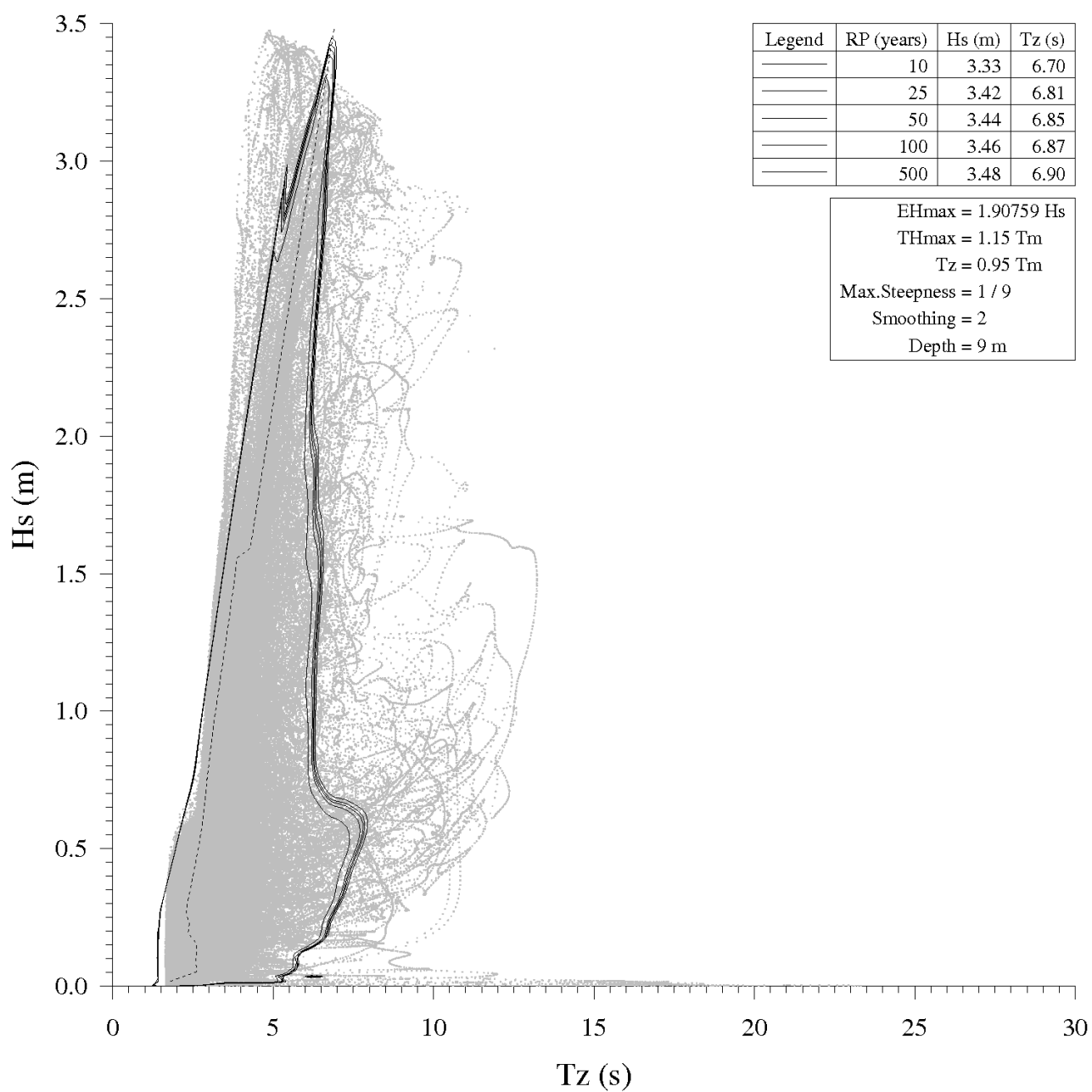
J3312 - Mardie_North - Hs vs Tp

Mardie_North



J3312 - Mardie_North - Hs vs Tz

Mardie_North



Mardie South

Design Criteria Supporting Documentation

Source File: weibull/weibull.WindSpd.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: WindSpd
Number of Events: 30
Observation Period: 225 years
Event Frequency: 0.133333
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.08482
Scale,a: 26.5165 m s-1
Location,b: 0 m s-1
Threshold,c: 27.0432 m s-1
RMS Error: 0.0240584

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	29.316492	29.652088	30.398390	31.390242	32.087570
25	36.196789	37.198883	39.089214	41.227001	42.655895
50	40.832741	42.085003	44.472370	47.463703	49.742847
100	44.802349	46.247711	49.226822	53.447433	56.900986
500	51.733242	53.784519	58.696388	66.799416	73.841408

Source File: weibull/weibull.Hs.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: Hs
Number of Events: 23
Observation Period: 225 years
Event Frequency: 0.102222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 84.2447
Scale,a: 2.63474 m
Location,b: 0 m
Threshold,c: 2.55974 m
RMS Error: 0.055819

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.562907	2.563924	2.566539	2.570734	2.574090
25	2.623887	2.628434	2.635549	2.642227	2.646202
50	2.641842	2.645491	2.651746	2.658761	2.663743
100	2.652589	2.655978	2.662430	2.670704	2.677160
500	2.666959	2.670671	2.678632	2.690151	2.699888

Source File: weibull/weibull.TideHeight.peak_WindSpd.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: TideHeight
Number of Events: 77
Observation Period: 225 years
Event Frequency: 0.342222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 1.49054
Scale,a: 1.19835 m
Location,b: 0 m
Threshold,c: 0.892892 m
RMS Error: 0.0135244

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	1.678005	1.731241	1.827162	1.931009	1.996887
25	2.176876	2.248926	2.386149	2.551299	2.668151
50	2.499137	2.588621	2.768970	3.003364	3.179677
100	2.783784	2.894479	3.127350	3.446817	3.697416
500	3.347425	3.515702	3.891558	4.449373	4.916883

Source File: weibull/weibull.WindSpd.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: WindSpd
Number of Events: 70
Observation Period: 225 years
Event Frequency: 0.311111
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 1.22753
Scale,a: 10.8709 m s-1
Location,b: 0 m s-1
Threshold,c: 19.7104 m s-1
RMS Error: 0.0405594

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	26.591351	27.120190	28.118734	29.248907	29.981237
25	32.049614	32.893421	34.499439	36.400715	37.712696
50	35.938469	37.015793	39.150421	41.834930	43.771423
100	39.550922	40.896191	43.678616	47.352108	50.074825
500	46.961502	49.087566	53.812325	60.520576	65.679665

Source File: weibull/weibull.Hs.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: Hs
Number of Events: 27
Observation Period: 225 years
Event Frequency: 0.12
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 4.36221
Scale,a: 1.28699 m
Location,b: 0 m
Threshold,c: 2.62612 m
RMS Error: 0.0815679

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.629713	2.630126	2.630992	2.632127	2.632965
25	2.647591	2.650017	2.655042	2.661537	2.666240
50	2.660889	2.664758	2.672760	2.683077	2.690565
100	2.673966	2.679226	2.690092	2.704138	2.714348
500	2.703256	2.711589	2.728947	2.751523	2.767964

Source File: weibull/weibull.TideHeight.peak_Hs.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: TideHeight
Number of Events: 71
Observation Period: 225 years
Event Frequency: 0.315556
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 2.09761
Scale,a: 1.51324 m
Location,b: 0 m
Threshold,c: 1.07738 m
RMS Error: 0.0190354

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	1.788169	1.834089	1.915451	2.001677	2.055418
25	2.203703	2.260549	2.366958	2.492221	2.579422
50	2.453468	2.520726	2.653832	2.823096	2.948637
100	2.664991	2.745004	2.910123	3.131587	3.302924
500	3.064112	3.177796	3.426057	3.784261	4.078994

Source File: weibull/weibull.WindSpd.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: WindSpd
Number of Events: 68
Observation Period: 225 years
Event Frequency: 0.302222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 0.806909
Scale,a: 5.27749 m s-1
Location,b: 0 m s-1
Threshold,c: 9.56526 m s-1
RMS Error: 0.0196446

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	16.513985	17.109842	18.253698	19.577765	20.452017
25	23.013184	24.080070	26.153013	28.674284	30.454130
50	28.059021	29.514919	32.462597	36.281322	39.114605
100	33.044258	34.962242	39.019451	44.559704	48.814831
500	44.135067	47.465023	55.060432	66.343208	75.497566

Source File: weibull/weibull.Hs.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: Hs
Number of Events: 33
Observation Period: 225 years
Event Frequency: 0.146667
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 10.0068
Scale,a: 2.44965 m
Location,b: 0 m
Threshold,c: 1.75253 m
RMS Error: 0.0533161

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.147573	2.184977	2.245183	2.300181	2.330127
25	2.450424	2.476941	2.521288	2.567490	2.597262
50	2.559484	2.583919	2.628933	2.682263	2.720059
100	2.632439	2.657685	2.707336	2.770372	2.817056
500	2.742794	2.772948	2.836032	2.921170	2.986877

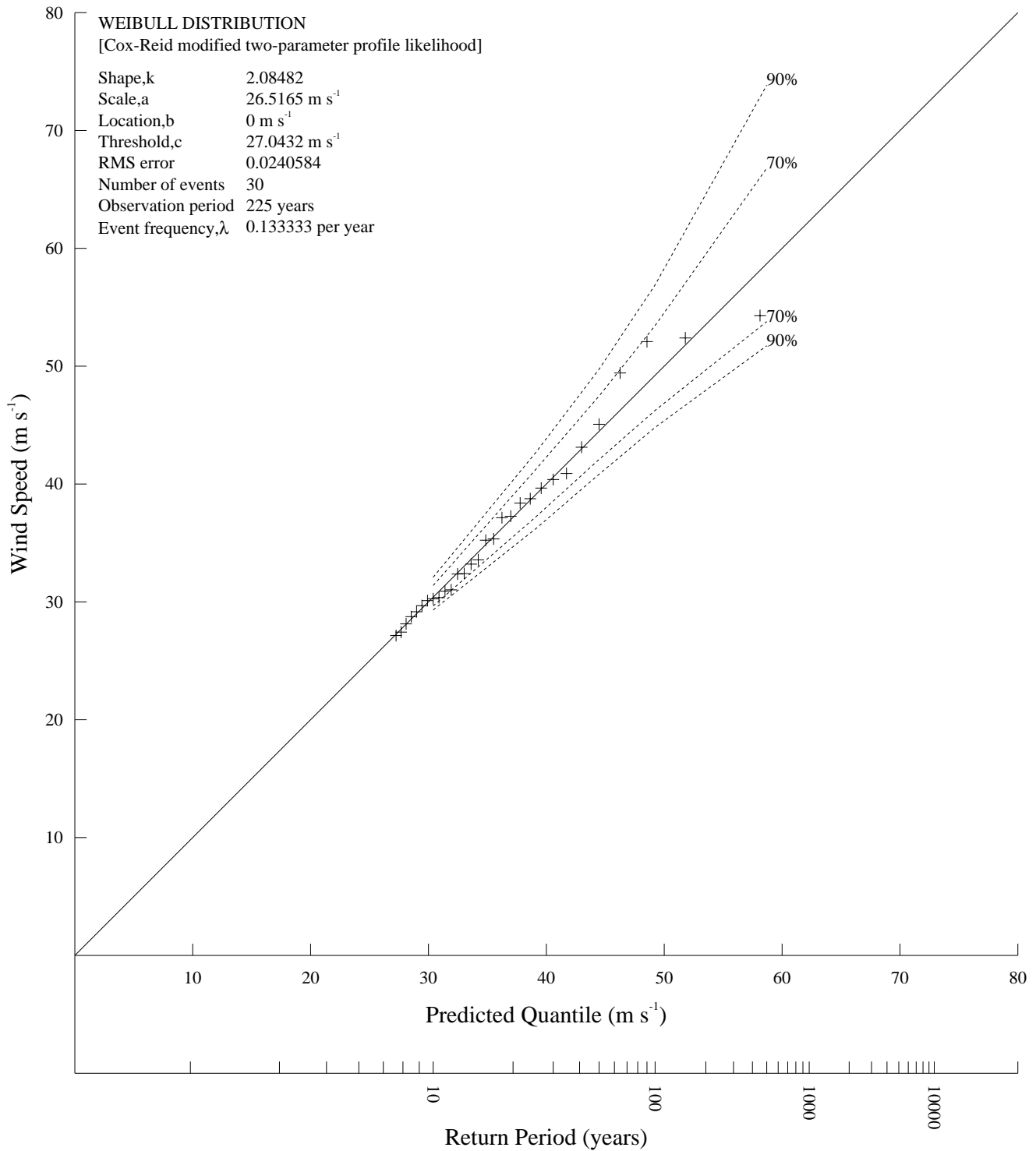
Source File: weibull/weibull.TideHeight.peak_TideHeight.nc
Client: BCI
Project: J3312
Location: Mardie_South
Latitude: -21.21
Longitude: 115.79
Data Variable: TideHeight
Number of Events: 23
Observation Period: 225 years
Event Frequency: 0.102222
Estimation Method: Cox-Reid modified two-parameter profile likelihood
Shape,k: 1.76286
Scale,a: 1.08311 m
Location,b: 0 m
Threshold,c: 2.72704 m
RMS Error: 0.0978512

RETURN	90%	70%	RETURN	70%	90%
PERIOD	LOWER	LOWER	VALUE	UPPER	UPPER
10	2.731710	2.732337	2.733706	2.735667	2.737266
25	2.924459	2.949345	3.001584	3.069446	3.118402
50	3.066686	3.107800	3.192661	3.301729	3.381299
100	3.204965	3.260686	3.375383	3.525074	3.636663
500	3.505019	3.590474	3.773136	4.024532	4.217751

EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

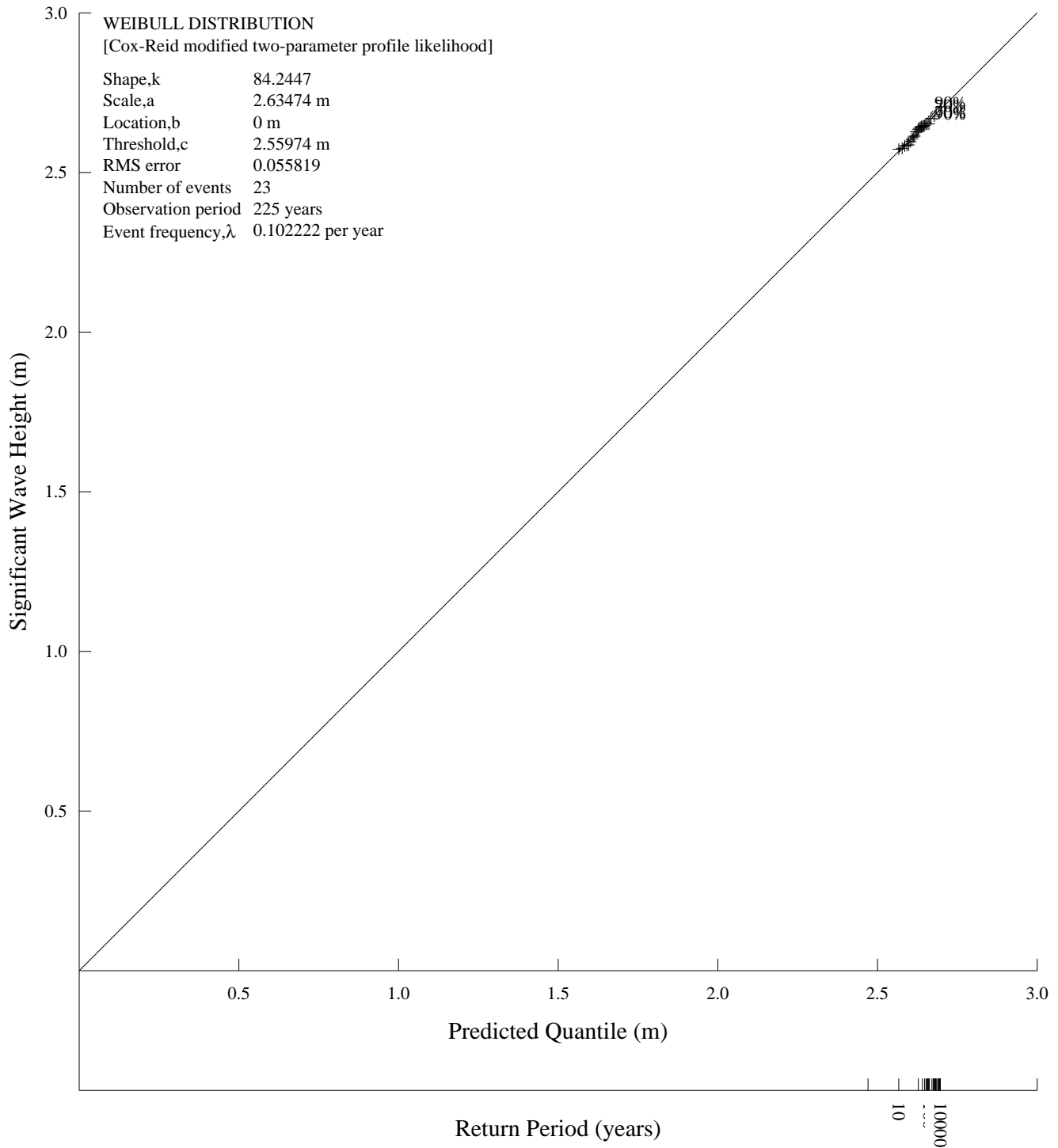
Mardie_South - WindSpd at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

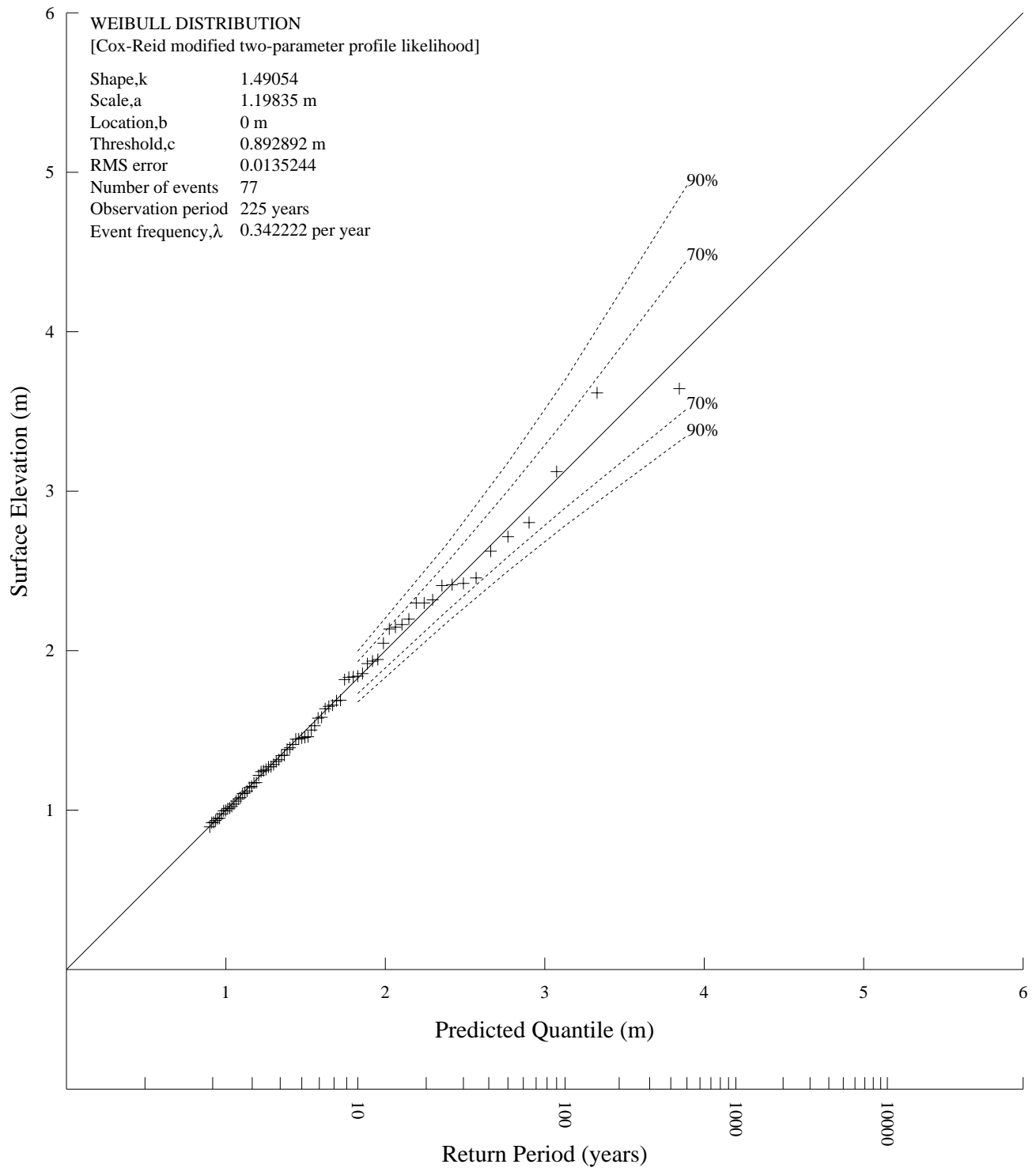
Mardie_South - Hs at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

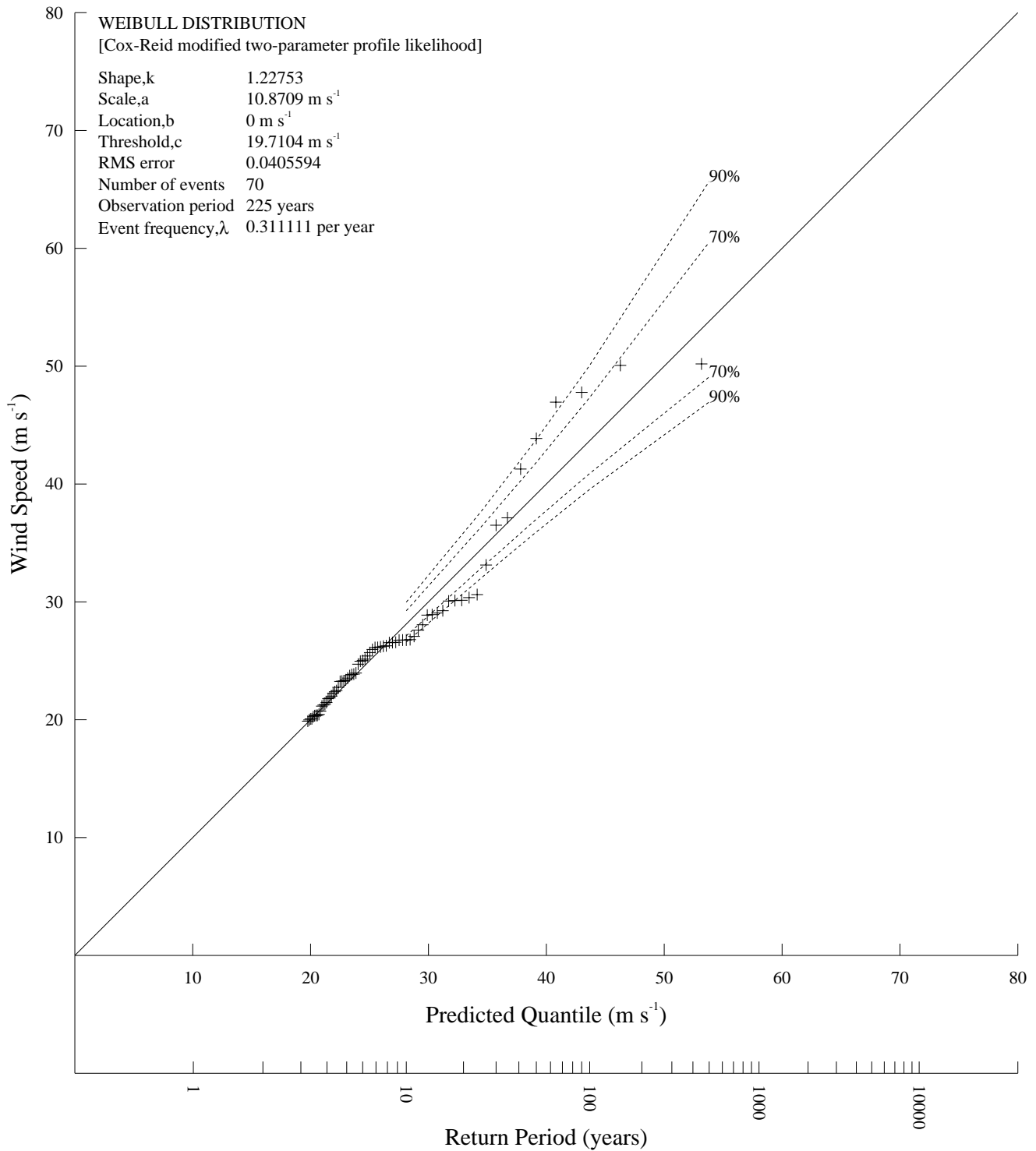
Mardie_South - TideHeight at peak WindSpd



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

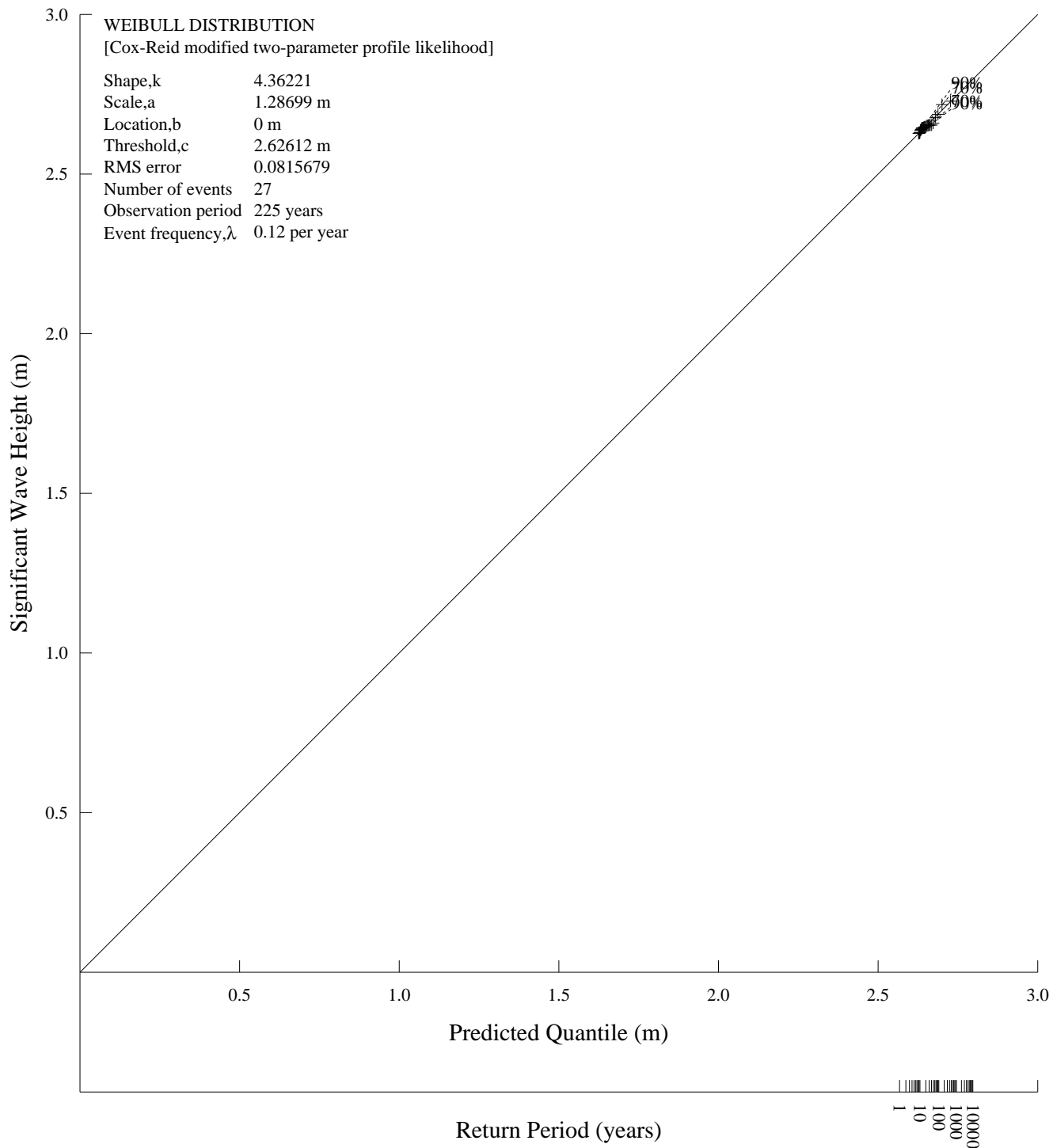
Mardie_South - WindSpd at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

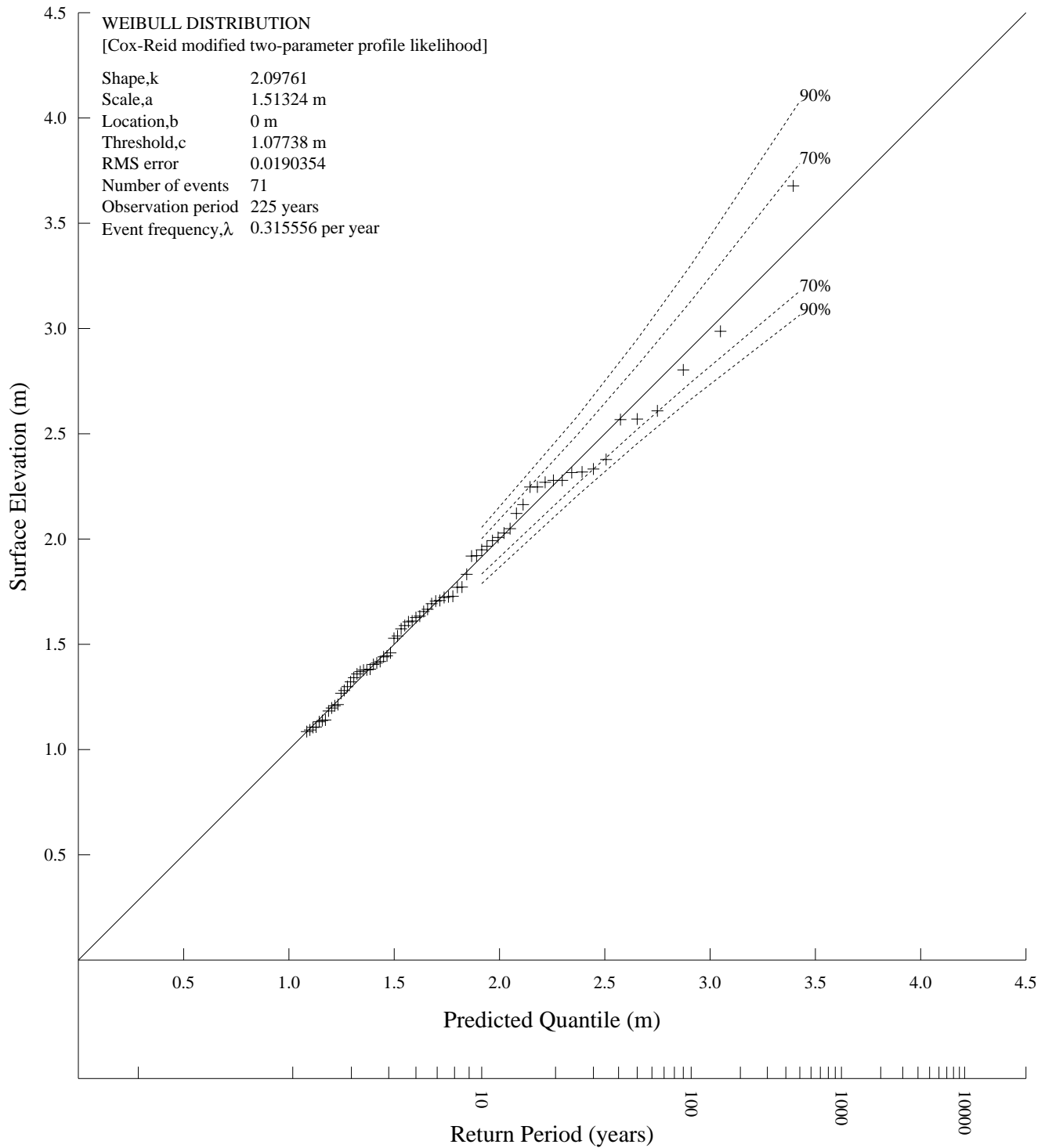
Mardie_South - Hs at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

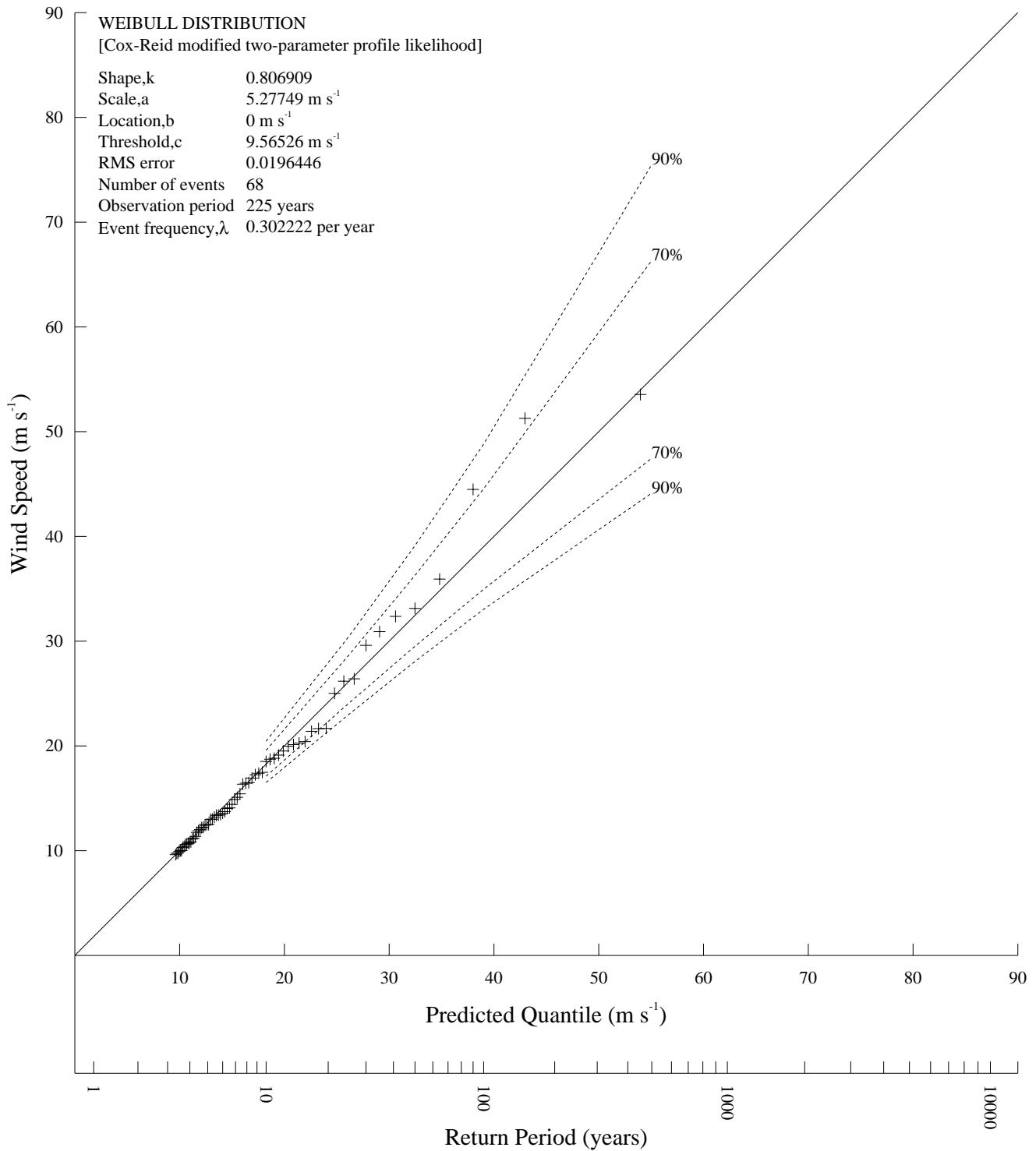
Mardie_South - TideHeight at peak Hs



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

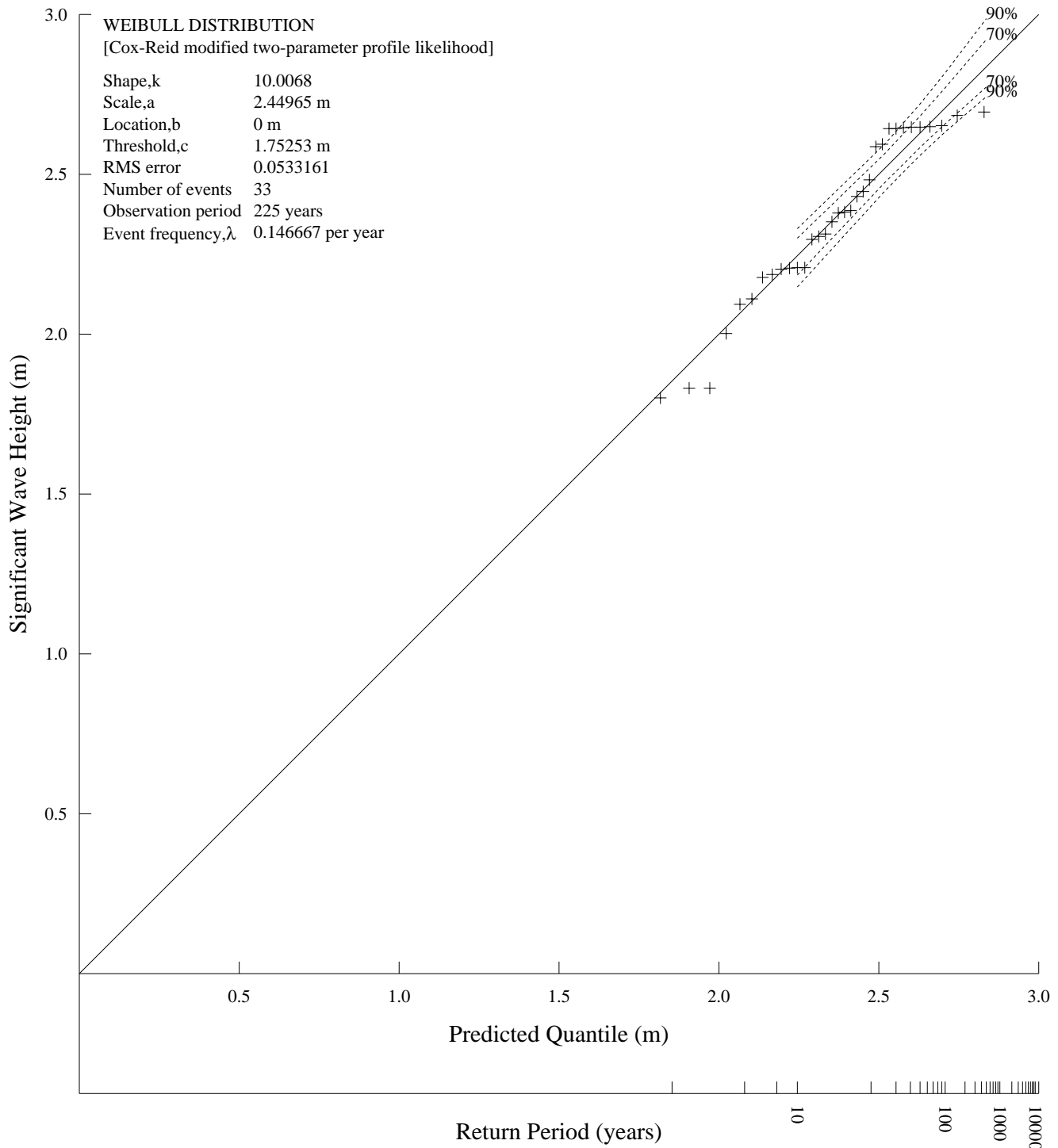
Mardie_South - WindSpd at peak TideHeight



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

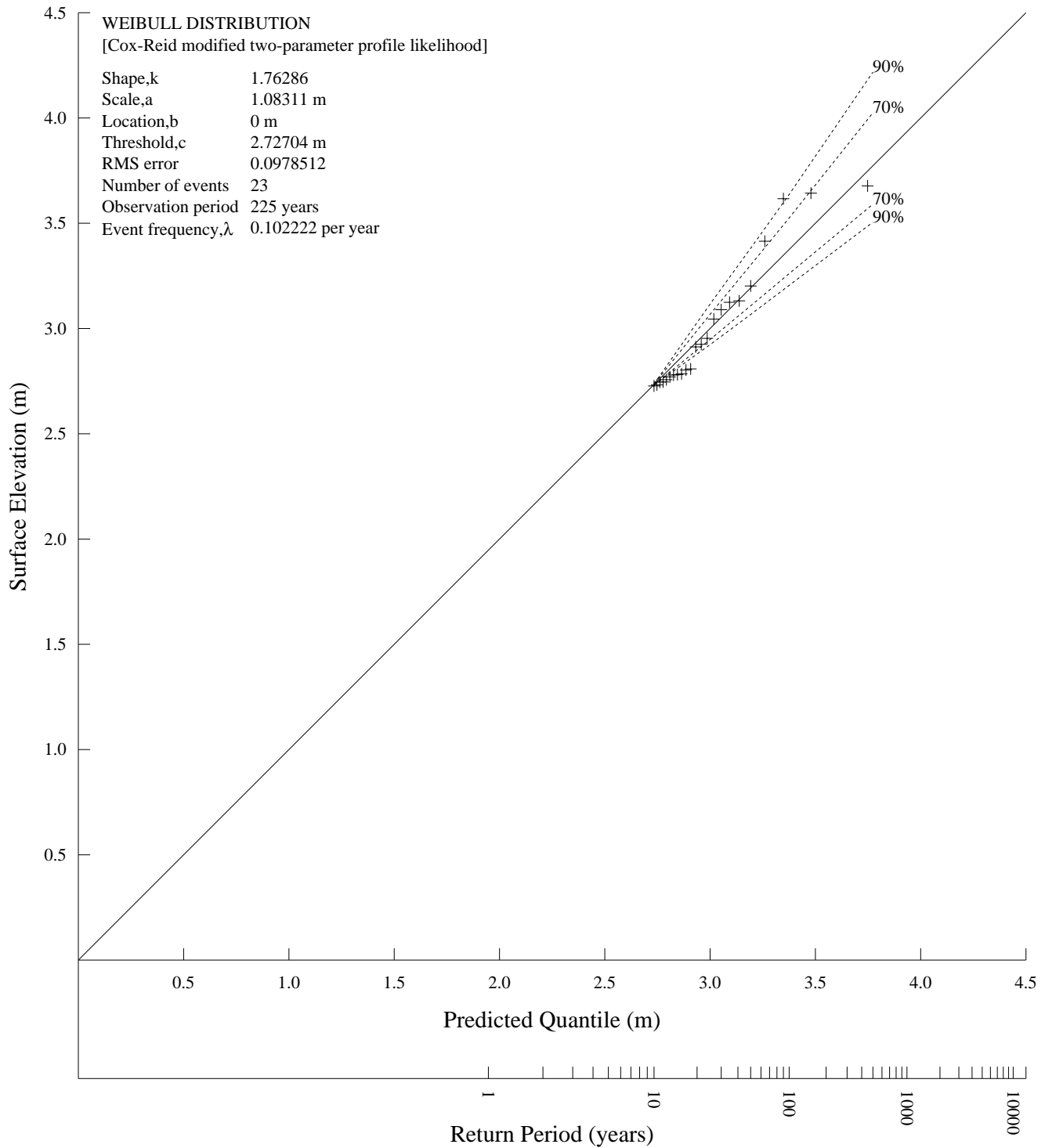
Mardie_South - Hs at peak TideHeight



EXTREME ANALYSIS

CONDITIONAL WEIBULL METHOD

Mardie_South - TideHeight at peak TideHeight

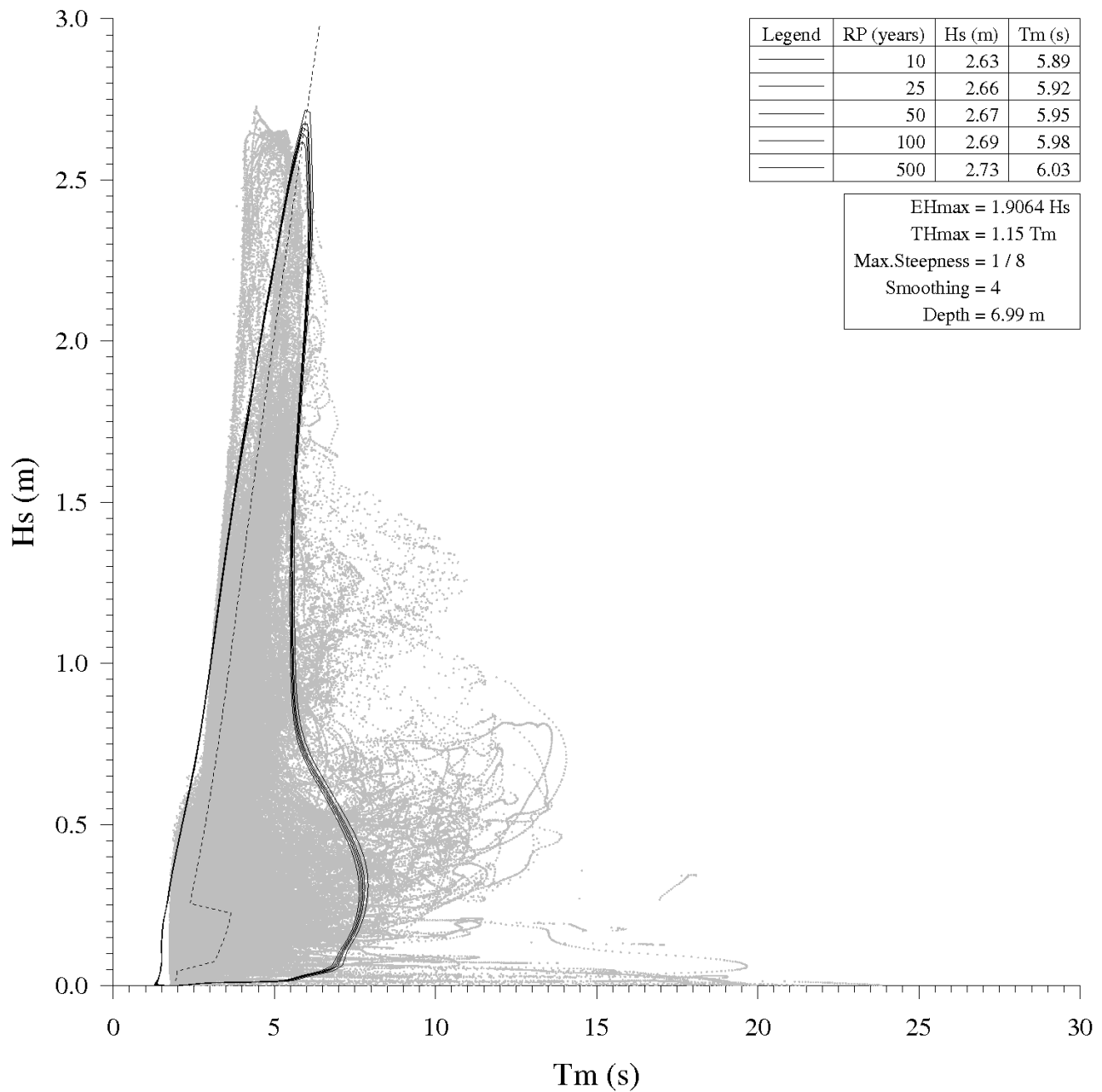


J3312 - Mardie_South - Hs vs Tm

Mardie_South

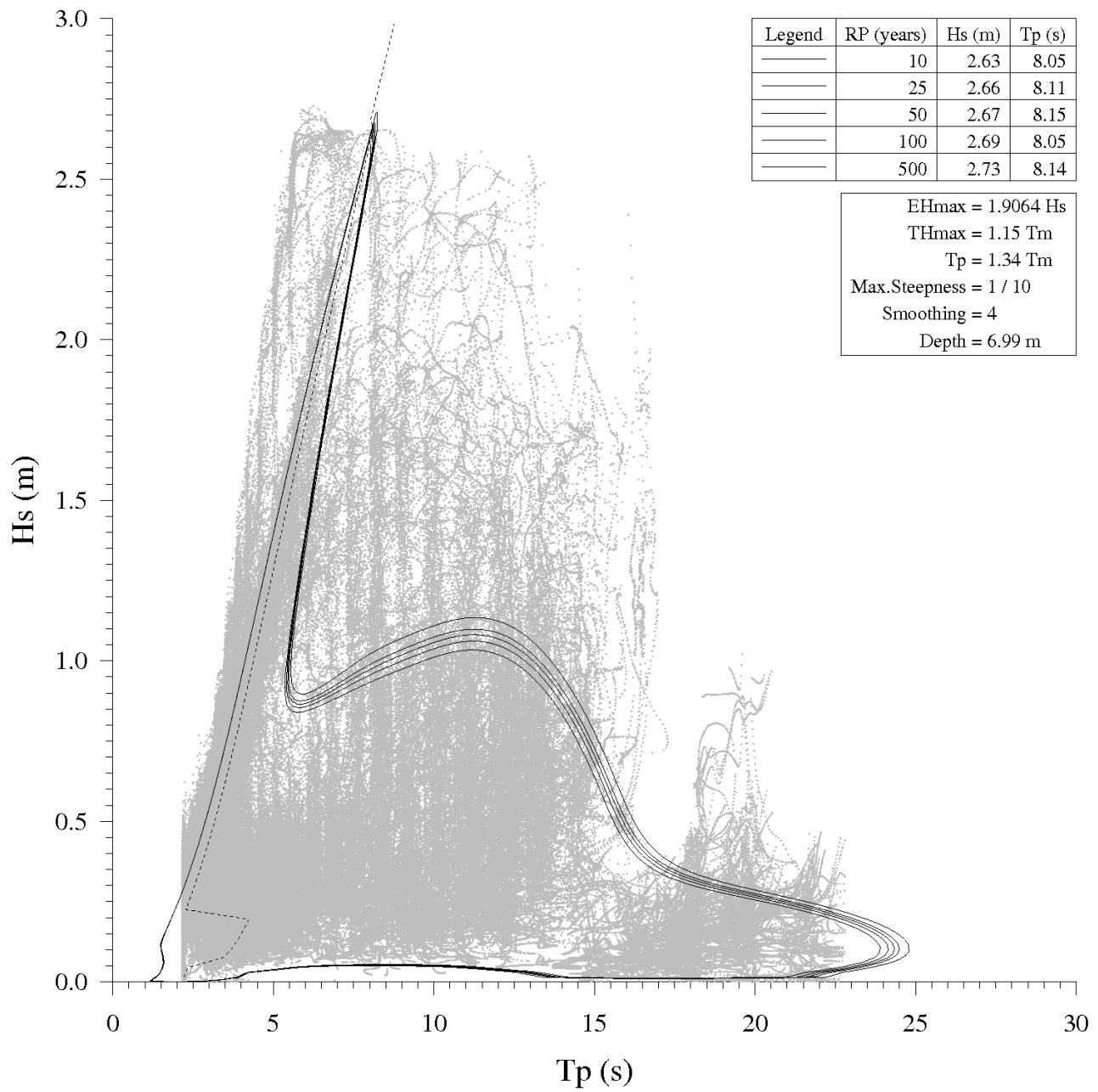
Legend	RP (years)	Hs (m)	Tm (s)
—	10	2.63	5.89
—	25	2.66	5.92
—	50	2.67	5.95
—	100	2.69	5.98
—	500	2.73	6.03

EHmax = 1.9064 Hs
THmax = 1.15 Tm
Max.Steepness = 1 / 8
Smoothing = 4
Depth = 6.99 m



J3312 - Mardie_South - Hs vs Tp

Mardie_South



J3312 - Mardie_South - Hs vs Tz

Mardie_South

