The Effects of Tropical Cyclone Characteristics on the Surface Wave Fields in Australia's North West Region

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Abstract

The numerical wave model SWAN (Simulating WAVes Nearshore) and historical wave buoy observations were used to investigate the response of surface wave fields to tropical cyclone (TC) wind forcing on the Australian North West Shelf (NWS). Analysis of historical wave data during TC events at a key location on the NWS showed that an average of 1.7 large TCs impacted the region each year, albeit with high variability in TC track, intensity and size, and also in the surface wave field response. An accurately modeled TC wind field resulted in a good prediction of the observed extreme wave conditions by SWAN. Results showed that the presence of strong background winds during a TC and a long TC lifetime with large variations in translation speed can provide additional energy input. This potentially enhances the generated swell waves and increases the spatial extent of the TC generated surface wave fields. For the TC translation speeds in this study, a positive relationship between TC translation speed and the resulting maximum significant wave height and wave field asymmetry was observed. Bottom friction across the wide NWS limited the amount of wave energy reaching the coastal region; consistently reducing wave energy in depths below 50 m, and in the case of the most extreme conditions, in depths up to 100 m that comprise much of the shelf. Nevertheless, whitecapping was still the dominant dissipation mechanism on the broader shelf region. Shelf-scale refraction had little effect on the amount of wave energy reaching the nearshore zone; however, refraction locally enhanced or reduced wave energy depending on the orientation of the isobaths with respect to the dominant wave direction during the TC.

Keywords

- Tropical cyclones
- Numerical wave modeling
- Wave transformation
- Bottom friction dissipation
- Australian North West Shelf

1 Introduction

Tropical cyclones (TCs), also known as hurricanes or typhoons depending on geographic convention, are common phenomena in tropical latitudes across the world. High wind speeds associated with TCs generate extreme surface waves, with the maximum wave heights typically found near the radius of maximum wind speeds (R_{max}), which subsequently decrease exponentially from the eye [e.g., Wang et al., 2005]. The time-dependent spatial distribution of this wave field is dependent on several properties of the TC, including but not limited to: wind speed, storm translation speed and track and, when in sufficiently shallow water, the characteristics of the shelf and coastal bathymetry. Shallow water effects are particularly relevant in shelf regions, such as the focus area of this study on the Australian North West shelf (NWS) (25 °S – 10 °S, 105 °E – 135 °E). The NWS is a sub-basin within the Australian TC region extending across northern Australia. It has Australia's highest TC activity and one of the major TC regions globally [Kuleshov et al., 2008], with ~5 TCs occurring each year [Goebbert and Leslie, 2010].

Studies of the ocean response to TCs have focused on either the induced surface wave field [Ou et al., 2002; Dietrich et al., 2011; Roland and Ardhuin, 2014] or the circulation and mixing in the interior [Zedler et al., 2002; Uhlhorn et al., 2013; Rayson et al., 2015]. Third generation spectral (phase-averaged) surface wave models (e.g., WaveWatch III and Simulating WAVes Nearshore (SWAN)) contain parametric source terms to describe linear and exponential wave growth, nonlinear energy transfers by quadruplet and triad wave-wave interactions, mechanisms of dissipation by whitecapping, depth-induced breaking and bottom friction, and these models have been used with various degrees of success in reproducing TC generated surface wave fields [e.g. Ou et al., 2002; Tolman and Alves, 2005; Babanin et al., 2011]. Accurately parameterizing the fine-scale air-sea interaction processes under cyclonic forcing is essential to accurately predicting TC waves [e.g. Anthes, 1982; Emanuel, 1986] and several studies have thus focused on developing new approaches to describe wind to wave energy transfer. In numerical wave models like

SWAN, following Komen et al. [1984] the friction velocity U_* is prescribed as $U_* = C_d U_{10}^2$, where U_{10} is the wind speed at 10 m elevation (averaged over a particular time period) and C_d is the surface drag coefficient. Earlier studies have considered the drag coefficient to be a linearly increasing function of the U_{10} [Wu, 1982], but recent studies have shown drag coefficients are reduced in high winds [e.g. Powell 2007; Zijlema et al. 2012; and Holthuijsen et al. 2012], thus suggesting that C_d values are not only dependent on the wind speed but also on the sea state.

The effects of TCs on surface wave fields can also be temporally and spatially complex. Previous studies have typically assumed TCs impact a region up to $10R_{max}$ [e.g. Young, 2006; Esquivel-Trava et al., 2015], yet studies have also shown that TC waves can have impacts very far from their track; for example, Beeden et al. [2015], have reported damage to coral reefs from TC-generated waves that were very remote from a TC path. Several studies [e.g. Young, 1988; Wang et al., 2005; Young and Vinoth, 2013] have described the decline of wave height as function of radial distance from the TC center by (semi-) empirical relationships. These relationships have been verified with either in situ observations from a single hurricane or altimeter data, which are assumed to be limited to $H_s < 8$ m [e.g. Wang et al. 2008; Queffelec and Crouzé-Fillon 2013], and do not include possible interactions with peripheral winds and waves. Therefore more verification is required to determine their predictive capabilities under a wide range of TC conditions, including in the presence of differing background wind fields. In addition, if the group velocity (based on the peak frequency) of the surface waves exceeds the TC translation speed, the waves will outrun the local influence of the TC and hence have less opportunity to grow. Conversely, when the group velocity of the waves is less than the TC translation speed, the waves will have an extended fetch and young waves are able to interact with previously generated swell waves. In the northern (southern) hemisphere, TC-generated waves tend to experience an extended fetch on the right (left) side of the track where waves are traveling in the same direction as the TC. A sensitivity study of idealized TCs by Liu et al. [2007] showed that the TC translation speed can cause an asymmetric surface wave field even if the wind field is symmetric, with the asymmetry of the wave field increasing at higher TC translation speeds. However, a high translation speed (e.g. > 12 m s⁻¹; Liu et al. 2007) may also reduce the amount of energy that can be transferred from the atmosphere to the ocean, effectively limiting wave growth. These diverse effects of a TC can counteract one another, and the relative contribution of these effects on surface wave fields under realistic TC conditions requires further study.

Previous studies of waves forced by TCs have typically focused on Northern Hemisphere regions, and also the TC waves generated under deep ocean conditions; for example, in the offshore regions of the Gulf of Mexico [e.g. Smith et al. 2013]. Young [2006] used wave observations at a single location on the NWS to show that wave spectra during a TC passage are generally dominated by low frequency swell in all quadrants of the TC. Wave spectra were found to be uni-modal, uni-directional and directionally skewed, and spectral parameters were found to be consistent with uni-directional wind conditions. However, the single observational location was mostly on the left side of the (southern hemisphere) TC tracks with respect to the TC translation direction. With winds rotating clockwise in the southern hemisphere around TCs, these observations were therefore mainly characterized by relatively mature waves (i.e. $U_{10} / c_p < 0.83$), where c_p is the phase velocity of the waves based on the peak frequency. Esquivel-Trava et al. [2015] performed a more extensive study based on several observation locations in the Gulf of Mexico to show that wave spectra are predominantly uni-modal in the right TC quadrants (left in the southern hemisphere), but become bi- or tri-modal in areas in the left quadrants (right in southern hemisphere).

In their study of the effects of TC trajectory on the NWS, McConochie et al. [2010] used synthetic linear TC tracks and, for the case where TCs were moving coast-parallel, they proposed that the generation of surface wave fields could be limited by wave refraction effects. This is based on the principle that wave energy would be refracted away from the high wind speed areas near the TC eye depending on the shelf bathymetry, potentially limiting the effective fetch of the TC. In addition to refraction, in other studies bottom friction was found to have a significant influence in water depths less than 30 – 40 m in the wide shelf of the Middle Atlantic Bight [Dalyander et al., 2013]. Ardhuin et al. [2003] similarly found that bottom friction attenuated large incoming swell waves, from a distant passing hurricane, by typically a factor of 2 in water depths between 49 and 8 m, whereas younger and smaller waves with weaker near bottom velocities, were little affected. While the Ardhuin et al. [2003] study reported substantial wave energy attenuation within this nearshore zone, wind energy was low and their swell wave heights did not exceed 4 m, and greater energy may reach the nearshore zone in more energetic conditions. Under TC conditions over the NWS where both significant wave heights and wind speeds are large and highly variable in direction, it is likely that bottom friction will be important but the detailed effects are not clear. In even shallower water (e.g. depths < 10 m), depth-limited breaking will dissipate wave energy as well prior to reaching a coastline. However, the primary focus of this study is on the broader shelf region (depths > 10 m) where the

effects of bottom-induced frictional dissipation and refraction may be important.

In summary, in locations such as the relatively shallow waters of the NWS, there is limited understanding of the interplay and relative importance of the various physical mechanisms that influence TC-generated surface wave fields. With a focus on the NWS, this paper will combine numerical modeling techniques using SWAN and field observations to assess the ability of phase-averaged numerical surface wave models to predict the spatial and temporal evolution of surface wave fields under TCs in shelf waters. Focusing on TCs with diverse trajectories, the goals are to identify which physical processes are dominant in affecting the surface wave fields and, in particular, to examine the effect of the limited depth and bottom friction on the evolution of the surface wave fields.

2 Climatology and site description

2.1 Wave climate and cyclone activity on the NWS

The Australian North West Shelf (NWS) represents the continental shelf region off northwestern Australia and is characterized by its generally wide and shallow shelf bathymetry (the 200 m contour is located 200-300 km offshore) and experiences a number of TCs each year (Fig. 1). The background seasonal wave climate on the NWS can be characterized as generally experiencing low to moderate wave energy with waves predominantly from the southwest, generated by distant Southern Ocean storms particularly during the austral winter months. Given that detailed published data on the wave climate on the NWS is very limited, we initially analyzed historical wave data between 1995 and 2013 at North Rankin A (NRA), a gas production platform located ~130 km northwest of Dampier in 125 m water depth. Results from this analysis indicate that significant wave heights (H_s) are usually less than 2 m at this location and waves are primarily from the southwest at ~240° (Fig. 2a,d). A secondary easterly wave direction (~90°) and lower periods can also be seen with larger waves (Fig. 2c,e,f). Most of the high energy wave conditions can be attributed to TC events during the austral summer months. These TCs usually develop in the Timor Sea or northern Kimberley region (15 °S –10 °S, 123 °E – 128 °E), then propagate in a southwesterly direction over the continental shelf parallel to the shelf break (200 m isobath). The implication is that the larger waves on the NWS are mainly locally generated and come from an easterly direction, while the smaller waves are remotely generated swell waves coming from a southwesterly direction.

Despite a common southwesterly translation direction, TC paths are highly variable and some TCs move in directions that are predominantly normal or oblique to local isobaths. Analysis of historical wave data during TC events at NRA shows that an average of 1.7 cyclones with $H_{s,max} > 3.0$ m impact this site per year. The tracks of all TCs and the location of NRA with respect to these tracks are summarized in Fig.1. To analyze the TCs that affected NRA between 1995 and 2013, relevant cyclone parameters such as the storm speed U_t and direction and radius of maximum winds R_{max} , were obtained from the Australian Bureau of Meteorology (BOM) at the closest approach of the TC center with respect to NRA. The minimum distance, r/R_{max} , between the TC center and NRA and corresponding cyclone parameters are shown in Table 1.

Table 1 shows high variability in both TC speed and direction. Most TCs followed a path from either northeast to southwest parallel to the isobaths ($15^\circ < \theta_t < 105^\circ$), or from northwest to southeast normal to the isobaths ($285^\circ < \theta_t < 15^\circ$). TCs with the two highest observed significant wave heights (11.3 m and 8.1 m for TCs Olivia and Vance, respectively) moved in a direction normal to the isobaths at relatively high translation speeds. Large waves (H_s of 7.2 m and 6.7 m for TCs Tiffany and Bianca, respectively) were also observed for TCs moving in a direction parallel to the isobaths at moderate to high translation speeds. While wave directions were generally highly variable, wave directions at $H_{s,max}$ were mostly from either the northeast parallel to the isobaths or northwest normal to the isobaths, but for a few TCs the wave direction at $H_{s,max}$ was from the southwest ($195^\circ < \theta_p < 285^\circ$) (shown in Fig. 3). Wave directions reflected the TC translation directions in some cases (e.g. TCs Vance and Bianca, 7° and 18° , respectively), were 90 degrees different in other cases (e.g. TCs Nicholas and Gwenda, 108° and 121° , respectively), and appeared completely unrelated in others (e.g. TCs Glenda and Lua, 149° and 160° , respectively). These high variabilities in wave amplitude and direction indicate that the specific TC track, speed and intensity in combination with the regional bathymetry collectively determine the local wave conditions at the NWS.

3 Methodology & data analysis

3.1 Model setup

A parametric double-vortex TC wind model [McConochie et al., 2004] was used to force the numerical spectral wave model SWAN (Simulating WAVes Nearshore, version 41.01

[Booij et al., 1999]). This wind model is largely based on Holland [1980] and Cardone et al. [1994] and specifies a primary and secondary atmospheric circulation. The pressure profile determines the surface wind profile, and the modeled wind field was blended with the hourly synoptic wind field at a spatial resolution of 0.2° (National Oceanic and Atmospheric Administration Climate Forecast System version 2 (NOAA CFSv2) [Saha et al., 2011]). A first order wind field asymmetry was applied to allow for the forward motion of the cyclone vortex. Data on the cyclone tracks, central pressures, maximum sustained wind speeds and the radii of maximum sustained wind speed of tropical cyclones were obtained from the Australian Bureau of Meteorology (BOM), while other parameters in the wind model were determined by a fitting process, where model output was compared with measured wind data for 22 available BOM weather stations throughout northwestern Australia [McConochie et al., 2004]. Wave parameters (H_s , T_p and θ_p), representing significant wave height, peak period and peak direction, were extracted from the NOAA WaveWatch III global hindcast runs (available at <http://polar.ncep.noaa.gov/waves/>), which have a spatial resolution of 0.5° and a temporal resolution of 3 h, and then these were applied to the open boundaries of the SWAN domain. Bathymetry for the NWS was obtained from the Australian Geoscience dataset with a gridded spatial resolution of 250 m. The model domain extended between 110°E and 125°E and 10°S and 25°S with a grid resolution of 0.05° and two nested model domains were run inside this large scale model to increase model accuracy near the measurement locations (Fig. 4). The large-scale model and Nest 1 were run with a SWAN time step of 10 min, while Nest 2 was run with a time step of 5 min. The frequency domain was discretized on a logarithmic scale into 30 frequency bins ($\Delta\sigma/\sigma = 0.08$), ranging from 0.04 to 0.4 Hz, and the directional domain was discretized homogeneously into 180 sectors ($\Delta\theta = 2^\circ$) to avoid the Garden-Sprinkler Effect [e.g. Tolman, 2002]. This directional resolution is higher than the more typical value of $\Delta\theta = 10^\circ$.

The physics in SWAN are resolved by solving the wave action balance [Booij et al., 1999] as:

$$\frac{\partial N}{\partial t} + \nabla_x \vec{c}_g N + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

where, $N = N(\vec{x}, t, \sigma, \theta)$ is the wave action density spectrum as a function of position $\vec{x}$, time t , relative wave frequency σ and wave direction θ . The first and second terms on the left side of Eq. (1) give the local and advective rates of change of wave action density, where $\vec{c}_g$ is the wave group velocity. The third and fourth terms represent the relative frequency shifting and refraction, respectively. Here c_σ and c_θ are the propagation speeds in σ - and θ -direction. The source and sink term on the right side of Eq. (1) accounts for all physical

processes which generate, dissipate or redistribute wave energy [Komen et al., 1984] as:

$$S_{tot} = S_{wind} + S_{nl,3} + S_{nl,4} + S_{wcap} + S_{fric} + S_{brk} \quad (2)$$

These source and sink terms include wind-generated wave growth (S_{wind}); nonlinear wave transfers due to triad ($S_{nl,3}$) and quadruplet ($S_{nl,4}$) wave-wave interactions; and wave energy dissipation due to depth-limited wave breaking (S_{brk}), bottom friction (S_{fric}) and whitecapping (S_{wcap}). The default case simulations used the exponential wave growth terms from Janssen [1989] and Janssen [1991] and include the linear wave growth term from Cavaleri and Rizzoli [1981]. Default values were used for the coefficient for determining the rate of whitecapping and the coefficient for the dependency of the whitecapping on the wave number and for the proportionally coefficient in the Cavaleri and Rizzoli [1981] term (4.5, 0.5 and 0.0015, respectively). After initial evaluation, the surface drag formulation by Zijlema et al. [2012] was used as default in the simulations (also the default formulation in SWAN since the SWAN 41.01 release). Depth-limited wave breaking (only relevant in shallow water) was calculated based on Battjes and Janssen [1978] using a default breaking index value of $\gamma = 0.73$ and the bottom friction was represented by the Madsen et al. [1988] formulation using a roughness length scale of 0.10 m that is typical of shelf regions [Guillou, 2014]. Quadruplet wave interactions and triad wave-wave interactions were calculated with the Discrete Interaction Approximation (DIA) [Hasselmann et al., 1985] and Lumped Triad Approximation (LTA) [Eldeberky and Battjes, 1996]. Refraction in SWAN is included by the directional turning rate of individual wave components in the 2D wave spectrum [Holthuijsen et al., 2003]. To investigate the effects of bottom friction and refraction, some of the SWAN simulations were run with these terms in the wave action equation turned off.

3.2 Choice of tropical cyclones

TCs Nicholas (2008), Bianca (2011), Lua (2012) and Christine (2013) were selected for detailed evaluation with the numerical modeling as they represented a diversity of tracks, translation speeds and intensities. Fig. 5 shows the proportion of the lifetime of each TC in differing water depth, storm speed, wind speed and storm radius. Large variations in these TC characteristics were generally observed between various TCs. For most TCs in this study, the TC eye was moving in deep water (>500 m depths) off the continental shelf for a majority of their lifetimes (Fig. 5a). The TCs in this study experienced large variations in the TC translation speed (Fig. 5b). TCs Nicholas and Christine were relatively slow moving ($U_{TC} < 5 \text{ m s}^{-1}$), whereas TCs Bianca and Lua both had periods of both slow and fast translation speeds within their lifetimes. Variations in wind speed were generally large and

Fig. 5c indicates that the most extreme wind speeds were only observed during a relatively small proportion of each TC's lifetime. In general, a higher TC intensity related to smaller R_{max} values, and the R_{max} values of each storm were typically in a lower range around 30 km (Fig. 5d). Only TC Christine showed a different trend, with a majority of $R_{max} > 50$ km.

TCs Nicholas and Bianca both had tracks primarily parallel to the 200 m isobaths; however, TC Nicholas moved over deep waters while TC Bianca moved over shallow waters. Although TC Nicholas was near maximum intensity when passing NRA, 10-min averaged wind speeds reached 22 m s^{-1} at NRA, due to the even closer approach to NRA during TC Bianca wind speeds reached 32 m s^{-1} (r/R_{max} of 7.2 versus 0.9, respectively (Table 1)). TC Nicholas was generally slow, with a translation speed of 2.9 m s^{-1} when passing NRA, whereas TC Bianca was a relatively fast storm with a translation speed of 7.1 m s^{-1} when passing near NRA. TC Lua initially approached NRA from the northwest as a tropical low, then reversed direction and moved away from the shelf while intensifying into a category 1 TC. TC Lua was then near-stationary in deep water, while intensifying into a category 3 TC, before intensifying to maximum strength with maximum 10-min averaged wind speeds of 46 m s^{-1} at R_{max} and moving in a southeasterly direction with a translation speed of 7.2 m s^{-1} towards the coast. TC Lua had strong variability of translation speed during, with a large proportion of its lifetime was spent near stationary ($0 \text{ m s}^{-1} < U_{TC} < 1 \text{ m s}^{-1}$), but near the end of its lifecycle TC Lua became the fastest moving TC in this study. Finally, TC Christine was less intense than TC Lua and moved in a southwesterly direction passing NRA at a distance with a storm speed of 4.2 m s^{-1} .

3.3 Field observations

An overview of all available in-situ wave data used for model verification is summarized in Table 2Error! Reference source not found., with the locations shown in Fig. 4. The most substantial data source was from NRA, where directional and spectral wave data were available for all selected TCs. Wave parameters (T_p and H_s) were available at the A1, B1, Rose, HPR2, HPR3 and Exmouth offshore buoys during specific TCs. Additionally, satellite wave altimeter data can be used if the timing and position of a satellite orbit coincides with a TC passage. Queffeuilou and Crouzé-Fillon [2013] assembled altimeter data from the eight altimeter missions ERS-1&2, TOPEX-Poseidon, GEOSAT Follow-ON (GFO), Jason-1, Jason-2, ENVISAT and CryoSat for a period of 20 years (1993-2013). Altimeter data (e.g. significant wave height) was extracted from this original product and screened according to quality flag values and corrected and homogeneous daily data files

were created. Altimeter data has already been used successfully in several previous studies, even under TC conditions [e.g. Smith et al. 2013].

3.4 Model performance

The hindcast model simulations were qualitatively compared to field observations by analyzing the model skill, root-mean-squared error and bias [Willmott, 1984], defined as:

$$skill = 1 - \frac{\sum |X_m - X_o|^2}{\sum (|X_m - \overline{X_o}| + |\overline{X_o} - X_o|)^2} \quad (3)$$

$$RMSE = \sqrt{(X_m - X_o)^2} \quad (4)$$

$$bias = \overline{X_m - X_o} \quad (5)$$

The subscripts m and o in Eqs. (3)-(5) denote the modeled and observed values, respectively, while X is a given variable being compared. The overbars denote time-averaged values. A model skill of 1 represents the best possible agreement between model output and observations, while a model skill of 0 represents no agreement.

4 Model verification

4.1 Effects of wind drag formulation

To assess the sensitivity of the predicted wave fields to the surface drag formulation, three different approaches to determining C_d values were evaluated: Wu [1982], Zijlema et al., [2012] and Holthuijsen et al., [2012]. Although the differences in the C_d values in the three formulations were found to be large during high wind speeds, the effects on the significant wave height tended to be relatively small overall. For example, the over-prediction of C_d by the Wu [1982] formulation resulted in an over-prediction of H_s by a maximum of ~8% (or 2 m) in a region around the radius of maximum winds during TC Lua. The formulation from Holthuijsen et al. [2012] resulted in a slight increase of H_s in the rear quadrants of the TC and a slight decrease in the left-front quadrant. Given these results, the recently updated formulation proposed by Zijlema et al, [2012] was used for all subsequent simulations in the study described below.

4.2 Wave response and model performance

Time series of H_s at NRA during TCs Nicholas, Bianca, Lua and Christine are shown in Fig. 6, comparisons of the modeled versus the observed H_s at all measurement locations

are shown in Fig. 7, and the overall model performance statistics are summarized in Table 3. In Table 3 we also summarize the performance of the wind model at several locations. Fig. 6 shows that while there was an overestimation of the wave heights during the peak of TCs Bianca and Lua, there was good agreement for TCs Nicolas and Christine. Moreover, when considering the full duration of the storm and performance statistics (Fig. 7 and Table 3), the model was able to provide robust predictions of the wave fields generated during all four TCs. We further note that any discrepancies between the observations and predictions may also not be primarily due to errors in the wave model and its formulations, as there are also uncertainties in model forcing (especially the wind fields, but also background wave fields), since small errors in the eye position and R_{max} can have a large effect on H_s if the measurement location is very close to the eye of the TC. TC Bianca passed NRA at a very close distance of $r/R_{max} = 0.9$ (Table 1), while the eye position uncertainty for TC Bianca was $0.8R_{max}$ when passing NRA. During TC Lua, NRA was mostly on the weak side (right quadrants), where interaction of waves with adverse winds and wind-induced currents could be responsible for differences between modeled and observed wave heights [Fan et al., 2009; Zieger et al., 2015; Ajjaz et al., 2016].

Comparisons between the observed and modeled wave energy spectral distributions, at the peak H_s , are shown in Fig. 8. The magnitude of the wave energy at the peak frequency was in a reasonable agreement for TCs Bianca, Lua and Christine, but there were mismatches in the spectral shape for TCs Nicholas, Bianca and Lua. Spectra for TCs Nicholas and Lua show that the model had a tendency to overestimate the wave energy at lower frequencies. NRA was on the left side of the TC track for TC Nicholas and Bianca, but TC Nicholas passed NRA at a much larger distance than TC Bianca with r/R_{max} of 7.2 versus 0.9, respectively (Table 1). For TC Nicholas (Fig. 8a) this resulted in a modeled peak frequency that was lower than observed. NRA was on the right side of the track for TC Lua and TC Christine, but TC Lua had a higher intensity, was of larger size and passed NRA at a large distance. The modeled uni-modal spectrum matched the observed wave spectrum during TC Christine, but the bi-modal or tri-modal wave spectra during TC Lua were not always correctly reproduced by the model which (again) overestimated the low frequency portion of the spectra. Possible explanations for these mismatches could be attributed the complex behavior of nonlinear wind input and whitecapping dissipation in TC conditions that are not being correctly parameterized [Donelan et al., 2006; Manasseh et al., 2006; Van Vledder et al, 2016], and too much energy transfer to low frequencies due to nonlinear wave-wave interactions due to mismatches in the DIA parameterization [Tolman et al., 2013]. Observations from the left side of TC Lua at A1 and B1 displayed

very uni-modal wave spectra, which were in good agreement with modeled wave spectra (error in wave energy at peak frequency ~5 %). To examine the spatial distributions, we used satellite-derived transects of wind speed and H_s , and in Fig. 9 we show there is good agreement between modeled and observed data; for the example of TC Nicholas, the model skill values for wind and waves along the transect were 0.94 and 0.80, respectively.

5 Results

5.1 Spatial characteristics

TC wind field forcing and the resulting wave fields are complex in both space and time. Adoption of a TC-following coordinate system, as introduced by Young [2006] and Esquivel-Trava et al. [2015], allows for averaging of the spatial wind and wave fields over the duration of a TC and comparison of spatial patterns between TCs. Each grid cell was classified based on the normalized distance to the TC center and the position with respect to the translation direction of the TC. Hereafter, values were averaged in bins with a width and height defined by R_{max} . For comparison of the spatial patterns over time, values for U_{10} and H_s were normalized by the maximum value at each hourly time step. The x-axis thus represents the direction normal to the TC translation direction (left is negative and right is positive), whereas the y-axis represents the TC translation direction (front is positive and rear is negative). This categorizes the spatial maps into four TC quadrants: left forward (LF), right forward (RF), left rear (LR) and right rear (RR). This coordinate system was used in Fig. 10 to illustrate the spatial response of the 4 TCs.

TCs Nicholas and Lua both show a slow spatial decay of wind speed and H_s in the radial direction, whereas U_{10} generally decayed quicker in the radial direction than H_s . Both TCs were of long duration with persistent large-scale background winds (of the order of 10-15 m s⁻¹ at latitudes of 10-12 °S, Fig. 9a,b). Given the large fetch of these storms, these background winds generated significant wave heights up to 5 m (Fig. 9c,d). During their initial stages, both TCs were near stationary and thus able to input energy to the surface wave field over a larger area. When the TC translation speed and intensity subsequently increased, the combination of the background waves and the TC generated waves produced the slow decay in H_s (Fig. 10b,h). TC Nicholas also coincided with a period of persistent “background” southerly winds off the coast of northwestern Australia (around 114 °E, 22 °S), adding wind and wave energy into the system from the southwest, and this extra energy input also reduced the spatial decay in this direction.

In comparison with TCs Nicholas and Lua, TCs Christine and Bianca showed a more rapid radial decay of H_s (Figure 10e,k), with H_s decaying at a similar rate to U_{10} . Both TCs had a short duration lifetime within the study area compared to TCs Nicholas and Lua, moved at average (3-5 m s⁻¹) to fast (> 5 m s⁻¹) translation speeds, and traveled closer to the coast over relatively shallow shelf waters. In the right-rear sector of TC Christine there was a relatively small radial decay in H_s . In both of the left quadrants, H_s decayed much more abruptly in the relatively shallow shelf waters with increased dissipation of wave energy due to bottom friction (see Fig. 4), as we discuss further below. For all 4 TCs, differences in the spatial characteristics of the surface wave fields can be attributed to the combination of the position of the TC tracks with respect to local bathymetry and differences in background wind fields.

The radial decay of H_s during a TC in deep water with negligible effects of local bathymetry on surface waves has been described by (semi-)empirical relationships [Young, 1988; Wang et al., 2005]. Based on detailed observations from Hurricane Ivan, Wang et al. [2005] suggested the significant wave height can be expressed an exponential function of the radial distance

$$\frac{H_s}{H_{s,max}} = a \left(\frac{r}{R_{max}} \right)^b \exp \left\{ - \left(\frac{r}{R_{max}} \right)^c \right\}, \quad (6)$$

where $a = 2.7$, $b = -0.96$ and $c = -0.94$ are the fitting coefficients that were observed for Hurricane Ivan. Eq. (6) can be applied for a specific TC and a specific quadrant, and the resulting fitting coefficients are shown in Table 4 and the results plotted in Fig. 11. When using the single set of coefficients suggested by Wang et al. [2005], this generally resulted in a poor prediction of the radial decay, but using coefficients specific to each TC and direction resulted in good fits with model output. Insufficient data points in deep water were available for a fit in the left direction with respect to the TC translation direction for TC Christine, due to its proximity to the coast. The variations in fitting coefficients between various TCs and quadrants highlight the limited predictive capabilities of Wang et al. [2005]'s simple expression. Young and Vinoth [2013] improved the parametric model introduced by Young [1988] where H_s is described as a function of the radial distance, radius to maximum winds, TC translation speed and wind speed, and a comparison between the model output and the Young and Vinoth [2013] model is also included in Fig. 11. The Young and Vinoth [2013] model shows a good prediction of the radial decay with an overall model skill of 0.89 for all four TCs. Fig. 12 shows that $H_{s,max}$ was much higher than predicted by the Young and Vinoth [2013] model for high wind speeds and TC translation speeds, particularly during TC Lua, but also for a period with relatively high wind speeds and low TC translation speeds during TC Nicholas. Highest wind speeds

($U_{10,max} > 30 \text{ m s}^{-1}$) during TCs Bianca and Lua corresponded with relatively high translation speeds ($U_{TC} > 5 \text{ m s}^{-1}$). Values for $H_{s,max}$ increased much quicker when these values for $U_{10,max}$ and U_{TC} were exceeded and were more scattered. This suggests that, under some circumstances, the local waves that are generated are no longer behaving as if they were fetch-limited. For the selected TCs in this study, U_{TC} rarely approaches or exceeds the group velocity c_g , and therefore in practice there is a positive relationship between U_{TC} and $H_{s,max}$.

Inverse wave age ($(U_{10} \cos \theta)/c_p$) can be used to assess the effects of the wind on the sea state, where c_p is the peak phase speed of the waves and θ the angle between the wind direction and the peak wave direction. By convention, the sea state is considered to be mixed (comprised of both wind sea and swell waves) for $0.15 < (U_{10} \cos \theta)/c_p < 0.83$, wind-driven (dominated by wind sea) for $(U_{10} \cos \theta)/c_p > 0.83$, wave-driven (swell dominated) for $0 < (U_{10} \cos \theta)/c_p < 0.15$, and experiences counter-swell conditions (wind direction opposite to wave direction) if $(U_{10} \cos \theta)/c_p < 0$ [e.g. Hanley et al., 2010]. We note that interpretation of wave age can locally become ambiguous near TCs, where the spectral-peak waves may propagate at large angles to the local wind that generated them; however, they can (when interpreted with caution) provide further insight into the different sea-states that surround a TC. Fig. 13 shows that TC Lua had a relatively long lifetime with an initial period of relatively low translation speeds followed by a period with rapid intensification and relatively high translation speeds. It thus serves as a useful case study for how sea states can evolve with changes in translation speed, even for the same storm. Separating this TC into periods of low translation speeds ($U_{TC} < 5 \text{ m s}^{-1}$) and high translation speeds ($U_{TC} > 5 \text{ m s}^{-1}$) shows that the spatial characteristics of the sea states changed as TC Lua moved faster (Fig. 13). Most of the left forward and left rear quadrants were wind-driven, while the right forward quadrant was in a mixed sea state, and the right rear quadrant was mostly in a mixed state but with a region of wind-driven sea states around $(-7R, -2R)$. Increased U_{TC} and intensity resulted in a transition from mixed to swell-dominated sea states in the left forward quadrant. As wind and wave direction were aligned in this region, waves were subjected to a high wind input for a longer duration according to the extended fetch principle. This resulted in a larger transfer of wave energy from high to low frequencies, increasing the overall wave energy.

For TC Lua, an opposite transition from mixed to wind-driven sea states was observed in the right rear quadrant and a transition from swell-dominated to counter-swell sea states in the right forward quadrant. In this quadrant, wind and wave directions were opposite for a longer duration, limiting the effective fetch. This resulted in steeper waves with increased

whitcapping dissipation (see below), locally decreasing the overall wave energy. Therefore, maximum inverse wave ages increased so that wind-driven regions became more wind-dominated and minimum wave ages decreased. Hence the asymmetry in the spatial wave field increased significantly as a result of the increased U_{TC} and intensity. Furthermore, the spatial inverse wave age composite maps of TCs Nicholas and Bianca (Fig. 10c,f) displayed similar general patterns, with a region of wind-driven seas in the right forward and left rear quadrant. However, these regions were larger and the inverse wave age was higher, while conversely inverse wave ages were lower in the right rear quadrant for TC Bianca with respect to TC Nicholas. This resulted in a higher asymmetry of the surface wave field during TC Bianca and can partly be associated with the higher translation speed and intensity during TC Bianca. On the other hand, the shallower water region in the left quadrants during TC Bianca resulted in more dissipation in the left quadrants (see below), also resulting in a higher asymmetry. Finally, the long lifetime of TC Nicholas resulted in a more energetic initial sea state so that more energy was transferred to low frequencies, leading to lower wave age.

5.2 Energy balances

5.2.1 Energy generation and dissipation

For TCs Nicholas, Bianca, Lua and Christine, the individual terms in the energy balance in Eq. (2) are shown for water depths out to 200 m (Fig. 14). These terms were integrated over all frequencies and directions. The total integral over the non-linear wave-wave interaction term (S_{nl4}) was assumed to be 0 and the depth-limited breaking term (S_{brk}) was mostly negligible and is therefore not shown in Fig. 14. During the majority of the lifetime of TCs Nicholas and Lua, more energy was dissipated on the shelf than generated [Fig. 14a], and hence the significant wave height decreased over the shelf. Unlike TC Nicholas, TC Lua eventually propagated in a direction normal to the 200 m, and more wave energy was generated on the shelf due to locally high wind speeds [Fig. 14b]. Because of the larger incoming waves during TC Lua, bottom friction started to affect the waves in very deep water (depths of ~130 m), almost twice the depth of influence of about 70 m for TCs Nicholas, Bianca and Christine. These three TCs all showed similar patterns for dissipation by bottom friction, but more energy was generated and dissipated due to whitcapping for depths below 100 m during TCs Bianca and Christine [Fig. 14c,d]. The lower values of wind generation and whitcapping below 100 m during TC Nicholas (compared to TCs Bianca and Christine) are related to its more offshore track in deeper waters. As TCs Bianca and Christine spent a larger portion of their lifetime (~55% and

~25%, respectively) on the shelf (depths < 200 m) (Fig. 5a), higher wind speeds on the shelf resulted in more local wave energy generation. Because the whitecapping term depends on the overall wave steepness, younger waves with a higher overall steepness resulted in higher dissipation due to whitecapping.

A comparison of the spatial variation in bottom friction dissipation of wave energy is shown in Fig. 15. In shallow water (depth < 50 m) and relatively close to the TC track, the relative contribution of bottom friction to the dissipation of wave energy was lower for TCs moving in a coast-normal direction (TCs Lua and Christine) compared to TCs moving in a coast-parallel direction. This is because the TC center, where the highest winds cause the highest local energy generation, moved over shallow water (depth < 50 m). For the coast-parallel moving TCs (Nicholas and Bianca), the TC center stayed in waters with a depth > 50 m. Further away from the TC track, bottom friction dissipated a substantial amount of wave energy in depths less than 50 m, thereby reducing the wave energy that reached the coastline. Dissipation due to depth-limited breaking was generally only relevant in very shallow coastal waters (depth < 10 m). However, Fig. 16 shows that before TC Lua made landfall, S_{brk} was significant from ~50 m depth in a relative small area on the left side of the TC track with respect to the TC translation direction. These higher values for S_{brk}/S_{tot} are related to very high waves ($H_s > 15$ m) in an area with the highest wind speeds around the 50 m isobath; while the relative contribution of the bottom friction, S_{fric}/S_{tot} , was much smaller in this area.

A more detailed overview of the attenuation of wave energy due to bottom friction is shown in Fig. 17, which highlights the difference between the maximum H_s between the model runs with and without bottom friction. The reduction in $H_{s,max}$ (defined as the modeled $H_{s,max}$ without bottom friction subtracted by the modeled $H_{s,max}$ including bottom friction) was generally around 1-2 m (up to ~50 %) once waves reached the 10 m isobath. However wave attenuation due to bottom friction was relatively small around the locations where TCs Lua and Christine crossed the 50 m isobath. For TC Lua, wave heights on the shelf were high enough to cause depth-limited breaking before waves could reach the 10 m isobath. However, $H_{s,max}$ along the 50 m isobath shows that around 123° E bottom friction reduced $H_{s,max}$ from ~10 m to ~7 m (up to ~30% attenuation due to bottom friction). In the case of TCs Nicholas and Bianca, which moved predominantly parallel to the 200 m isobath, a similar amount of wave energy reached the 10 m isobath if bottom friction was turned off. However, due to bottom friction, the wave attenuation during TC Nicholas was higher than during TC Bianca. Differences in $H_{s,max}$ due to bottom friction for depths deeper than 200 m were generally small (< 1 m). This shows that generally a large portion of the wave energy

is attenuated by bottom friction over the shelf before reaching the coastal zone, and only when the TC center moves over very shallow water (depth < 50 m) does attenuation due to bottom friction becomes relatively less dominant.

Directional wave spectra at selected locations along a transect normal to the isobaths were averaged for all quadrants during TC Christine to assess the spectral evolution of waves across the shelf, including the role of bottom friction [Fig. 18]. Since TC Christine moved across the shelf at an angle, the distance towards the TC center increased from deep to shallow water for the locations on the left side of the track, while the distance towards the TC center increased from shallow to deep water for the locations on the right side of the track. Directional spectra were mostly unimodal in the left forward quadrant, with a weak presence of background swell from the west-southwest. The peak direction in the left forward quadrant was close to the TC propagation direction, but slowly shifted from north-northeast to north-northwest when moving from deep to shallow water. Most energy was found at a peak frequency around 0.1 Hz, but a long tail with frequencies between 0.1 and 0.2 Hz that corresponded to the local wind direction was also observed. Wave energy was mostly attenuated by bottom friction at the low frequency peak direction, while little wave energy was attenuated at the higher frequencies. In the left rear quadrant, wave spectra were found to be bi-modal with a peak direction from the north, corresponding to the local wind direction, and a secondary peak from the west-southwest with frequencies <0.1 Hz as remote swell from TC Christine moved away. Wave spectra in the right forward quadrant were generally weak with a much broader directional spectrum, because the wind direction was mostly opposite to TC translation direction. As waves propagated from the 50 m towards the 200 m isobath, wave energy was slowly transferred to lower frequencies, but relatively large directional spreading remained. The largest waves in the right rear quadrant had a relatively high frequency broad peak, which was aligned with the local wind direction. Bottom friction did not appear to have a large influence on the spectrum in the right rear quadrant.

Even though bottom friction played a major role in dissipating wave energy on the shelf towards the coastline, whitecapping still made the dominant contribution to the total energy dissipated on the shelf. Even in shallow water of about 20 m, S_{wcap} could be of similar magnitude to S_{fric} [Fig. 14c,d]. Finally, the depth-limited breaking term S_{brk} was most often negligible on the shelf, but had a contribution to the total energy dissipated in shallow water below a depth of 50 m during TC Lua. Some deeper locations between 40 m and 50 m also showed substantial depth-limited breaking due to the localized shallow topography. This was the case, for example, at the Rowley Shoals near 117.3 °E, 19.2 °S (not shown),

where large waves interact with these offshore bathymetric features.

5.2.2 Influence of refraction

The effects of refraction on wave heights over the shelf appeared to be controlled by the orientation of isobaths with respect to the translation direction of the TC and incoming wave direction, with a similar pattern observed for TCs with either tracks normal or parallel to the 200 m isobath for the majority of their lifetime [Fig. 19]. In some local regions, refraction had a relatively strong influence on the maximum significant wave height. Amplification or reduction of the wave height depended on the wave direction with respect to deflections in the depth contours on the shelf. Large incident waves during TC Lua caused refraction up to a maximum of 20% of the wave energy from a depth of 200 m. However, the effects of refraction on $H_{s,max}$ were relatively small close to the track of TC Lua as the wave direction was normal to the bathymetry contours [Fig. 19c-Fig. 20]. For other TCs, refraction generally started to have some effect on total energy propagation within the 100 m isobath. The highest ratios of refracted wave energy during the TCs were found in the areas with largest wave lengths: for TC Bianca in the southwest and for TC Lua in the northeast, both in the left TC quadrants [Fig. 19b and c]. Overall, certain hotspot areas for enhanced wave energy due to the orientation of isobaths can be found southwest of Barrow Island (115 °E, 21 °S) and northwest of Broome (122 °E, 18 °S) with adjacent areas of decreased wave energy during all selected TCs. However, Fig. 15 shows that the spatially bin-averaged wave energy was not strongly dependent on refraction, as the overall H_s in the nearshore zone did not change significantly due to of refraction. Directional wave spectra can be used to analyze spectral evolution on the shelf due to refraction, in a similar way as described for bottom friction [Fig. 18]. Wave spectra directionally narrowed as waves refracted towards a direction normal to the local isobaths in depths < 200 m, and energy loss was highest around the peak frequency.

6 Discussion and conclusions

The Australian North West Shelf (NWS) is a wide and relatively shallow continental shelf that regularly experiences high wave conditions generated by TCs during the austral summer months. Analysis of long-term historical wave data during TC events at a key location (NRA) on the NWS showed an annual average of 1.7 cyclones impacts (with $H_{s,max} > 3.0$ m), with high variability in TC characteristics and surface wave field

characteristics. At this site, TCs that moved in a direction normal to the isobaths at relatively high translation speeds generated the highest observed wave heights. TCs moving in a direction parallel to the isobaths at moderate to high translation speeds also generated large waves. These highly variable responses indicate that the specific TC track, speed and intensity are all important factors in determining the local wave conditions during TC conditions on the NWS.

In general, with a good representation of the TC wind field we found that SWAN was able to hindcast the observed extreme wave conditions with reasonably good accuracy. Model performance statistics showed relatively good performance under complex behavior of wind input, but peak wave heights tended to be overestimated during some storms. In particular when the wave spectra became very bi-modal and bi-directional, SWAN tended to overestimate the low frequency portion of the wave spectra. Possible reasons are interactions of waves with adverse winds and wind-induced currents, complex behavior in whitecapping dissipation and inaccuracies in parameterizing nonlinear wave-wave energy transfers. Future work focusing on further improving these physics should lead to even better TC wave field predictions; in particular in the highest wind regions and weak side of TCs. The spatial distribution of the surface wave field was directly related to the spatial distribution of the wind speed. As found in previous studies, a good representation of the TC wind velocities is essential for the prediction of surface wave fields [e.g. Tolman and Alves, 2005; Roland and Ardhuin, 2014]. Liu et al. [2007] found the prediction of the surface wave fields in the initial period of a TC can be improved by merging the background wind field into the TC wind field, but the effects on the maximum significant wave height in the domain were limited. However, this study showed that the presence of the background winds during a TC can be responsible for additional wind energy input, and this extra energy can both enhance the swell waves generated by the TC and increase the area over which a TC impacts.

While the radial decay of the waves away from the TC center can be described by an exponential function like Eq. (6), we found the fitting coefficients vary for each TC and for different directions (quadrants). With an accurate representation of U_{10} , U_{TC} and R_{max} as input into the parametric model by Young and Vinoth [2013] generally resulted in a good spatial radial decay pattern. However, TCs with a long lifetime generated surface wave conditions that were more energetic than predictions based on Young and Vinoth [2013]. Under these conditions, mature waves developed over a large area, interacting with younger waves after the TC translation speed increased. The combined effect of this interaction with additional wind energy input outside the typical TC-influenced radius, led

to extremely high $H_{s,max}$ values (> 20 m) and an extremely large spatial extent ($> 20 R_{max}$) of the TC generated surface wave field during TC Lua. Here, the spatial extent was verified by observations, but a lack of observations close to the TC track at maximum intensity prevented verification of the highest modeled $H_{s,max}$ values. This has implications for extreme value design criteria that generally rely on synthetic TCs (e.g. constant TC translation speed and direction and intensity) and neglect background wind- and wave fields, which may also cause maximum values to be underestimated.

In agreement with Liu et al. [2007], the asymmetry of the surface wave field increased with both TC intensity and propagation speed. A comparison of the inverse wave age for both slow and fast translation stages during TC Lua illustrated this increased asymmetry. The position of the TC track with respect to the continental shelf affected the spatial pattern of the wave field. For TCs Bianca and Christine that predominantly moved over the continental shelf, waves were dissipated more rapidly in the left (relatively shallow) quadrants. TC Nicholas moved in a similar direction as TC Bianca, but was off the continental shelf in relatively deep water and therefore did not show comparable dissipation in the left quadrants. These results clearly show that the effects of the wind speeds outside the typical TC influenced radius can have a large influence on the spatial distribution of the resulting wave fields.

In the areas adjacent to where TCs made landfall, the effects of bottom friction were relatively small compared to local whitecapping dissipation; however, further away from the TC track, bottom friction became efficient in dissipating wave energy in depths less than 50 m, thereby reducing the wave energy that reached the coastal zone. Only during TC Lua, when $H_{s,max}$ on the shelf was much higher than during other TCs, was a substantial reduction of wave energy due to bottom friction ($>20\%$) observed in depths between 50 and 100 m from. In a relatively small region, that experienced highest wind speeds on the strong side of TC Lua, depth-limited breaking was an important dissipation term for depths < 50 m. These effects became most apparent when comparing the wave energy that reached the coastal zone during TC Lua with TCs Nicholas and Bianca, both moving parallel to the isobaths but predominantly over deep and shallow waters, respectively. Modeled H_s values were similar at the 200 m isobaths, but more energy was dissipated due to bottom friction on the shelf during TC Nicholas. This effect of the shelf acting as a zone that effectively limits the amount of wave energy reaching the coastal region corresponds well with swell wave attenuation on a wide continental shelf observed by Ardhuin et al. [2003]. With the exception of TC Lua, depth-limited was only important in very shallow water (depth < 10 m) during the TCs and could therefore mostly be

neglected. In general, results from our study indicate that bottom friction attenuated less wave energy near the TC center as younger waves with higher frequencies in this region were less affected by bottom friction.

When evaluating the TC wave energy balances across the scale of the whole NWS, bottom friction was an important factor that regulated the amount of energy that reached the coastal zone. However, energy dissipation on the broader shelf region was still mostly dominated by whitecapping and, even in very shallow water (depths around 20 m), whitecapping dissipation and frictional dissipation were often of the same order of magnitude. Only during TC Lua did depth-limited wave breaking make a contribution to the total energy dissipation in greater depths up to 50 m, because of the much larger waves on the shelf (H_s reaching over 15 m at a depth of 50 m) during TC Lua compared to other TCs. Refraction did not substantially increase or decrease the amount of wave energy that reached the coastline on a large scale; however, the orientation of isobaths with respect to the wave direction created local areas with enhanced or reduced wave energy.

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Tables

Name	Date	$H_{s,max}$ (m)	T_p (s)	θ_p (°)	U_t (m s ⁻¹)	θ_t (°)	r/R_{max} (-)
Frank	9 Dec 1995, 16:00	7.1	12.5	3	4.6	25	-
Gertie	21 Dec 1995, 10:00	3.0	5.7	211	3.4	74	-
Jacob	4 Feb 1996, 4:00	6.7	10.5	79	5.7	43	-
Olivia	10 Apr 1996, 7:00	11.3	13.3	324	7.8	338	-
Phil	30 Dec 1996, 19:00	3.4	8.7	65	3.8	67	-
Tiffany	27 Jan 1998, 10:00	7.2	11.1	59	4.4	83	-
Billy	4 Dec 1998, 10:00	4.6	8.7	46	1.4	43	-
Vance	21 Mar 1999, 7:00	8.1	12.5	6	6.5	13	-
Gwenda	7 Apr 1999, 10:00	4.7	9.5	87	7.7	326	-
Steve	6 Mar 2000, 16:00	4.7	8.7	230	2.9	53	-
Inigo	7 Apr 2003, 19:00	4.6	10.5	325	6.2	337	1.8
Monty	29 Feb 2004, 01:00	6.5	9.5	85	2.8	43	1.2
Willy	11 Mar 2005, 22:00	3.5	9	347	5.1	60	13.8
Clare	9 Jan 2006, 01:00	3.3	10	64	4.3	34	4.1
Daryl	21 Jan 2006, 10:00	4.2	8.7	283	2.6	67	0.2
Emma	28 Feb 2006, 4:00	3.8	9.1	16	6.3	351	0.4
Glenda	30 Mar 2006, 4:00	6.5	11.1	227	5.4	16	1.8
Hubert	6 Apr 2006, 16:00	5.9	8.7	359	3.4	25	2.5
Melanie	29 Dec 2007, 16:00	4.8	10.5	34	5.1	73	7.3
Nicholas	18 Feb 2008, 7:00	5.9	10.5	307	2.9	55	7.2
Ophelia	3 Mar 2008, 22:00	3.0	9.1	28	5.1	78	-
Billy	25 Dec 2008, 10:00	3.6	10.5	30	5.8	129	12.5
Dominic	26 Jan 2009, 01:00	3.2	7.1	62	4.9	29	0.7
Laurence	21 Dec 2009, 23:00	3.0	7.7	246	1.3	9	24.1
Bianca	26 Jan 2011, 16:00	6.7	10.5	90	7.1	72	0.9
Dianne	17 Feb 2011, 20:00	4.5	11.8	296	3.6	16	16.6
Carlos	22 Feb 2011, 19:00	4.8	9.1	282	6.8	51	10.2
Iggy	27 Jan 2012, 7:00	5.3	13.3	312	4.5	317	8.9
Lua	15 Mar 2012, 19:00	5.1	9.1	94	7.2	294	11.9
Christine	30 Dec 2013, 12:00	3.9	7.1	91	4.2	43	4.0

Table 1: Characteristics of TCs impacting NRA between 1995 and 2013 at the moment of maximum observed significant wave height at NRA. The observed significant wave height, peak period and peak wave direction at NRA at the observed time are shown. The storm speed U_t and the storm direction θ_t are the speed and nautical direction of the TC at the indicated time. r/R_{max} indicates the distance r of the TC center to NRA, normalized by the radius of maximum winds according to the BOM database, if available.

Name	Duration	Lon (°)	Lat (°)	Depth	Description
NRA	Dec 1995 - Mar (discontinuous)	116.12	-19.60	125	Spectral wave data (Directional)
HPR2	Dec 2013 - Apr 2014	117.03	-18.75	372	Spectral wave data
HPR3	Dec 2013 - Apr 2014	117.04	-19.52	83	Spectral wave data
Rose	Feb 2008	116.35	-20.33	40	Integrated wave
Exmouth	Oct 2006 - Jul 2012 (discontinuous)	114.10	-21.70	100	Integrated wave
A1	Feb 2012 - Jun 2012	121.74	-16.67	40	Spectral wave data
B1	Feb 2012 - Jun 2012	121.64	-16.00	73	Spectral wave data

Table 2: Overview of available in situ wave data.

	U_{10} Skill	U_{10} RMSE (m s ⁻¹)	U_{10} Bias (m s ⁻¹)	H_s Skill	H_s RMSE (m)	H_s Bias (m)
TC Nicholas						
NRA	0.72	1.83	-0.64	0.96	0.47	-0.12
Rose				0.82	0.59	-0.48
EXM				0.73	1.08	0.37
TC Bianca						
NRA	0.89	3.08	1.69	0.94	0.89	0.69
TC Lua						
NRA	0.91	2.4	1.5	0.79	1.15	0.93
A1	0.86	3.7	2.0	0.96	0.55	0.09
B1				0.95	0.90	0.62
TC Christine						
NRA	0.90	4.0	1.4	0.94	0.47	-0.07
HPR2	0.91	3.0	1.6	0.97	0.50	-0.35
HPR3	0.91	3.6	2.2	0.98	0.46	-0.20

Table 3: Model skill, root-mean-square error and bias for wind speeds U_{10} and wave height H_s for TCs Nicholas, Bianca, Lua and Christine calculated over a 72 hours period around time of $H_{s,max}$.

TC name	b_{left}	b_{right}	b_{front}	b_{rear}	b_{total}
Nicholas	-0.52 ± 0.13	-0.43 ± 0.11	-0.40 ± 0.09	-0.49 ± 0.09	-0.47 ± 0.11
Bianca	-0.87 ± 0.05	-0.58 ± 0.19	-0.52 ± 0.04	-0.85 ± 0.12	-0.66 ± 0.21
Lua	-0.44 ± 0.11	-0.48 ± 0.14	-0.53 ± 0.11	-0.50 ± 0.11	-0.48 ± 0.12
Christine	-0.95 ± 0.04	-0.65 ± 0.12	-0.72 ± 0.12	-1.06 ± 0.12	-0.75 ± 0.18
Total	-0.51 ± 0.15	-0.51 ± 0.16	-0.56 ± 0.17	-0.59 ± 0.22	-0.54 ± 0.18
	c_{left}	c_{right}	c_{front}	c_{rear}	c_{total}
Nicholas	-0.67 ± 0.25	-0.52 ± 0.15	-0.48 ± 0.18	-0.60 ± 0.21	-0.58 ± 0.21
Bianca	-1.29 ± 0.08	-0.63 ± 0.45	-0.60 ± 0.06	-1.04 ± 0.30	-0.77 ± 0.44
Lua	-0.49 ± 0.20	-0.51 ± 0.33	-0.64 ± 0.25	-0.52 ± 0.22	-0.53 ± 0.26
Christine	-0.99 ± 0.06	-0.94 ± 0.36	-1.15 ± 0.33	-1.39 ± 0.28	-1.11 ± 0.37
Total	-0.63 ± 0.27	-0.61 ± 0.34	-0.79 ± 0.40	-0.72 ± 0.36	-0.68 ± 0.35

Table 4: Radial decay fitting coefficients c from Eq. (6) for all TCs in four directions.

Figures

Figure 1: The study domain of the North West Shelf (NWS) of Australia. Bathymetry contours for the 50, 100, 200 and 500 m isobaths are denoted by the black solid lines. The tracks of TCs affecting NRA (denoted by the *) between 1995 and 2013 are plotted as thin blue solid lines.

Figure 2: Histograms of wave parameters measured at NRA over the period 1995-2012 showing: a) significant wave height H_s ; b) wave directional spreading at peak period; c) peak period T_p ; d) peak wave direction (nautical convention). e) and f) show the peak period and peak direction as in c) and d), but restricted to only high wave conditions defined as $H_s > 3$ m.

Figure 3: Peak direction (nautical) and magnitude of $H_{s,max}$ at NRA for all TCs in

Table 1. Circles indicate the magnitude of $H_{s,max}$ and the red line marks the orientation of the local isobath.

Figure 4: Map of the wave measurement sites (denoted by the *'s) with bathymetry contour lines. The tracks of TC Nicholas, TC Bianca, TC Christine, TC Lua are plotted, where the color of the cyclone tracks indicates the local maximum wind speed according to the BOM database.

Figure 5: Proportion of TC lifetime spent a) at a specific water depth range (position of TC center); b) moving at a specific translation speed (U_{TC}); c) with a specific maximum wind speed ($U_{10,max}$); d) with a specific radius to maximum winds (R_{max})

Figure 6: Time series of modeled and observed significant wave height at NRA during a) TC Nicholas, b) TC Bianca), c) TC Lua and d) TC Christine.

Figure 7: Modeled versus observed significant wave height at NRA during a) TC Nicholas, b) TC Bianca), c) TC Lua and d) TC Christine.

Figure 8: Observed (red) and modeled (blue) normalized wave energy spectra for TCs Nicholas (a), Bianca (b), Lua (c) and Christine (d) at NRA (a,b,c) and HPR3 (d) at the time when the peak $H_{s,max}$ was observed (Table 1). Each spectrum is normalized by its peak value.

Figure 9: Wind speed and significant wave height at 18 Feb 2008 (06:00) during TC Nicholas. *a)* The spatial distribution of the modeled wind speed, where the black line indicates the track of TC Nicholas and the satellite (Jason-1) derived wind speeds are plotted on top of the modeled wind speeds. *b)* The modeled wind speed versus the satellite-derived values as a function of the distance along the satellite track (ascending from south to north). *c)* and *d)* are similar to plots *a)* and *b)* but show significant wave heights.

Figure 10: Spatial map of $1R_{max} \times 1R_{max}$ bin-averaged values of U_{10} (left), H_s (center) and inverse wave age (right) for TCs Nicholas, Bianca, Lua and Christine. U_{10} and H_s are normalized by the maximum U_{10} and H_s for each TC, and the values in each bin are averaged over the duration of the TC. The coordinate x is positive towards the right side of the TC and negative towards the left, while y is positive in front of the TC and negative for the rear. Empty cells indicate a lack of data due to a land mass. In the right column, dashed lines denote the separation between wind driven seas and mixed seas, while the dash-dotted line denotes the separation between mixed seas and wave driven (swell) seas. The dotted line denotes the separation between positive and negative values. Negative values indicate wind directions opposite to wave directions.

Figure 11: Time-averaged spatial distribution of H_s per cross-section and TC from the best fit of SWAN simulations to Eq. (6) (Table 4). H_s was normalized by the maximum H_s within each direction and TC. Error bars indicate the time-averaged $H_s/H_{s,max}$ and standard deviation per $0.5r/R_{max}$ bin from the SWAN simulations. Blue lines show the spatial distribution towards the left ($-r/R_{max}$) and right (r/R_{max}) with respect to the TC translation direction. Red lines show the spatial distribution towards the front ($-r/R_{max}$) and rear (r/R_{max}) with respect to the TC translation direction. Included on each plot are the spatial distributions predicted from the parametric model of Young and Vinoth [2013] and the suggested exponential function in Wang et al. [2005] [Eq. (6)], which are plotted as dash-dotted and dashed lines, respectively.

Figure 12: Maximum modeled H_s as a function of U_{TC} and $U_{10,max}$ for all TCs in deep water (depth > 200 m), where triangles indicate TC Nicholas, circles TC Bianca, squares TC Lua, and diamonds TC Christine. Dashed and dash-dotted lines, respectively, show contour lines for the relationship between $H_{s,max}$ and U_{TC} as a function of $U_{10,max}$, and the line with $c_g = U_{TC}$ following Young and Vioth [2013] is for the case of $R_{max}=30$ km.

Figure 13: Spatial map of $1R_{max} \times 1R_{max}$ bin average of the inverse wave age for TC Lua when a) TC Lua was moving relatively slowly ($U_{TC} < 5 \text{ m s}^{-1}$) and b) moving relatively fast ($U_{TC} > 5 \text{ m s}^{-1}$).

Figure 14: Overview of wave energy generation and absolute values of dissipation terms on the NWS, normalized by the total energy propagation, showing TCs Nicholas, Bianca, Lua and Christine. Values were depth bin-averaged using a bin-width of 5 m and normalized by the total wave energy (E_{tot}). Error bars denote the standard deviation, while the solid lines denote the average values for a) Total energy generation due to wind (S_{wind}) minus total energy dissipation (S_{tot}); b) total energy generation due to wind; c) dissipation due to bottom friction (S_{fric}); d) dissipation due to whitecapping (S_{wcap}).

Figure 15: Spatial variability in the effects of bottom friction showing the difference in maximum H_s for each cell between the default model run and a run with bottom friction turned off for a) TC Nicholas, b) TC Bianca, c) TC Lua and d) TC Christine. The difference in $H_{s,max}$ ($\Delta H_{s,max}$) normalized by $H_{s,max}$. Solid black lines represent the isobaths at 200 m and 50 m, and the thick magenta lines show the TC tracks.

Figure 16: Spatial variability in the effects of bottom friction and depth limited breaking, showing the relative amount of dissipation due to a) bottom friction and by b) depth-limited wave breaking during TC Lua. Dissipation values at $H_{s,max}$ for each cell were normalized by the total dissipation. Solid black lines represent the isobaths at 200 m and 50 m, and the thick magenta lines show the tracks of TC Lua.

Figure 18: Directional wave spectra during TC Christine, averaged for the left forward quadrant (top row), left rear quadrant (second row) along a coast-normal transect with decreasing depth from left to right. Likewise for right forward quadrant (third row) and right rear quadrant (bottom row), but along a coast-normal transect with increasing depth from left to right. Locations on the left side from left to right are (120.41 °E, 17.48° S); (120.66 °E, 17.83 °S); (121.36 °E, 17.73 °S); (121.76 °E, 18.37 °S), locations on the right side from left to right are (117.07 °E, 19.07 °S); (117.26 °E, 19.42 °S); (117.40 °E, 19.96 °S). Dashed and solid circles indicate the frequencies (0.04 – 0.2 Hz), where the first dotted circle corresponds to a frequency of 0.1 Hz. The circles also scale with the TC propagation speed (white dot) and wind speed (black dot), where the first dashed circle corresponds to $U_{TC} = 2 \text{ m s}^{-1}$ and $U_{10} = 10 \text{ m s}^{-1}$. The size of the white markers represents the radius of maximum winds (R). The magenta line indicates the orientation of the local isobath. Average relative distance to the TC center and wave height are shown in all subplots.

Figure 19: Spatial patterns of the relative importance of wave refraction, showing the difference in maximum H_s for each cell between the default model run and a run with refraction turned off for a) TC Nicholas, b) TC Bianca, c) TC Lua and d) TC Christine. Solid black lines represent the isobaths at 200m and 50m and the thick magenta lines show the TC tracks.

Figure 20: Response of refracted wave energy E_θ on the NWS normalized by the total wave energy for each TC. Values were depth bin averaged using a bin-width of 5 m. Error bars indicate the standard deviation, while the solid lines show the average values.