SPECTRAL ANALYSIS OF STORM-INDUCED WAVES BY CYCLONE ASHOBAA IN ARABIAN SEA AND GULF OF OMAN

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Extensive field measurements along the north coast of the Gulf of Oman are analyzed to study the spectral characteristics of the generated waves of Ashobaa along the path of cyclone. The data showed a maximum significant wave height of about 3.2 meters on Iranian coasts. MLMST algorithm was used to process the directional wave. The measured wave spectra were bimodal (or trimodal) when the cyclone was far from the measuring stations. Approaching closer to the stations, the waves turned to unimodal spectra, with the highest measured wave energies at the time of minimum distance between the cyclone eye and the stations. Wave spectrum became bimodal again at the time of landfall, including the local seas and swell waves of the cyclone. After dissipation of the cyclone, swell waves dominate resulting in unimodal wave spectra. Study of 2D wave spectra reveals that minimum values of directional spreading correspond to peak frequencies.

Keywords: Field Measurements; Cyclone Ashobaa; Gulf of Oman; Wave Spectrum

INTRODUCTION

Tropical cyclones (TCs), resulting in huge waves and high storm surges, are among the most devastating natural hazards of the world. The highest recorded TC generated waves exceed 30 m for hurricane Luis. However, Gonu was the most intense TC on record in the Arabian Sea with the maximum wave height of about 6 m. Waves are more complicated during the passage of TCs due to different influencing factors such as local winds and travelling swell waves.

2D directional wave measurements can be employed for the analyses of complex wave fields. Different instruments, including airborne scanning radar altimeters (Walsh et al., 2002; Wright et al., 2001) and directional wave buoys (Esquivel-Trava et al., 2015; Young, 2006), are utilized for directional measurements of the spectral waves. Various spectral partitioning techniques have been proposed to identify individual wave systems (partitions) in the time series of 2D-wave spectra.

Wright et al. (2001) found the highest and longest (swell) wave in the right forward and the lowest one in the left rear quadrant of the hurricane Bonnie in open ocean. In another research, they reported similar spectral behavior of the TCs waves in open ocean and close to the locations of landfalls (Walsh et al., 2002) and concluded that these waves can be reproduced by simple parameters such as maximum wind speed, the radii of maximum and gale-force winds, and the recent motion of the eye. Moon et al. (2003) simulated hurricane Bonnie and studied wave spectra along different sections toward the coastline, noting that the TCs generated waves are significantly characterized by the radius of maximum wind and hurricane translation speed.

Young (2006) reported that the shape of directional wave spectra is affected by non-linear wave interaction between lower frequency swells and higher frequency seas, while the energy of wave field is significantly determined by input and dissipation. Kennedy et al. (2011) pointed out that while TCs are approaching to the coastal zones, much flatter and sometimes multi-peaked spectra appears. After the landfall, a sharply peaked form is generated on the strong (right) side and the broader part, with often multiple peaks, belongs to the weak (left) side of TCs.

Studying fourteen hurricanes with four directional buoys, Esquivel-Trava et al. (2015) concluded that unimodal spectrum is observed at the vicinity of the TCs, but bimodal and trimodal spectra are more frequent by distancing the TCs in front or rear sides.

Hu and Chen (2011) studied seven hurricanes using the data of 14 buoys. They reported four different types of bimodal spectra as distinct features of swells and local wind seas, bimodal in frequency with very different direction, bimodal in frequency with two close peaks in similar mean wave direction, and shallow water waves that are highly affected by the coasts.

Young (2017) parameterized TCs wave spectrum at different sides of TCs, using 30 years of measurements. Employing well-known parametric models, he concluded that these models are suitable for the waves with an extended fetch and suggested to utilize 3rd generation wave models to characterize more complex cases.

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Analyzing the simultaneous wave measurements along the north coast of the Gulf of Oman, the present study offers the temporal and spatial characteristics of measured wave spectra during cyclone Ashobaa. The data were adopted from the field measurements in 2015.

STUDY AREA AND FIELD MEASUREMENTS

Cyclone Ashobaa formed on June 6, 2015 as a deep depression over the Arabian Sea at (14.5° N, 68.5° E). It further upgraded to a cyclonic storm on June 8 while approaching to (21.3°N, 62.1°E). Its intensity was retained for the next two days and then weakened before making landfall on eastern coasts of Oman at (20.8°N, 59.5°E).

Starting from August 2006, a large project of “monitoring and modeling studies” is performing along the Iranian coasts by the Iranian Ports and Maritime Organization (PMO). The extensive field measurements program includes tide, wave and current measurements at different stations, disturbed and undisturbed sediment sampling, suspended sediment measurements, coastline change monitoring, and beach profile surveys along the shoreline. Eight Acoustic Doppler Current Profilers (ADCPs) were installed along Makran coasts in south of Iran, among which five ADCPs simultaneously recorded the induced waves and currents during the passage of Ashobaa (Fig. 1). Considering the track of Ashobaa in Fig. 1, it is observed that all stations are located in the right (strong) side of the cyclone.

Table 1 presents the location of the employed instruments and their installation depths. The Nortek ADCPs include two Aquadopps and three AWACs, equipped with AST (Acoustic Surface Tracking) system. This vertically oriented transducer in the center of the AWAC directly measures the distance to the sea surface by a simple echo sounder, which allows for both time series and spectral analysis. MLMST (Maximum Likelihood Method with Surface Tracking) was used for the processing of measurements, which provides better directional estimates than just the purely velocity based solution.

The induced spectral waves are examined at four times during the propagation of the cyclone. The selected times are June 9 when the cyclone was approaching to the north coastline of the Gulf of Oman but not enough close to the stations, June 10 with the minimum distance between the cyclone eye and measurement stations, the time of cyclone landfall in June 12, and post-landfall decay in June 20.

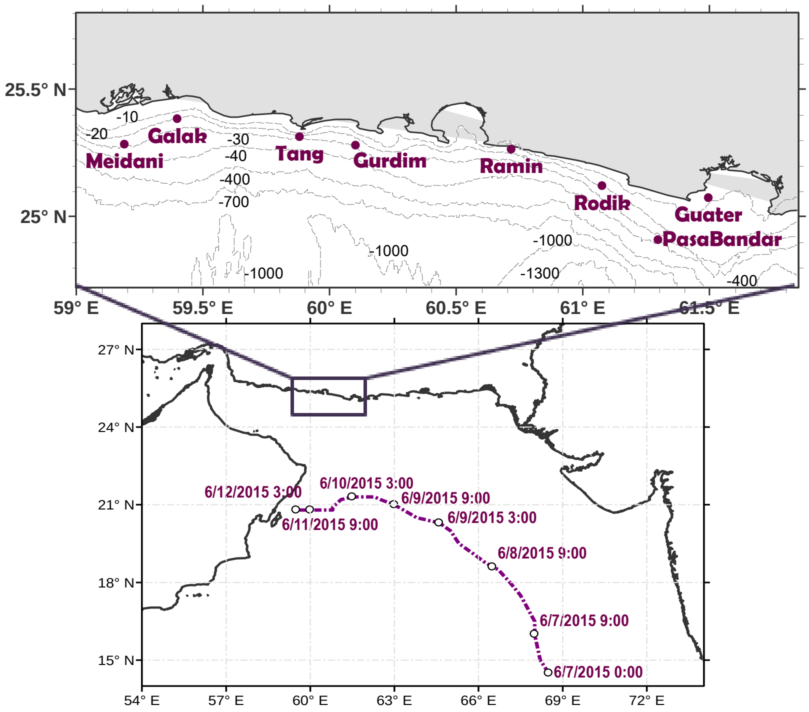

Figure 1. Field measurement stations (top) and the track of cyclone Ashobaa (bottom)

Table 1. Details of measurement stations

Station	Instrument	Installation depth (m)	Lat (°)	Lon (°)
Guater	Aquadopp	10	25.075	61.496
PasaBandar	AWAC	40	24.910	61.297
Rodik	AWAC	25	25.122	61.077
Ramin	AWAC	25	25.266	60.718
Gurdim	Aquadopp	10	25.346	60.104

RESULTS AND DISCUSSION

Fig. 2 shows the measured wave parameters at all stations. It is observed that Guater experienced the highest waves along the Iranian coastlines, up to about 3.2 meters. The peak periods show a smooth decrease from the stage of formation of Ashobaa to its landfall. Approaching the cyclone to the measurement stations, the dominated waves gradually convert from swells to seas. The cyclone generated swell waves can be distinguished by the sudden increase of peak period on June 9. The mean wave periods, on the other hand, show limited variations in this area within the range of seas. It is observed that the variation of mean wave direction is considerable during the passage of cyclone, which can be related to the changes of the cyclone location along its track. After the landfall, the mean direction is fixed on about 180 degrees, which is the direction of incoming swell waves from the north and south Indian Ocean.

Figure 2. Time series of measured wave parameters during passage of Ashobaa.

Fig. 3 depicts 2D directional wave spectra at different stations on selected times. As the cyclone induced waves are not dominated on June 9, wave energy is distributed over wide ranges of frequencies and directions. The lowest directional spreading, as well as the highest wave energy, can be found on June 10, when the cyclone was at the closest distance from the stations. It is observed that the wave spectra are highly dominated by the energy of cyclone waves. Directional spreading is maximized on June 12 and 20, at the time of landfall and passing over the land, with a lower frequency band on June

20. It is also observed that the peak wave energies decrease when the right rear quadrant faces the shelf of Iran, i.e. June 12. After the storm landfall, peak frequencies persist in the range of swell waves.

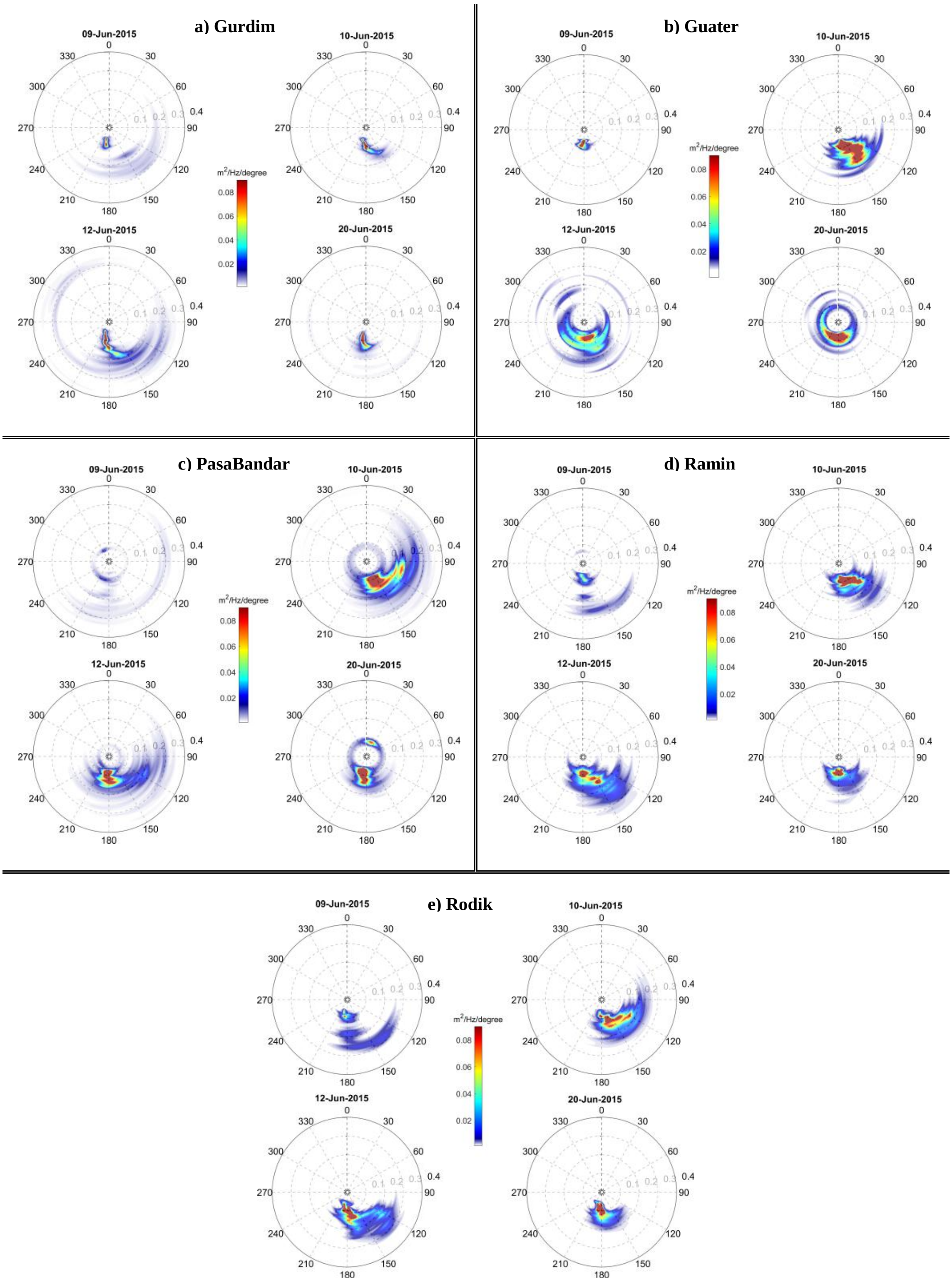

Figure 3. Directional spectra of all measurement stations during passage of Ashobaa

Figs. 4 and 5 show the developments of wave spectra, mean directions and directional spreading at different stations during cyclone propagation (June 9 and June 10) and after the storm (June 12 and

June 20), respectively. Bimodal and trimodal spectra are observed in June 9, representing both sea and swell waves. When the cyclone got closer to the stations on June 10, a wideband single peak spectrum was formed. The maximum recorded wave energy corresponds to the lowest distance with the cyclone eye (Fig. 1). Similar behavior have been reported in other basins, where swell dominated waves were observed in all quadrants of the tropical storms (Hu and Chen, 2011; Young, 2006).

Figs. 4 and 5 also present the variations of mean wave directions versus frequencies during and after the passage of Ashobaa. An overall decrease of the mean direction by the increase of wave frequency is observed for the frequency range of 0.1-0.3 Hz, i.e. mostly wind waves. High fluctuations of mean wave direction is observed at Guater, particularly after the cyclone landfall.

The measurement stations were in the rear side of cyclone at the time of cyclone landfall on June 12. Thus, a considerable decrease of peak energy can be observed, comparing wave spectra on June 10 (Fig. 4) and June 12 (Fig. 5). The wave spectrum changed to bimodal, with two close peak frequencies, at the time of cyclone landfall. It is also observed that the lowest directional spreading corresponds to maximum recorded energy, i.e. Guater. After the landfall, the wave energy is mostly dominated by swell waves (see Fig. 5 on June 20). Fig. 4 also confirms the higher concentration of the wave energy in Guater. The differences of directional spreading are minimum on June 10, when the cyclone eye is at the minimum distance with the stations. A rather large scatter of directional spreading exist in the observations of all stations, with the minimum values at peak frequencies. The data shows that cyclone was more effective on the stations with lower wave energy. The directional spreading considerably increases at Gurdim, with the lowest peak wave energy, after Ashobaa enters the land.

The privilege of swell waves on June 12 can be attributed to the very slow motion of the cyclone as the lower translation speed generally allows more time to individual waves to propagate. However, local wind waves, with lower energies comparing to the swell waves, also contribute in the wave spectra. It should be noted that the frequencies of seas on June 9, when the cyclone was far away from the stations, were much higher than those on June 12.

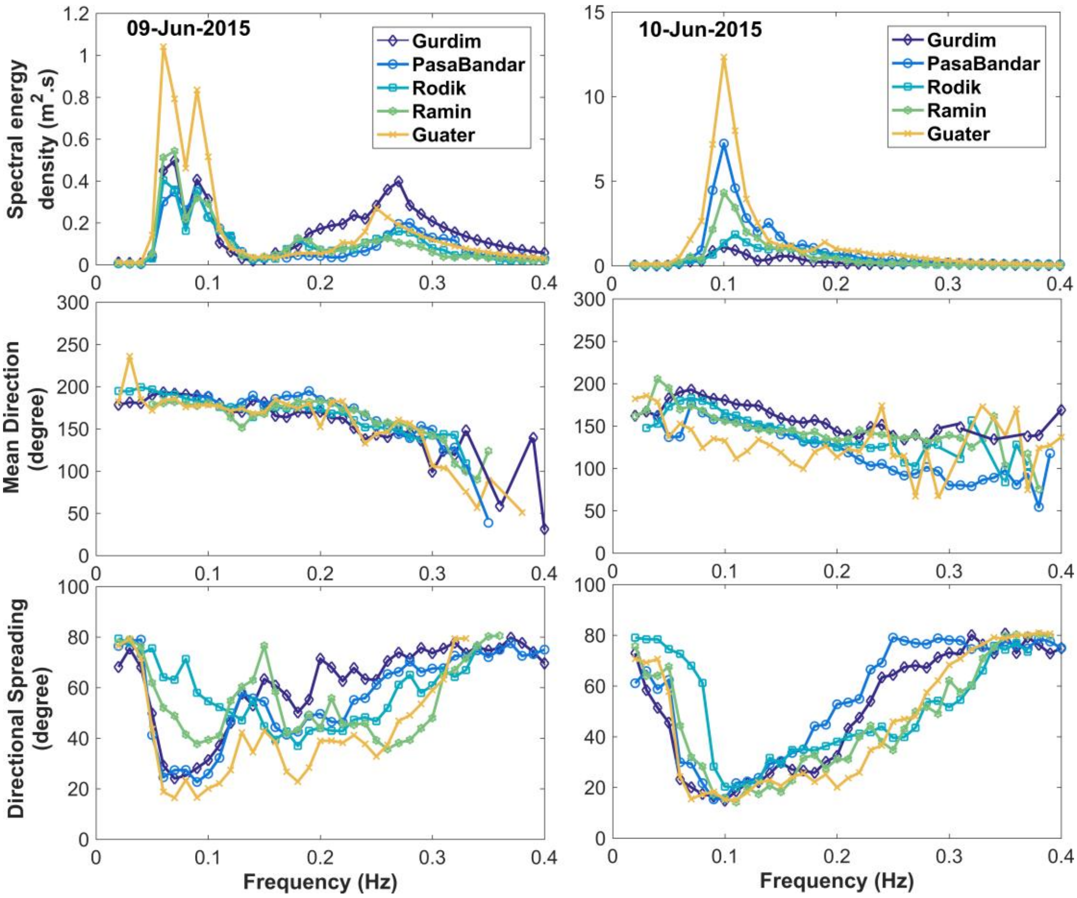

Figure 4. Spectral energy density (top), mean direction (middle), and directional spreading (bottom) of waves along Iranian coastlines during passage of Ashobaa

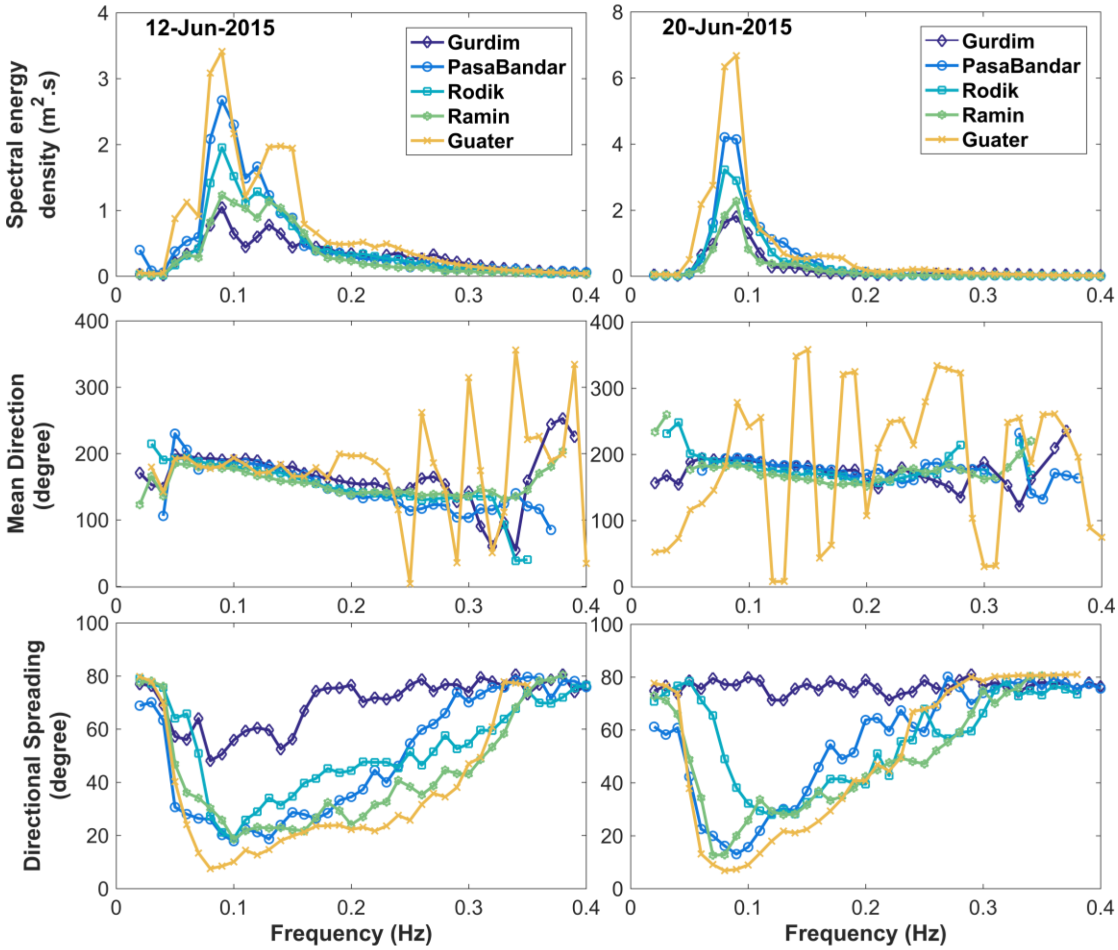

Figure 5. Spectral energy density (top), mean direction (middle), and directional spreading (bottom) of waves along Iranian coastlines after landfall of Ashobaa

SUMMARY AND CONCLUSION

Cyclone Ashobaa was generated on June 6, 2015 and made landfall on June 12 on Omani coastline. A number of installed ADCPs simultaneously recorded the wave and current data along the Iranian coastlines during the passage of Ashobaa, where their measurements were utilized to study the spectral characteristics of induced waves.

The wave spectrum is either bimodal or trimodal when the cyclone is far away from the stations, which reveals the combination of cyclone induced swell waves and local wind waves. Seas become dominant when the cyclone eye locates at the minimum distance of the measuring stations, resulting in unimodal spectra. The maximum energy of the spectrum is observed as the stations were located on the right front side of the cyclone. Wave spectrum became bimodal at the time of landfall, consisting of swell waves of the cyclone and local seas.

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REFERENCES

Esquivel-Trava, B., Ocampo-Torres, F.J., Osuna, P., 2015. Spatial structure of directional wave spectra in hurricanes. *Ocean Dyn*. 65, 65–76. https://doi.org/10.1007/s10236-014-0791-9

Hu, K., Chen, Q., 2011. Directional spectra of hurricane-generated waves in the Gulf of Mexico. *Geophys. Res. Lett*. 38, 1–7. https://doi.org/10.1029/2011GL049145

Kennedy, A.B., Gravois, U., Zachry, B.C., Westerink, J.J., Hope, M.E., Dietrich, J.C., Powell, M.D., Cox, A.T., Luettich, R.A., Dean, R.G., 2011. Origin of the Hurricane Ike forerunner surge. *Geophys. Res. Lett*. 38, n/a-n/a. https://doi.org/10.1029/2011GL047090

Moon, I.-J., Ginis, I., Hara, T., Tolman, H.L., Wright, C.W., Walsh, E.J., 2003. Numerical Simulation of Sea Surface Directional Wave Spectra under Hurricane Wind Forcing. *J. Phys. Oceanogr*. 33, 1680–1706. https://doi.org/10.1175/2410.1

Walsh, E.J., Wright, C.W., Vandemark, D., Krabill, W.B., Garcia, A.W., Houston, S.H., Murillo, S.T., Powell, M.D., Black, P.G., Marks, J.D., 2002. Hurricane directional wave spectrum spatial variation at landfall. *J. Phys. Oceanogr*. 32, 1667–1684. https://doi.org/10.1175/1520-0485(2002)032<1667:HDWSSV>2.0.CO;2

Wright, C.W., Walsh, E.J., Vandemark, D., Krabill, W.B., Garcia, A.W., Houston, S.H., Powell, M.D., Black, P.G., Marks, F.D., 2001. Hurricane directional wave spectrum spatial variation in the open ocean. *J. Phys. Oceanogr*. 31, 2472–2488. https://doi.org/10.1175/1520-0485(2001)031<2472:hdwssv>2.0.co;2

Young, I.R., 2017. A review of parametric descriptions of tropical cyclone wind-wave generation. *Atmosphere* (Basel). 8. https://doi.org/10.3390/atmos8100194

Young, I.R., 2006. Directional spectra of hurricane wind waves. *J. Geophys. Res. Ocean*. 111. https://doi.org/10.1029/2006JC003540