Response to the comments of Reviewer 1:

Generally, this work presents an impressive data set spanning 5 years. The data appear largely to be a new contribution to the literature, and if so, should qualify the work for publication as a case study. Having recognized that, there are several concerns with potential to change this assessment.

1) It appears that a significant portion of this data may have been published elsewhere.
For example, here: Glejin, J., Sanil Kumar, V., Amrutha, M.M. and Singh J., Characteristics of long-period swells measured in the in the near shore regions of eastern Arabian Sea, Int. J. Naval Architecture and Ocean Engineering, 8, 312-319, 2016.

Reply: From the wave data collected for two years period (2011 and 2012) at the study location, swells of period more than 18 s and significant wave height less than 1 m were separated and used to study the characteristics of low-amplitude long-period swells by Glejin et al. (2016). Glejin et al. (2016) presented the wave characteristics of low-amplitude long-period swells which occur for 1.4 to 3.6% of the time in a year. Statistics presented in Glejin et al. (2016) is different than that presented in this paper. Study on wave spectral shape and the interannual variations over a period of 5 years for this location has not been attempted so far. This information is now added in the revised paper.

2) Why is the broader-context not communicated? It seems peculiar that several existent publications by the authors use verbatim text describing the area, methods and motivation, as well as the same analysis techniques and products, but those works are referenced only narrowly in regard to specific details. For example, data collected over nearly the same period of record (March 23, 2010 to November 6, 2014) only a few kilometers up the coast, and with essentially the same analysis is reported here:

Anjali Nair, M. & Kumar, V.S., Spectral wave climatology off Ratnagiri, northeast Arabian Sea, Nat Hazards (2016) 82: 1565. doi:10.1007/s11069-016-2257-5

These publications share significant portions of text and techniques:
Glejin, J., Sanil Kumar, V., Sajiv, P.C., Singh, J., Pednekar, P., Ashok Kumar, K., Dora, G.U., and Gowthaman, R., Variations in swells along eastern Arabian Sea during the summer monsoon, Open J. Mar. Sci., 2 (2), 43–50, 2012.

Glejin, J., Sanil Kumar, V., Amrutha, M.M. and Singh J., Characteristics of long-period swells measured in the in the near shore regions of eastern Arabian Sea, Int. J. Naval Architecture and Ocean Engineering, 8, 312-319, 2016.

Indeed, there appears to be such a plethora of work in the area that a recent compendium was published:

P. Vethamony, R. Rashmi, S.V. Samiksha, V. M. Aboobacker M, Recent Studies on Wind Seas and Swells in the Indian Ocean: A Review, The International Journal of Ocean and Climate Systems, Vol 4, Issue 1, pp. 63 - 73.

Informing the reader of the broader context in which these measurements exist, and to clarify novel differences between published work and data presented in this paper is warranted.

Reply: Earlier the above publications were referred only at appropriate places in the manuscript. Now as per suggestion of the reviewer, we have added a paragraph in the introduction to provide a broader picture of the studies carried out in the eastern Arabian Sea and to clarify the differences between published work and the data presented in this paper.

3) The expressed objective of the work is: "This study addresses two main questions: (1) How the high-frequency tail of the wave spectrum varies in different months? (2) What are the spectral parameters for the best-fit theoretical spectra?"

The first objective is questionable since the method to assess slopes of the spectral tails is not revealed. The second objective is questionable since an ad hoc method consisting of a piecewise concatenation of different theoretical spectral functions is used. Specifics of how the concatenated frequency bands are determined is not provided, nor is an assessment of the physical assumptions inherent in concatenation of these different spectra.

The authors have attempted to clarify the data with statistical analysis, but the specific methods and algorithms are not provided, a prime deficiency. If there is desire to improve understanding and interpretation of the data, some effort to connect the data/statistics to underlying physical processes could improve the publication value. For example, you have argued that "Understanding of the wave spectral shapes is of primary importance for the design of marine facilities" yet little effort is made to quantify or relate physical parameters/forcings pertaining to the change in spectral slopes/peaks.

Reply: We used the statistical curve fitting techniques to assess slopes of the spectral tail. Now we have added the below details.

An exponential curve $y = k.f^b$ is fitted for high frequency part of the spectrum and the exponent (value of b) is estimated for the best fitting curve based on statistical measures such as least square error and bias. The slope of the high-frequency part of the wave spectrum is represented by the exponent of the high-frequency tail.

Specifics of how the concatenated frequency bands are determined is now added. Now we have deleted the representation of double-peaked wave spectrum with the theoretical spectrum.

For the present study JONSWAP spectrum is tested by fitting for the whole frequency range of the measured wave spectrum. It is found out that the JONSWAP spectra do not show good fit for higher frequency range, whereas Donelan spectrum shows better fit for high-frequency range. Hence, JONSWAP spectrum is used for lower frequency range up to spectral peak and Donelan spectrum is used for the higher frequency range from the spectral peak for single-peaked wave spectrum. Theoretical wave spectra is not fitted to the double-peaked wave spectra.

Now we have also added the plots showing the variation of high frequency tail with significant wave height, mean wave period, wind speed and inverse wave age.

4) Please address the lack of consistency in precision of your statistical estimates and the lack of standard error or confidence limits. For example, wave frequencies are variously reported with precisions of 1, 2 or 3 decimal places, even in the same sentence. Slopes of the wave spectra are reported with 1 or 2 decimal point precision. Kindly adopt a uniform usage for expressing the precision of your estimates, ideally ones that reflect physically pertinent cutoffs. Please add error estimates or confidence bounds to your estimates, or address quantitatively why they are not germane.

Reply: Consistency in precision is maintained now in the text. The wave spectrum is with a resolution of 0.005 Hz from 0.025 Hz to 0.1 Hz and is 0.01 Hz from 0.1 to 0.58 Hz. It is now added.

5) You quote estimates of the slope of high-frequency portions of the wave spectra, but never define how those estimates are made.

Reply: Now it is explained as mentioned under 3.

6) You plot and describe "normalized" spectral densities, but never detail how this normalization is applied. One is then left to question whether the normalization is specific to each time period, or normalized across all periods so that direct comparisons of different years is meaningful.

Reply: Now it is added as below.
Normalisation of the wave spectrum is done to know the spread of energy in different frequencies. Since the range of maximum spectral energy density in a year is large (~ 60 m^2/Hz), each wave spectrum is normalised through dividing the spectral energy density by the maximum spectral energy density of that spectrum to understand the distribution of energy in different frequencies, specifically in the wind-sea and swell regions.

7) Line92 "The average monthly sea level at Karwar varies from 1.06 m (in September) to 1.3 m (in January)" You are apparently quoting geodetic elevations here, but there is no reference datum specified.

Reply: They are with respect to chart datum and is now added.

8) Line 100 "The data for every 30 minutes from the continuous records at 1.28 Hz are processed as one record. From the time series data, the wave spectrum is obtained through fast Fourier transform (FFT)."

My understanding of waverider spectral processing is that motion samples are recorded at a sample rate of fs = 2.56 Hz, not 1.28 Hz. The bandwidth of the spectral estimate is fs/2 = 1.28 Hz. I do not believe that the data over 30 minutes are processed as one record. In standard

Datawell processing, records of length 200 seconds are collected (N = 512 samples). 17 records are then FFT'd, windowed, and averaged with a 50% overlap to produce the 30 minute power spectral density estimate. Kindly verify your description, and if it differs from the standard Datawell spectral processing, detail and justify the differences.

Reply: We used DWR-MKIII and the sampling interval is 3.84 Hz for this system. A digital high-pass filter with a cut off at 30 s is applied to the 3.84 Hz samples. At the same time it converts the sampling rate to 1.28 Hz and stores the time series data at 1.28 Hz (Datawell, 2009). From the time series data for 200s, the wave spectrum is obtained through fast Fourier transform (FFT). During half an hour 8 wave spectra of a 200 s data interval each are collected and averaged to get a representative wave spectrum for half an hour (Datawell, 2009). These are now corrected in the paper. 2.56 Hz is correct for WR-SG. Now we have mentioned the type of buoy also to avoid confusion to the reader.

9) Line 185 - 189 Here you describe dispersion relation impacts characterizing the wave spectrum of your data, you might consider moving this information to the beginning of the section.

Reply: Moved to the beginning of the section

10) Line 268 "Contour plots of spectral energy density (normalized) clearly show the predominance of wind-seas and swells during the non-monsoon period (Fig. 9)."

Here you have apparently applied the unspecified 'normalization' to month long temporal windows of spectral density averaged over years. Is the normalization value specific to each month, or is it over the entire ensemble so that meaningful intercomparisons can be made? The normalization, as well as the averaging must be defined.

Reply: In Figure 9, each wave spectrum at 30 minutes interval is normalised through dividing the spectral energy density at each frequency by the maximum spectral energy density of that spectrum. Each normalised wave spectrum will have a maximum spectral energy density of 1. This is now explained in the paper.

Since the frequency bins over which the wave spectrum estimated is same in all years, the monthly and seasonally averaged wave spectrum is computed by taking the average of the spectral energy density at the respective frequencies of each spectrum over the specified time. Here normalisation is not done.

11) Line 281 "To study the characteristics of different wave systems, average mean wave direction and average wave spectral energy density grouped under different peak frequency bins are plotted in Fig. 10." The meaning of "wave systems" is not clear. The meaning of "average mean" is not clear.

Reply: Here the wave systems refers to wind-seas and swells approaching from different directions. Anyway this paragraph is now removed.

12) Line 281 - 294 It isn't clear to me that this section along with figures 10 and 11 provide meaningful analysis that isn't already discernible from the previous results, rather this seems like part of the exploratory data analysis and seems redundant. My recommendation is to remove this section and figures.

Reply: Figures 10 and 11 removed and the paragraph deleted.

13) Line 296 "The behavior of the high-frequency part of the spectrum is governed by the energy balance of waves generated by the local wind fields. When the wind blows over a long fetch or for a long time, the wave energy for a given frequency reaches the equilibrium range and the energy input from the wind are balanced by energy loss to other frequencies and by wave breaking."

You have argued that the change in slope is indicative of a change from local wind dominated to swell waves, a physical connection. And have recognized that the dynamic equilibrium between generation and dissipation processes are what control this slope... but fail to make any meaningful physical connection between the slope behaviour and the underlying physics. This is not required in a paper that only presents data, but you have invested some effort in quantifying the spectra, it would seem natural to attempt a physical connection to sea state, wave height, wave age, wind speed or some physical parameter.

Reply: We could not find a physical connection between the slope behaviour and the underlying physics. Slope is represented by the exponent of the high frequency tail. We have added the scatter plot between exponent of the high frequency part of wave spectrum and significant wave height, mean wave period, wave age and wind speed.

14) Line 296 - 313 This section seems to try and convey in detail a very simple observation that more energetic wave spectra have steeper high-frequency tail slopes. If this needs explanation at all, it seems it should be much simpler. Again, how the slopes are computed is not defined.

Why are slopes in table 4 and figure 12 numerically negative, yet in the text are all positive? You refer to slopes as increasing, but are they not becoming more negative?

Reply: The methodology on computation of exponent of the high-frequency tail which represents the slope is now added.

The exponent is negative. As the exponent reduces, the slope of the spectral tail increases. Now it is corrected.

15) Line 307 "It is shown in Fig. 12 that the slope also increases as the mean wave period increases."

Figure 12 presents an interesting association between high frequency wave spectra slope and monthly mean wave height, but there is only one sentence referring to it with no exploration of its physical significance. It suggests a nonlinear saturation of slope as a function of wave height. You may wish to consider the suggestion following the comments.

Reply: Added the suggested analysis at the end.

16) Line 312 "The slope of the high-frequency end of the wave spectrum becomes milder when the wave nonlinearity increases. The study shows that the tail of the spectrum is influenced by the local wind conditions."

An attempt to physically connect your observations/statistics to physical forcing.
Good. But this is unsatisfying. You are arguing that by virtue of large Hm0 alone
that nonlinearity increases? This seems speculative at best.

Reply: Now we have added a Figure showing the variation of the skewness of the sea surface elevation data with the significant wave height to show that the nonlinearity increases with increase in Hm0. The below sentences are also added.

The most obvious manifestations of nonlinearity is sharpening of the wave crests and the flattening of the wave troughs and these effects are reflected in the skewness of the sea surface elevation (Toffoli, 2006). No skewness indicates linear sea states, positive skewness value indicate that the wave crests are bigger than the troughs. Figure 10 shows that nonlinearity increases with increase in Hm0.

17) Line 315 4.3 Theoretical wave spectra

This section is very unsatisfying. How the fits to the theoretical spectra are determined is not provided, the only clue is: 'values for α and ϒ were randomly varied within a range'. That this is not explained at all is a serious deficiency.

Reply: Explanation is given above for Qn. No 3. Equations used and parameters are also explained in Section 'Data and Methods'

18) Line 317 "The monthly average wave spectra for the year 2015, is compared with JONSWAP and Donelan theoretical wave spectra."

Why was the only the year 2015 used in the monthly average wave spectra fits? Is there reason to believe that interannual variability is insignificant and can be ignored, figure 6 suggests not. How then can monthly means from one year be considered representative of the wave climate? Year 2015 is reported to have 14772 observations, while years 2011, 2012 and 2014 have 17300. How do you justify extracting mean statistics on a data set missing 15% of the data?

Reply: There was no reason for selection of 2015. Now we have used 2011 during which 99.98% of data collected.

19) Line 320 - 326 "For these months the first peak is fitted with JONSWAP spectrum and second with Donelan, and the fitted spectrum shows a good match with the measured one. In the monsoon period, the spectrum is single peaked with high spectral energy density and during this period JONSWAP spectrum is fitted up to the peak frequency and after that Donelan spectrum is used. During the months May, October and November, after the peak frequency, the measured spectrum is not smooth and hence for this part, Donelan spectrum is fitted in two parts in order to obtain the best fit."

The ad hoc piecewise fitting of spectra is unsatisfying. A uniform criteria from which spectra are fit to different portions of the data does not seem to exist. How can an adhoc scheme be deemed useful to those engaged in the "design of marine facilities"?

How does one interpret the physical basis of these piecewise spectra? Does it make physical sense to apply an ad hoc piecewise spectral concatenation? Are the essential assumptions inherent in the different piecewise spectra being satisfied?

In absence of answering these questions, an alternative approach would be to fit the different theoretical spectra over the entire frequency band, present the results, and perhaps hypothesize/speculate why the different inherent assumptions in the theoretical spectra result in different fit fidelity over the different frequency bands/environmental conditions.

Reply: We tried fitting the spectra for the entire frequency range. Since it is not matching, we have fitted JONSWAP spectra in the low frequency range upto peak frequency and the Donelan spectrum for high frequency range from peak frequency. Now we deleted the fits of rdouble-peaked spectrum.

20) Figure 3 The color bands need improvement. For example, in a) there are two yellow bands with only slightly different saturation, but widely different amplitudes. It is difficult to discern which amplitude corresponds to the sections in the plot.

Reply: Color bands changed.

21) Figure 8 Instead of scaling the ordinal axis for each plot to maximize the dynamic range of the curves, it would be more informative to have a single uniform axis for all plots with the same angular range.

Reply: Now uniform axis is made for all plots with the same range.

22) Figure 9 This is commonly referred to as a spectrogram. The amplitude scale has not been defined. No units are shown.

Reply: The amplitude scale is 'normalised spectral energy density' and hence no unit.

23) Figure 10 - recommend removing this figure and section To make figure 10 more informative for relative comparison across spectral bands, the ordinal axes should have uniform ranges, both for spectral amplitude and direction. This will allow the reader to immediately discern important differences between bands.

Reply: Figure 10 removed.

24) Figure 11 - recommend removing this figure and section Abcissal axes need labels and units.

Reply: Figure 11 removed.

25) Figure 12 Needs to explicitly label ordinates as slopes.

Reply: Corrected in figure

26) Figure 13 In contradiction to the text describing this figure, I'm unable to see where the Donelan spectrum was applied.

Reply: Now it is explained as replied under 19.

Suggested Analysis

As mentioned above, Figure 12 presents an interesting association between high frequency wave spectra slope and monthly mean wave height suggesting a nonlinear saturation of slope as a function of wave height.

The introduction contains a nice discussion of findings that quantify high-frequency slopes, both theoretically and experimentally, with substantial support that in your oceanographic setting that the expected high-frequency decay would be affine with f -4. You mention in general terms how this decay represents an equilibrium between dissipation and energy input dominated by local winds, it may be useful to think about specific processes. For example Donelan et al. (2012) find that in addition to the k-4 dissipation that swells modulate the equilibrium in breaking waves dependent on the mean surface slope, while Melville (1994) also quantified a relation between wave packet slopes and dissipation rate. These results are specific to breaking waves, but one might expect similar relations between surface dynamics and dissipation rate for non breaking waves. If you do not find existing literature pertinent to non-breaking wave dissipation, then perhaps a functional representation of the data shown in figure 12 might be useful in revealing something about the physical connection, and at the very least would provide a predictive basis relating spectral slopes with mean wave heights as a basis for future research.

To that end, you might wish to fit a function of the form: A * exp(λ Hm0) + s0, with initial parameters of A = 8, λ = -2.4, s0 = -3.7 to the data of figure 12. This is exemplified with a subset of your data below. With optimized parameter values you will then have a functional representation of your spectral slopes based on Hm0. Presumably, Hm0 along with other parameters (wavelength, wind...) may lead you or others to a hypothesis relating your spectral slopes to sea surface physics.

Reply: Thanks for the suggestion. We have added the above in the paper.

Response to the comments of Reviewer 2

All the suggested English language corrections carried out.

L42: define JONSWAP acronym. Add “field campaign” after JONSWAP.
Reply: Added

L60: add following reference: Ranjha, R., M. Tjernström, A. Semedo, G. Svensson, 2015: Structure and Variability of the Oman Coastal Low-Level Jet. Tellus A, 67, 25285, http://dx.doi.org/10.3402/tellusa.v67.2528
Reply: Added the reference

L61: define “AS” acronym. (It is defined lat- ter in the text but it should be defined the first time it is used.)
Reply: Defined

L67: You should state early in the text the monsoon, pre-monsoon, non-monsoon, etc. periods (time ranges in months) as soon as possible in the text.
Reply: Now it is stated.

L76: measured how. State where the data is from.
Reply: Modified.

L100: sentence starting with “The data. . .”is confusing. Re-write.
Reply: Modified

L110: Consider using “U10” instead of “U”. You will have to explain what you are using U10 for. You mention it here only, and then it seems that you do not use it, since it is never mentioned in the text.
Reply: Now it is mentioned.

L168 and in some other parts of the text: Are you sure it is sea breeze. By definition sea breeze is (1) a rather local feature mid-afternoon feature, and (2) from the ocean to land. I am afraid this is not the case.
Reply: Deleted.

L183: how do you know they are swells?
Reply: Based on sea swell separation.

L193: normalized by what. Please provide additional information.

Reply: Now it is mentioned.

L196: how do you separate the swells? Sentence starting with “Over an. . .” should be explained better.

Reply: It is added under data and methods. Now the sentence is corrected.

L212: why do you shift to frequency when you when talking about periods?

Reply: Now it is corrected.

L222: sentence starting with “Except. . .” is confusing. Re-write.
Reply: Corrected.

L 242: sentence starting with “Maximum. . .” is confusing. Re-write.
Reply: Corrected.

L254: what do you mean by monsoon spectra?
Reply: It is the wave spectra averaged over monsoon period. Now it is corrected.

L255: I am afraid that the idea in the sentence starting with “Interannual. . .” cannot be stated like that.
Reply: Corrected as "Interannual variations within the spectrum are more for wind-sea region compared to swell region"

L315: why this section (and the name of the section should be revised). What do you gain in adding this section? What exactly do you want to prove and add by adding the theoretical wave spectra. Where is the science here? You need to explain and defend this or else this section should be removed.

Reply: We wanted to show that with suitable modification, we can fit a theoretical wave spectrum to the measured data. The coefficients obtained in fitting the spectrum are presented in Table 4.

We have revised the manuscript considering the comments of both the reviewers.

Wave spectral shapes in the coastal waters based on measured data off Karwar, west coast of India

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Abstract

Understanding of the wave spectral shapes is of primary importance for the design of marine facilities. In this paper, the wave spectra collected from January 2011 to December 2015 in the coastal waters of the eastern Arabian Sea using the moored directional waverider buoy are examined to know the temporal variations in the wave spectral shape. Over an annual cycle, for ~~For~~ 31.15% of the time, peak frequency is between 0.08 and 0.10 Hz and the significant wave height is also relatively high (~ 1.55 m) for waves in this class. The slope of the high-frequency tail of the monthly average wave spectra is high during the Indian summer monsoon period (June-September) compared to other months and it increases with increase in significant wave height. There is not much interannual variation in slope for swell dominated spectra during the monsoon, while in the non-monsoon period, when wind-seas have much influence, the slope varies significantly. Since the exponent of the high-frequency part~~slope~~ of the wave spectrum is within the range from -4 to -3~~-4~~ during the monsoon period, Donelan spectrum shows better fit for the high-frequency part of the wave spectra in monsoon months compared to other months.

Key Words: Ocean surface waves, wind waves, Arabian Sea, wave spectrum, high-frequency tail

1. Introduction

Information on wave spectral shapes are required for designing ~~the~~ marine structures (Chakrabarti, 2005) and almost all the wave parameters computations are based on the wave spectral function (Yuan and Huang, 2012). The growth of waves and the correspondent spectral shape is due to the complex ocean-atmosphere interactions, while the physics of air-sea interaction is not completely understood (Cavaleri et al., 2012). The shape of the wave spectrum depends on the factors governing the wave growth and decay, and a number of spectral shapes have been~~are~~ proposed in the past for different sea states (see Chakrabarti, 2005 for a review). The spectral shape is maintained by nonlinear transfer of energy through nonlinear four-wave interactions (quadruplet interactions) and white-capping (Gunson and Symonds, 2014). The momentum flux between the ocean and atmosphere govern the high-frequency wave components (Cavaleri et al., 2012). According to Philips, the equilibrium ranges for low-frequency and high-frequency region is proportional to f^{-5} and f^{-4} (where f is the frequency) respectively. Several field studies made since JONSWAP (Joint North Sea Wave Project) field campaign reveals~~reveal~~ an analytical form for wave spectra with the spectral tail proportional to f^{-4} (Toba, 1973; Kawai et al., 1977; Kahma, 1981; Forristall, 1981; Donelan et al., 1985). Usually, there is a predominance of swell fields in large oceanic areas, which is due to remote storms (Chen et al., 2002; Hwang et al., 2011; Semedo et al., 2011). The exponent used in the expression for the frequency tail has different values (see Siadatmousavi et al., 2012 for a brief review). For shallow water, Kitaigordskii et al. (1975) suggested f^{-3} tail, Liu (1989) suggested f^{-4} for growing young wind-seas and f^{-3} for fully developed wave spectra. Badulin et al. (2007) suggested f^{-4} for frequencies where nonlinear interactions are dominant. The study carried out at Lake George by Young and Babanin (2006) revealed that in the frequency range $5f_p < f < 10f_p$, the average value of the exponent 'n' of f^{-n} is close to 4. Whereas, some studies in real sea conditions indicate that high-frequency shape of f^{-4} applies up to few times the peak frequency (f_p) and then decays faster with frequency. The spectra for coastlines in Currituck Sound with short fetch condition showed a decay closer to f^{-5} when f is greater than two or three times the peak frequency (Long and Resio, 2007). Gagnaire-Renou et al. (2010) found that the energy input from wind and dissipation due to white-capping have a significant influence on the high-frequency tail of the spectrum.

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The physical processes in the north Indian Ocean have a distinct seasonal cycle (Shetye et al., 1985; Ranjha et al., 2015)~~1985)~~ and the surface wind-wave field is no exception (Sanil Kumar et al., 2012). In the eastern Arabian Sea (AS),~~AS,~~ significant wave height (H_{m0}) up to 6 m is measured in the monsoon period (June to September), and during rest of the period, H_{m0} is normally less than 1.5 m (Sanil Kumar and Anand, 2004). Sanil Kumar et al. (2014) observed that in the eastern AS, the wave spectral shapes are different at two locations within 350 km distance, even though the difference in the integrated parameter like H_{m0} is marginal. Dora and Sanil Kumar (2015) observed that waves at 7-m water depth in the nearshore zone off Karwar are high energy waves in the monsoon and low to moderate waves in the non-monsoon period (January to May and October to December).~~.~~ Dora and Sanil Kumar (2015) study shows similar contribution of wind-seas and swells during the pre-monsoon (February to May), while swells dominate the wind-sea in the post-monsoon (October to January) and the monsoon period. A study was carried out by Glejin et al. (2012) to find the variation in wave characteristics along the eastern AS and the influence of swells in the nearshore waves at 3 locations during the monsoon period in 2010. This study shows that the percentage of swells in the measured waves was 75 to 79% at the locations with higher percentage of swells in the northern portion of AS compared to that at the southern side. Wind and wave data measured at a few locations along the west coast of India for short-period, one to two months as well as the wave model results were analysed to study the wave characteristics in the deep as well as nearshore regions during different seasons (Vethamony et al., 2013). From the wave data collected for two years period (2011 and 2012) along the eastern AS, the swells of period more than 18 s and significant wave height less than 1 m which occur for 1.4 to 3.6% of the time were separated and their characteristics were studied by Glejin et al. (~~Earlier~~2016). Anjali Nair and Sanil Kumar (2016) presented the daily, monthly, seasonal and annual variations in the wave spectral characteristics for a location in the eastern AS and reported that over an annual cycle, 29 % of the wave spectra are single-peaked spectra and 71 % are multi-peaked spectra. Recently Amrutha et al. (2017) by analysing the measured wave data in October reported that the high waves (significant wave height > 4 m) generated in an area bounded by 40-60° S and 20-40° E in the south Indian Ocean reached the eastern AS in 5-6 days and resulted in the long-period waves. The earlier studies indicate that the spectral tail of the high-frequency part shows large variation and its variation with seasons are not known. Similarly, the shape of the parametric spectra are also different and hence it is important to identify the spectral shapes based on the measured data covering all the seasons and different years.

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The ~~previous~~ discussion above shows that there is a strong inspiration to study the high-frequency tail of the wave spectrum. For the present study, we used the directional waverider buoy measured wave spectral data at 15-m water depth off Karwar, west coast of India, over 5 years during 2011 to 2015 and evaluated the nearshore wave spectral shapes in different months. This study addresses two main questions: (1) How the high-frequency tail of the wave spectrum varies in different months, and ~~?~~ (2) What are the spectral parameters for the best-fit theoretical spectra. ~~?~~ This paper is organized as follows: the study area is introduced in section 2, details of data used and methodology in section 3. Section 4 presents the results of the study and the conclusions are given in section 5.

2. Study area

The coastline at Karwar is 24º inclined to the west from the north, and the 20 m depth contour is inclined 29º to the west. Hence, large waves in the nearshore will have an incoming direction close to 241º, since waves get aligned with the depth contour due to refraction. At 10, 30 and 75 km distance from ~~-~~Karwar, the depth contours of~~-~~ 20, 50 and 100 m are present (Fig. 1). The study region is under the seasonally reversing monsoon winds, with winds from the northeast during the post-monsoon and from the southwest during the monsoon period. The monsoon winds are strong and the total seasonal rainfall is 280 cm. The average monthly sea level at Karwar varies from 1.06 m (in September) to 1.3 m (in January) with respect to chart datum and the average tidal range is 1.58 m during spring tides and 0.72 m during neap tides (Sanil Kumar et al., 2012).

3. Data~~Materials~~ and methods

The waves off Karwar (14° 49’ 56” N and 74° 6’ 4” E) were~~are~~ measured using the directional waverider buoy (DWR-MKIII) ~~(Barstow and Kollstad, 1991)~~. Measurements are carried out from 1 January 2011 to 31 December 2015. The data of heave and two translational motion of ~~for every 30 minutes from~~ the buoy are sampled~~continuous records~~ at 3.84 Hz. A digital high-pass filter with a cut off at 30 s is applied to the 3.84 Hz samples. At the same time it converts the sampling rate to 1.28 Hz and stores the time series data at 1.28 Hz.~~are processed as one record.~~ From the time series data for 200s, the wave spectrum is obtained through a fast Fourier transform

(FFT). During half an hour 8 wave spectra of a 200 s data interval each are collected and averaged to get a representative wave spectrum for half an hour (Datawell, 2009). The wave spectrum is with a resolution of 0.005 Hz from 0.025 Hz to 0.1 Hz and is 0.01 Hz from 0.1 to 0.58 Hz. Bulk wave parameters; significant wave height (H_{m0}) which equals $4\sqrt{m_o}$ and mean wave period (T_{m02}) based on second order moment, which equals $\sqrt{m_0/m_2}$) are obtained from the spectral moments. Where m_n is the n^{th} order spectral moment ($m_n = \int_0^\infty f^n S(f)df$, n=0 and 2), S(f) is the spectral energy density and f is the~~at~~ frequency.~~ f.~~ The spectral peak period (Tp) is estimated from the wave spectrum and the peak wave direction (Dp) is estimated based on circular moments (Kuik et al., 1988). The wind-seas and swells are separated through the method described by Portilla et al. (2009) and the wind-sea and the swell parameters are computed by integrating over the respective spectral parts. Measurements reported here are in Coordinated Universal Time (UTC), which is 05:30 h behind the local time. U_{10} is the wind speed at 10-m height obtained from reanalysis data of zonal and meridional components at 6 hourly intervals from NCEP / NCAR (Kalnay et.al., 1996) and is used to study the influence of wind speed on the spectral shape.~~.~~

Since the frequency bins over which the wave spectrum estimated is same in all years, the monthly and seasonally averaged wave spectrum is computed by taking the average of the spectral energy density at the respective frequencies of each spectrum over the specified time.

Wave spectrum continues to develop through non-linear wave-wave interactions even for very long times and distances. Hence, most of the wave spectrum is not fully developed and cannot be represented by Pierson-Moskowitz (PM) spectrum (Pierson and Moskowitz, 1964). Accordingly, an additional factor was added to the PM spectrum in order to improve the fit to the measured spectrum. The JONSWAP spectrum (Hasselmann et al., 1973) is thus a PM spectrum multiplied by an extra peak enhancement factor ~~-~~γ. The high-frequency tail of the JONSWAP spectrum decays in a form proportional to f^{-5}. A number of studies reported that high-frequency decay is by a form proportional to f^{-4}. Modified JONSWAP spectrum including Toba's formulation of saturation range was proposed by Donelan et al. (1985). The JONSWAP and Donelan spectrum used in the study are given in eqns. (1) and (2).

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[-(f-f_p)^2 / 2\sigma^2 f_p\right]} \qquad \ldots\ldots\ldots\ldots\ (1)$$

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^4 f_p} \exp\left[-\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[-(f-f_p)^2 / 2\sigma^2 f_p^2\right]} \qquad \ldots\ldots\ldots\ldots\ (2)$$

Where γ is the peak enhancement parameter; α is Philip's constant; f is the wave frequency; g is the gravitational acceleration -and σ is the width parameter.

$$\sigma = \begin{Bmatrix} 0.07, & f < f_p \\ 0.09, & f \geq f_p \end{Bmatrix}$$

An exponential curve $y = k.f^b$ is fitted for high-frequency part of the spectrum and the exponent (value of b) is estimated for the best fitting curve based on statistical measures such as least square error and bias. The slope of the high-frequency part of the wave spectrum is represented by the exponent of the high-frequency tail.

For the present study, JONSWAP spectrum is tested by fitting for the whole frequency range of the measured wave spectrum. It is found out that the JONSWAP spectra do not show a good fit for higher frequency range, whereas Donelan spectrum shows better fit for the high-frequency range. Hence, JONSWAP spectrum is used for the lower frequency range up to spectral peak and Donelan spectrum is used for the higher frequency range from the spectral peak for single-peaked wave spectrum. Theoretical wave spectra are not fitted to the double-peaked wave spectra.

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4. Results and discussions

4.1 Bulk wave parameters

Mostly the wave conditions (~ 75%) at the buoy location are intermediate and shallow-water waves (where water depth is less than half the wavelength, d < L/2), this condition is not satisfied during ~ 25% of the time due to waves with mean periods of 4.4 s or less. This study, therefore, deals with shallow, intermediate and deepwater wave climatology. Hence, bathymetry will significantly influence the wave characteristics.

The persistent monsoon winds generate choppy seas with average wave heights of 2 m and mean wave period of 6.5 s. Fig. 2 shows that inIn the monsoon, the observed waves had a maximum H_{m0} of about 5 m, with H_{m0} of 2-2.5 m more common during this period. The and the maximum H_{m0} measured during the study period is on 21 June 2015 17:30 UTC (Fig. 2a). Mean wave periods (T_{m02}) at the measurement location ranged from 4-8 s (Fig. 2b). Wave direction during monsoon is predominantly from the west due to refraction towards the coast. The fluctuation in H_{mo} due to the southwest monsoon is seen in all the years (Fig. 2a). High waves (H_{m0} > 2 m) during 27-29 November 2011 areis due to the deep depression ARB04 formed in the AS.Arabian Sea (AS). During the study period, the annual average H_{m0} is same (~1.1 m) in all the years (Table 1). In 2013, the data during August could not be collected and hence resulted in lower annual average H_{m0}. Over the 5 years, small waves (H_{m0} < 1 m) account for a large proportion (63.94%) of measured data and only during 0.16% of the time, H_{m0} exceeded 4 m (Table 2). The 25th and 75th percentiles of the H_{m0} distribution over the entire analysis period are 0.6 and 1.4 m.

Waves with low heights Small waves (H_{m0} < 1 m) are with the mean period in a large range (2.7-10.5 s), whereas high waves (H_{m0} > 3m) have mean wave period in a narrow range (6.1-9.3 s) (Table 2). For waves with H_{m0} higher more than 3 m, the Tp never exceeded 14.3 s and for waves with H_{m0} less than 1 m, Tp up to 22.2 s are observed (Fig. 2c) and the long period swells (14-20 s) are with H_{m0} < 2.5 m. Around 7% of the time during 2011-2015, waves have peak period more than 16.7 s (Table 3). Peak frequenciesfrequency between 0.08 and 0.10 Hz, equivalent to a peak wave period of 10 - 12.5 s areis observed in 31.15% of the time and the H_{m0} is also relatively high (~ 1.55 m) for waves in this class. During the annual cycle, the wave climate is dominated by low waves (0.5 > H_{m0} >1m), intermediate-period (Tp ~10-16s) south-westerly swell. Waves from the northwest are with Tp less than 8 s (Fig. 3).

The wave roses during 2011-2015 indicate that around 38% of the time during the period 2011 to 2015, the predominant wave direction is SSW (225°) with long period (14 - 18s) and intermediate period (10 - 14s) waves (Fig. 3). A small percentage of long-period waves having H_{m0} more than 1m are observed from the same direction in which more than 80% are swells (Fig. 3c).

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Intermediate period waves observed having H_{m0} less than 1m, contain 20 - 60% of swells. Around 10-15% of the waves observed during the period are from the west, which includes intermediate and short period waves with H_{m0} varying from 1.5 to 3m. These intermediate period waves from west having H_{m0} between 2.5 - 3m contain more than 80% of swells. Waves from NW are short period waves with H_{m0} between 0.5 and 1.5; in which swell percentage is very less showing the influence of wind-sea generated by sea breeze (Fig. 3d). High waves observed in the study area consists of more than 80% swells.

Date versus year plots of significant wave height (Fig. 4) shows that H_{m0} has its maximum values (H_{m0} >3m) during the monsoon period with a wave direction of WSW and peak wave period of 10 - 12s (intermediate period). The mean wave period shows its maximum values (6 - 8s) during the monsoon period. During January–May in all the years, H_{m0} is low (H_{m0} < 1m) with waves from SW, W and NW directions. NW waves observed are the result of strong sea breezes existing during this period. Both long-period (Tp > 14s), intermediate-period (10 < Tp <14s) and short-period (Tp < 8s) waves are observed during this period and hence, the mean wave period observed is low compared to the monsoon (Fig. 4d). During October to December, similar to the pre-monsoon period, H_{m0} observed is less than 1m, but the wave direction is predominantly from SW and W, with least NW waves. Short period waves are almost absent during this period, and the condition is similarsame for all the years. The interannual variations in H_{m0} are less than 15% (Fig. 4). Primary seasonal variability in waves is due to the monsoonal wind reversal. During January-March, there is a shift in the occurrences of northwest swells.

Most4.2 Wave spectrum

of the wave conditions (~ 75%) are to be intermediate and shallow water waves at the buoy location (where water depth is less than half the wavelength, d < L/2), this condition is not satisfied during ~ 25% of time due to waves with mean periods of 4.4 s or less. This study, therefore, deals with shallow, intermediate and deepwater wave climatology. Hence, bathymetry will significantly influence the wave characteristics.

Normalisation of the wave spectrum is done to know the spread of energy in different frequencies. Since the range of maximum spectral energy density in a year is large (~ 60 m^2/Hz), each wave spectrum is normalised through dividing the spectral energy density by the maximum spectral energy density of that spectrum. 4.2 Wave spectrum

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The normalized wave spectral energy density contours are presented for different years to know the wind-sea/swell predominance (Fig. 5). The predominance of both the wind-seas and swells are observed in the non-monsoon period, whereas in the monsoon only swells are predominant (Fig. 5). The separation of swells and wind-seas indicates that over~~Over~~ an annual cycle, around 54% of the waves are ~~due to~~ swells. Glejin et al. (2012) reported that the dominance of swells during monsoon is due to the fact that even though the wind at the study region is strong during monsoon, the wind over the entire AS also will be strong and when these swells are added to the wave system at the buoy location, the energy of the swell increases (Donelan, 1987) and will result in dominance of swells. The spread of spectral energy to higher frequencies (0.15 to 0.25 Hz) is predominant during January-May (Fig. 5) due to sea-breeze in the pre-monsoon period (Neetu et al., 2006; Dora and Sanil Kumar, 2015). In the monsoon during the wave growth period, the spectral peak shifts~~shifted~~ from 0.12-0.13 Hz to 0.07-0.09 Hz (lower frequencies).

An interesting phenomenon is that the long-period (> 18 s) swells are present for 2.5% of the time during the study period. The buoy location at 15 m water depth is exposed to waves from northwest to south with the nearest landmass at ~ 1500 km in the northwest (Asia), ~ 2500 km in the west (Africa), ~ 4000 km in the southwest (Africa) and ~ 9000 km in the south (Antarctica) (Amrutha et al., ~~2016).~~2017). Due to its exposure to the Southern Oceans and the large fetch available, swells are present all year round in the study area and the swells are dominant in the non-monsoon (Glejin et al., 2013). Throughout the year, waves with period more than 10 s (~~the~~ low-frequency ~~(~~< 0.1 Hz~~)~~ waves) are the southwest swells whereas with seasons the direction of short-period~~high frequency~~ waves changes (Fig. 5). Amrutha et al. (2017)~~(2016)~~ reported that the long-period waves observed in the eastern AS are the swells generated in the south Indian Ocean. In the monsoon season, the waves with high-frequency are predominantly from west-southwest, whereas in the non-monsoon they are from the northwest. In the non-monsoon period, the predominance of wind-seas and swells fluctuated and hence the mean wave direction also changed frequently (Fig. 5). The average direction of waves with H_{m0} < 1m shows the northwest wind-seas and the southwest swells, whereas, for high waves (H_{m0} > 3m), the difference between the swell and wind-sea direction decreases. This is because the high waves get aligned to the bottom contour before 15 m water depth on its approach to the shallow water.

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The interannual changes of wave spectral energy density for different months in the period 2011-2015 are studied by computing the monthly average wave spectra for all the years (Fig. 6). In~~Except during~~ the non-monsoon period, the wave spectra observed is double-peaked, indicating the presence of wind-seas and swells, whereas during the monsoon, due to the strong southwest winds, single peaked spectrum is observed, i.e. the swell peak with low-frequency and high spectral energy density. Along the Indian coast, Harish and Baba (1986), Rao and Baba (1996) and ~~-~~Sanil Kumar et al. (2003) found out that wave ~~the~~ spectra are generally multipeaked and that the double peaked wave spectra are more frequent during low-sea states (Sanil Kumar et al., 2004). Sanil Kumar et al. (2014), Sanil Kumar and Anjali (2015) and Anjali and Sanil Kumar (2016) have also observed that double-peaked spectrum in the monsoon period in the eastern AS are due to the locally generated wind-seas and the south Indian Ocean swells. In the study area, from ~~From~~ January to May and October to December, the swell peak is between the frequencies 0.07 and 0.08 Hz ~~-~~(12.5 < Tp < 14.3s),~~14.28s),~~ but in the monsoon period, the swell peak is around 0.10 Hz, in all the years studied. This shows long-period swells (Tp > 13s) in the non-monsoon period and intermediate period swells (8 < Tp <13s) in the monsoon. Glejin et al. (2016), also observed the presence of low-amplitude long-period waves in the eastern AS in the non-monsoon period and intermediate period waves in the monsoon period. This is because of the propagation of swells from the southern hemisphere is more visible during the non-monsoon period due to the calm conditions (low wind-seas) prevailing in the eastern AS. Whereas during the monsoon period, these swells are less due to the turbulence in the north Indian Ocean (Glejin et al., 2013). Large interannual variations are observed for monthly average wave spectrum in all months except in July. This is because July is known to be the roughest month over the entire annual cycle and southwest monsoon reaches its peak during July. Hence, the influence of temporally varying wind-seas on the wave spectrum is least during July compared to other months. Due~~Maximum spectral energy observed is during June 2013 due~~ to the early onset (on 1 June) and advancement of monsoon during 2013 compared to other years, the monthly average value of the maximum spectral energy is observed in June 2013 (Fig. 6).~~years.~~ The wave spectra of November 2011 is distinct from that of other years, with low wind-sea peak frequency, i.e. 0.13 Hz due to the deep depression ARB04, occurred south of India near Cape Comorin, during 26 November–1 December, with a sustained wind speed of 55 km/h. During October 2014, the second peak is observed at 0.11 Hz with comparatively high energy showing the influence of cyclonic storm NILOFAR. It is an extremely severe cyclonic storm that occurred during the period 25-31 October 2014, originated from a lowpressure area between Indian and Arabian Peninsula, with the highest wind speed of 215 km/h and affected the areas of India, Pakistan and Oman. Significant interannual variation is observed in the wind-sea peak frequency. Wave spectra averaged over each season (Fig. 7) shows that the interannual variations in energy spectra averaged over full year period almost follows the pattern of wave spectra averaged over monsoon period,spectra, indicating the strong influence of monsoon winds over the wave energy spectra in the study area. Interannual variations within the spectrum are more for wind-sea regions compared to swell region.s. During the study period, the maximum spectral energy observed is during 2011 monsoon.

For different frequencies, the monthly average wave direction isare shown in -Fig. 8. It is observed that throughout the year the mean wave direction of the swell peak is southwest (200-250^{o}). In the non-monsoon period, the wind-sea direction is northwest (280-300°), except in October and November. This is due to the wind-seas produced by sea breeze which has the maximum intensity during the pre–monsoon season. Interannual variability in wave direction is highestmore during October and November, where the wind-seas from southwest direction are also observed. This is because, during these months, the wind speed and the strength of the monsoon swell decreases, which makes the low energy wind-seas produced by the withdrawing monsoon winds more visible.

Contour plots of spectral energy density (normalized) clearly show the predominance of wind-seas and swells during the non-monsoon period (Fig. 9). In the monsoon period, the spectral energy density is mainly confined to a narrow frequency range (0.07-0.14 Hz) and the wave spectra are mainly single peaked with maximum energy within the frequency range 0.08-0.10 Hz, having direction 240^{o}.. Glejin et al. (2012) reported that in the monsoon season, the spectral peak is between 0.08 and 0.10 Hz (12-10s) for ~ 72% of the time in the eastern AS. Earlier studies also reported dominance of swells in the eastern AS during the monsoon (Sanil Kumar et al., 2012; Glejin et al., 2012). Above 0.15 Hz, energy gradually decreases, with the lowest energy observed between 0.30 and 0.50 Hz. Wind-sea energy is comparatively low during October, November and December and occurs mostly in the frequency range less than 0.20 Hz, whereas, during January-May, the frequency exceeds 0.20 Hz. In the pre-monsoon period, wind-sea plays a major role in nearshore wave environment (Rao and Baba, 1996). Wind-sea energy is found to be low during

April 2015 (Fig. 6), because of reduction in local winds. The occurrence of wind-seas is very less during most of the time in November except during 2011, due to the deep depression ARB04.

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~~To study the characteristics of different wave systems, average mean wave direction and average wave spectral energy density grouped under different peak frequency bins are plotted in Fig. 10. Wave spectrum is mostly single peaked at low frequency bins and multi-peaked at higher frequencies. Within the frequency range 0.07 to 0.15 Hz, the spectrum observed is a smooth single peaked spectrum, with high energy density. Maximum energy observed is within the frequency range 0.08-0.1 Hz, having direction 240° which indicates the monsoon swells. Above 0.15 Hz, even though the spectrum is multi-peaked, energy gradually decreases, with the lowest energy observed between 0.3 and 0.5 Hz. Between 0.15 and 0.5 Hz, waves observed are from the northwest direction (300°) and represents the wind seas produced by local winds. Long period swells (Tp > 14s) are also observed from the southwest. The average direction of waves with H_{m0} < 1m shows the northwest wind-seas and the southwest swells, whereas for high waves (H_{m0} > 3m), the difference between the swell and wind-sea direction decreases (Fig. 11). This is because the high waves get aligned to the bottom contour before 15 m water depth on its approach to the shallow water.~~

The behavior of the high-frequency part of the spectrum is governed by the energy balance of waves generated by the local wind fields. When the wind blows over a long fetch or for a long time, the wave energy for a given frequency reaches the equilibrium range and the energy input from the wind is~~are~~ balanced by energy loss to lower~~other~~ frequencies and by wave breaking (Torsethaugen and Haver, 2004). The high-frequency tail slope of the monthly average wave spectrum in different years ~~(Table 4)~~ shows that the slope is high (b< -~~(>~~3.1), during June to September and the case is same for all the years studied (Table 4). During all other months, the exponent in the expression for the frequency tail ~~slope~~ is within the range ~~1.5~~- 3.1 to -1.5. The distribution of exponent~~slope~~ values for different significant wave height ranges shows that the slope increases (exponent decrease from -2.44 to -4.20) as the significant wave height increases and reaches a saturation range. For frequencies from 0.23~~0.229~~ to 0.58 Hz in the eastern AS during January-May, Amrutha et al. (2017)~~(2016)~~ observed that the high-frequency tail has $f^{-2.5}$ pattern at 15 m water depth and for frequencies ranging from 0.31~~5~~ to 0.55 Hz, the high-frequency tail follows f^{-3} at 5 m water depth. ~~It is shown in Fig. 12 that the slope also increases as the mean wave~~

~~period increases.~~ Since H_{mo} is maximum during the monsoon period, the slope is also maximum during June to September. There is no much interannual variation in slope for swell dominated spectra during the monsoon, while in the non-monsoon period when wind-seas have much influence, the slope varies significantly. ~~The slope of the high-frequency end of the wave spectrum becomes milder when the wave nonlinearity increases. The study shows that the tail of the spectrum is influenced by the local wind conditions.~~

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~~4.3 Theoretical wave spectra~~

~~The monthly average wave spectra for the year 2015, is compared with JONSWAP and Donelan theoretical wave spectra. It is found that JONSWAP and Donelan spectra with modified parameters describe well the wave spectra at low frequencies and high frequencies respectively.~~ The most obvious manifestations of nonlinearity are sharpening of the wave crests and the flattening of the wave troughs and these effects are reflected in the skewness of the sea surface elevation (Toffoli, 2006). Zero skewness indicates linear sea states, positive skewness value indicate that the wave crests are bigger than the troughs. Figure 10 shows that nonlinearity increases with increase in H_{m0}. The slope of the high-frequency end of the wave spectrum becomes steeper when the wave nonlinearity increases. Donelan et al. (2012) find that in addition to the k^{-4} dissipation that swells modulate the equilibrium in breaking waves dependent on the mean surface slope, while Melville (1994) also quantified a relation between wave packet slopes and dissipation rate. These results are specific to breaking waves, but one might expect similar relations between surface dynamics and dissipation rate for non breaking waves. A function of the form: $A * \exp(\lambda H_{m0}) + s0$, with initial parameters of $A = 8$, $\lambda = -2.4$, $s0 = -3.7$ is found to fit the exponent of the high-frequency tail data with the significant wave height (Fig. 11a). The functional representation of the exponent of the high-frequency tail data with H_{m0} shown in Fig. 11a might be useful in revealing the physical connection, and at the very least would provide a predictive basis relating spectral slopes with mean significant wave heights as a basis for future research. It is shown in Fig. 11b that the exponent decreases (slope increases) as the mean wave period increases. The study shows that the tail of the spectrum is influenced by the local wind conditions (Fig. 11c) and the influence is more with the zonal component (u) of the wind than on the meridional component (v) (Figs. 11e and 11f). The exponent of the high-frequency tail decreases with the increase of the inverse wave age (U_{10}/c), where c is the celerity of the wave.

4.3 Comparison with theoretical wave spectra

From Fig. 13, we can see that spectrum is double peaked during January-April and December. For these months the first peak is fitted with JONSWAP spectrum and second with Donelan, and the fitted spectrum shows a good match with the measured one. In the monsoon period, the spectrum is single peaked with high spectral energy density and during this period JONSWAP spectrum is fitted up to the peak frequency and after that Donelan spectrum is used. The monthly average wave spectra during the monsoon period for the year 2011, is compared with JONSWAP and Donelan theoretical wave spectra in Figure 12. During the months May, October and November, after the peak frequency, the measured spectrum is not smooth and hence for this part, Donelan spectrum is fitted in two parts in order to obtain the best fit. Here also JONSWAP shows best fit, up to the peak frequency.

It is found that JONSWAP and Donelan spectra with modified parameters describe well the wave spectra at low frequencies and high frequencies respectively. The values for α and ϒ were randomly varied within a range to find out the values for which, the theoretical spectrum best fits the measured spectrum and those values were used to plot the theoretical spectrum. The values of α and ϒ thus obtained, for June, July, Augusteach month and Septemberthe range of frequencies for which each spectrum is plotted are given in Table 6. From the table, the average values of α and ϒ, for the monsoon monthsover 1 year period are obtained as 0.000900.0050 and 1.821.33 for JONSWAP spectra and 0.027400.0254 and 1.641.27 for Donelan spectra respectively. These values are less than the generally recommended values of α and ϒ; 0.0081 and 3.3. α is a constant that is related to the wind speed and fetch length. For all the data, Donelan spectrum fitted is proportional to f^{n}, where n is the exponent value of the high-frequency tail.From the table, it can be seen that α has the highest values during the months June to August and is the same for both JONSWAP and Donelan spectrum. This may be due to the high wind speed during monsoon. High values of α were also observed during November, February and April, since these are the months during which sea breeze has maximum influence, high α values is due to the influence of local winds. There is no seasonal variation observed in the values of ϒ. For all the months, Donelan spectrum fitted is proportional to f^{-4}, except during May and November, where spectrum is proportional to $f^{-2.8}$ and $f^{-2.5}$, above frequencies 0.15 Hz and 0.28 Hz respectively. The theoretical spectrum JONSWAP and

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Donelan cannot completely describe the high-frequency tail of the measured spectrum since the high-frequency tail in these spectrum decays in the form of f^{-5} and f^{-4} respectively. Since the exponent of the high-frequency tail~~slope~~ of the wave spectrum is within the range ~~3~~-4 to -3 during the monsoon period, Donelan spectrum shows better fit for monsoon spectra compared to other months (Fig. 11).~~13).~~

5. Concluding remarks

In this paper, the variations in the wave spectral shapes in different months for a nearshore location are investigated, based on in situ wave data obtained from a moored directional waverider buoy. Interannual variations within the spectrum are more for wind-seas compared to swells. The maximum significant wave height measured at 15 m water depth is 5 m and the annual average H_{m0} has similar value (~1.1 m) in all the years. Over the 5 years, small waves (H_{m0} < 1 m) account for a large proportion of measured data (63.94% of the time). The study shows that high waves (H_{m0} > 2 m) are with spectral peak period between 8 and 14 s and the long period swells (14-20 s) are with H_{m0} < 2.5 m. The high-frequency slope of the wave spectrum (the exponent decreases~~varies~~ from -2.44 to -4.20)~~ and it~~ increases with increase in significant wave height and mean wave period. During the monsoon period, Donelan spectrum shows better fit for monsoon spectra compared to other months since the exponent of the high-frequency part~~slope~~ of the wave spectrum is within the range ~~3~~-4 to -3. The decay of~~-~~ the high-frequency waves are fastest with depth and hence, the high-frequency tail values observed in the study will be different for different water depths.

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Figure captions

Figure 1. Study area along with the wave measurement location in eastern Arabian Sea

Figure 2. Time series plot of a) significant wave height, b) mean wave period, c) peak wave period and d) mean wave direction from 1 January 2011 to 31 December 2015. Thick blue line indicates the monthly average values

Figure 3. Wave roses during 2011-2015 (a) significant wave height and mean wave direction, (b) peak wave period and mean wave direction, (c) percentage of swell, (d) percentage of wind-sea and mean wave direction

Figure 4. Date verses year plot of a) significant wave height b) mean wave direction, c) peak wave period and d) mean wave period

Figure 5. Temporal variation of normalized spectral energy density (top panel) and mean wave direction (bottom panel) with frequency in different years

Figure 6. Monthly average wave spectra in 2011 to 2015

Figure 7. Wave spectra averaged over a) pre-monsoon (February-May), b) monsoon (June-September), c) post-monsoon (October-January) and d) full year in different years

Figure 8. Monthly average wave direction at different frequencies in different months

Figure 9. Temporal variation of normalized spectral energy density in different months (data from 2011 to 2015 used)

Figure 10. Scatter plot~~Plot~~ of significant~~average spectral energy density and average mean~~ wave height with skewness~~direction~~ of the sea surface elevation in~~waves grouped under~~ different years~~peak frequency bins~~

Figure 11. Plot of exponent~~a) average spectral energy density and b) average mean wave direction~~ of the~~waves under different H_{m0} with frequency~~

~~Figure 12. Plot of~~ high-~~-~~frequency tail with a) significant wave height, b) ~~(left panel) and with~~ mean wave period, c) wind speed, d) inverse wave age, e) u-wind and f) v-wind ~~(right panel)~~

Figure 12.~~13.~~ Fitted theoretical spectra along with the monthly average wave spectra for different month

Table 1. Number of data used in the study in different years along with range of significant wave height and average value

Year	Significant wave height (m)		Number of data	%of data
	Range	Average		
2011	0.3-4.4	1.1	17517	99.98
2012	0.3-3.7	1.1	17323	98.61
2013	0.3-3.6	0.9*	14531	82.94
2014	0.3-4.5	1.1	17284	98.65
2015	0.3-5.0	1.1	14772	84.32

* average value is estimated excluding the July~~August~~ month data

Table 2. Characteristics of waves in different range of significant wave height

Significant wave height range	Number (percentage)	Range of Tp (s)	Mean Tp (s)	Range of T_{m02} (s)	Mean T_{m02} (s)
$H_{m0} < 1$ m	52062 (63.94)	2.6-22.2	12.2	2.7-10.5	4.9
$1 \leq H_{m0} < 2$ m	18297 (22.47)	3.6-22.2	10.5	3.4-10.7	5.7
$2 \leq H_{m0} < 3$ m	9839 (12.08)	6.2-18.0	10.8	5.0-8.9	6.5
$3 \leq H_{m0} < 4$ m	1096 (1.35)	10.0-14.3	11.8	6.1-9.1	7.2
$4 \text{ m} \leq H_{m0}$	133 (0.16)	10.5-14.3	12.6	7.2-9.3	7.8

Table 3. Average wave parameters and number of data in different spectral peak frequencies

Frequency (f_p) range (Hz)	Number of data and %	H_{m0} (m)	T_{m02} (s)	Peak wave period (s)
$0.04 < f_p \leq 0.05$	318 (0.39)	0.73	5.24	20.19
$0.05 < f_p \leq 0.06$	5341 (6.56)	0.82	5.48	17.16
$0.06 < f_p \leq 0.07$	14764 (18.13)	0.75	5.22	14.73
$0.07 < f_p \leq 0.08$	18221 (22.38)	0.80	5.05	12.96
$0.08 < f_p \leq 0.10$	25364 (31.15)	1.55	5.76	10.88
$0.10 < f_p \leq 0.15$	9459 (11.62)	1.25	5.35	8.07
$0.15 < f_p \leq 0.20$	6355 (7.80)	0.76	4.43	5.72
$0.20 < f_p \leq 0.30$	1487 (1.83)	0.78	3.86	4.36
$0.30 < f_p \leq 0.50$	118 (0.14)	0.66	3.22	3.09

Table 4. Exponent ~~Slope~~ of the high~~-~~-frequency tail of the monthly average wave spectra in different years

Months	Exponent of the high-~~High~~ frequency tail					
	2011	2012	2013	2014	2015	2011-2015
January	-2.08	-2.93	-2.97	-2.72	-2.81	-2.72
February	-2.41	-3.02	-2.74	-2.99	-3.06	-2.85
March	-2.75	-2.91	-2.82	-2.76	No data	-2.81
April	-2.56	-2.74	-2.64	-2.71	-2.19	-2.60
May	-2.59	-2.67	-2.63	-2.42	-2.51	-2.56
June	-3.64	-3.53	-3.55	-3.82	-3.58	-3.55
July	-3.76	-3.55	No data~~-3.40~~	-3.82	-3.63	-3.70
August	-3.63	-3.58	-3.40~~No data~~	-3.52	-3.65	-3.58
September	-3.41	-3.44	-3.16	-3.38	-3.00	-3.30
October	-2.02	-2.77	-3.03	-2.52	-2.61	-2.68
November	-1.78	-2.43	-1.77	-1.55	-1.65	-1.84
December	-1.69	-2.23	-1.95	-2.06	-1.79	-1.94

Table 5. Exponent of the high-~~High~~ frequency tail of the average wave spectra in different wave height ranges

Range of H_{m0} (m)	Exponent of the high-~~High~~ frequency tail ~~parameter~~
0-1	-2.44
1-2	-3.26
2-3	-3.67
3-4	-4.21
4-5	-4.21

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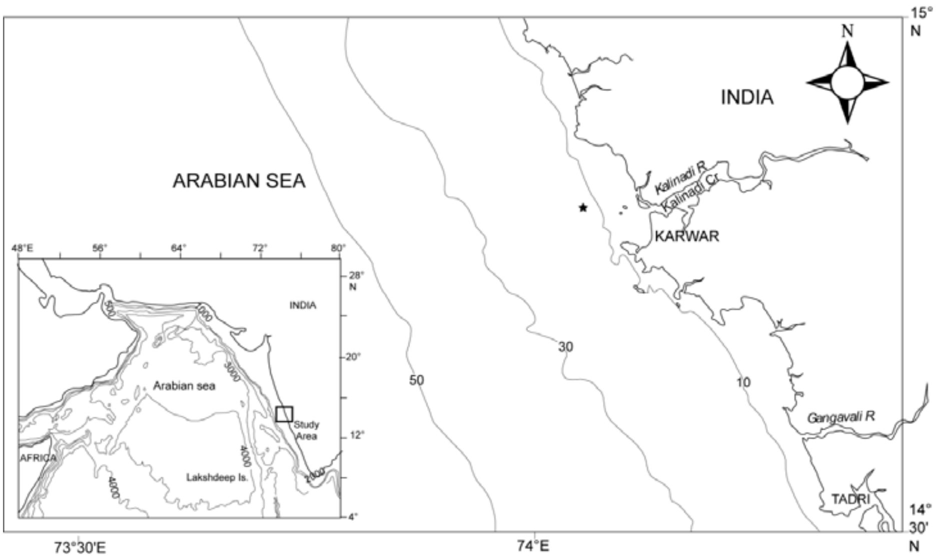
Table 6. Parameters of the fitted wave spectrum in different years~~months~~

Year		JONSWAP spectrum		Donelan spectrum	
		α	ϒ	α	ϒ
2011	June	0.0013	2.2	0.0028	2.0
	July	0.0016	1.5	0.0021	1.7
	August	0.0013	1.8	0.0029	1.7
	September	0.0004	2.3	0.0021	1.6
2012	June	0.0015	1.6	0.0029	2.0
	July	0.0010	2.1	0.0031	1.9
	August	0.0009	2.2	0.0032	1.7
	September	0.0006	2.0	0.0024	1.8
2013	June	0.0006	3.3	0.0030	1.9
	July	No data			
	August	0.0012	1.1	0.0038	1.4
	September	0.0005	1.9	0.0042	1.4
2014	June	0.0010	1.1	0.0010	1.6
	July	0.0006	2.5	0.0019	1.2
	August	0.0006	1.5	0.0021	1.2
	September	0.0011	1.1	0.0032	1.4
2015	June	0.0011	1.4	0.0023	1.8
	July	0.0011	1.9	0.0024	1.8
	August	0.0008	1.8	0.0024	1.4
	September	0.0006	1.3	0.0043	1.6



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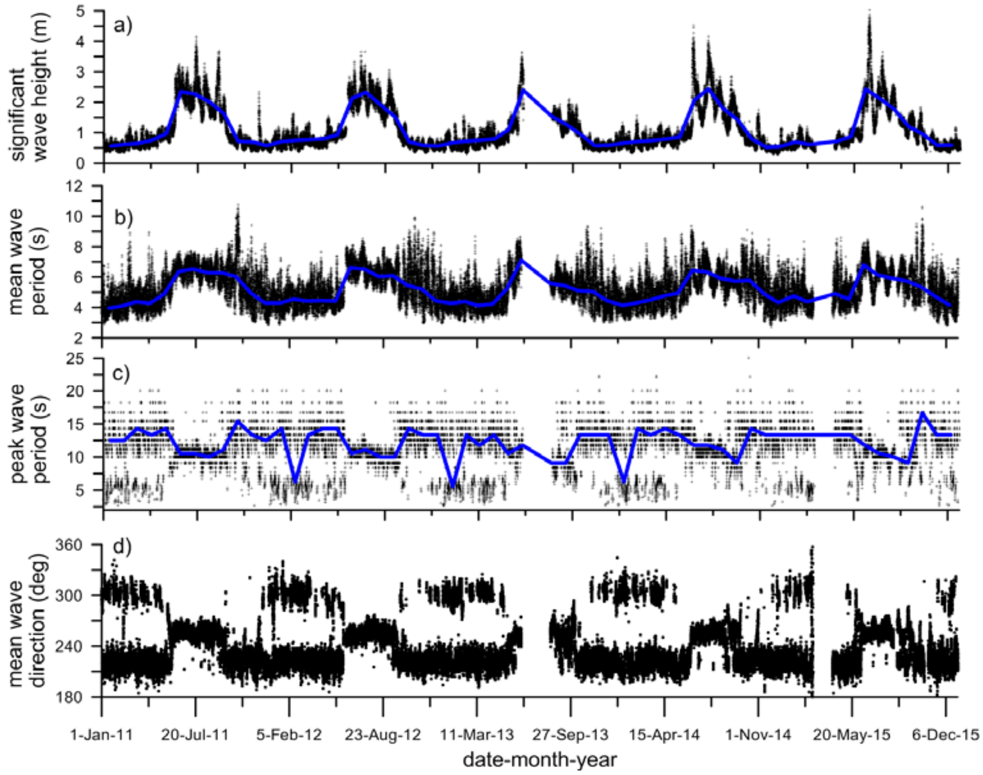
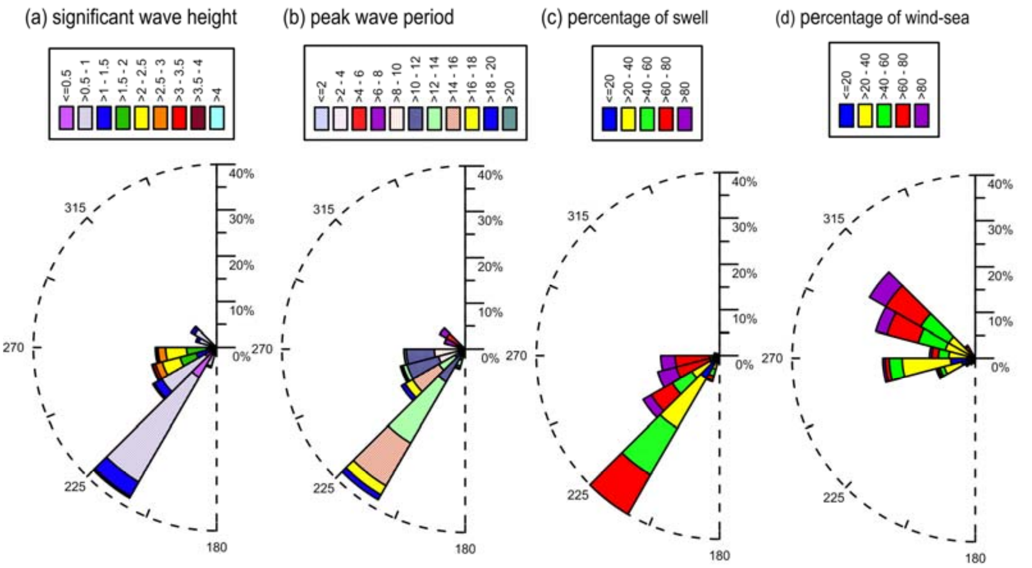
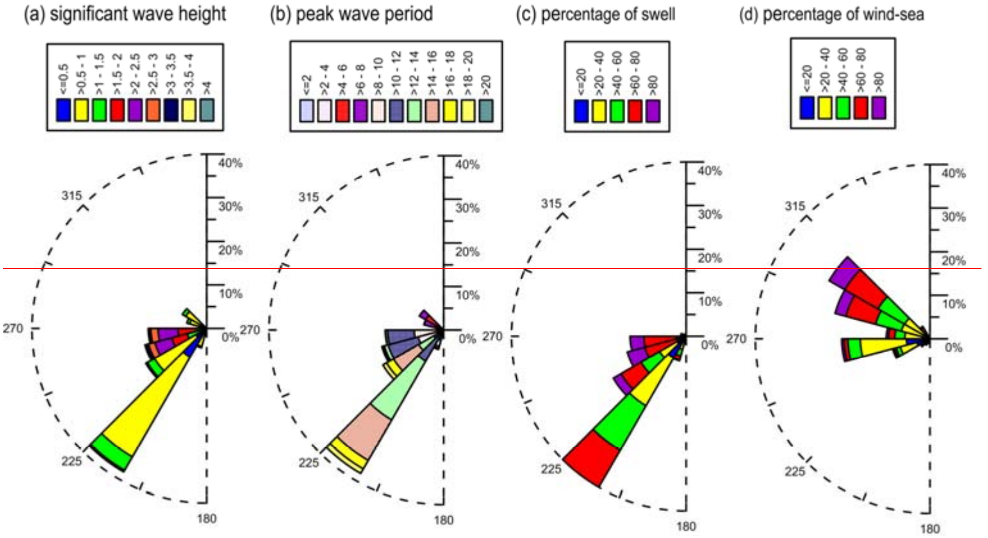


Figure 2. Time series plot of a) significant wave height, b) mean wave period, c) peak wave period and d) mean wave direction from 1 January 2011 to 31 December 2015. Thick blue line indicates the monthly average values





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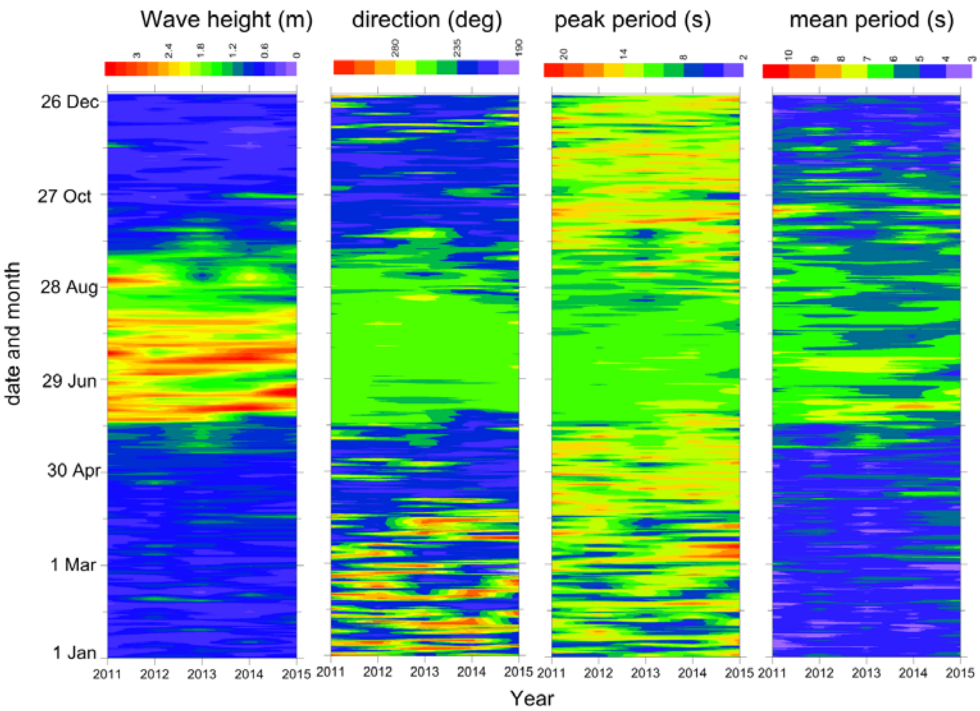


Figure 4. Date verses year plots of a) significant wave height b) mean wave direction, c) peak wave period and d) mean wave period.

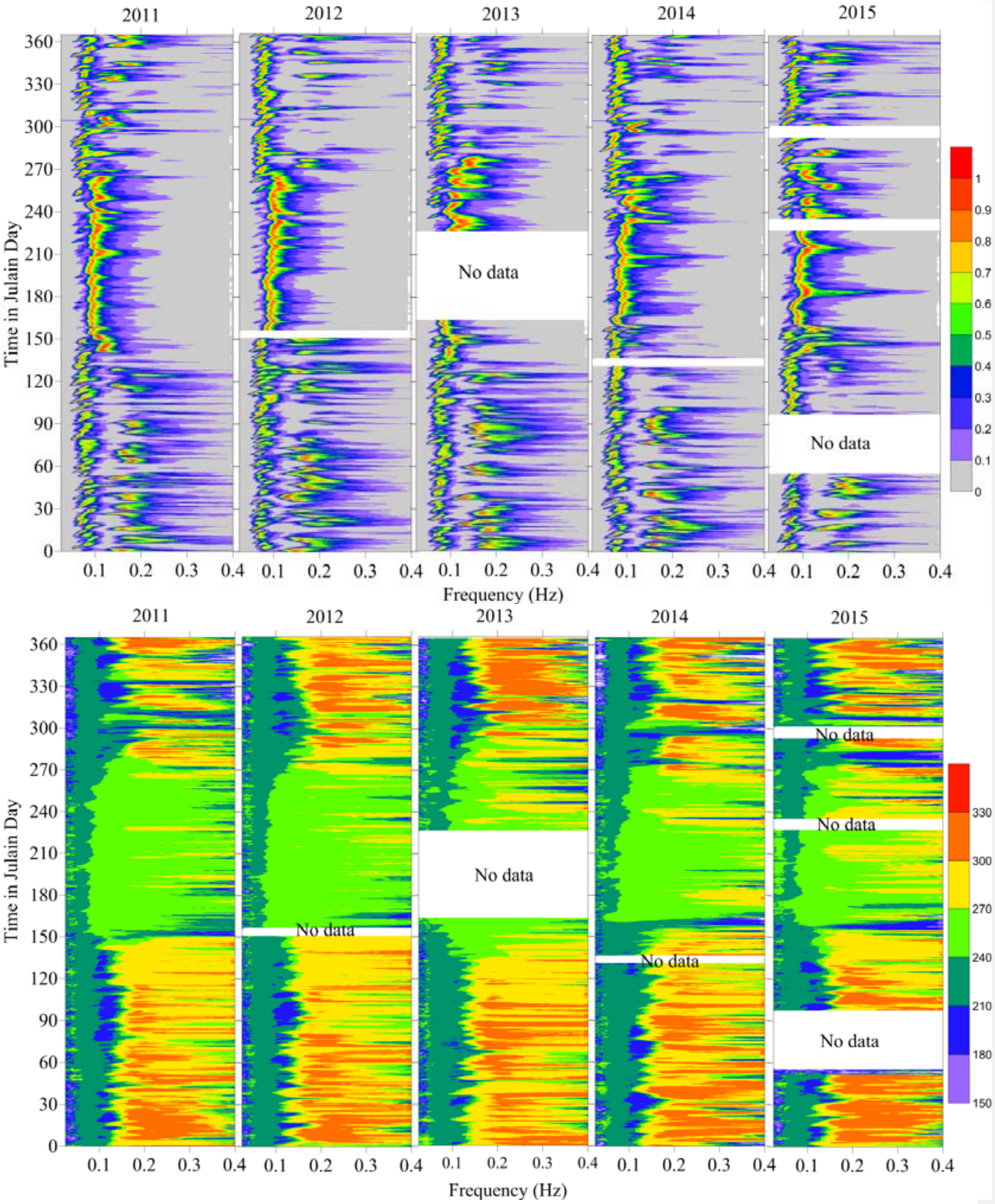
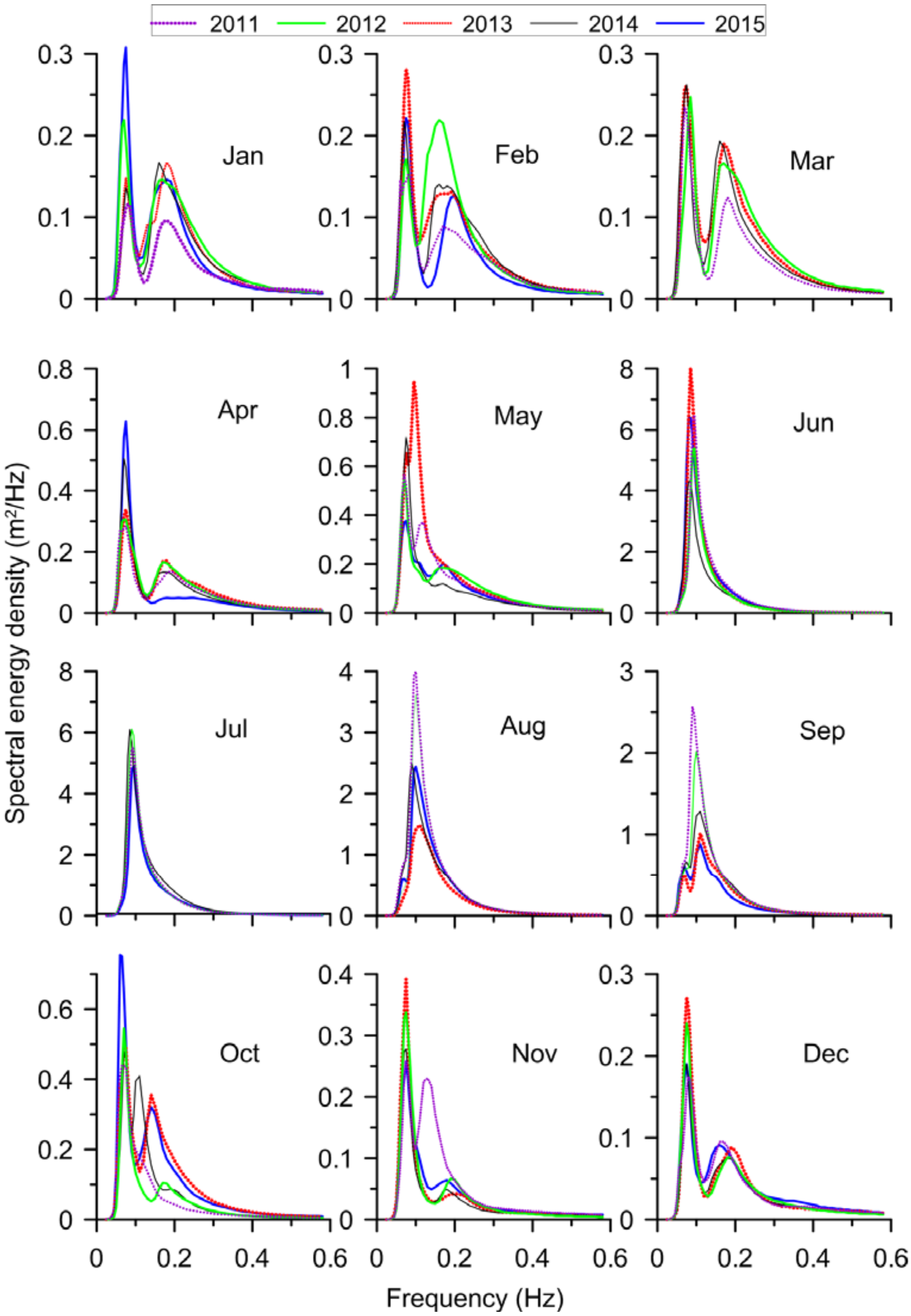


Figure 5. Temporal variation of normalized spectral energy density (top panel) and mean wave direction (bottom panel) with frequency in different years



723
724 Figure 6. Monthly average wave spectra in 2011 to 2015

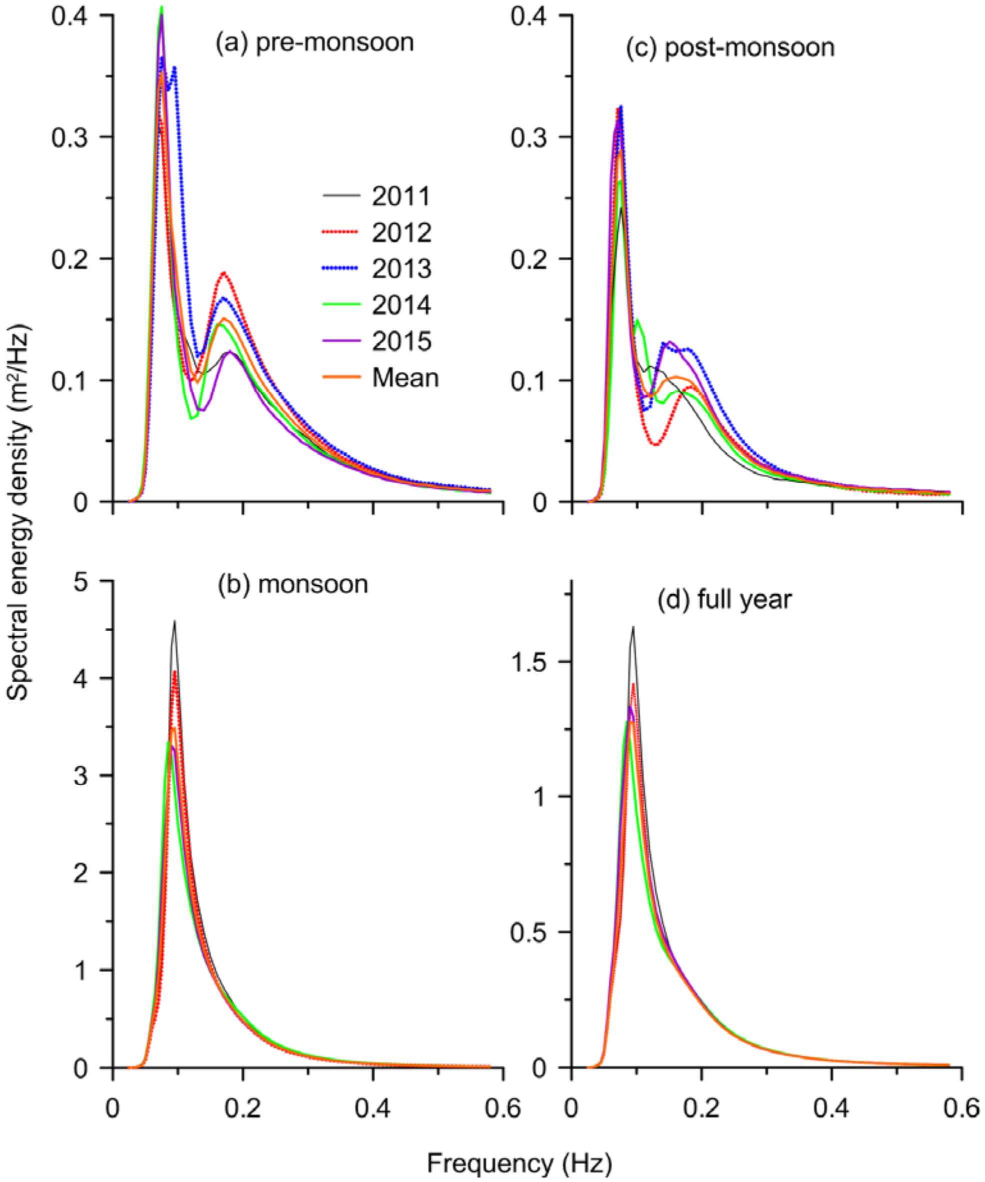
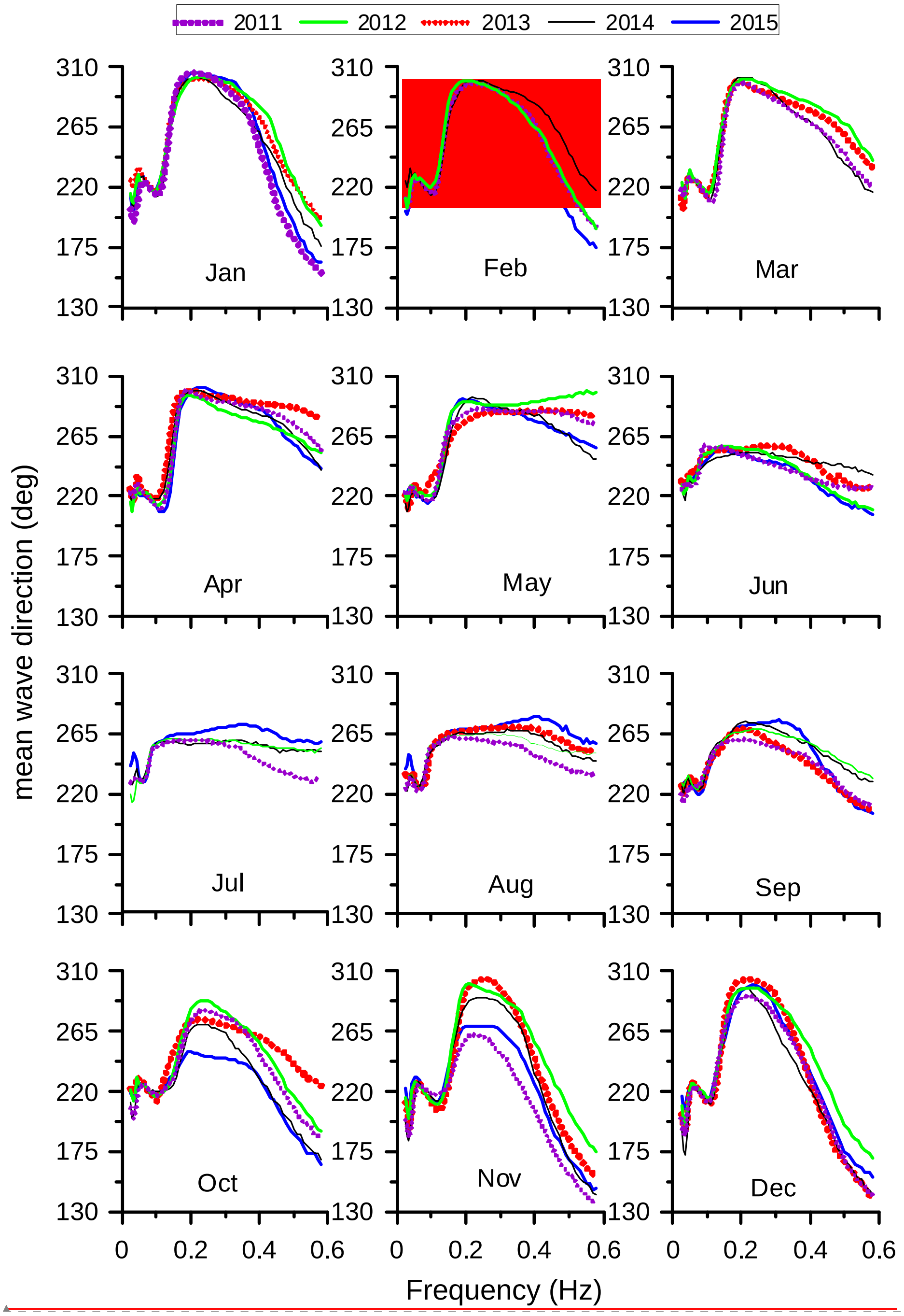


Figure 7. Wave spectra averaged over a) pre-monsoon (February-May), b) monsoon (June-September), c) post-monsoon (October-January) and d) full year in different years



2011
2012
2013
2014
2015
mean wave direction (deg)
310
265
220
175
130
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0
0.2
0.4
0.6
Frequency (Hz)

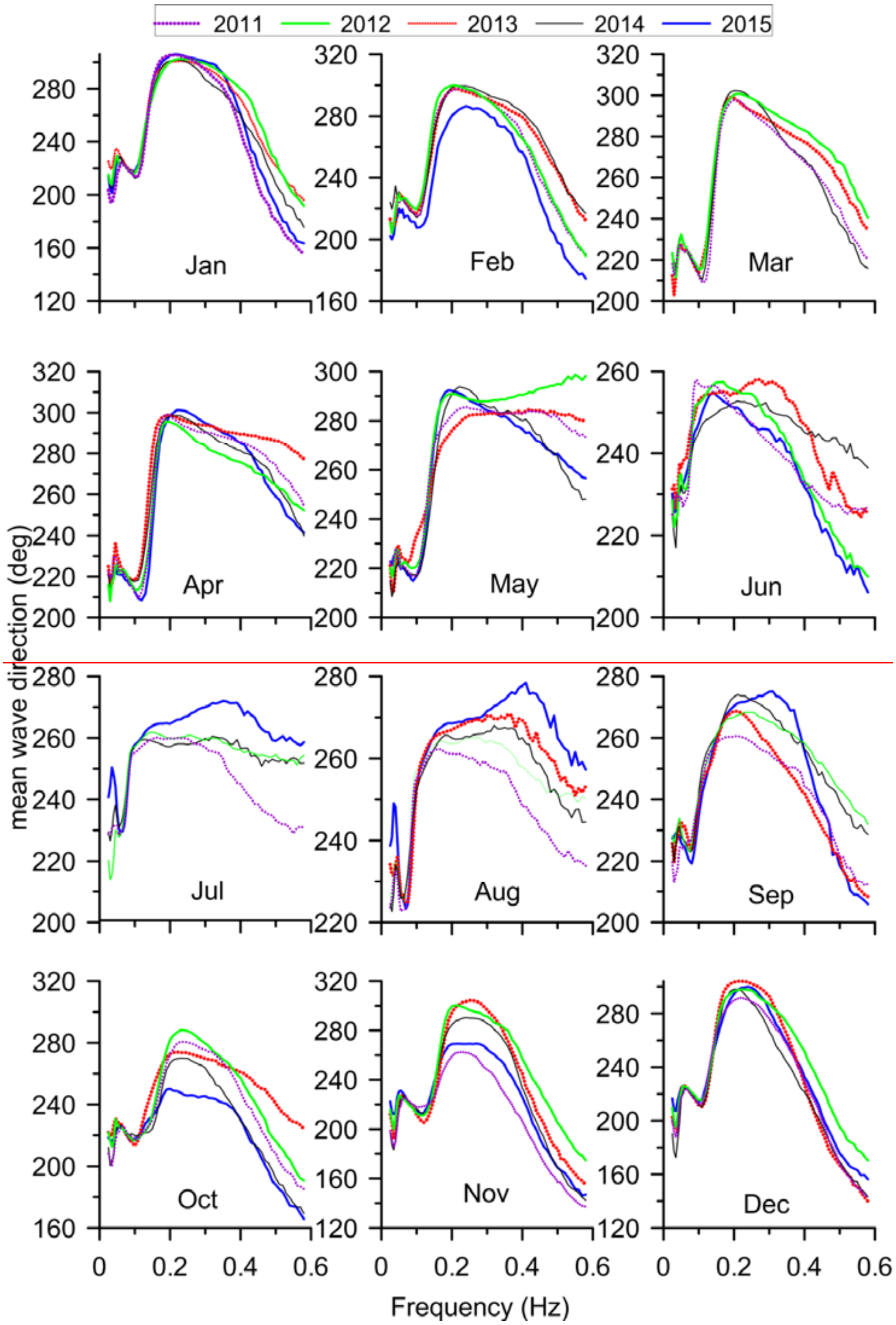


Figure 8. Monthly average wave direction at different frequencies in different months

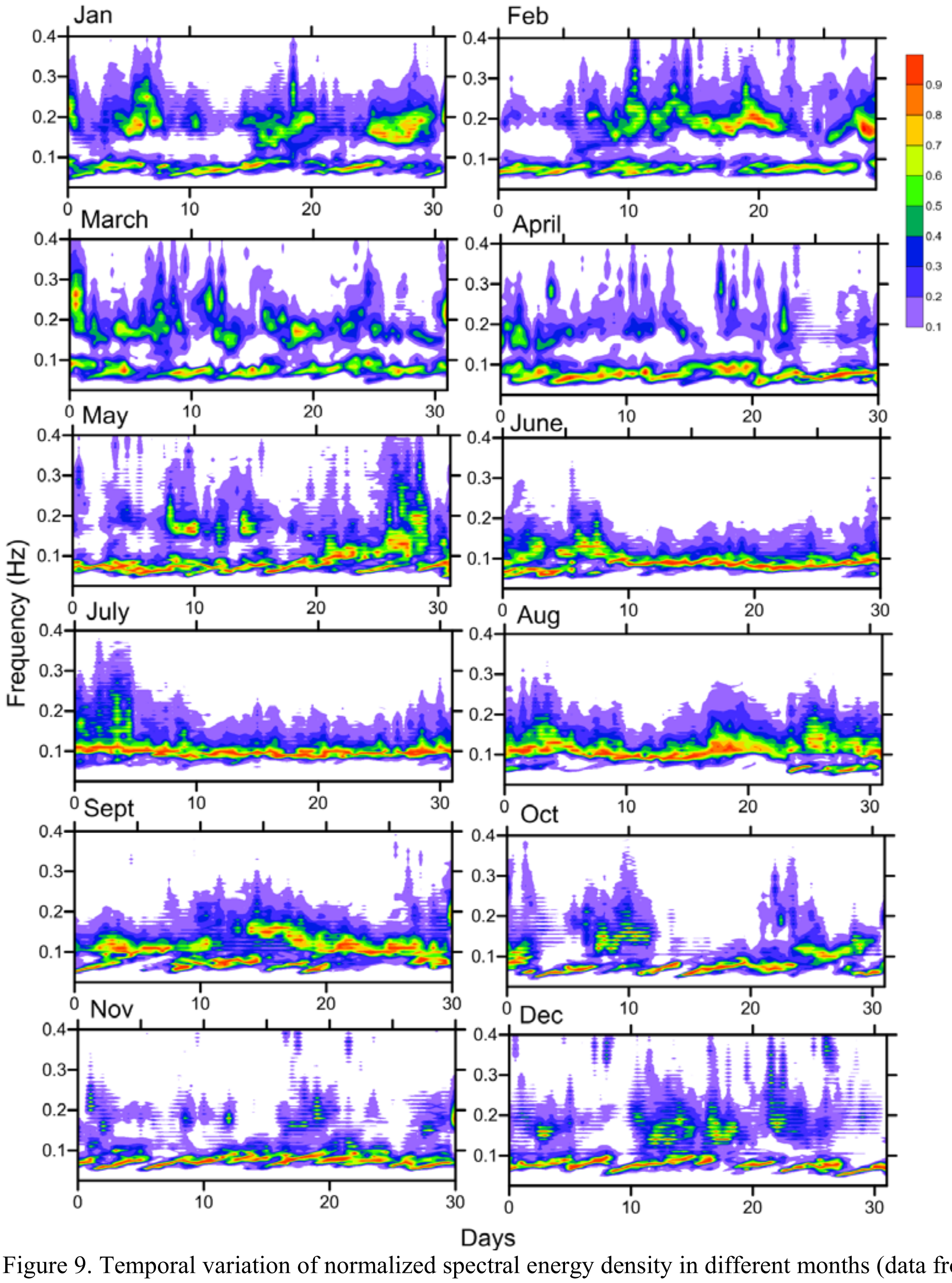
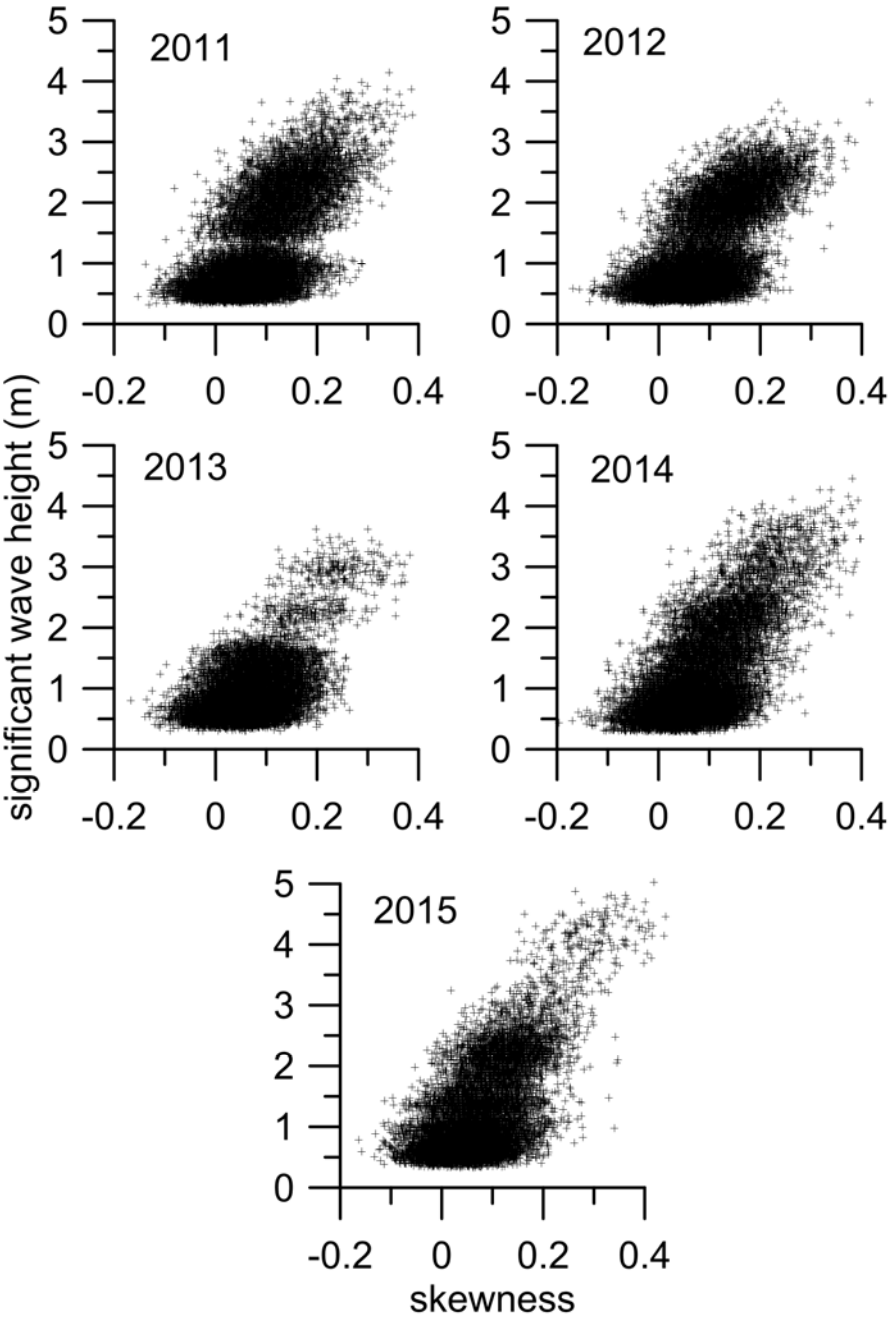


Figure 9. Temporal variation of normalized spectral energy density in different months (data from 2011 to 2015 used)



2011
2012
2013
2014
2015
significant wave height (m)
skewness
0
1
2
3
4
5
-0.2
0
0.2
0.4

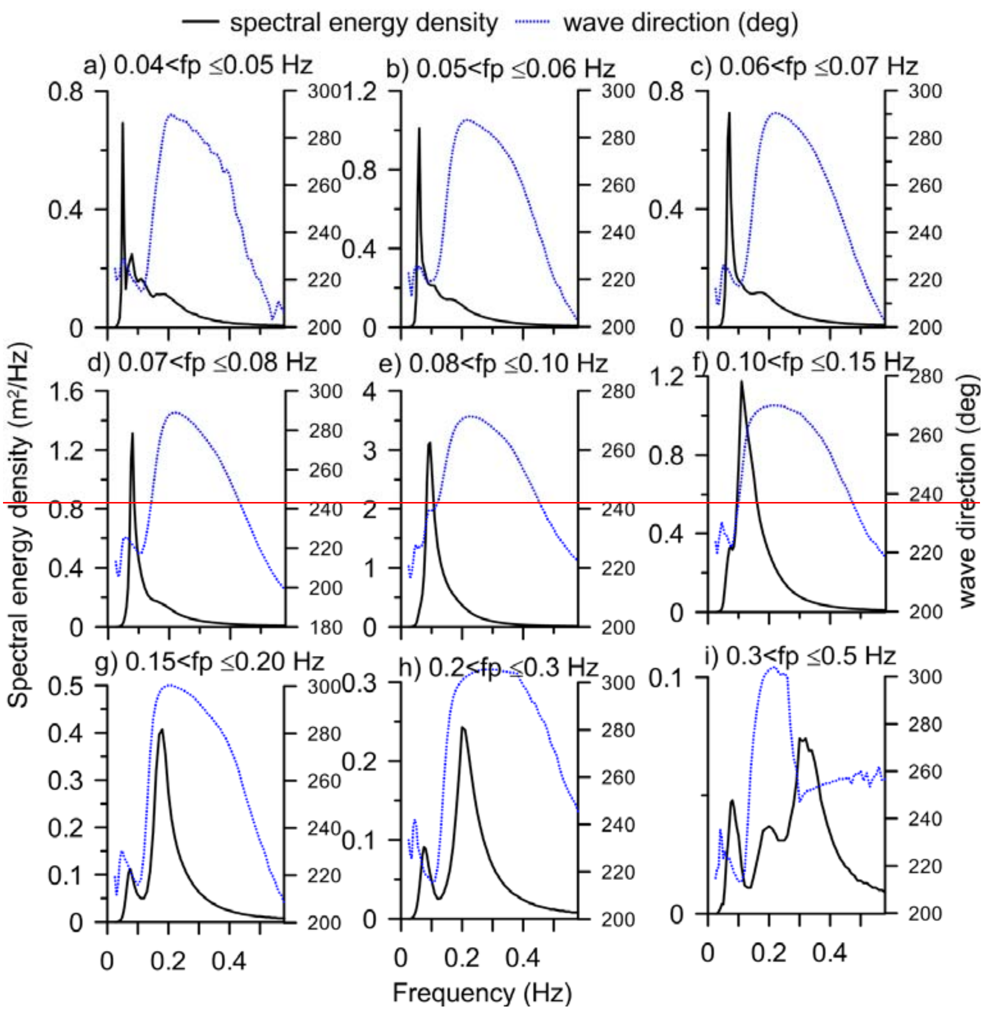
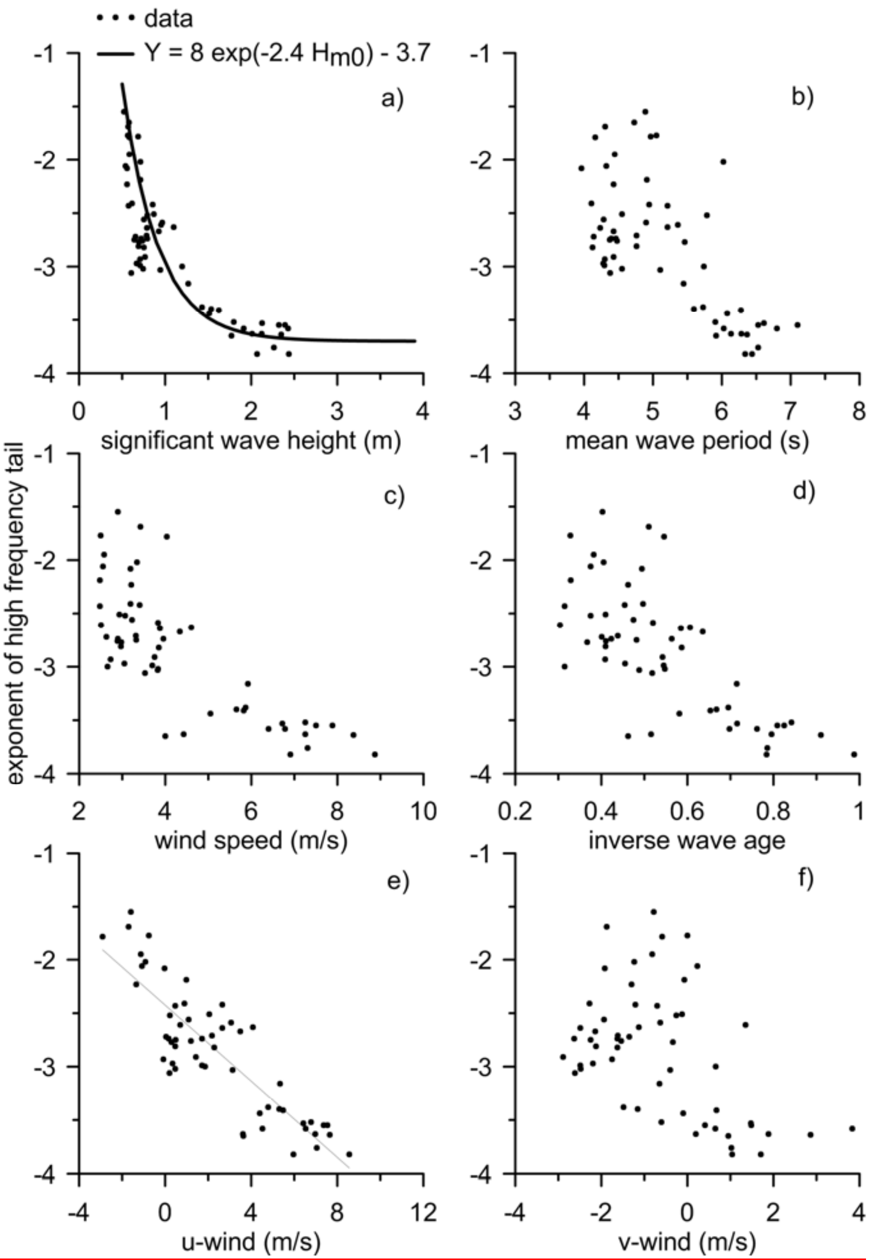


Figure 10. Scatter plot~~Plot~~ of significant~~average spectral energy density and average mean~~ wave height with skewness~~direction~~ of the sea surface elevation in~~waves grouped under~~ different years~~peak frequency bins~~


data
Y = 8 exp(-2.4 Hm0) - 3.7
a)
b)
c)
d)
e)
f)
exponent of high frequency tail
significant wave height (m)
mean wave period (s)
wind speed (m/s)
inverse wave age
u-wind (m/s)
v-wind (m/s)

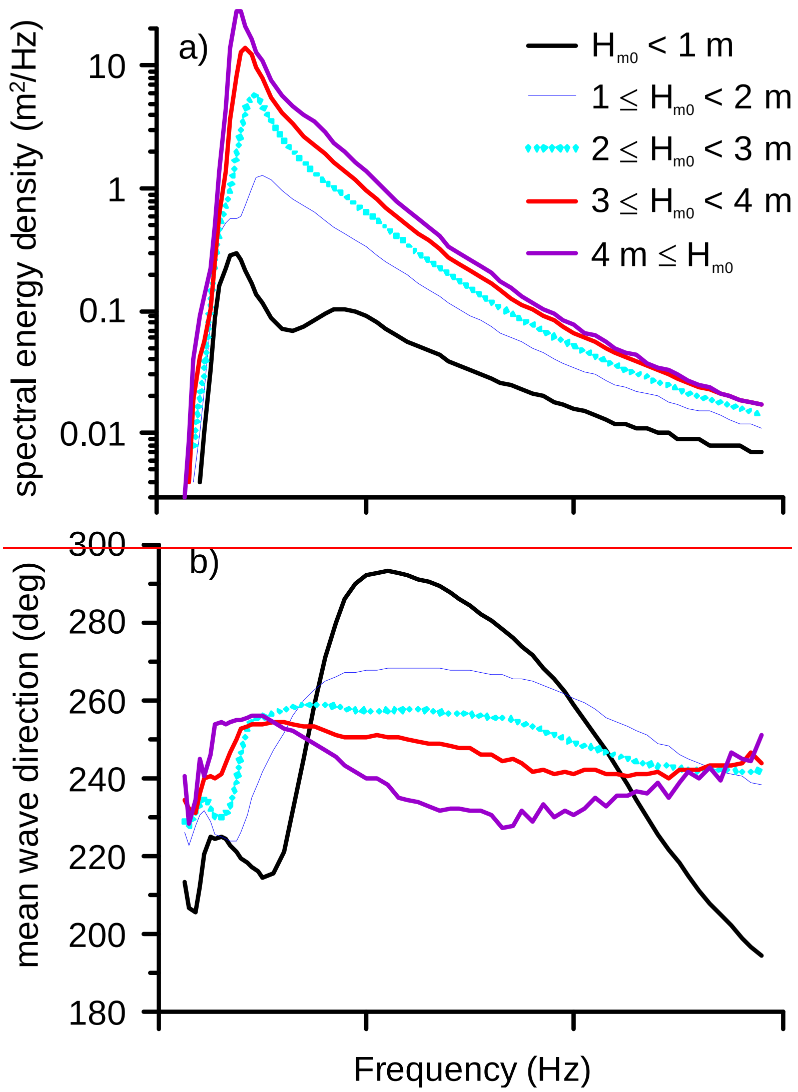


Figure 11. Plot of exponent of the high-a) average spectral energy density and b) average mean wave direction of waves under different H_{m0} with frequency

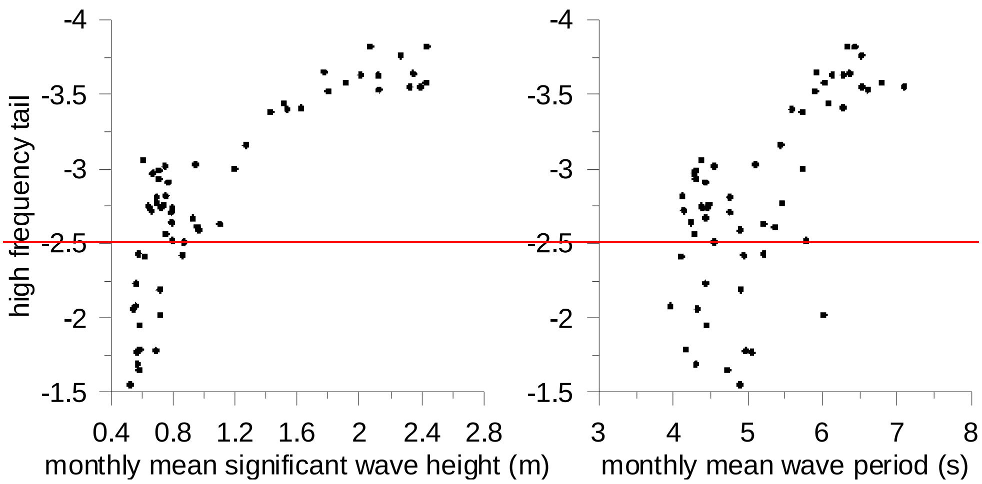


Figure 12. Plot of high frequency tail with a) significant wave height b) (left panel) and with mean wave period, c) wind speed, d) inverse wave age, e) u-wind and f) v-wind (right panel)

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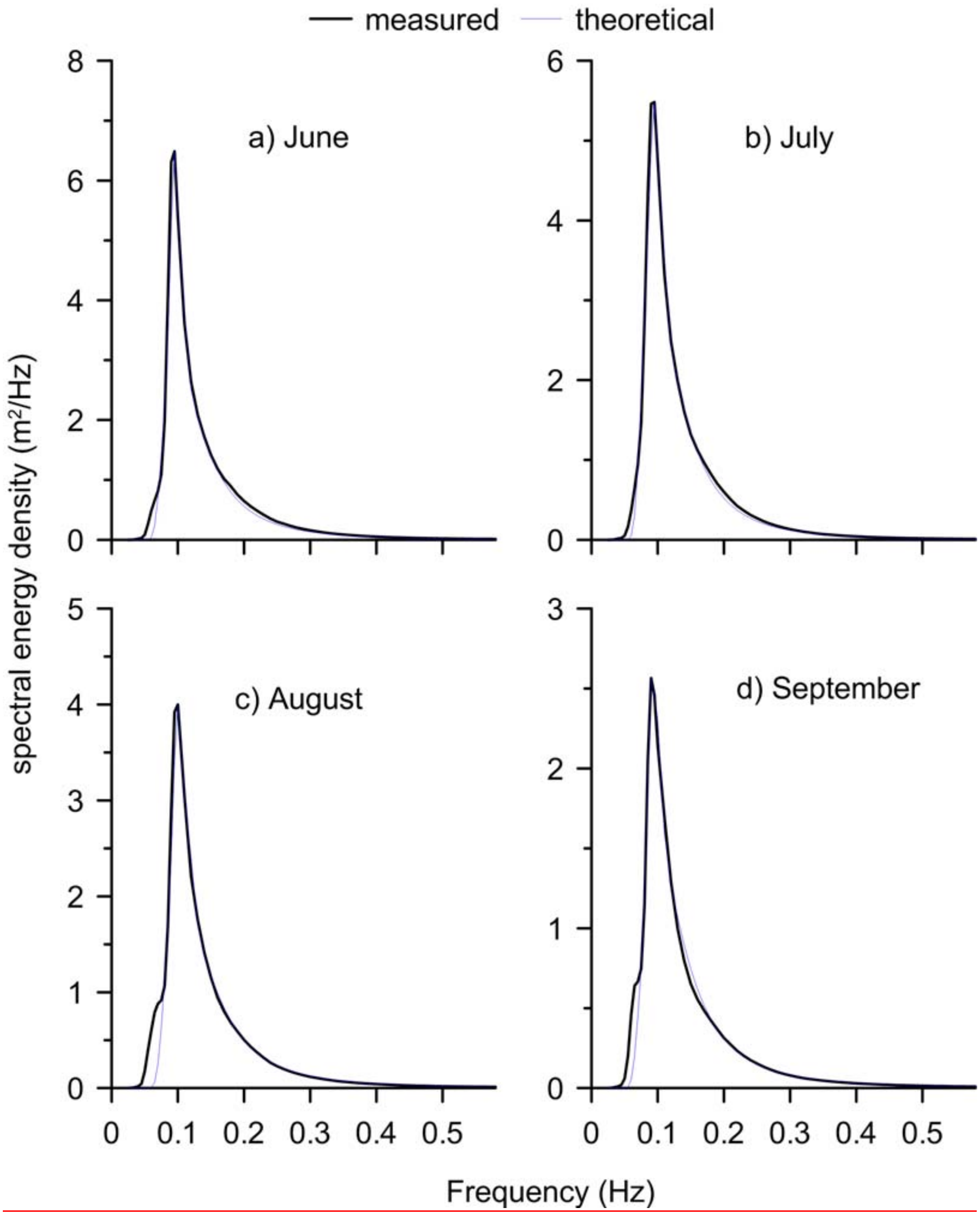
measured
theoretical
a) June
b) July
c) August
d) September
spectral energy density (m2/Hz)
Frequency (Hz)
0
0.1
0.2
0.3
0.4
0.5

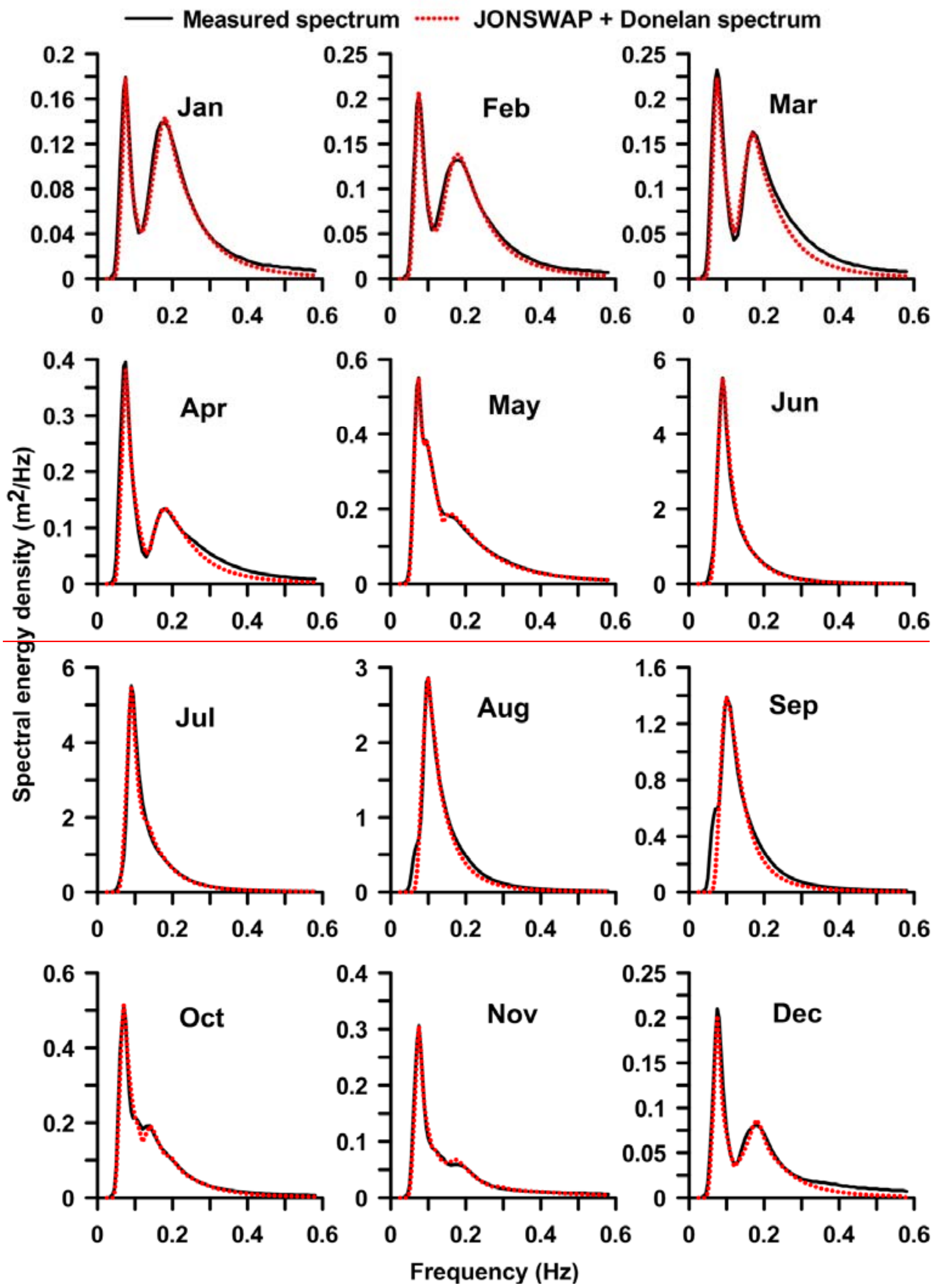

Figure 12. 13. Fitted theoretical spectra along with the monthly average wave spectra for a) June, b) July, c) August and d) September different month