

Steepness of surface gravity waves measured in the eastern Arabian Sea during peak monsoon months

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Abstract

Information on wave steepness is required to design marine facilities and plan safe maritime navigation. In this work, the steepness of the individual waves measured in the coastal waters at five locations using wave rider buoys during the peak monsoon months (June and July) are examined along the west coast of India, covering a distance of ~950 km. A nearly constant value of ~0.025 for average wave steepness is observed for all locations except the southern location (~0.018). At different locations, the maximum wave height ranged from 5.40 to 8.33 m, and the steepness of the largest waves varied from 0.047 to 0.082 and is much smaller than that for the wave-breaking limit. The steepness of the highest waves is larger than its average during the peak monsoon months. The mean wave height during June-July shows less spatial variation over ~325 km except at the south-eastern Arabian Sea, and the mean wave period is approximately the same at all locations. Significant wave steepness based mean wave period compares well with the average of the steepness of waves measured during the 30-minutes period. Interannual variations in the average steepness in June-July during ten years are up to 9.1%.

Key Words: Wind waves, ocean sciences, wavelength, wave steepness

1. Introduction

Wave steepness (S), the ratio between the height and length of the wave, indicates wave stability, with steeper waves representing a greater hazard for navigation. The wave would become unstable and break when the particle velocity at the crest exceeds the phase velocity. In terms of wave profile, this corresponds to a wave having an angle between two lines tangent to the surface profile at the wave crest of 120° (i.e., 60° on each side). In deep water, the breaking wave limit corresponds to a maximum S of 0.1428 (Michell, 1893). Higher steepness causes white capping and wave breaking in deep waters and is the main sink of energy in the ocean (Perlin et al., 2013). In coastal waters, S increases since the wave height increases and the wavelength decreases. As the steepness increases, the wave becomes unstable and breaks at water depth d when S reaches the Stokes limit of $0.1428 \tanh(kd)$ (Stokes, 1880). In shallow water, the waves also break when it meets the breaking criteria related to water depth (the wave height limit is ~ 0.55 to $0.78 d$). In the North Atlantic, areas with many ship accidents were associated with high mean wave steepness values (Guedes Soares et al., 2001). Analysis of global ship accident data between January 1995 to April 1999, along with the sea state parameters, indicate that more than 50% of the incidents occurred for wave steepness values higher than 0.035 (Toffoli et al., 2005). Pecher and Kofoed (2017) reported that the power performance of a wave energy converter (WEC) improves under steep waves since the WEC motions will be slower and smaller in long waves. Ning et al. (2020) observed that the hydrodynamic efficiency of the Oscillating Water Column device decreases with the increase of wave steepness. Mendes and Oliveira (2021) reported that the most severe storms in Northeast Atlantic have steepness values larger than their yearly average. Wave steepness can have a significant influence on coastal erosion (Chen et al., 2023). Steep waves have more energy and are more powerful, meaning that they can erode the coastline more rapidly and severely than less steep waves (Kraus and Larson, 1988).

In the earlier studies, the spectral wave steepness or the integral wave steepness, or the significant wave steepness (S_s) estimated based on significant wave height (H_s or $H_{1/3}$) and either peak wave period (T_p) or mean wave period (Taylor and Yelland, 2001) are examined. In most studies, the mean apparent wave period (T_{m02}) is used as the mean wave period. Some studies used the mean wave period (T_{m01}) resulting from the ratio between spectral moment m_0 and m_1 . The T_p dictates the velocity of the dominant waves and is critical to forecasting the arrival time of waves at the coast. In the real world, waves come from four sources: wind-sea (periods generally between 2 and 7 s) generated by local winds; swells (periods 7-25 s) generated by storm systems far away and infra gravity waves (periods 25-300 s) resulting from the swell interacting with the coastline (Munk,

1950). These waves form a spectrum that may be a single hump or could have four humps, one for each wave type. Thus, the mean period of a set of waves during a storm depends upon the type of storm. The local weather could be calm, and the storm is entirely from swell waves that have been generated thousands of kilometres away, giving mean wave periods of 15 s or more, or there could be strong local winds causing high wind-seas giving mean wave periods < 7 s. The long-period waves cause problems to the mooring of the large of vessel (Shen et al., 2016). For simulated waves from a model, the lower frequency limit in the model is set arbitrarily by the modeller. The mean wave period, T_{m02} , is sensitive to the high-frequency cut-off. For buoy data, the cut-off frequency is generally at 0.58 to 0.6 Hz, and for the model, the cut-off is generally at 0.5 Hz, and it can result in a difference in the parameter estimated from the model from that measured. The earlier studies have shown that T_{m02} gives the closest result to the period, $T_{1/3}$, obtained from the zero-crossing method. T_{m-10} is the one used to characterize wave energy. The results produced by these methodologies are different and should be selected depending on the application. Hence, it is important to examine the variations in the S_s estimated based on different wave periods. It is important to know how S_s compare with the steepness of the individual waves recorded in a 30-minute record.

Seasonally reversing monsoon winds act on the coastal region of the eastern Arabian Sea (EAS), with winds coming from the SW in the summer monsoon period (June-September) and from the NE in the winter monsoon period (October-January). The variations in significant wave height and mean period of monsoon waves in the EAS are studied by many scholars (Rao and Baba, 1996; Kumar et al., 2000; Amrutha and Kumar, 2017). During June and July, the waves in the coastal waters of the EAS are with large wave heights due to the strong winds generated by the Asian summer monsoon (Kumar et al., 2014; Anoop et al., 2015). In the EAS, the depression formed during the summer monsoon resulted in the highest wave heights along this coast, even though they are short-lived, lasting a few days (Kumar et al., 2020). Earlier studies also indicate that waves in the EAS during the summer monsoon period are higher than those due to the tropical cyclones formed during the non-monsoon period (Kumar et al., 2020). The maximum wave height from 2010 to 2018 in the EAS occurred either in June or July (Nair et al., 2021). Monthly mean wave steepness in the coastal waters of the west coast of India is high in July (Kumar and Mandal, 2022). The earlier studies indicate that there are spatial variations in wave characteristics along the central west coast of India (Kumar and George, 2016). Hence, examining the corresponding variations in wave steepness along the EAS is essential.

Against this background, the present study aims to shed light on the steepness of high waves measured in the EAS at multiple locations. This study is based on the continuous wave buoy data

measured from June to July 2014 at five locations. The rest of the paper is structured as follows. Data and methods are described in Section 2. Section 3 deals with the results, Section 4 discusses the findings of the study, and Section 5 summarizes and concludes the study.

2. Data and Methods

2.1 Data and methodology

The measured wave data by the moored 0.9 m diameter Datawell Directional Waverider MkIII buoy from 1 June to 31 July 2014 at four coastal locations and from 1 June to 31 July during 2010-2019 at one location in the EAS is used in the study. The locations selected for the study include Ratnagiri, Karwar, Honnavar (at 9 and 30 m water depth) and Kollam along the EAS (Fig. 1). The geographical coordinates of the locations and the water depth are presented in Table 1. Ratnagiri (northernmost location) and Karwar is at a spatial distance of ~255 km and the distance between Karwar and Honnavar is ~70 km, and Kollam is at a distance of ~630 km from Honnavar. The study is concentrated during the peak monsoon months during the year 2014 and there is no data gap for the period selected. At each location, 2928 data of 30-minute duration are used in the analysis. The interannual variations in the wave steepness during June-July from 2010 to 2019 are examined based on data collected at Ratnagiri. The waverider buoy is moored using an anchor chain with a dead weight of about 450 kg, a 30 m long 35 mm diameter rubber cord and a 30 m long 16 mm diameter polypropylene rope. The waverider buoy measures the vertical and horizontal acceleration of the sea surface and the buoy stores data at 1.28 Hz (Datawell, 2009). Heave is measured with 3% accuracy and 1 cm resolution. The wave heights (H) of the individual wave are obtained from the zero up-crossing method (Tucker, 1991). The maximum height in a 30-minute duration is maximum wave height (H_{\max}). Through a fast Fourier Transform (FFT), the wave spectrum of surface elevation is estimated from the measured heave data at every 30 minutes. The wave spectrum is with a resolution of 0.005 Hz from 0.025 Hz to 0.1 Hz and after that, it is 0.01 Hz up to 0.58 Hz. For the Datawell buoy used in the study, the cut-off frequency is 0.58 Hz. The mean wave period (T_{m02}) is computed from the spectral moments. Mean wave direction is estimated following Kuik et al. (1988). The peak wave period (T_p) is obtained from the wave spectrum, and the period of maximum wave height ($T_{H_{\max}}$) and significant wave period ($T_{1/3}$) is from the individual waves measured during 30-minute interval. The spectral width parameter (ν) (Longuet-Higgins, 1975) is estimated from the moments of the spectrum to examine the narrowness of the wave spectrum. For narrow band spectrum $\nu \leq 0.6$.

Wavelength (L) corresponding to various wave periods is estimated from the respective wave period and the water depth by iteratively solving the wave dispersion relation. The water depth at the buoy location is considered constant while estimating the wavelength, which is not the case since the average tidal range in the study region is ~2 m, and there will be a change in water depth due to the tide. Wave steepness of the individual wave is estimated as the ratio between wave height (H) and wave length (L). From the half-hourly data, the 99, 90, 75, 50 and 25-percentile wave steepness is also computed. Significant wave steepness (S_s) is computed from the ratio of the significant wave height to the L based on T_{m02} , T_p , T_{Hmax} , $T_{1/3}$.

Waves having length less than half the water depth are classified as deep-water waves, while those with a length more than $1/20^{\text{th}}$ of water depth are classified as shallow-water waves and the rest as intermediate water waves (Holthuijsen, 2007).

3. Results

3.1 Distribution of wave height, wave period, wavelength and wave steepness

The time series plots of half-hourly mean values of wave height, wave period, wavelength, and wave steepness from 1 June to 31 July at different locations are presented in Figure 2. The maximum wave height at different locations varied from 5.4 to 8.3 m, whereas the maximum value of $H_{1/3}$ varied from 3.0 to 4.4 m (Table 2). Although large discrepancies are found between maximum wave heights at different locations, records clearly show that the mean wave height during June-July is almost similar at all locations except at the southern location. At the southern location (Kollam), relatively smaller wave heights are observed, except during the first few days of June, compared to other locations. The influence of the Findlater jet (Findlater, 1969) is low in the southern location and hence wave heights are small in the southern location compared to other locations (Fig. 7 in George and Kumar, 2020). Geographical location and the presence of Maldives and Lakshadweep islands could be another factor for the decrease in wave height at the southern location. Wave periods associated with the highest waves are in the range of 9-10 s. Associated wavelengths (L) are in the range of 89-133 m (Table 2). For such wavelengths, the measurement locations represent intermediate water depth with a depth to L ratio ranging from 0.10 to 0.22.

The temporal distribution of wave steepness shows significant variations during the study period due to the change in the intensity of the monsoon. The changes in wave steepness are similar in the coastal waters of the central west coast of India over ~325 km, but shows large difference in the south-eastern Arabian Sea (Fig. 3). The change in wave steepness within a day is not significant during June and July (Fig. 3). Figure 4(a) shows the probability of exceedance of wave steepness for

five locations. At all locations in the study area, with the exception of a few waves that have a period less than 2 s and a height less than 0.3 m, the steepness is less than that for the wave breaking limit ($0.142 \tanh kd$) at the locations analysed (Fig. 4a). In the half-hourly record, the mean wave steepness value ranged from 0.018 to 0.025, while the maximum values ranged from 0.158 to 0.238, which exceeds the wave breaking limit due to a low wave period and wave height. Among the locations studied, the maximum value of 99 percentile wave steepness in the 30-minute record varied from 0.104 to 0.118. For all the waves measured during June-July, the 99 percentile value ranged from 0.055 to 0.076 and the 90 percentile value varied from 0.032 to 0.045 (Table 1). Since wave energy converters (WEC) function substantially better in steep waves, locations with average wave steepness greater than 0.015 are favoured for installation of WEC (Pecher and Kofoed, 2017), and at all locations studied, the average wave steepness exceeds 0.015 (Fig. 5).

The distribution of height of individual waves measured during June-July in different locations indicates that relatively higher high waves ($H > 4$ m) are more at 30 m water depth off Honnavar, whereas they are lower at Kollam (Fig. 4b). Only 0.01 to 0.18% of the waves are with height more than 5 m at different locations. The distribution of the period of individual waves during June-July in different years indicates that relatively higher period waves ($T > 12$ s) are present for 4 to 6.5% of the time at the locations studied. Half hourly mean values of the wave period show a maximum value at Kollam (Fig. 4c). The value for T_{Hmax} varied from 9.2 to 10.1 s for five locations, with a maximum value of 10.1 s at the Honnavar-9m location. The distribution of mean wavelength for every 30 minutes is shown in Figure 4d for the locations at different depths. Differences can be seen in the wavelength values as the locations have varying depths.

For the five locations analysed in the study, Table 1 presents the standard deviation, average, maximum and minimum of wave steepness, wave height and wave period considering all the data during the study period. The number of waves varied from 724093 to 800648 at different locations. Among the five locations, a greater number of waves are observed at Karwar. The standard deviation of wave steepness shows a low deviation from the mean value of wave steepness, and it ranges from 0.010-0.015. The average wave height is more (1.46 m) at Honnavar-30m depth and varies from 1.16 to 1.32 m for other locations. Figure 5 shows the daily average value of wave steepness, wave height, wave period and wavelength from 1 June to 31 July at different locations.

The characteristics of the wave with a maximum height at different locations are listed in Table 2. Relatively smaller values of H_{max} and wave steepness are observed at Kollam. For the locations studied, the highest wave during June and July is recorded at Honnavar-30m with a wavelength of 133 m and a height of 8.33 m. At other locations, the maximum wavelength is from

89 to 113 m and the height ranges from 5.40 to 8.15 m. At different locations, the steepness of the longest wave ranged from 0.003 to 0.007. The steepness of the highest waves ranged from 0.048 to 0.082, with the northern location having the highest value and the southern location having the lowest value. The steepness of the highest waves is larger than its average during the peak monsoon months.

3.2 Comparison between average wave steepness (S_{av}) and significant wave steepness (S_s) based on T_{m02} , T_p , T_{Hmax} , $T_{1/3}$

Most of the earlier studies on steepness described the significant wave steepness (S_s) estimated based on H_s and either T_{m02} , T_p (Taylor and Yelland, 2001). In order to know how S_s values compare with the steepness of the individual wave, S_s based on T_{m02} , T_p , T_{Hmax} and $T_{1/3}$ is compared with the average wave steepness (S_{av}) of the waves recorded in a 30-min record. Figures 6a to 6t represent the scatter diagram and regression analysis between S_{av} and S_s based on T_{m02} , T_p , T_{Hmax} and $T_{1/3}$ values for different locations. The comparison shows that S_s based on T_{m02} , T_p , T_{Hmax} , $T_{1/3}$ is around 0.89 to 1.72 times the S_{av} for Ratnagiri and shows a correlation of 0.81 to 0.99 when all the parameters are statistically analysed (Fig. 6a to 6d). In the case of Ratnagiri, S_s based $T_{1/3}$ is 1.04 times S_{av} , and has a correlation value of 0.95 (Fig. 6d). Table 3 shows the variability of average, minimum and maximum values for S_s based T_{m02} , T_p , T_{Hmax} and $T_{1/3}$ among the different locations. The maximum values of S_s based T_{m02} are 0.061, 0.058, 0.062, 0.057 and 0.050 for Ratnagiri, Karwar, Honnavar-9m, Honnavar-30m and Kollam and the average values range from 0.028-0.041.

For all locations in the present study, S_s based on T_p and T_{Hmax} show a wide scatter, and the minimum values for T_p ranged between 0.004 and 0.005 and the maximum values between 0.035 and 0.041 with average values varying from 0.014 to 0.022 and the maximum values for T_{Hmax} show a maximum range from 0.078 to 0.108 and has average values ranging from 0.028 to 0.38. When compared to the S_{av} , S_s based on T_p exhibits a greater scatter, demonstrating the significance of taking individual wave steepness into account during the design computation. At Karwar, the scatter between S_{av} and S_s based T_{m02} (Fig. 6e) and $T_{1/3}$ (Fig. 6h) shows a correlation of about 0.99 and 0.92. Scatter between S_{av} and S_s based T_p (Fig. 6f) and T_{Hmax} (Fig. 6g) shows a correlation of about 0.75 and 0.73. The S_s based T_{m02} , T_p , T_{Hmax} , $T_{1/3}$ is about 0.98-1.83 times higher than S_{av} (Figs. 6i to 6l) at Honnavar-9m and 0.73 to 1.62 times higher than S_{av} at Honnavar-30m (Figs. 6m to 6p), better correlation is found for S_s based T_{m02} , but S_s based $T_{1/3}$ for all location provides the best match against S_{av} and correlation is 0.93 for honnavar-9m and Honnavar-30m. A greater scatter similar to the other locations is observed in Figs. 6n and 6o, which represent average wave steepness against S_s based T_p and T_{Hmax} for the Honnavar-30m region, which is around 0.73 and 1.62 times higher than

the S_{av} . Among the other locations, the correlation between S_s and S_s based T_p (Fig. 6r) and T_{Hmax} (Fig. 6s) is low for Kollam and is about 0.49 and 0.59; meanwhile better correlation is obtained between S_{av} and S_s based T_{m02} (Fig. 6q) and S_s based $T_{1/3}$ (Fig. 6t) with a correlation value of 0.98 and 0.95. The maximum values of S_s based $T_{1/3}$ at the study locations are 0.040, 0.036, 0.040, 0.034 and 0.030 at Ratnagiri, Karwar, Honnavar-9m, Honnavar-30m and Kollam and the average values are 0.023, 0.021, 0.025, 0.020 and 0.016. Even though at all locations, S_s based T_{m02} provides a high correlation value, the S_s based $T_{1/3}$ best matches with S_{av} . Based on the one-year measured time-series data at four locations covering ~500 km of the western Indian coastline, Kumar and Mandal (2022) reported that the mean wave steepness of the 30-minute record is ~22% higher than the conventionally reported S_s based on T_{m02} .

3.3 Relation of significant wave height ($H_{1/3}$) with root mean square wave height (H_{rms}) and maximum wave height (H_{max})

According to Rayleigh distribution, the significant wave height is linked to root mean square wave height by the equation, $H_{1/3} = \sqrt{2} H_{rms}$. The values of H_{rms} and $H_{1/3}$ are plotted from the given datasets for different locations (Figs. 7a to 7e), a line representing the above equation is drawn in the scatter plot, and a linear relationship is observed. The plot of $H_{1/3}$ and H_{rms} falls on a straight line (Figs. 7a to 7e) and shows a linear relationship between the variables. The $H_{1/3}$ is the parameter that is most frequently used to describe how severe sea conditions are, and on many occasions, it serves as the sole design parameter (Guedes Soares et al., 2004). Therefore, $H_{1/3}$ comparison with the other parameters has a prior importance. The $H_{1/3}$ values range from 0.65 m to a maximum of 4.43 m (Figs. 7f to 7j) for various locations. The H_{rms} values varied from 0.46 to 3.12 m for the entire study region. $H_{1/3}$ is plotted against H_{max} and a best-fit line is plotted, which shows that H_{max} is 1.50 to 1.66 times $H_{1/3}$ (Figs. 7f to 7j). The half-hourly values of H_{max} have a maximum value of 8.33 m at Honnavar-30m depth and a minimum of 5.40 m at Kollam.

3.4 Interannual variations in wave steepness

Analysis of interannual variation in wave steepness is carried out at 13 m depth off Ratnagiri from 2010 to 2019. Figure 8 shows the probability of exceedance of wave steepness at Ratnagiri in different years. Among the years analysed, a greater number of waves are observed for the year 2015. A maximum value of wave steepness is observed in the year 2015 and a minimum is observed in 2010. The 99 percentile values of wave steepness in June-July varied from 0.063 in 2010 to 0.074 in 2018, indicating interannual variations in 99 percentile steepness are up to 9.4% (Table 4). The 90 percentile value of steepness varied from 0.037 to 0.044, with interannual variations of 10.3%. The

75 percentile value of steepness varied from 0.027 to 0.033 with interannual variations of 10%. The average steepness for June-July is minimum (0.022) in 2010 and a maximum (0.027) in 2013, with interannual variations up to 9.1% (Table 4). The mean value of S_s based on $T_{1/3}$ ranged from 0.021 to 0.025 in different years, and the interannual variations are up to 9.2% (Table 4).

4. Discussions

The maximum values of S_s based $T_{1/3}$ at the study locations Ratnagiri, Karwar, Honnavar-9m, Honnavar-30m and Kollam are 0.040, 0.036, 0.040, 0.034 and 0.030 and the average values during June-July are 0.023, 0.021, 0.025, 0.020 and 0.016 at the respective locations. For high extreme sea states, according to DNV rules (DNV, 2000), the 100-year S_s is 0.067 and as per UK Department of Energy (1990), it is 0.050-0.063. For the Northern North Sea, Torsethaugen (1993) reported that for high sea states, the extreme S_s is 0.067-0.071. S_s close to 0.067 is also obtained by Bitner-Gregersen et al. (1998) for the Norwegian Sea. The low S_s in the present study is due to the fact that the maximum H_s of the waves is much lower (2.36 to 3.57 m) compared to the values in the North Sea ($H_s > 5$ m). The mean value of the S_s in the Norwegian continental shelf is 0.045 for H_s in the range 2.11-2.34 m (Myrhaug, 2018). Please note that larger wave steepness values may also be associated with different values of the JONSWAP peak enhancement factor (Myrhaug, 2018). Myrhaug (2018) has shown that the expected value of S_m ranges from 0.031 to 0.046 for the JONSWAP peak enhancement factor from 1 to 5. The JONSWAP peak enhancement factor for the present study area (Ratnagiri) is 1.7 in June and 2.8 in July (Nair and Kumar, 2016), and the average value of S_s during this period is 0.023. At NDBC buoy number 44025, located off the coast of Long Island, New York (water depth 36 m), for maximum values of H_s , S_s varied from 0.06 to 0.07 (Ed Mackay and Johanning, 2018). At 1000 m water depth of the Portugal mainland, during storm conditions (mean and maximum H_s is 2.36 m and 11.03 m), the values of S_s (based on T_{m02}) ranged between 0.020 and 0.072 with a mean value of 0.032 (Mendes and Oliveira, 2021). Kumar and Mandal (2022) observed that the maximum value of S_s (based on T_{m02}) in the coastal waters of the eastern Arabian Sea is 0.033, and the steepness of the waves with height more than 5 m varied from 0.025 to 0.097 with an average value of 0.052. The S_s also can be different for single-peaked and multi-peaked wave spectra (Mendes and Oliveira, 2021). Since the present study is for the peak monsoon months, the wave spectra at all five locations are mainly single peaked and the monthly average wave spectra are with peak frequencies at 0.085 and 0.09 Hz indicating the predominance of swells (Figs. 9a and 9b). The wave spectrum is narrow with mean spectral width parameter varying from 0.5 to 0.55 at the locations studied (Table 1). During June and July, due to the strong southwest winds, a single-peaked spectrum is observed in the coastal waters of the central west coast of India, i.e., a swell peak with a

low frequency and a high spectral energy density (Anjali Nair and Kumar, 2017). Nair and Kumar (2016) observed that during June and July, 72% of the wave spectra are single-peaked swell spectra in the eastern Arabian Sea. The predominant direction of swells in the study area is from the sector between 235° and 255° and the long-period waves are from $220\text{-}240^\circ$ (Figs. 9c and 9d).

5. Conclusions

This article presents the steepness of waves during the peak monsoon period using the data recorded at various locations covering ~ 950 km in the eastern Arabian Sea using the wave rider buoys. The maximum wave height of 8.33 m is observed at Honnavar-30 m depth. The analysis showed that the wave height is higher in the northern part compared to the southern part among the studied locations. Individual wave height distribution along different locations during June and July shows that higher waves with $H > 4.0$ m are higher at Honnavar-30m and lower at Kollam. The maximum steepness for the largest wave is 0.082 and is observed at Ratnagiri and the mean wave period remains similar at all the locations. The average wave steepness is compared with significant wave steepness based T_{m02} , T_p , T_{Hmax} , $T_{1/3}$ and the result show a good correlation and best match for significant wave steepness based $T_{1/3}$. The average wave steepness values are higher than the S_s based T_p and $T_{1/3}$ and lower than S_s based T_{m02} and T_{Hmax} . The largest wave has significant wave height values high at Ratnagiri and the maximum wave height is off Honnavar at 30 m depth. Even though measurements are made in the coastal waters, $H_{1/3}$ shows a good linear relationship with H_{rms} and H_{max} . Generally, it is derived that significant wave height and steepness in terms of mean values change around 10% along the eastern Arabian Sea. Interannual variations in the average steepness in June-July during ten years are up to 9.1%.

Author Contributions:

Anju T M - data analysis and original draft

Sanil Kumar -data analysis and editing

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Table 1. Wave statistics for the period of 1 June to 31 July 2014 at five locations

Location	Position	Water depth (m)	Standard deviation of wave steepness	Average wave height (m)	Maximum wave height (m)	Average wave steepness	99 percentile wave steepness	90 percentile wave steepness	Maximum wave steepness	Average wave period (s)	Mean spectral width parameter	Number of waves
Ratnagiri	16.980° N; 73.258° E	13	0.014	1.33	8.15	0.025	0.073	0.044	0.194	6.8	0.53	770672
Karwar	14.822 N; 74.052 E	15	0.015	1.23	7.38	0.025	0.076	0.045	0.212	6.5	0.55	800648
Honnava r	14.304° N; 74.391° E	9	0.013	1.32	6.62	0.025	0.068	0.042	0.166	7.2	0.55	724093
Honnava r	14.224° N; 74.291° E	30	0.015	1.46	8.33	0.024	0.076	0.044	0.238	6.9	0.53	762136
Kollam	8.978° N 76.445° E	22	0.010	1.16	5.40	0.018	0.055	0.032	0.158	7.1	0.50	737586

Table 2. Characteristics of wave with maximum height at different locations

Location	Month	day	hour	H_{\max} (m)	$T_{H_{\max}}$ (s)	H_c (m)	H_t (m)	$H_{1/3}$ (m)	length (m)	steepness
Ratnagiri	July	18	00	8.15	9.7	4.71	3.44	3.57	99	0.0821
Karwar	June	10	05	7.38	9.2	4.68	2.70	3.38	98	0.0751
Honnavar-9m	July	14	22	6.62	10.1	4.38	2.24	3.32	89	0.0742
Honnavar-30m	July	14	23	8.33	9.8	4.84	3.49	3.55	133	0.0626
Kollam	July	13	03	5.40	9.3	3.25	2.15	2.36	113	0.0477

Table 3. Maximum, minimum and average values for S_s based T_{m02} , T_p , T_{Hmax} , $T_{1/3}$

Location	S_s based T_{m02}	S_s based T_p	S_s based T_{Hmax}	S_s based $T_{1/3}$
Ratnagiri	0.012-0.061 (0.039)	0.004-0.041 (0.019)	0.007-0.095 (0.038)	0.007-0.040 (0.023)
Karwar	0.013-0.058 (0.038)	0.004-0.038 (0.016)	0.007-0.108 (0.033)	0.006-0.036 (0.021)
Honnavar-9m	0.014-0.062 (0.041)	0.005-0.042 (0.022)	0.009-0.086 (0.040)	0.008-0.040 (0.025)
Honnavar-30m	0.014-0.057 (0.037)	0.003-0.036 (0.015)	0.006-0.095 (0.033)	0.006-0.034 (0.020)
Kollam	0.017-0.050 (0.028)	0.005-0.035 (0.014)	0.008-0.078 (0.028)	0.009-0.030 (0.016)

Table 4. Maximum, 99, 90, 75, 50 and 25 percentile and average value of steepness of waves measured from 1 June to 31 July in different years at Ratnagiri along with mean significant wave steepness based on $T_{1/3}$

year	maximum	percentile					average	Number of waves	mean S_s based on $T_{1/3}$
		99	90	75	50	25			
2010	0.151	0.063	0.037	0.027	0.020	0.014	0.022	735845	0.021
2011	0.188	0.068	0.041	0.030	0.022	0.016	0.024	762715	0.023
2012	0.190	0.068	0.040	0.029	0.021	0.015	0.024	745982	0.022
2013	0.179	0.073	0.044	0.033	0.024	0.017	0.027	744260	0.025
2014	0.193	0.073	0.044	0.031	0.022	0.015	0.025	770672	0.023
2015	0.201	0.072	0.043	0.031	0.022	0.015	0.025	788030	0.023
2016	0.170	0.067	0.040	0.029	0.021	0.015	0.024	752962	0.022
2017	0.188	0.069	0.042	0.030	0.022	0.015	0.025	751568	0.023
2018	0.200	0.074	0.044	0.033	0.023	0.016	0.026	744262	0.025
2019	0.190	0.070	0.041	0.030	0.021	0.014	0.024	769014	0.022
Percentage variation									
2010	-18.5	-9.4	-10.3	-10.0	-9.0	-7.5	-9.1	-2.7	-8.3
2011	1.5	-2.9	-2.2	-1.1	0.4	2.4	-0.1	0.8	0.4
2012	2.8	-2.5	-3.4	-4.1	-3.8	-2.2	-2.9	-1.4	-3.9
2013	-3.0	5.1	6.5	8.1	10.2	13.0	8.9	-1.6	9.2
2014	4.7	5.0	4.6	3.5	0.8	-4.2	1.1	1.9	0.4
2015	8.5	3.9	3.4	2.2	0.4	-1.5	1.1	4.2	0.4
2016	-8.2	-3.2	-3.6	-3.1	-2.9	-2.8	-3.4	-0.5	-3.9
2017	1.7	-1.7	-0.2	-0.1	0.4	1.8	0.3	-0.7	0.4
2018	8.0	6.0	6.5	7.1	7.8	7.7	7.3	-1.6	9.2
2019	2.5	-0.2	-1.2	-2.4	-4.3	-6.8	-3.4	1.7	-3.9

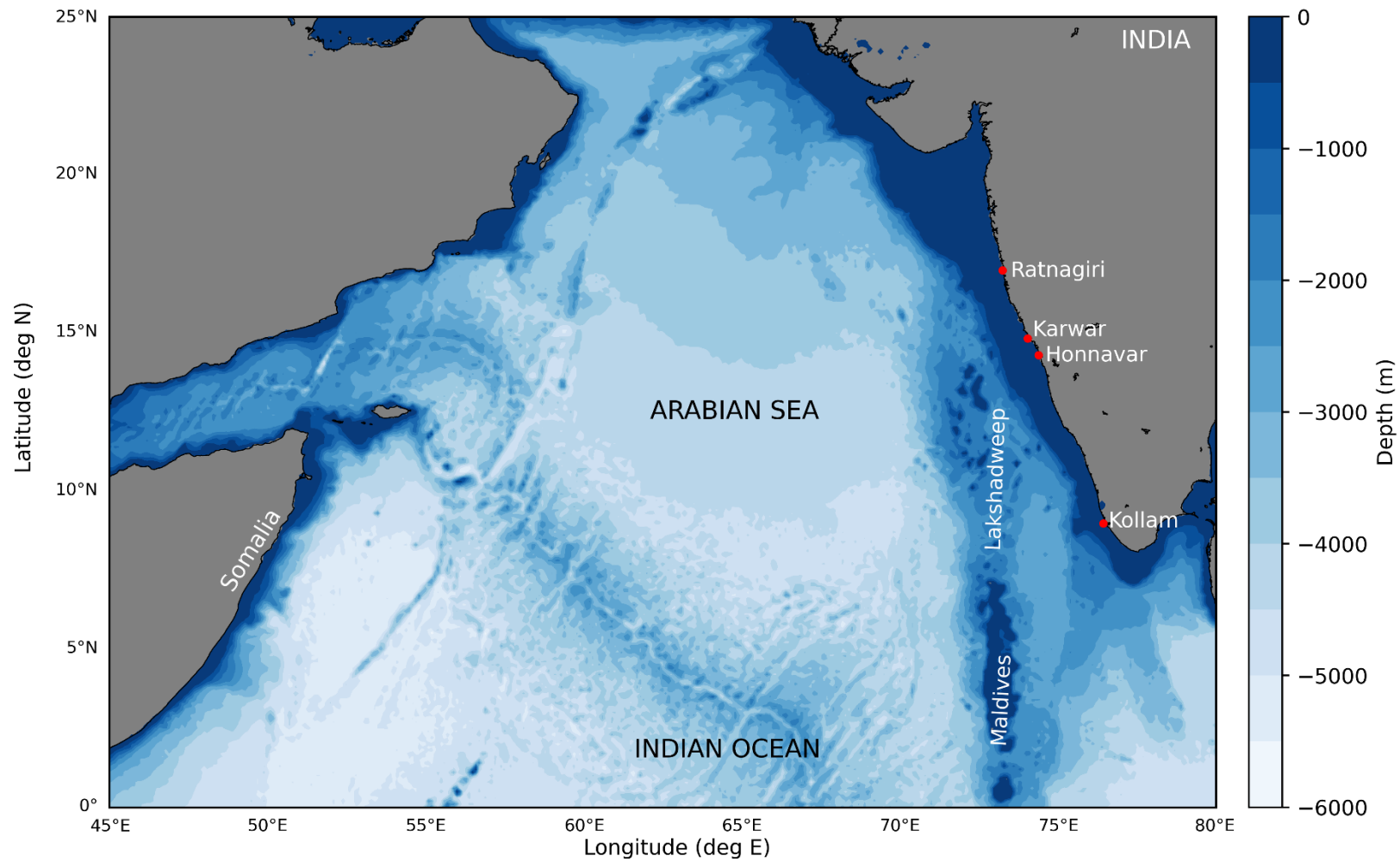


Figure 1. Map showing the study area and geographical locations of waverider buoys in the eastern Arabian Sea. Shaded contour levels indicate the water depth

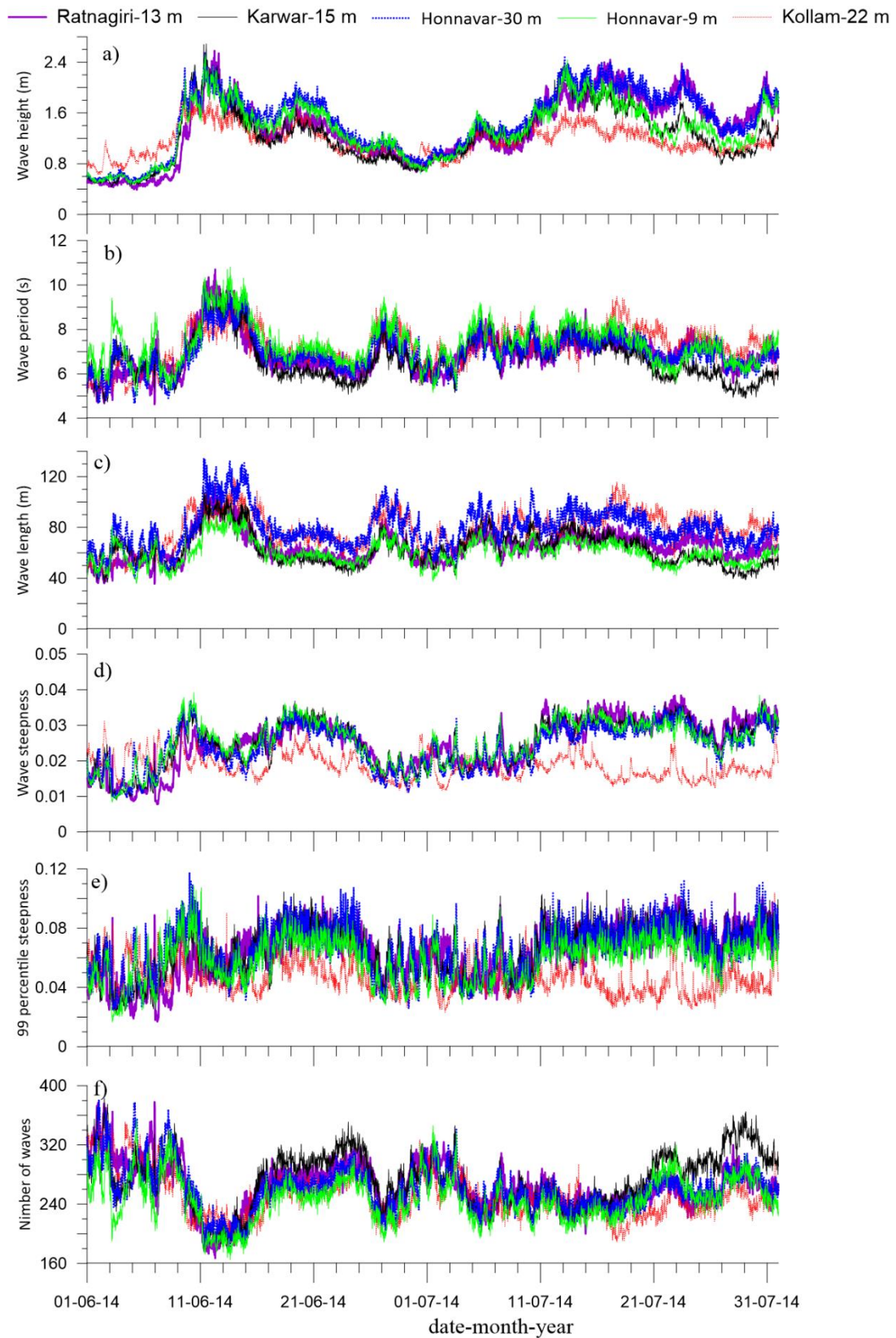


Figure 2. Time series plots of half-hourly mean values of a) wave height, b) wave period, c) wavelength, d) wave steepness, e) 99 percentile wave steepness and f) number of waves from 1 June to 31 July 2014 at different locations

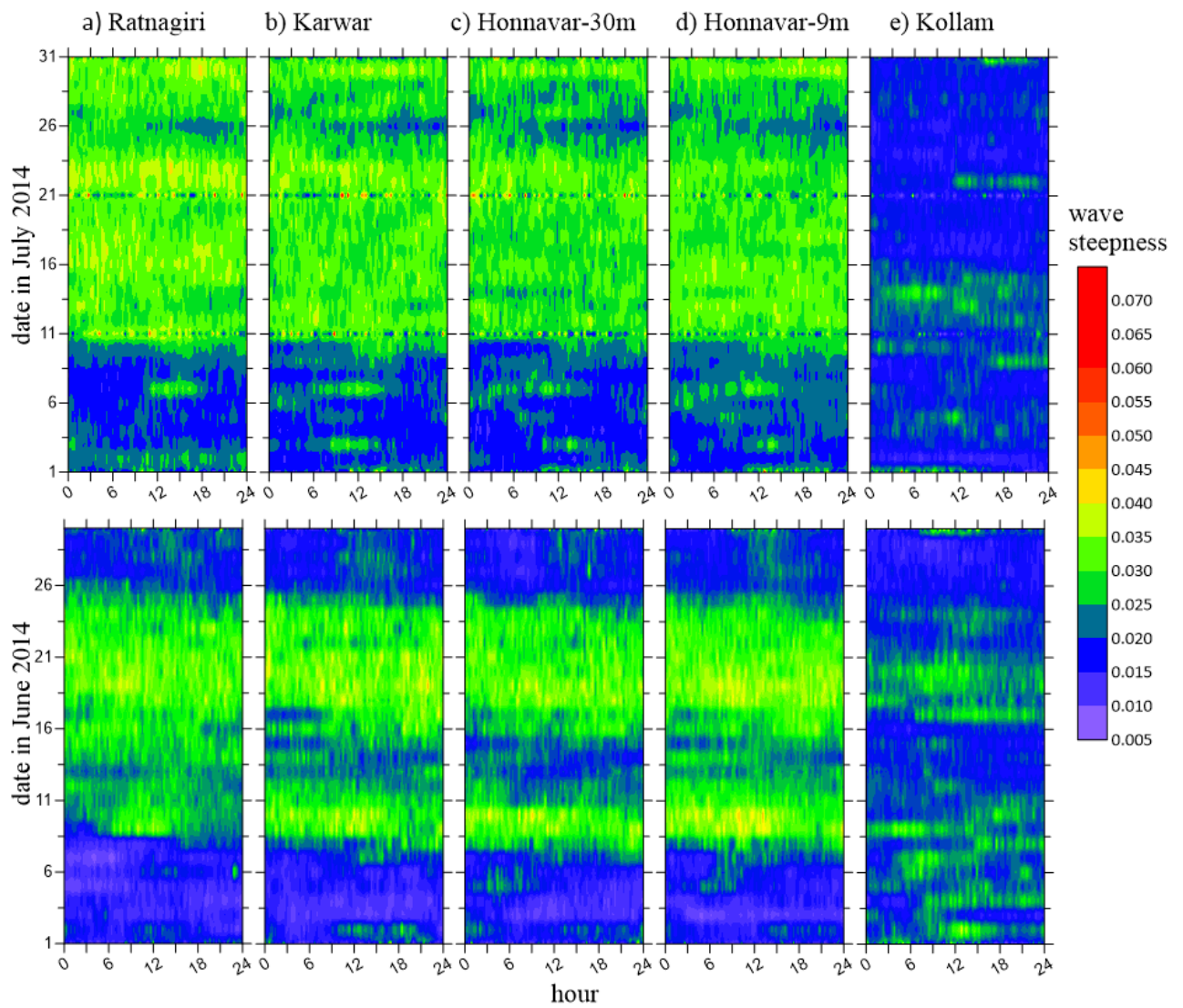


Figure 3. Steepness of waves with time and date at different locations. Top plot is for July 2014 and bottom plot is for June 2014

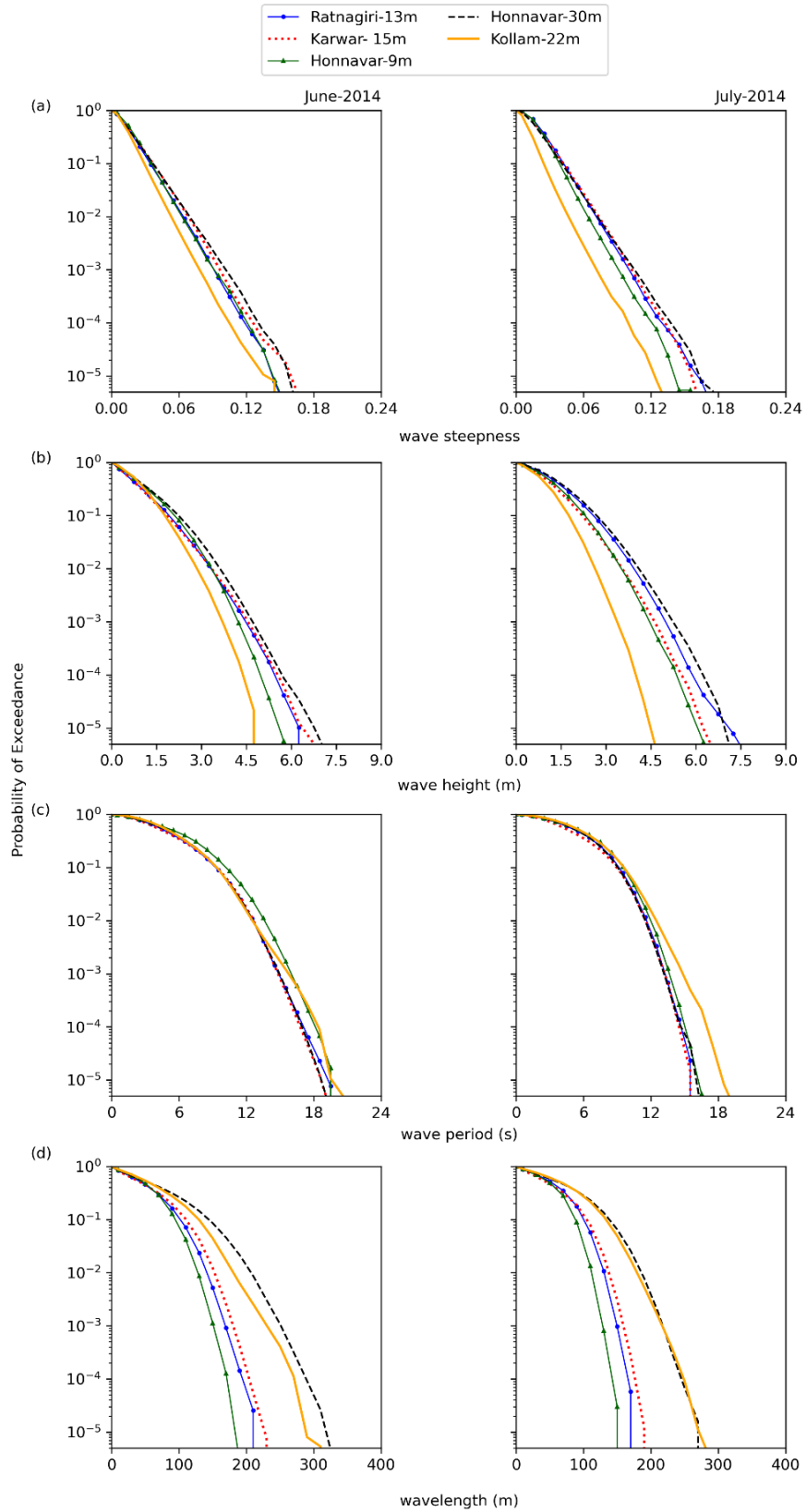


Figure 4. Distribution of a) wave steepness, b) wave height, c) wave period and d) wavelength at five locations. Left panel is for June 2014 and right panel is for July 2014

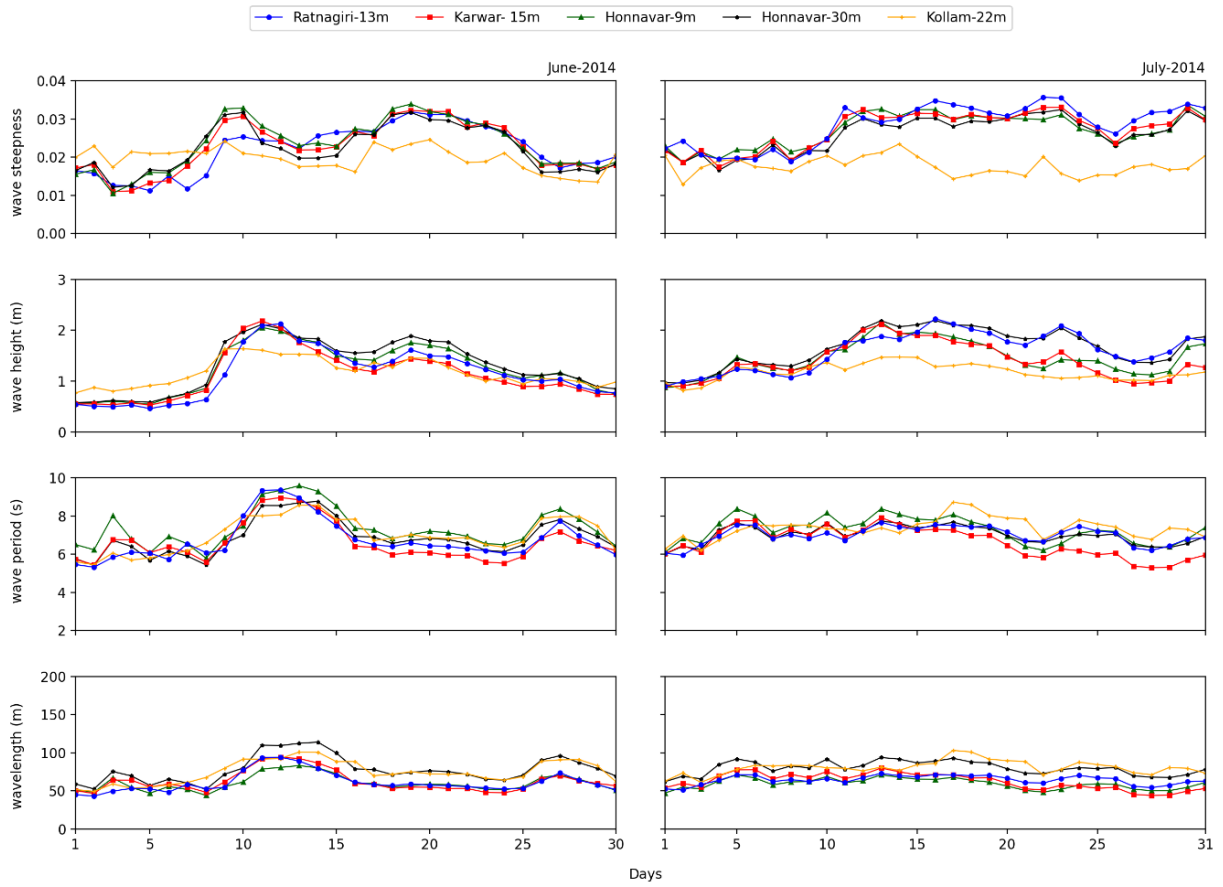


Figure 5. Daily average distribution of wave steepness, wave height, wave period and wavelength for June 2014 and July 2014 at five locations

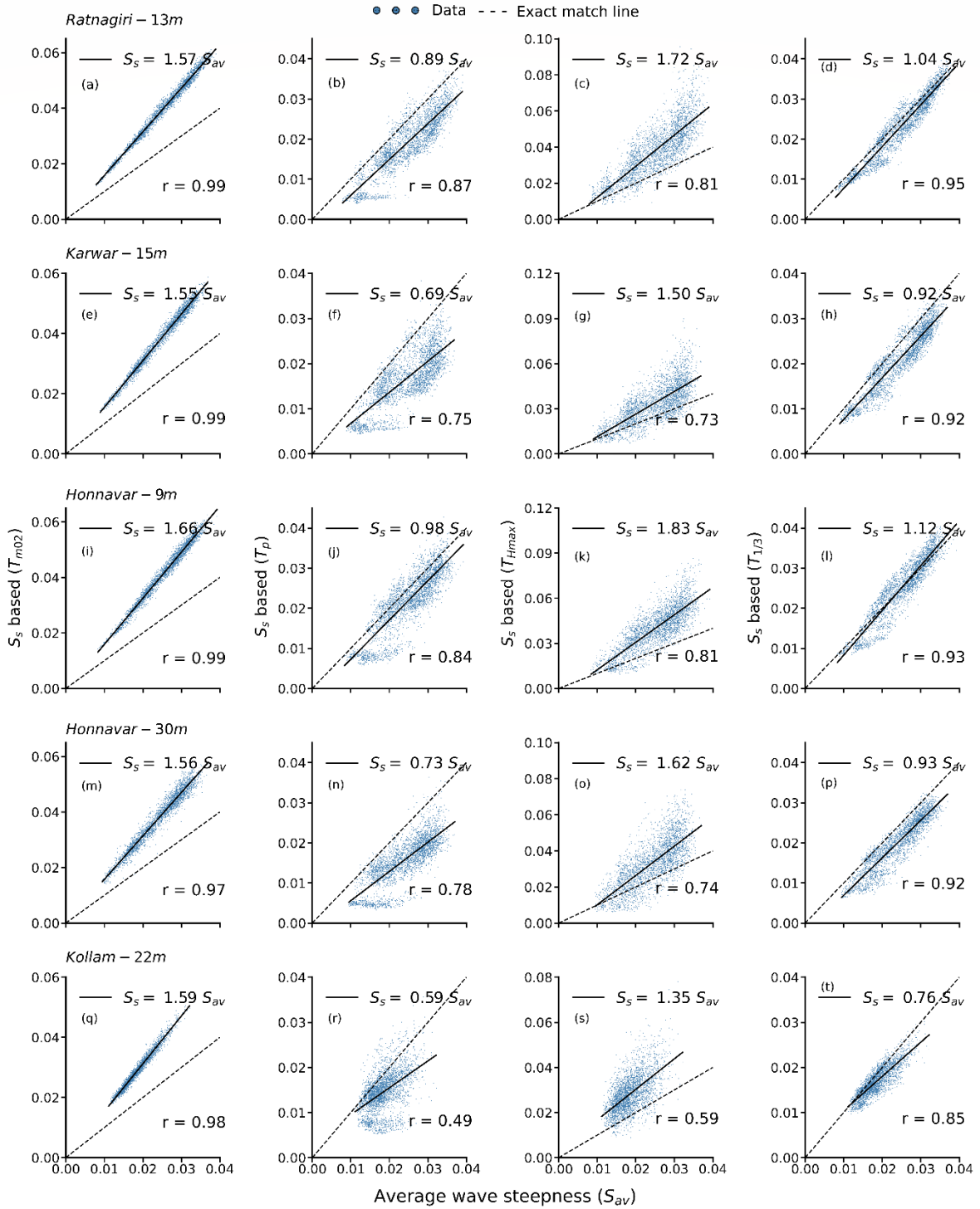


Figure 6 (a to t). Scatter diagrams for average wave steepness (S_{av}) of 30-minutes record and the corresponding significant wave steepness (S_s) based on mean wave period (T_{m02}), peak period (T_p), period of maximum wave height (T_{Hmax}) and significant wave period ($T_{1/3}$) at the 5 locations of study

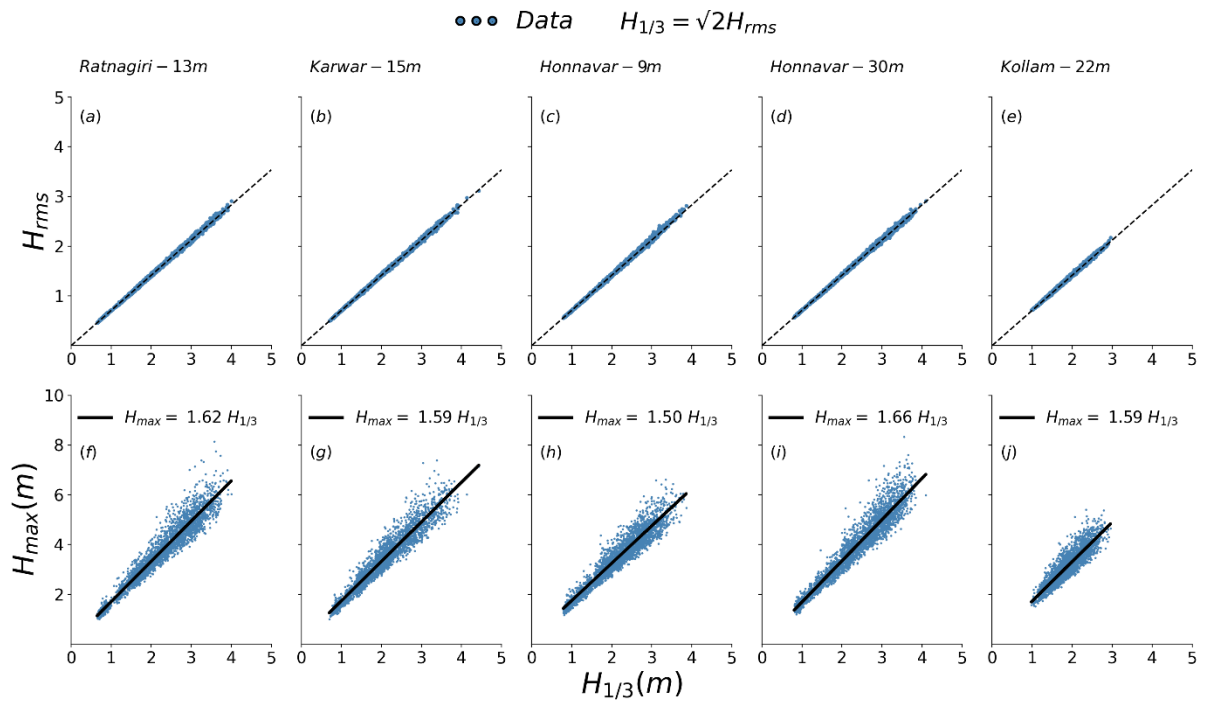


Figure 7(a to e). Scatter diagram between significant wave height ($H_{1/3}$) and root mean square wave height (H_{rms}), f to j) between significant wave height ($H_{1/3}$) and maximum wave height (H_{max}) for different locations

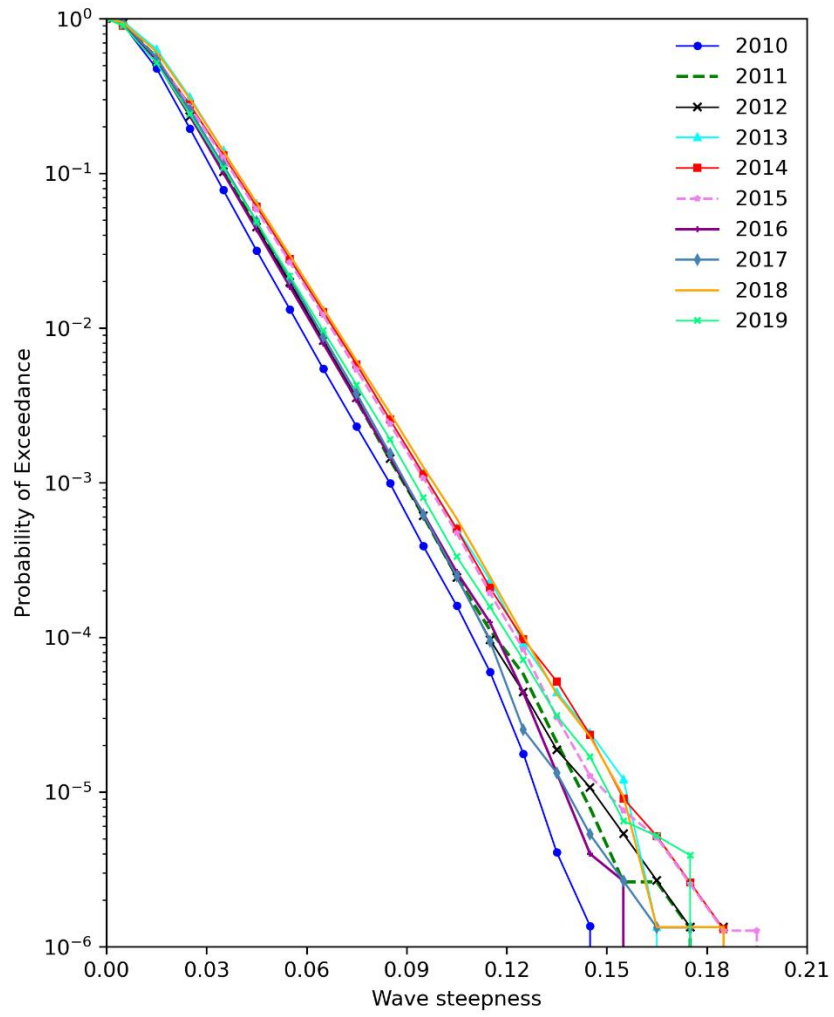


Figure 8. Interannual variations in distribution of wave steepness at Ratnagiri during June-July

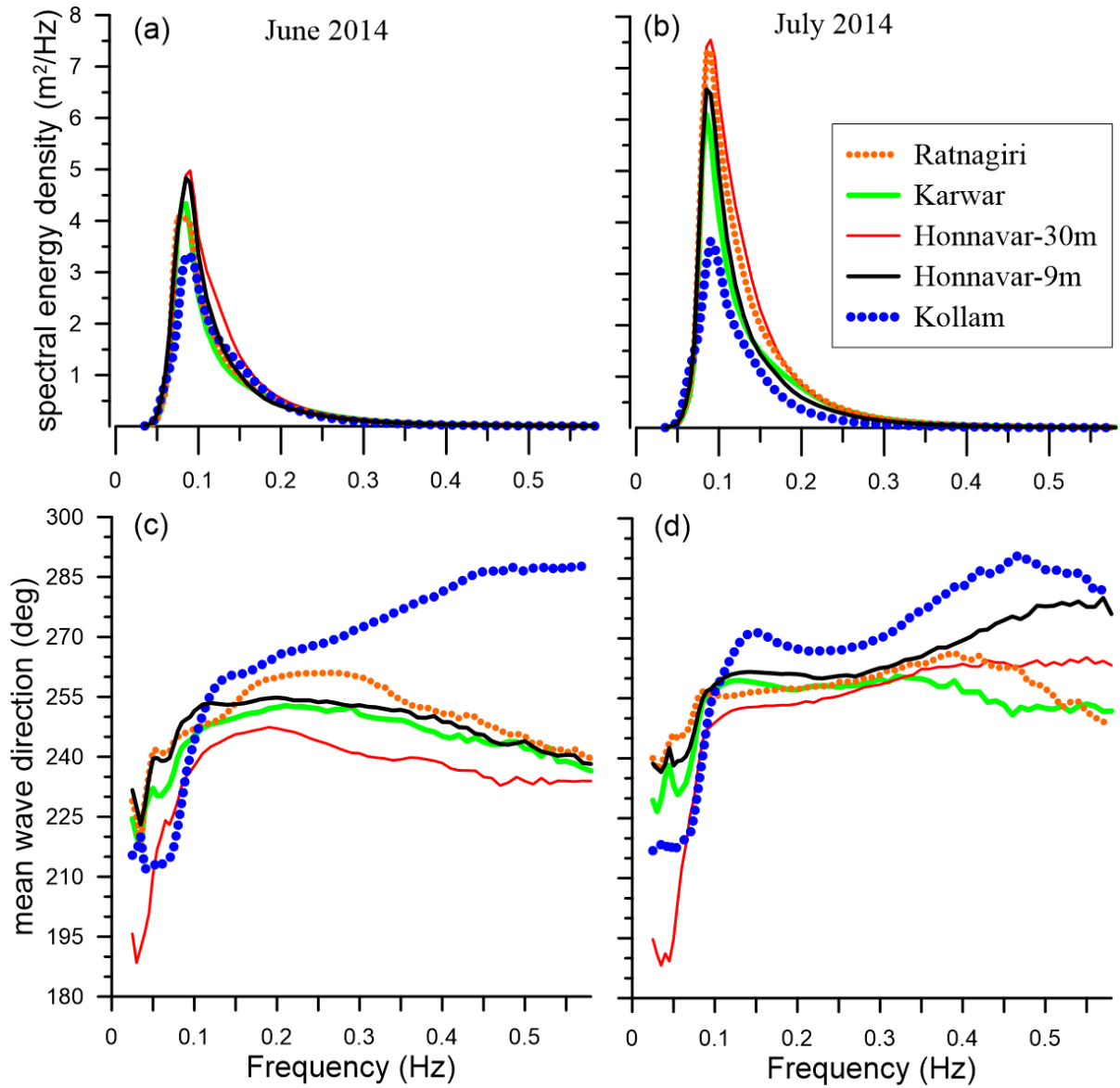


Figure 9. Monthly average wave spectra and the wave direction for June and July 2014 at different locations