

Consistency of wave power at a location in the coastal waters of central eastern Arabian Sea

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Abstract

Wave energy assessment at a regional scale is required for planning installation of wave energy converters. Based on continuously measured wave data at 14 m water depth in the central eastern Arabian Sea from January 2011 to December 2017, the temporal distribution of wave power potential is studied in detail along with statistical analysis of the wave power and wave parameters. Long-term variability in wave power is examined based on reanalysis data from 1979 to 2017. The study also evaluates the wave power technologies such as Oyster, WaveDragon and WaveStar for the study location. Significant inter-annual variations in the wave power are observed from June to September due to the fluctuations in the Indian summer monsoon. The annual mean wave power is 7.85 kW/m with year-to-year variability up to 13% from 2011 to 2017. During 24.7% of the time (~90 days) in a year, the wave power is more than 10 kW/m and is less than 5 kW/m during 68% of the time in a year. Most (90.4%) of the available wave power is from a narrow band between west and southwest. A spatial variability of ~12% in the annual mean wave power is observed along the central eastern Arabian Sea based on the measured wave data at three locations in 14-15 m water depth. The study shows that WaveDragon and WaveStar energy converter produces the electric power during 81 and 85% of the time in a year, whereas Oyster gives output during 59% of the time. The capacity factor of WaveStar is high (27-34%) compared to other technologies considered in the study.

Key words: Renewable energy, ocean energy, wave power potential, North Indian Ocean, resource assessment, Wave Energy Converters.

1.Introduction

Due to the increase in population, economic expansion and increase in transportation, the global demand for energy consumption have increased in the last 50 years. The main sources used globally to generate electricity in 2014 are coal (41%), natural gas (22%), hydropower (18%) and nuclear (11%) (Neill and Hashemi 2018). The global carbon dioxide emissions can be significantly reduced by replacing the present energy sources with renewable energy sources (Clement et al. 2002). Currently, renewable energy sources like wind, solar and biomass contributes only ~5% of the energy source (Neill and Hashemi 2018). Oceans of the earth represent a vast source of renewable energy. The ocean energy sector comprises a number of different technologies from tides, currents, waves, salinity gradient and ocean thermal energy conversion. High energy density is contained in ocean waves and hence have the potential to become an economically viable renewable energy source (Das et al. 1990; Clement et al. 2002). The waves in the oceans are produced by wind action and hence the wave energy is an indirect form of the solar energy. Ocean wave energy resource assessments have been performed on a global and regional level. The potential of wave energy worldwide is ~32,000 TWh/year (Mork et al. 2010), whereas the global electricity production in 2015 is ~23,950 TWh (Neill and Hashemi 2018). The wave energy level is expressed as power per unit length along the wave crest. The highest global wave energy is found in the 40°-60° latitude (Gunn and Williams 2012). The measured wave data by surface following buoys are with a low relative error and are required for accurate wave power estimation. Studies have shown that coastal locations are more suitable for installing wave energy converter (WEC) than offshore locations since the economic viability of the project depends on the length of underwater transmission cables and the mooring cost (Teillant 2012; Rusu 2014). Arrays of WECs installed in the coastal waters can also protect the coast from erosion and can act as a major element in coastal management in addition to the main objective of carbon-free energy generation (Abanadesa et al. 2018).

Due to the lack of measured wave data in the coastal areas, wave energy resource assessment is a significant challenge faced by wave energy plant developers. The consistency of wave power availability at a location is an important input parameter for the effective harnessing of wave power from that location. The bulk wave parameters (significant wave height, peak wave period, mean wave period and wave energy period) provide a good account of the wave characteristics in cases of uni-modal seas, but they fail to adequately represent waves in more complex situations such as multi-modal seas observed in most of the coastal areas (Kumar et al. 2014; Portilla et al. 2015). Measurement of wave parameters over a long period of time at a location is a difficult and expensive task and hence wave data obtained from numerical models, which are capable of reproducing the

bulk wave parameters similar to the measured data is widely used for assessing the wave energy at a location (Cornett 2008). Most of the numerical models reproduce the bulk wave parameters reasonably well, but the reproduction of the wave spectrum still requires further research (Cavaleri et al. 2018). A 10 to 20% error in significant wave height (H_s) could result in a 20 to 50% error in wave energy (Amrutha and Sanil Kumar 2016). Hence, it is important to know the difference in wave power estimate from the bulk wave parameters and from the wave spectrum.

The earlier studies in the eastern Arabian Sea indicate that the wave characteristics can be described by grouping into 3 seasons; i) February-May is the period in which wind-seas from the northwest are predominant, ii) June-September is the period of strong westerly waves due to the Indian summer/southwest monsoon (hereafter monsoon) and iii) October-January is the period in which long-period swells from south and southwest are predominant (Glejin et al. 2013; Kumar et al. 2014; Anoop et al. 2015; Amrutha et al. 2017). Accordingly, in the present study, wave power during three seasons; pre-monsoon (February-May), monsoon (June-September) and post-monsoon (October-January) are examined. Also, the earlier studies indicate that the waves in the region are predominantly swells superimposed on wind-seas and the surface height variance due to wind-seas varies with the season (Kumar et al. 2014). For selecting a wave power plant orientation, the directional distribution of wave power is required and Amrutha and Sanil Kumar (2016) observed that high wave energy (>20 kW/m) in the coastal waters of the central west coast of India is essentially from the directional sector $245-270^\circ$ and it contributes to 75% of the total annual wave energy. Along the west coast of India, even though the bulk wave parameters are similar for a stretch of 350 km, there is a large variation in the distribution of wave spectral energy in frequency scale due to the variations in the wind-seas induced by the local winds and swells (Kumar et al. 2014) and hence can change the peak wave direction. Kumar et al. (2013) examined the variation in the wave power over a period of one year based on the measured wave data at four shallow water locations around India and observed large seasonal variations due to the monsoon. Kumar and Anoop (2015) examined the inter-annual variations at 19 deep-water locations in the Indian shelf seas during 1979 to 2012 based on the bulk wave parameters (significant wave height and energy period) of ERA-Interim (Dee et al. 2011) reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

Energies from waves are harnessed using WECs. The wave energy resource at a location is to be integrated with characteristics of WECs to design wave energy projects. Number of WECs have been developed since the 1940s (Karimirad 2014), but only a few of them are commercially

demonstrated in the actual sea conditions. More than 200 WECs are under development in 2017 with varying degrees of maturity (Babarit 2017). Progress from pre-commercial, full-scale prototype testing to the commercialization of WECs has been relatively slow (Neill and Hashemi 2018). Even though several WEC concepts have been tested, due to the harsh ocean environment, at present most of the concepts are not commercially viable. Another issue is related to the survivability of the WECs during storms or extreme wave conditions. A review of the wave power technology, characterisation of the global resource, most suitable places to be exploited and the different types of WECs are presented by López et al. (2013). Four classes of devices such as oscillating water column (OWC), point absorbers, attenuators and oscillating wave surge converters account for 80% of research efforts (Magagna et al. 2016). 64% of WECs are designed for the offshore application. Vannucchi and Cappiotti (2016) estimated and evaluated the performance of six WECs for the Italian seas, where the wave energy resource is 4 to 10 kW/m and their study demonstrates that the devices that suits are WaveDragon and Pelamis because of their capacity factor. The study of Vannucchi and Cappiotti (2016) indicates that WaveDragon is a device which produces high mean power output as well as the maximum capture width for offshore areas and depicts that the WaveStar is the most suited device for all areas of the Italian seas in terms of higher values of capacity factor. In nearshore waters, the effect of wave propagation is observed in the whole water column and hence a WEC can be placed at any depth inside the water column for power generation. The average annual wave power (1.8–7.6 kW/m) along the coastal locations around India is lower than that in the temperate zones (Kumar et al. 2013). Even though the high energetic environments are promising sites for installation of the WECs, they also have increased survivability dangers associated with higher extreme events (Lavidas 2016). It is important to select a WEC that correspond well to regional metocean conditions, striking a balance between costs and extracted power (Lavidas 2018). Hence, WEC deployed at a milder environment is better for energy production with lower risks.

In the present study, in particular, we assess the seasonal and inter-annual variability of wave power. We also compared the wave power estimation based on bulk wave parameters and that based on the wave spectrum to better understand the validity of the equation based on bulk wave parameters in the coastal waters. The power from a few wave energy devices such as; multiple-point absorber (WaveStar), overtopping (WaveDragon) and oscillating wave surge converter (Oyster) are also estimated for the study location.

2. Materials and methods

Directional wave information recorded at half-hourly interval by Datawell Directional WaveRider (DWR) buoy in the central eastern Arabian Sea at Ratnagiri (14 m water depth; geographical position 16.980° N, 73.258° E) from January 2011 to December 2017 is used in the study (Figure 1). Measurement location is 1.5 km from the nearest land. Although buoy records are one of the most reliable sources of wave data, they suffer from data loss due to drifting from deployed locations and retrieval for routine maintenance. But in the study location in all years, 90.7–100% data recovery rates are obtained (Table 1). The details of the length of data used in the study along with the range and mean of the significant wave height, wave energy period and wave power are presented in Table 1.

Accelerometers housed inside the Datawell DWR measure waves with heights up to 40 m with a vertical resolution of 0.01 m and periods in the range of 1.6–30 s. The displacement of the buoy is sampled at a rate of 3.84 Hz and the data are stored in buoy's memory card with a sampling frequency of 1.28 Hz. By applying the fast Fourier Transform (FFT) to the heave time series data of the buoy, the wave spectrum is obtained. The significant wave height (H_s) and the wave energy period (T_e) are obtained from the spectral moments using Equations 1 and 2.

$$H_s = 4\sqrt{m_0} \quad (1)$$

$$T_e = \frac{m_{-1}}{m_0} \quad (2)$$

Where m_n is the n th order spectral moment and given by $m_n = \int_0^\infty f^n S(f) df$ and $S(f)$ is the spectral energy density (m^2/Hz) at frequency f .

The wave directionality is estimated from the north and west displacement of the buoy following Kuik et al. (1988). Wave parameters are converted to wave power per unit of crest length (kW/m) by using the below expression [3].

$$P = \rho g \int_0^{2\pi} \int_0^\infty C_g(f, d) S(f, \theta) df d\theta \quad (3)$$

Where, ρ is seawater density (kg/m^3), $C_g(f, d)$ is the group velocity (m/s), g is gravitational acceleration (m/s^2), d is the water depth (m), $S(f, \theta)$ is the directional wave spectral energy density ($m^2/Hz/deg$), f is the frequency (Hz) and θ is the wave direction (deg).

Wave power is also estimated from the bulk wave parameters (H_s and T_e), based on the equation (4) derived for the deep water condition to know the difference between the estimated value from this approximation and that from equation (3).

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (4)$$

When the wave energy period (T_e) values are not available, the same is estimated from the peak wave period (T_p) using the expression $T_e = 0.9T_p$. The wave power estimated from this method is also compared with that obtained from the wave spectrum.

Consistency index (CT) of the wave energy is calculated as the ratio of the average wave power in a month to the annual average wave power (Wan et al. 2015). The wave power variability is determined through the coefficient of variation, monthly variability index and seasonal variability index as described by Cornett (2008).

Since the measured wave data is only for seven years, to know the wave power variability for a longer period (~39 years), the ECMWF climate reanalysis data (ERA5) from 1979 to 2017 for the nearest location (17° N; 73° E) is used. ERA5 is the fifth generation of ECMWF atmospheric reanalyses of the global climate and it provides hourly estimates of the variables on a 30 km grid (Hersbach and Dee 2016).

The performance characteristics of a given WEC is typically specified by manufacturers in terms of a power generation matrix which relates power generation to a given sea state condition as defined by the H_s and T_e . The power captured by each WEC is the product of the power matrix of each device and the number of occurrence of the sea state represented by the bivariate distribution of wave height and energy period. In contrast with other renewable energy devices, there is not one single established WEC that consistently presents the best performance globally. Most of the WECs are designed to be deployed in deep water to take advantage of the resource (which is larger). However, the deployment of WECs at shallower waters presents undoubted advantages as lower mooring costs or cheaper and easier connection to the electrical network, which can compensate for a lower resource (as a consequence of energy dissipation due to bottom friction). Table 2 provides some of the WECs developed. In the present study, three technologies given below are selected for 14 m water depth and the power matrix of these technologies are presented in Tables 3 to 5. Technologies like Archimedes, Wavebob, AquaBuOY, OWC and Pelamis are not considered in the study since they are generally proposed for water depth > 50 m.

a) Oyster (Aquamarine Power): It is a large bottom hinged buoyant oscillator that oscillates along the surge action of the water column from the ocean surface to the seabed. 18 m wide and 12 m high unit with a rated power of 315 kW is considered in this study. A hydraulic piston is driven by the surging action of waves and the pressurized water to shore via high-pressure pipelines. This water is fed to the Pelton wheel provided in the onshore hydroelectric plant. The turbine connected to it generates electricity and the power matrix is presented in Table 3.

b) WaveDragon (Wave Dragon A/S): WaveDragon is a floating WEC and works under the principle of overtopping. It comprises of an overtopping ramp over which the waves overtop and a floating reservoir which gets filled with overtop water. This water is fed through the number of turbines provided inside the reservoir. The waves are guided to the device through reflectors which increase the head of water by storing more energy. This potential energy of waves is converted into electricity by a permanent magnet generator that is mounted along with the turbine. The power produced as per the power matrix (Table 4) is delivered into the grid through subsea cables.

c) WaveStar (Wave Star Energy): WaveStar energy converter is a multiple point absorber installed in nearshore wave conditions. It consists of a number of point absorbers connected to the platform generators for capturing the upward and downward movement of waves. These floats are attached with a floating arm that activates the pumps pressurizes the hydraulic fluid to drive the hydraulic motor. Each floating absorber consists of the piston inside every individual cylinder which induces pressure on the hydraulic fluid to drive the motor when the absorber gets lifted up. The generator is driven by the motor producing electrical power and the power matrix is presented in Table 5.

3. Results

3.1 Wave energy resource

During the seven years (2011 to 2017), H_s varied from 0.23 to 5.50 m with an average value of 1.14 m and the average wave energy period of 7.4 s (Figure 2). During the same period, the wave power varied in a wide range from 0.16 to 158.86 kW/m (Figure 2b). The greatest contribution (~44%) to the total annual wave power comes from the sea state with H_s between 1.5 and 3 m and T_e between 5 and 9 s, corresponding to wave power of 10–30 kW/m. Sea state having wave power more than 30 kW/m occurred during 6.2% of the time and contributed to 35% of the annual wave power. For wave power, the standard deviation (11.85 kW/m) is higher than the mean (7.85 kW/m) indicating that the wave power is very widely distributed with positive skewness.

The distribution of sea states with wave height and energy period for the period 2011 to 2017 is presented in Table 6. Majority of the waves (~59%) are with H_s between 0.5 and 1.5 and ~80% of the waves are with T_e between 5-9 s. The wave power resource in terms of the wave periods and heights for the typical year 2015 are shown using the joint distribution graphs (Figure 3). These graphics represent the wave energy for diversified wave conditions. The range of energy periods is broad and the majority of wave energy is offered by sea states having significant wave heights of 3–5.5 m and wave energy periods of 6–16 s.

In the study area, during 28.9% of the time (~ 105 days per year), northwest waves are predominant and in the remaining period, waves from southwest and west are predominant. The northwest waves are with peak wave period less than 8 s and their mean H_s is 0.8 m. These northwest waves contain less wave power with a mean wave power of 2.6 kW/m (Figure 2). The wave with peak wave period more than 8 s are from the southwest and west with mean H_s of 1.3 m and the annual mean wave power of these waves are 9.88 kW/m. The directional distribution of the wave power is examined using wave power roses having directional bins of 5° (Figure 4). The wave rose diagram and Figure 2 indicates that the study area has three different wave regimes; i) northwest waves with spectral period less than 8 s and these waves are mainly during February-May, ii) southwest-west waves with relatively high energy and are observed only during monsoon period (June-September), iii) southwest waves with relatively larger spectral peak period observed during non-monsoon period (Figure 4). Annually 90.4% of the wave power at the study location is due to the waves from southwest and west. Northwest waves contribute only 10.6% of the total wave power. Around 80% of the total wave power is essentially from the narrow directional sector $245\text{--}270^\circ$ with an average wave power of 19.3 kW/m having average H_s of 2 m. Narrowband directional distribution is a result of depth-induced shoaling and wave refraction.

The monthly average values of significant wave height, energy period and the wave power are used to study the intra-annual variability (Figure 5). The highest monthly average wave power (>20 kW/m) is in July in most of the years and in 2011 and 2015, the highest value is in June. The lowest monthly average wave power (~ 1 kW/m) is either in November or December. Intra-annual variability is clearly evident with June and July exhibiting monthly average wave powers that are 10-20 times as large as those in November and December. This variability of the wave resource will significantly affect the power performance of the WEC. The wave power varies largely between the seasons. The monsoon is the season with more wave power, with an average of 19.5 kW/m, followed by pre-monsoon with 2.4 kW/m and post-monsoon with 1.4 kW/m. In the pre-monsoon period, the

seasonal mean wave power varied from 2.1 kW/m (in 2014) to 3 kW/m in 2016. In the post-monsoon season, swells originated in the Southern Ocean are observed in the north Indian Ocean (Kumar et al. 2019), but their energy gets dissipated along the way leading to waves with $H_s < 1.5$ m. The seasonal mean wave power in post-monsoon varied from 1.2 kW/m in 2011 to 1.6 kW/m in 2013 with an average value of 1.3 kW/m. The wave power is larger in the pre-monsoon compared to the post-monsoon due to the strong local winds from the northwest. During the monsoon period, the average wave power varied from 17.1 kW/m in 2015 to 21.8 kW/m in 2014. The annual average and the monsoon average wave power were least in 2015, but the annual maximum wave power (158.9 kW/m) is in 2015.

In addition to the seasonal variations, one important component which influences the performance of the WEC systems is the inter-annual variation in wave power. The annual mean H_s varied from 1.07 m (in 2015) to 1.21 m (in 2013) with inter-annual variations up to 6.2% (Table 1). Accordingly, the annual mean wave power varied from 6.9 kW/m in 2015 to 8.9 kW/m in 2013 with an average value of 7.85 kW/m indicating that 2013 is the most energetic year. The inter-annual variations in annual mean wave power are up to 13% (Table 1). In the annual maximum wave power, large variations are observed (55.0 kW/m in 2012 to 158.9 kW/m in 2015) with a mean value of 91 kW/m. The large inter-annual variation (up to 74%) in annual maximum wave power is due to the large variation in the annual maximum H_s . Annual maximum H_s is lowest (~ 3.54 m) in 2012 and is maximum (~ 5.50 m) in 2015. A depression ARB02 (IMD, 2015) developed 650 km northwest of Ratnagiri generated high waves with H_s up to 5.50 m on 23 June 2015 and a wave power of 158.9 kW/m. After 2015, the next highest annual maximum wave power of 100.6 kW/m is in 2014.

The inter-annual variations in wave parameters are presented in date versus year plots (Figure 6). H_s has its maximum values ($H_s > 3$ m) during the monsoon period with a wave direction of WSW and wave energy period of 7 - 10 s. During the pre-monsoon period in all the years, H_s is low ($H_s < 1$ m) with waves from SW, W and NW directions. During post-monsoon, similar to the pre-monsoon period, H_s observed is less than 1 m, but the wave direction is predominantly from SW and W, with least NW waves (Figure 6d). Due to the early onset (on 1 June) and advancement of monsoon during 2013, the H_s reaches high in June early compared to other years. Similarly, the monthly mean wave power in June is also maximum (31 kW/m) in 2013 compared to other years. The large variation (0.2 to 4.6) in the consistency index is found in different months (Figure 7a). Consistency index close to 1 indicates constant wave energy throughout the year. Inter-annual variations in the monthly average wave power are observed mainly from May to September due to the alterations in the monsoon

intensity. The variations in December are due to the Tropical Cyclone Okhi (Figure 7b). Tropical Cyclone Okhi is a result of the depression formed off the southeast coast of Sri Lanka on 29 November 2017 and moved along the west coast of India. The inter-annual variations in the seasonal average wave power are also high during the monsoon period (Figure 7c) and are least during the post-monsoon period. The inter-annual variations in the percentage of waves with wave power less than 5 kW/m are less than 7%, whereas large variation (up to 40%) is observed in the percentage of waves with wave power 5 to 10 kW/m (Figure 7d). The coefficient of variation indicates that the wave power variability is low (~ 1.3) in 2012 and relatively high (~ 1.8) in 2015 (Figure 8). The seasonal variability index varied from 2.2 in 2013 to 2.5 in 2014. Cornet (2008) reported seasonal variability greater than 1.25 for the northern hemisphere and 0.5 to 1 for the southern hemisphere. Locations with low seasonal variability compared to those with high energy are suitable for sitting wave power plant. The monthly variability index varied from 3.0 in 2011 to 4.3 in 2014 indicating that the differences in wave power between the most energetic month and the least energetic month are 3 to 4.3 times the annual mean wave power. Significant variation in the monthly variability index indicates that the wave power is not steady in the study area. The yearly variability index, the ratio of the difference between the wave power of the most energetic year and the least energetic year to the average wave power is 0.25.

Earlier studies in the eastern Arabian Sea show diurnal variation in wave parameters during pre-monsoon due to the sea breeze (Kumar and Anjali 2015). Sea breeze influence on wave power is important because they occur mainly during the summer afternoons which is the peak energy demand periods. To get a better insight on wave power variation in a day, the half-hourly average wave power in monthly is computed and the variation in the wave power due to the sea breeze is presented through the plot of half-hourly averaged wave power with time (Figure 9). During January to May and in December, the wave power is highest from 1400 to 1700 UTC (Figure 9).

The wave power estimate based on the deep water equation (4) is 5% less than that estimated based on wave spectrum (Table 7). Since the study location is intermediate water depth, the wave power estimate based on approximate equation (4) derived for the deep water lead to underestimation of wave power. Since in the study area, long period swells ($T_p > 12$ s) are present, the wave power estimate using $0.9T_p$ as the wave energy period lead to overestimation of wave power with a bias of 0.9 to 1.3 kW/m in different years (Table 7). Earlier studies (Kumar et al. 2013; Amrutha and Sanil Kumar 2016) also found that the expression $T_e = 0.9T_p$ is not valid at shallow water locations around India.

For the feasibility of the wave energy project, the ratio of the annual maximum H_s to the annual average H_s is to be low (Barstow 2008). The annual mean wave power depends on the annual mean H_s , whereas the annual maximum H_s governs the design parameter for the wave energy plant and in-turn the investment cost. The ratio of the annual maximum H_s to the annual mean H_s varied from 3.2 to 5.1 in different years with an average value of 3.8. In most of the years, the ratio is between 4 and 4.3 and the highest value of 5.1 is due to the storm in 2015. In the year 2015, the wave height is low during July and August and hence the annual average H_s and the wave power is least in 2015 (Figure 7b).

In order to know the spatial variation of the wave power resource along the central eastern Arabian Sea, the wave power for the year 2017 is estimated for Vengurla (~130 km south of Ratnagiri) and Karwar (~260 km south of Ratnagiri) based on the DWR measured data collected at 15 m water depth (Figure 10). The annual mean wave power in 2017 is 7.9, 6.4 and 7.6 kW/m at Karwar, Vengurla and Ratnagiri showing a variation of ~12% along the central eastern Arabian Sea. The variations in the monthly average wave power at these locations during the monsoon is up to 15% and during the non-monsoon period is up to 30%.

The hourly wave power estimated from the ERA5 at 50 m water depth varied from 0.4 to 136.1 kW/m to with an annual mean value of 8.3 kW/m from 1979 to 2017 (Figure 11a). The annual mean wave power varied from 6.4 (in 1987) to 10.3 kW/m (in 1994) (Figure 11b). The inter-annual variability in annual mean wave power is up to 25% since in 1994 annual mean significant wave height is higher due to the occurrence of two tropical cyclones in the Arabian Sea (IMD, 1995). Compared to the wave power based on measured data, the wave power estimate from ERA5 is higher since the ERA5 estimates are for 50 m water depth and when the wave propagates from deep water to the coast, the wave field is modified by several processes (refraction, shoaling and bottom friction) leading to significant changes in the nearshore wave energy distribution. Wave energy is generally lower in the nearshore than in deep water. ERA5 data shows an increase of 0.025 kW/m/year in wave power from 1979 to 2017, whereas the buoy data from 2011 to 2017 shows a decrease of 0.022 kW/m/year (Figure 11b). Aarnes et al. (2014) have shown that trends in the analysis wave height from reanalysis data are spuriously affected by the introduction of altimeter wave height observations in the analysis system in late 1991. Looking at the trend before and after 1992 shows that the trend is negligible from 1979-1991 and is -0.025 kW/m/year from 1992 onwards, which is similar to the trend (-0.022 kW/m/year) observed from the buoy data from 2011 to 2017 (Figure 11b). During 2011 to 2017, as expected higher wave power (~8.3 kW/m) is observed in deeper waters than at the buoy location (~7.85 kW/m).

3.2 Wave power from different wave energy converters

Power matrices of the different WECs are used to arrive at the extractable wave power. The power production from Oyster having rated power 315 kW, WaveDragon with rated power 7000 kW and WaveStar with rated power 600 kW are calculated based on the measured wave data during 2011 to 2017 (Figure 12 and Table 8). In a year no power is produced by the Oyster during 33-45% of the time, 15-22% of the time by WaveDragon and 12-18% of the time by WaveStar (Table 8). Annually total power obtained from Oyster, WaveDragon, WaveStar is 1001642 kW, 10074384 kW, 3234347 kW respectively. In the case of Wave Star, it is incapable of harvesting wave power for sea states with H_s above 4 m.

The capture width, i.e., the ratio of the WEC power output to the wave power for the location, is used to estimate the portion of the wavefront from which it is considered that a WEC system generates power (Rusu and Onca 2016). The locations with moderate wave energy may have a higher capture width. In different years, the annual mean capture width varies from 84 to 133 for WaveDragon, 31 to 42 for WaveStar and 9 to 10 for Oyster (Table 8). The WaveStar is more efficient than WaveDragon since it covers only 39 m wavefront, compared 118 m for WaveDragon. The capacity factor, which is the ratio of the electric power expected to be generated by each WEC and the rated power of each system, is estimated to evaluate the performance of the WEC. The capacity factor varied from 16 to 20% for Oyster, 8 to 9% for WaveDragon and 27 to 34% for WaveStar (Table 8).

4. Discussion

Quantifying the uncertainties concerning the available resources is required to plan and design the WECs and attract investors. The large variation in the wave power over the annual cycle is due to the variations in H_s (0.2-5.5 m) and the T_e (3.7 to 16.1 s) mainly caused by the monsoon on the waves in the eastern Arabian Sea. The monsoon winds generate high waves and high wave power (90th percentile = 23.3 kW/m) in the study area especially during June to August, while wave activity during the pre-monsoon is limited (10th percentile = 0.69 kW/m). Earlier studies also showed a large seasonal variation in the wave height of the Arabian Sea due to the monsoon (Glejin et al. 2013). From the comparison between the wind-sea and swell wave energy in monsoon, it can be seen that, despite the local intensification of the wind speed in the Arabian Sea, swell waves in the study area still carry more energy than the former (Figure 2). Longer and still relatively high swell carrying a great amount of energy reach the study area. The wind-sea wave height, when compared

to the swell height, is clearly lower with large amounts of energy in the swell frequency and less in the wind-sea frequency.

Few of the WEC (e.g., Pelamis) require a minimum wave power of 5 kW/m to generate electricity (Stopa et al. 2011). In the study area, during 68% of the time (~248 days) in a year, the wave power is less than 5 kW/m with a mean value of 1.73 kW/m and 24.7% of the time (~90 days), wave power is more than 10 kW/m with a mean value of 24.65 kW/m. In a year during 13% of the time (~47 days) the wave power is more than 20 kW/m. The maximum H_s for the study period observed is 5.5 m (in June 2015) and in all other years, the maximum H_s is less than 5 m. Generally, the WECs cannot operate under strong wave conditions and are usually turned off for sea states with H_s more than 4.5 m and such sea states are found only in the year 2015 during the storm for 34 h. The infrequent extreme conditions at the deployment location dictate the structural design of the WEC, which is directly related to the capital costs of it (Chozas 2013). The extreme wave conditions in the study area are not harsh like the waves ($H_s \sim 12$ to 16 m) in the 40° - 60° latitude and hence are favourable from the economic point of view. The study area experiences a relatively small number of extreme events compared to the east coast of India and since the area is close to the coast (~ 1.5 km from shoreline), the directional spreading is also low and hence is comparatively more feasible for a wave energy plant. Since the location is close to the mainland, the capital investment towards building the wave farm and placing the cable will be less compared to locations far off from the mainland. The annual mean wave power available at the study location is higher than that reported for 9 m water depth in the eastern Arabian Sea, which is 350 km south of the present study area. Mean annual wave power of 6 kW/m and inter-annual variations up to 19.3% are observed during 2009-2014 at Honnavar (Amrutha and Sanil Kumar, 2016).

It has to be noted that the average conversion rate between the wave energy available and the electricity produced for most of the WEC is 20-30% (Babarit 2017). In the case of the WaveStar matrix, power is not produced for $H_s > 4.5$ m and $T_p > 15$ s. The wave conditions in the study area are moderate with significant wave height < 5 m and frequent occurrence of tropical cyclones are not present. The moderate wave climates imply lesser costs of installation, operation and maintenance of WEC. WaveStar achieves peak production at lower wave heights (< 3 m) and shorter periods similar to the wave condition in the study area and hence no power production time is least (~18%) for WaveStar. The capacity factor of WaveStar is high (27-34%) compared to other WECs considered in the study. Earlier studies also indicate that WaveStar is a more universal device performing well at most case study locations, except for extremes (O'Connor 2013). At different locations in the Greek Seas, Lavidas and Venugopal (2017) evaluated six wave energy converters and showed that the best

device is the WaveStar due to its ability to generate nominal power at low wave heights and periods. In the present study, only three WECs are considered in the analysis which is fairly limited given the number of different technologies that currently exist.

5. Conclusions

Wave power is an important ocean resource and its assessment plays a major role in the planning, design and operation of wave energy plants. In this study, we evaluated the wave power using observational data from 2011 to 2017 at 14 m water depth in the central eastern Arabian Sea. Wave power estimation based on bulk wave parameters underestimates the wave power in coastal waters compared to that based on the wave spectrum since these approximations are valid for deep waters. We showed that inter-annual variability is up to ~13% of the average wave power from 2011 to 2017 and the inter-annual variability increases to ~25% when long-term data (38 years) are considered. The spatial variability of the annual mean wave power along the central eastern Arabian Sea at 14-15 m water depth is ~12%. The wave power during the summer monsoon months (June-September) is considerably greater than that during the remaining periods. Since the wave conditions in the study area are strongly influenced by seasons, during 68% of the time in a year, the wave power is less than 5 kW/m and 24.7% of the time, wave power is more than 10 kW/m. Hence, using annual average wave power (~7.85 kW/m) for assessing the wave energy potential can be misleading. From the economical point of view, wave conditions are advantageous since the study area is devoid of extreme wave conditions, with maximum H_s of 5.5 m and hence the wave energy converters can avoid the situation of switching into the survival mode. The instances of no power production for WaveStar is comparatively lower than that for WaveDragon and Oyster. The capacity factor of WaveStar is high (27-34%) compared to other WECs considered in the study.

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Notations and abbreviations

CSIR - Council of Scientific and Industrial Research, New Delhi

CT - Consistency index

DWR - Directional WaveRider

ECMWF - European Centre for Medium-Range Weather Forecasts

ERA5 - fifth generation ECMWF climate reanalysis data

FFT - fast Fourier Transform

RMSE - root mean square error

SI - RMSE relative to the mean value

UTC - Coordinated Universal Time

WEC - Wave energy converter

θ - wave direction

$C_g(f,d)$ - group velocity

d - water depth

f - frequency

g -gravitational acceleration

H_s - significant wave height

m_n - nth order spectral moment

$S(f)$ - wave spectral energy density

$S(f,\theta)$ - directional wave spectral energy density

T_e - wave energy period

T_{m02} - mean wave period

T_p - peak wave period

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Table 1. Time intervals of the data used in the study in different years along with the range and mean of the significant wave height, wave energy period and wave power

Year	Number and % of data used in study	H _s (m)		T _e (s)		Wave power (kW/m)	
		range	mean	range	mean	range	Mean
2011	17517 (99.9%)	0.3-4.3	1.14	3.8-15.0	7.3	0.2-88.2	7.79
2012	17463 (99.4%)	0.3-3.6	1.13	4.1-12.8	7.2	0.3-55.0	7.24
2013	15882 (90.7%)	0.3-4.2	1.21	3.9-14.4	7.3	0.3-77.2	8.88
2014	16927 (96.6%)	0.2-4.3	1.12	4.1-14.6	7.5	0.2-100.6	8.34
2015	17511 (99.9%)	0.3-5.5	1.07	3.7-15.5	7.6	0.3-158.9	6.91
2016	17568 (100%)	0.2-4.1	1.18	3.9-16.1	7.4	0.16-80.43	8.23
2017	17515 (99.9%)	0.3-4.0	1.14	3.8-15.4	7.4	0.22-76.36	7.55

Table 2. List of some of the Wave Energy Devices

Wave Energy Devices	Rated power (kW)	Water depth	Reference
Aquabuoy	250	>50 m	Silva et al. (2013)
Archimede Wave Swing (AWS)	2500	>25 m	http://www.awsocan.com/archimedes-waveswing
CETO	260	25-30 m	https://www.carnegiece.com/wave
Langlee	132	Deep water	Babarit et al. (2012)
Ocean Energy Buoy (OEBuoy)	-	Deep water	Babarit et al. (2012)
Oceantec	-	30–50 m	Rusu (2014)
Oscillating Water Column (OWC)	85	< 10m & Deep water	Veigas et al. (2012)
Oyster	315	10-15m	Silva et al. (2013)
Pelamis	750	50-70	Silva et al. (2013)
Pontoon Power Converter	-	Deep water	Babarit et al. (2012)
PowerBuoy	40	>25m	https://www.oceanpowertechnologies.com/pb3
Seabased	-	30–50	Babarit et al. (2012)
Wavebob	1000	>50m	Babarit et al. (2012)
WaveDragon	7000	> 20 m	Veigas et al. (2012)
Waveroller	1000	8-20 m	http://aw-energy.com/waveroller/
WaveStar	600	10-20 m	http://wavestarenergy.com

Table 3. Power matrix of Oyster - rated power 315 kW (Silva et al. 2013)

Power Matrix of Oyster (in kW)									
H _s (m)	Wave energy period. T _e (s)								
	5	6	7	8	9	10	11	12	13
0.5	0	0	0	0	0	0	1	2	3
1	20	30	38	42	44	44	45	47	45
1.5	80	85	92	97	102	103	104	100	104
2	140	147	152	158	155	155	160	161	156
2.5	192	197	208	202	203	209	211	201	204
3	241	237	237	241	243	230	236	231	235
3.5	0	271	272	269	268	267	270	260	260
4	0	291	290	290	280	287	276	278	277
4.5	0	291	290	290	280	287	276	278	277
5	0	0	290	290	280	287	276	278	277
5.5	0	0	290	290	280	287	276	278	277
6	0	0	290	290	280	287	276	278	277

Table 4. Power matrix of WaveDragon -rated power 7000 kW (Silva et al. 2013)

Power Matrix of WaveDragon (in kW)													
H _s (m)	Peak wave period, T _p (s)												
	5	6	7	8	9	10	11	12	13	14	15	16	17
1	160	250	360	360	360	360	360	360	320	280	250	220	180
2	640	700	840	900	1190	1190	1190	1190	1070	950	830	710	590
3	0	1450	1610	1750	2000	2620	2620	2620	2360	2100	1840	1570	1310
4	0	0	2840	3220	3710	4200	5320	5320	4430	3930	3440	2950	2460
5	0	0	0	4610	5320	6020	7000	7000	6790	6090	5250	3950	3300
6	0	0	0	0	6720	7000	7000	7000	7000	7000	6860	5110	4200
7	0	0	0	0	0	7000	7000	7000	7000	7000	7000	6650	5740

Table 5. Power matrix of WaveStar - rated power 600 kW

Power Matrix of WaveStar (in kW)														
H _s (m)	Mean wave period, T _{m02} (s)													
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	0	0	46	71	85	89	88	84	79	74	69	66	62	59
1.25	0	50	121	182	212	215	206	192	178	166	155	145	136	128
1.75	0	95	231	339	381	374	350	322	296	274	254	237	222	208
2.25	0	154	375	535	579	554	511	466	426	391	361	336	314	295
2.75	0	228	552	600	600	600	600	600	563	516	475	441	412	386
3.25	40	319	600	600	600	600	600	600	600	600	600	600	600	480
3.75	53	425	600	600	600	600	600	600	600	600	600	600	600	557

Table 6. Bivariate distributions of the parameters significant wave height (H_s) and wave energy period (T_e) corresponding to sea states from the 7-year data from January 2011 to December 2017. The values are the percentage occurrence.

H_s (m)	Wave energy period (s)														Total
	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	
0.0-0.5	0.004	0.509	2.444	3.710	3.092	2.186	1.396	0.562	0.233	0.060	0.020	0.006	-	-	14.222
0.5-1.0	0.036	3.814	12.484	11.720	8.241	5.119	2.571	1.414	0.860	0.446	0.332	0.169	0.023	0.001	47.230
1.0-1.5	-	0.665	2.833	2.863	3.222	1.980	0.458	0.141	0.053	0.012	-	-	-	-	12.227
1.5-2.0	-	0.002	0.136	1.381	3.498	3.327	1.002	0.092	0.010	0.001	-	-	-	-	9.449
2.0-2.5	-	-	0.006	0.308	2.651	4.010	1.656	0.208	0.003	-	-	-	-	-	8.842
2.5-3.0	-	-	-	0.013	0.749	2.681	1.195	0.229	0.012	-	-	-	-	-	4.879
3.0-3.5	-	-	-	-	0.073	0.924	1.154	0.133	0.042	-	-	-	-	-	2.326
3.5-4.0	-	-	-	-	0.002	0.176	0.415	0.015	0.044	-	-	-	-	-	0.652
4.0-4.5	-	-	-	-	-	0.002	0.059	0.042	0.007	0.001	-	-	-	-	0.111
4.5-5.0	-	-	-	-	-	-	0.015	0.042	-	-	-	-	-	-	0.057
5.0-5.5	-	-	-	-	-	-	-	0.005	-	-	-	-	-	-	0.005
Total	0.04	4.99	17.903	19.995	21.528	20.405	9.921	2.883	1.264	0.52	0.352	0.175	0.023	0.001	100.00

Table 7. The statistical measures between the wave power estimate from the wave spectrum and that based on the deep water approximation

Year	Mean wave power from spectrum (kW/m)	Mean wave power based on empirical equation (kW/m)	Bias (kW/m)	RMSE (kW/m)	SI	Correlation coefficient
statistical measures between wave power estimate from wave spectrum and that based on deep water approximation (Eq. 4)						
2011	7.79	7.59	-0.207	0.545	0.070	0.999
2012	7.24	7.03	-0.215	0.488	0.067	0.999
2013	8.88	8.57	-0.305	0.625	0.070	1.000
2014	8.34	8.13	-0.205	0.595	0.069	0.999
2015	6.91	6.88	-0.035	0.481	0.070	0.999
2016	8.23	8.14	-0.086	0.478	0.058	0.999
2017	7.55	7.47	-0.084	0.498	0.066	0.999
statistical measures between wave power estimate from wave spectrum and that based on deep water approximation (Eq. 4) using peak wave period						
2011	7.79	8.75	0.955	2.069	0.266	0.993
2012	7.24	8.18	0.938	1.725	0.238	0.994
2013	8.88	10.07	1.191	2.406	0.271	0.995
2014	8.34	9.59	1.249	2.520	0.302	0.995
2015	6.91	8.12	1.209	2.604	0.377	0.995
2016	8.23	9.52	1.288	2.603	0.238	0.994
2017	7.55	8.60	1.047	2.145	0.218	0.994

Table 8. Details of power production by each device in different years along with capacity factor and capture width

Year	Total electric power estimated (kW)			Percentage of times no power production			Capacity factor (%)			Capture width (m)		
	Oyster	WaveDragon	WaveStar	Oyster	WaveDragon	WaveStar	Oyster	WaveDragon	WaveStar	Oyster	WaveDragon	WaveStar
	2011	1042361	10241640	3404383	45.14	21.31	17.69	18.89	8.35	32.39	10	126
2012	1017603	9741580	3377348	41.90	18.04	15.00	18.50	7.97	32.23	10	126	41
2013	1008453	10370670	3234430	32.69	14.69	12.11	20.16	9.33	33.94	9	120	40
2014	958996	10130300	2993864	41.91	21.54	17.10	17.99	8.55	29.48	10	125	40
2015	874839	9357370	2879068	44.51	16.52	12.84	15.86	7.63	27.40	10	133	42
2016	1100212	10536720	3481498	37.65	19.93	16.47	19.88	8.57	33.03	10	113	39
2017	1009029	10142410	3269840	41.11	17.91	13.82	18.29	8.27	31.11	10	84	31

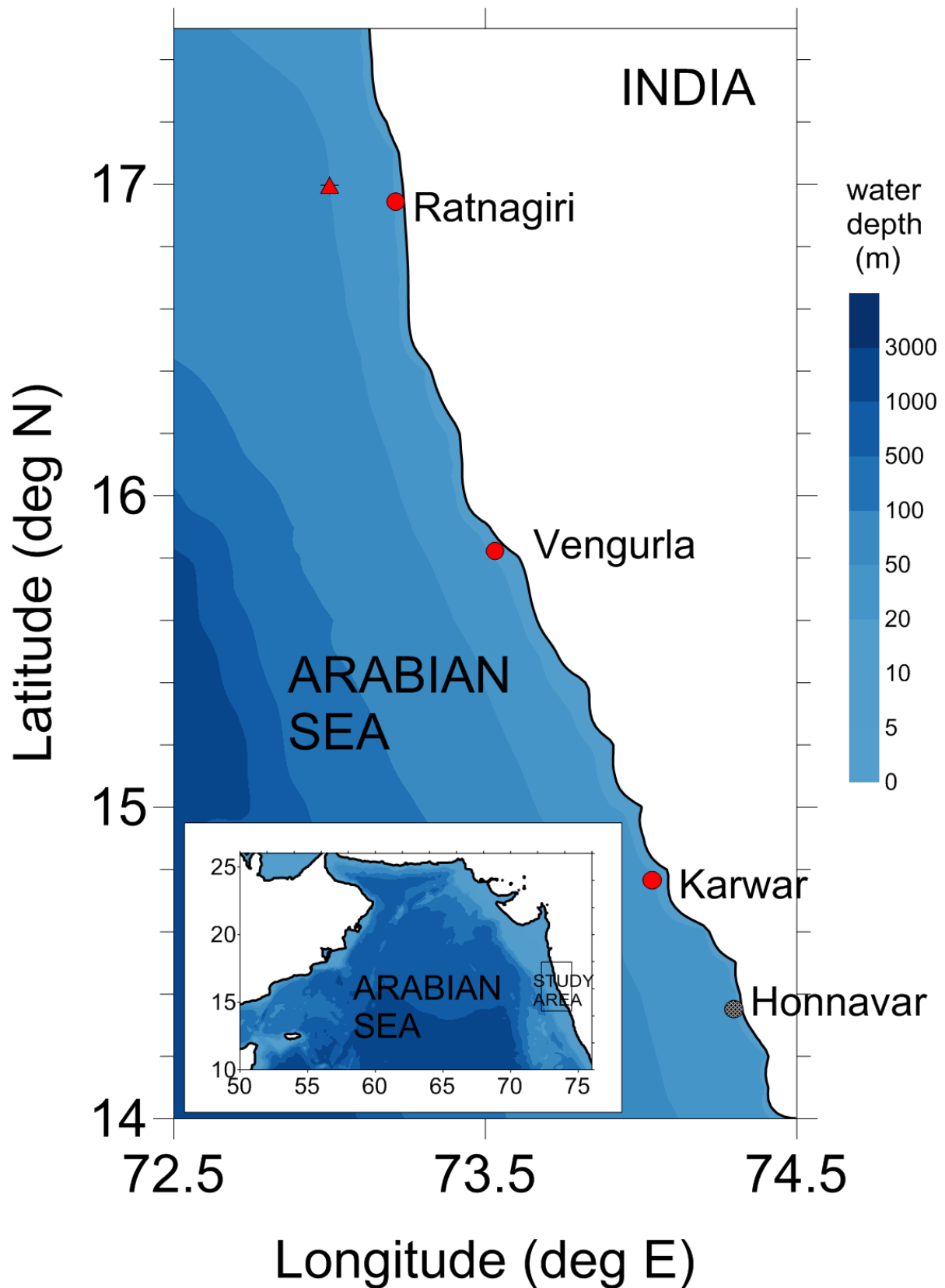


Figure 1. Area showing the study location off Ratnagiri in central eastern Arabian Sea. The waverider buoy locations are shown in the red circle (off Ratnagiri, Vengurla and Karwar) and the ERA5 data point (off Ratnagiri) in the red triangle

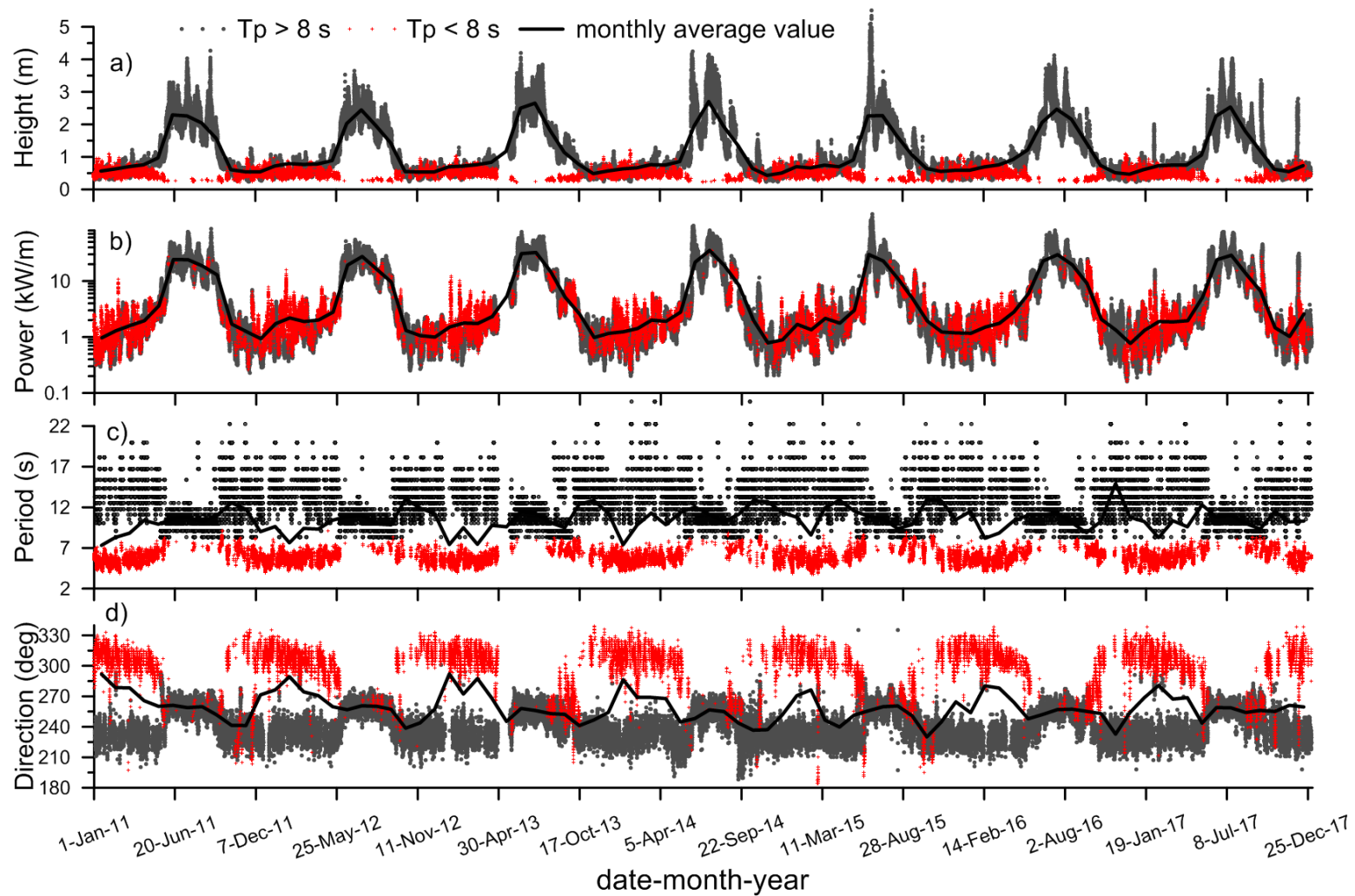


Figure 2. Time series plot of a) significant wave height, b) wave power, c) peak wave period and d) mean wave direction from January 2011 to December 2017 off Ratnagiri. Waves with spectral peak period more than 8 s and less than 8 s are with a different symbol. The monthly average value is indicated with a solid line

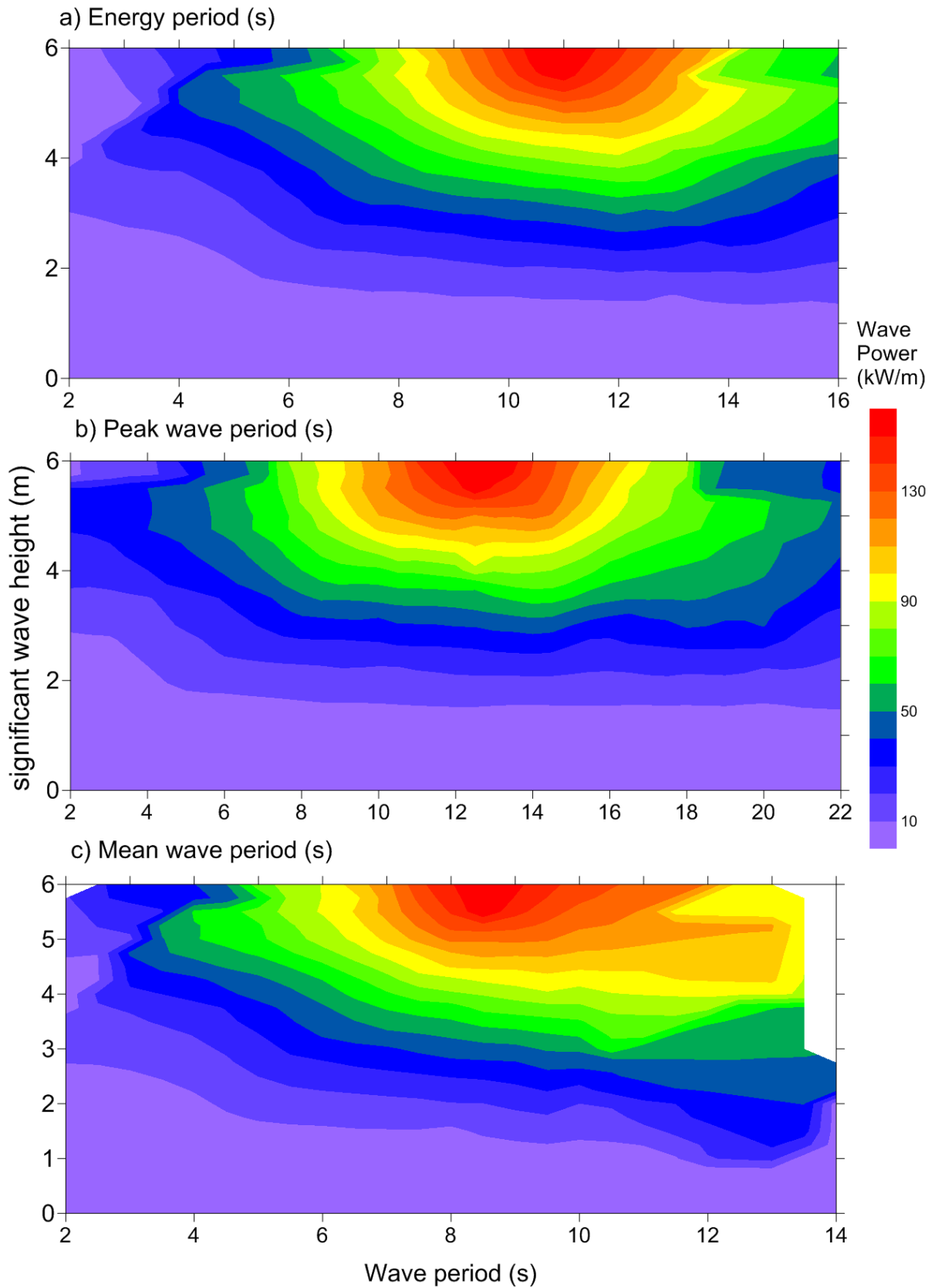


Figure 3. Joint distribution of wave power resource with significant wave height and (a) energy period, (b) peak wave period and (c) mean wave period. The estimates are based on wave data off Ratnagiri for the year 2015

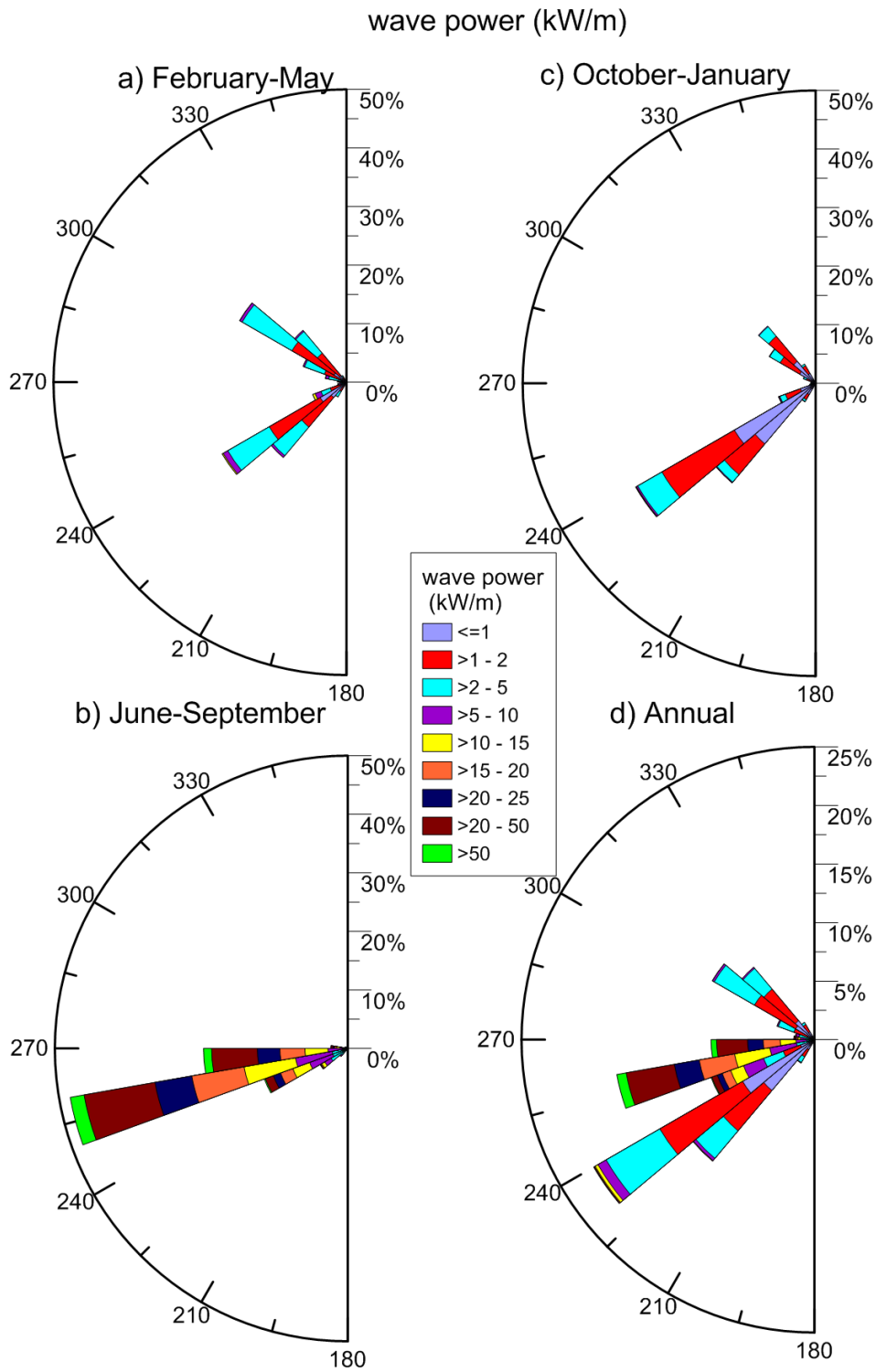


Figure 4. Rose diagram based on wave power off Ratnagiri during a) February-May, b) June-September, c) October-January and d) January-December. All data from 1 January 2011 to 31 December 2017 are used

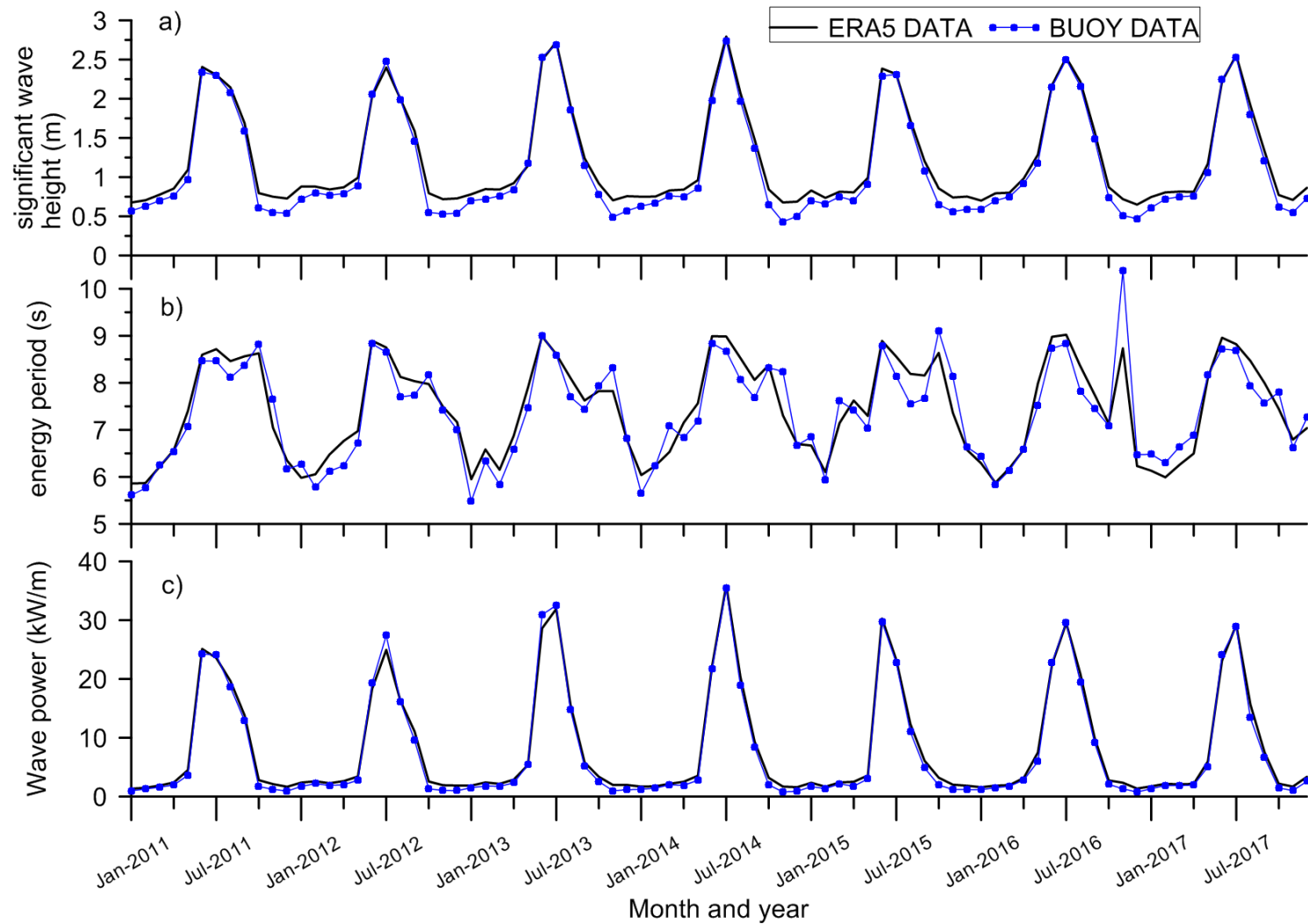


Figure 5. Variation of the monthly average value of a) significant wave height, b) energy period and c) wave power from January 2011 to December 2017. The blue line with a solid circle are the parameters from buoy data and the black line are from ERA5 data

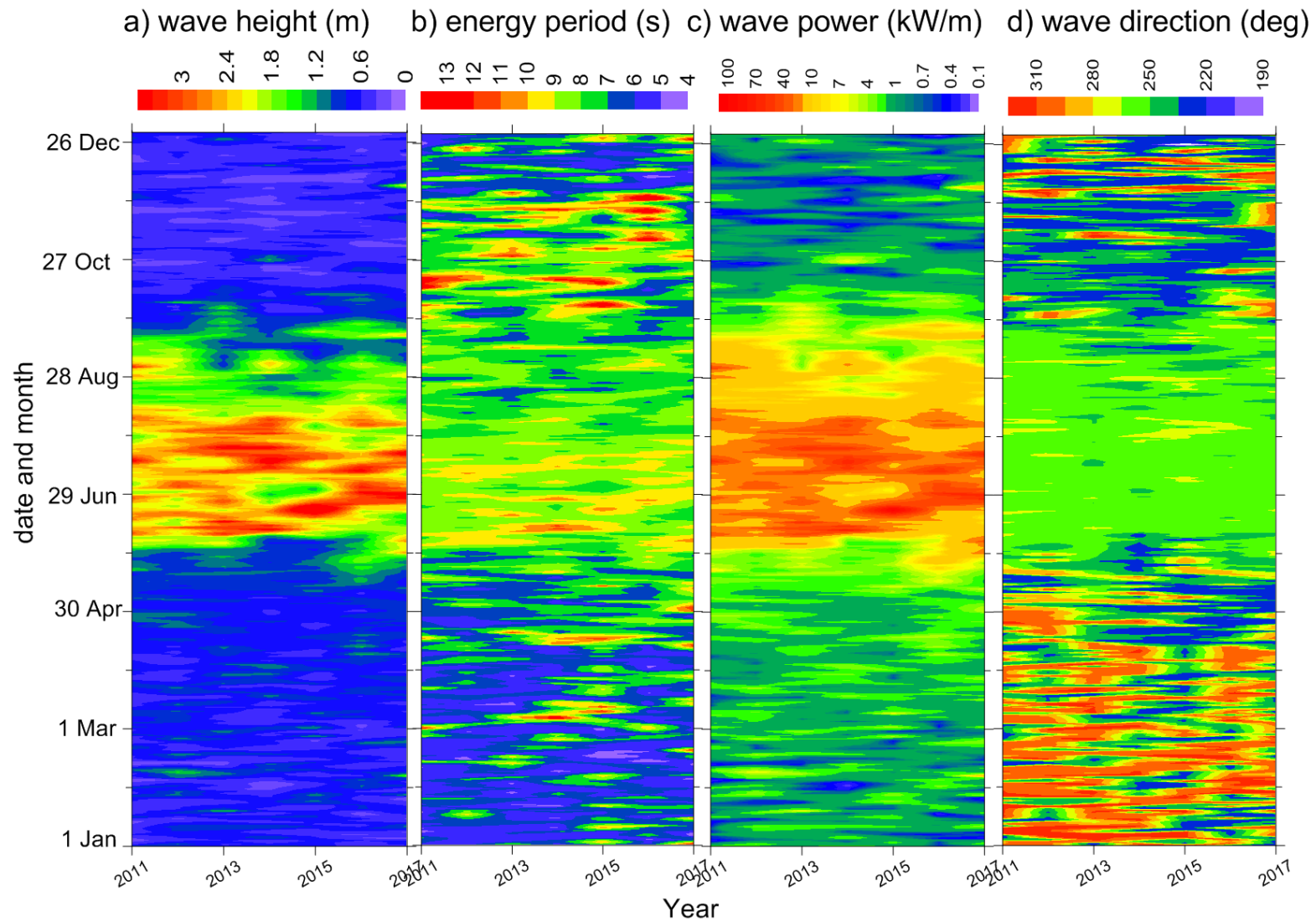


Figure 6. Date versus year plots of a) significant wave height, b) energy period, c) wave power and d) mean wave direction during 2011-2017 off Ratnagiri

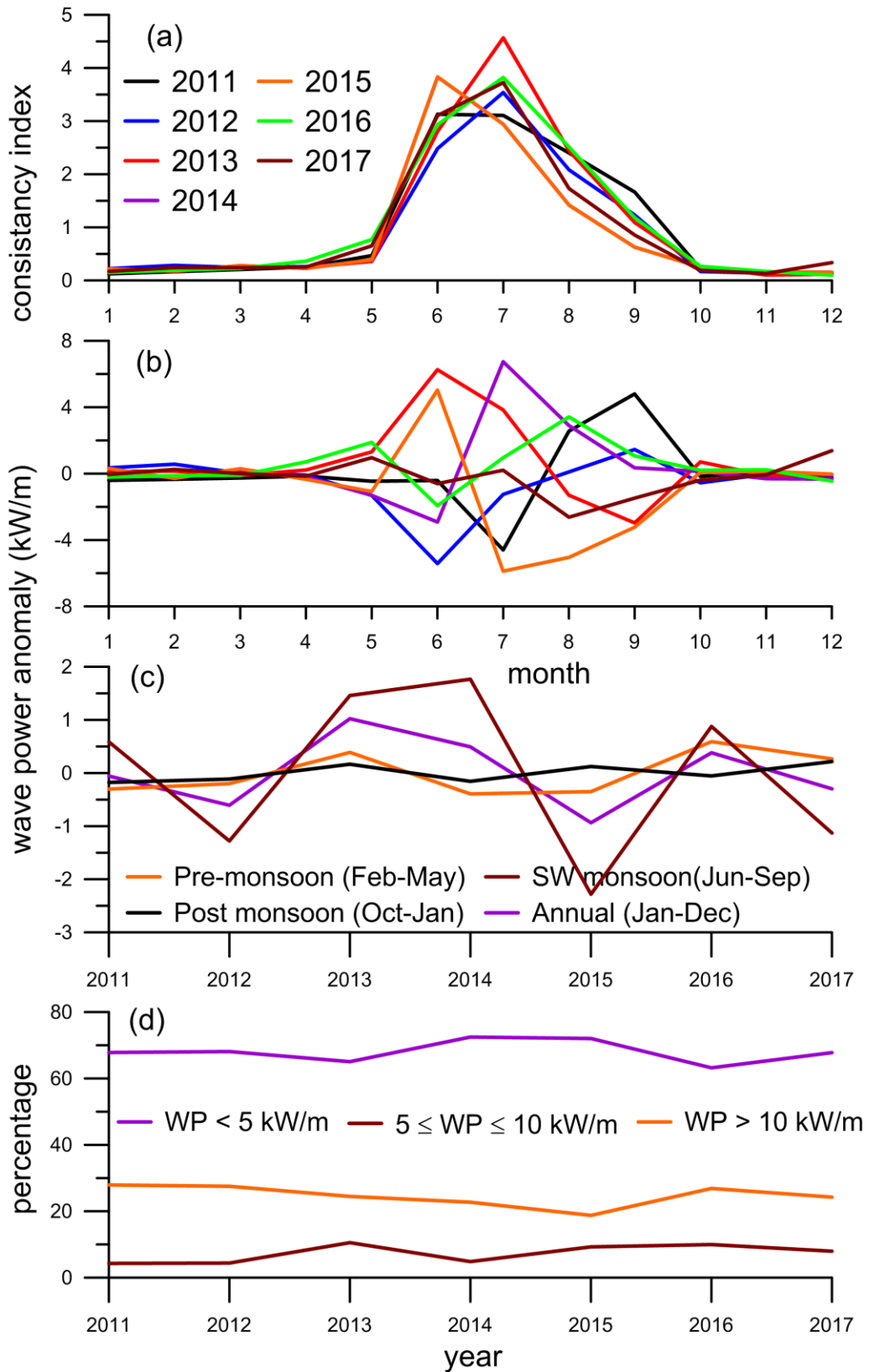


Figure 7. a) Consistency index of wave power, b) Anomaly of monthly average wave power in different years, c) anomaly to seasonal average and annual average wave power in different years and d) the percentage of wave power in different ranges (<5, 5 to 10 and > 10 kW/m) in various years

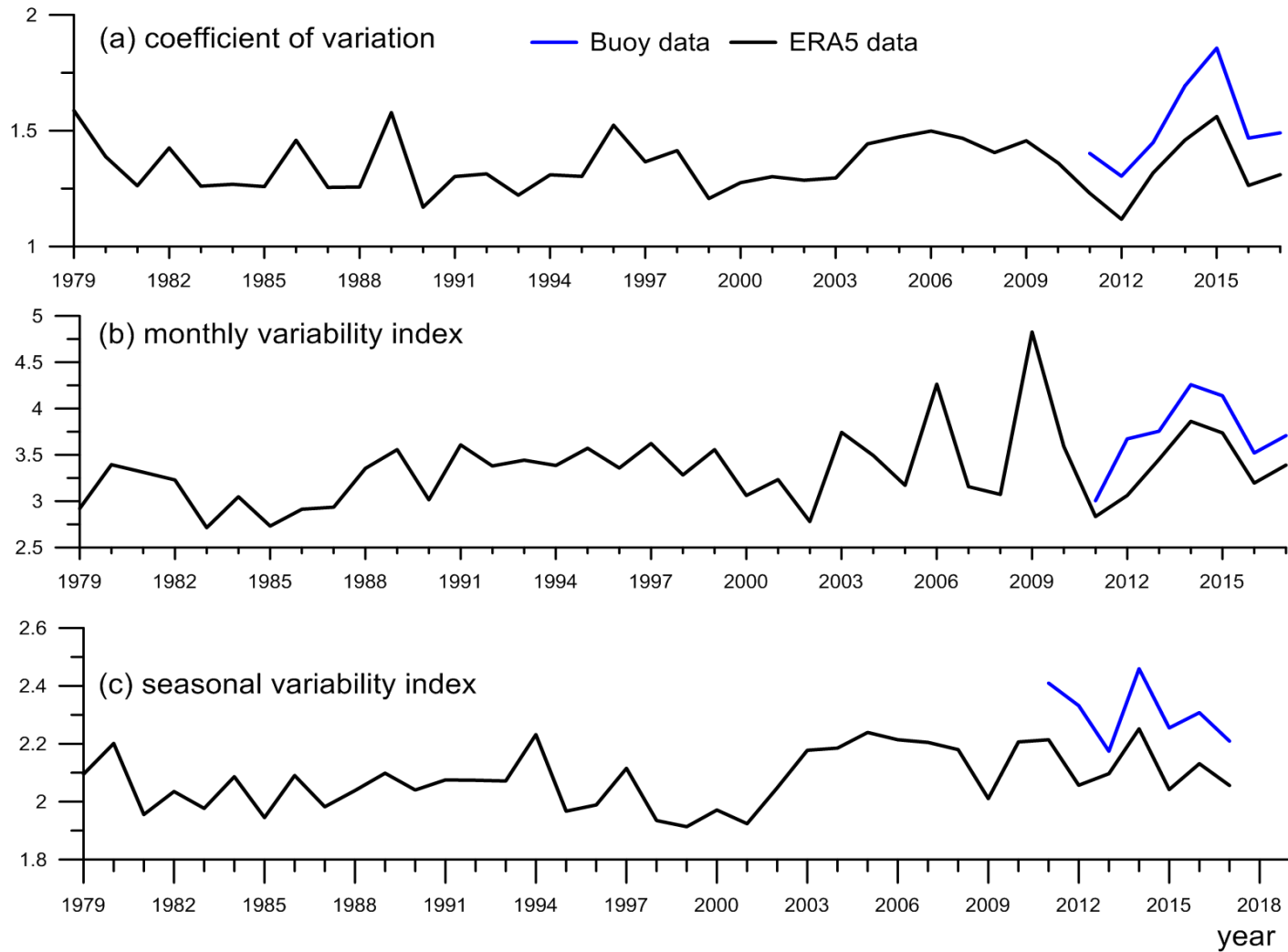


Figure 8. a) coefficient of variation, b) monthly variability index and c) seasonal variability index of wave power in different years. Blue thick line is based on buoy data from 2011 to 2017 and the black line is based on ERA5 from 1979 to 2017

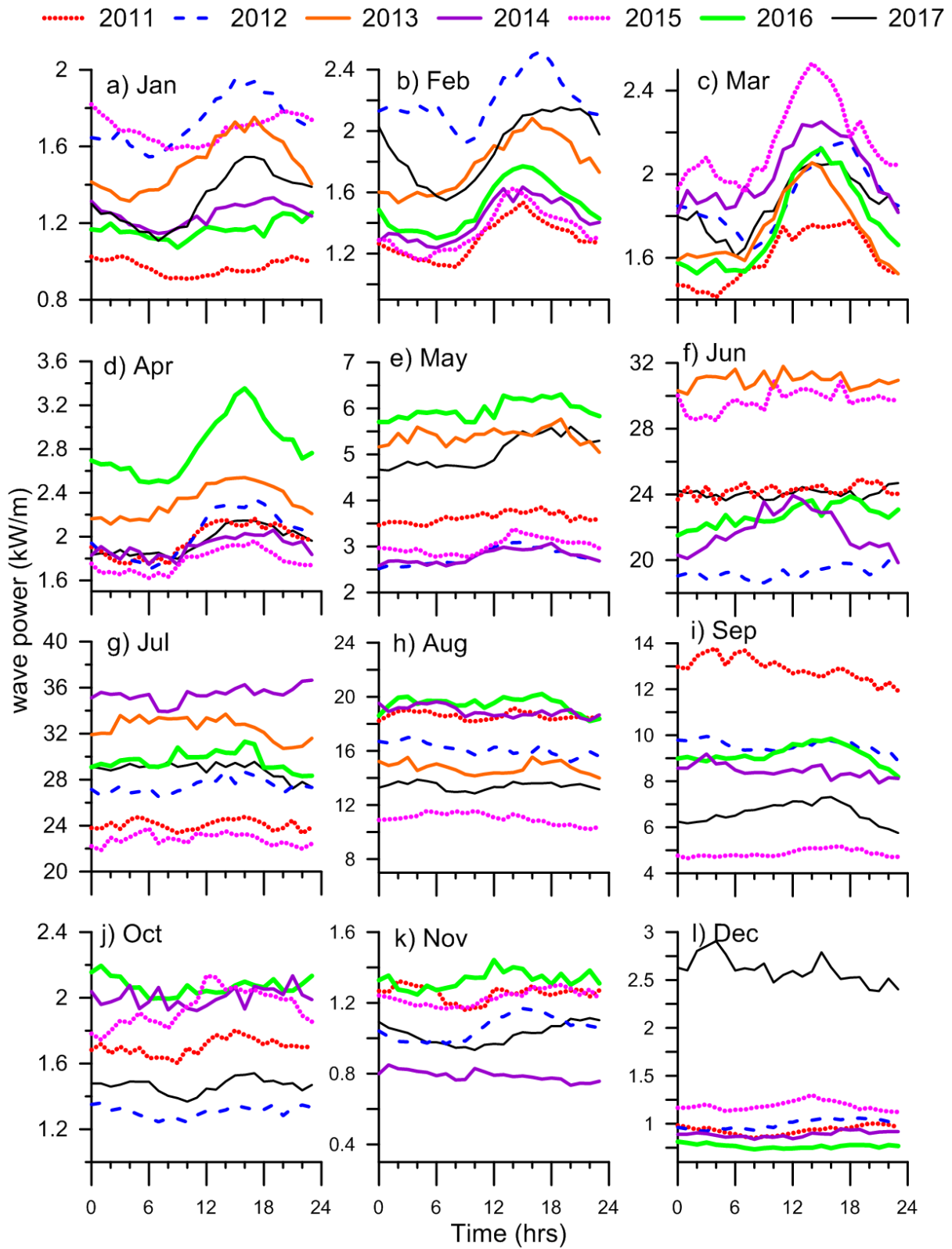


Figure 9. Diurnal cycle of half-hourly wave power in different months of 2011 to 2017

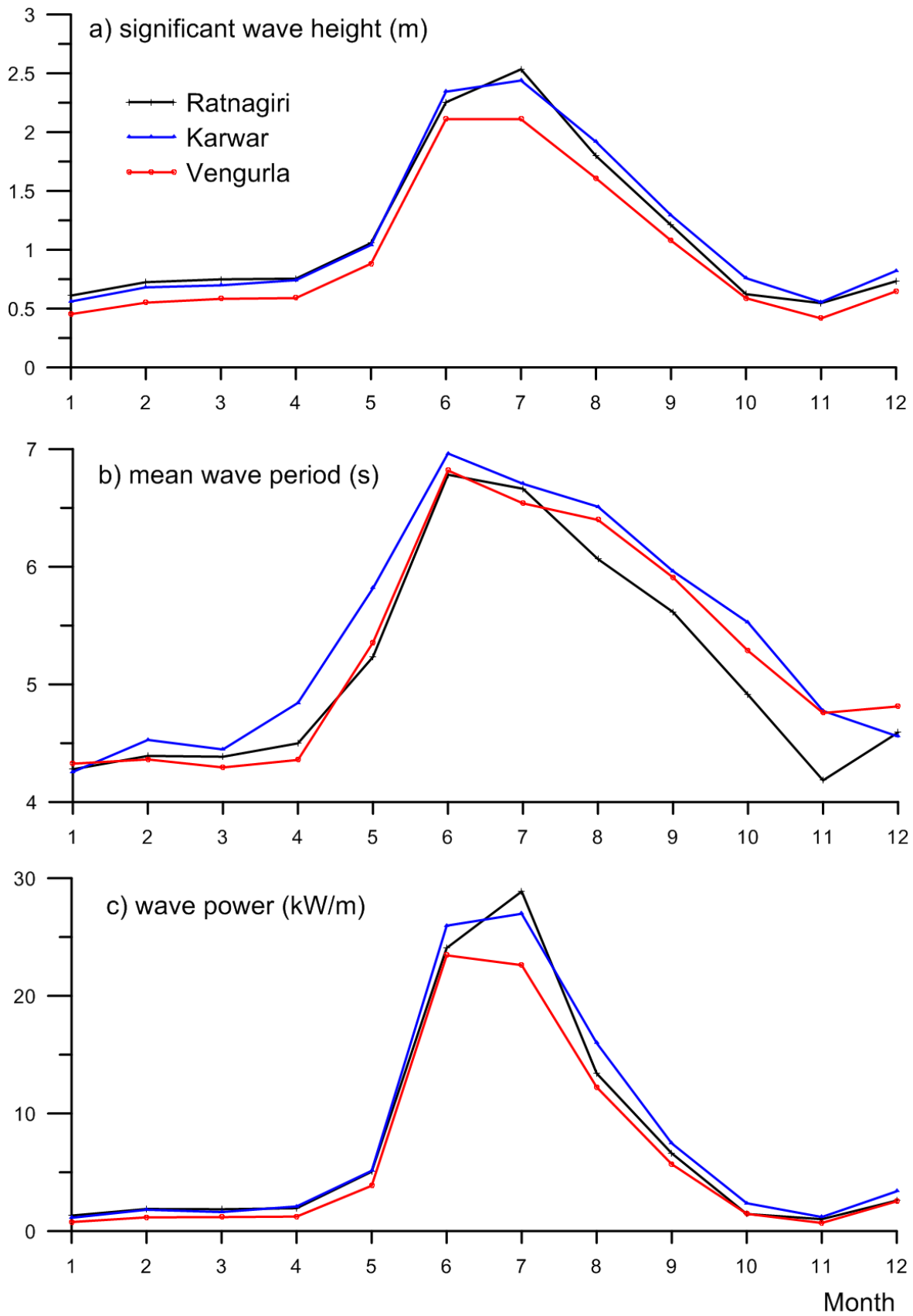


Figure 10. Monthly average values of a) significant wave height, b) mean wave period and c) wave power at Ratnagiri, Vengurla and Karwar in 2017

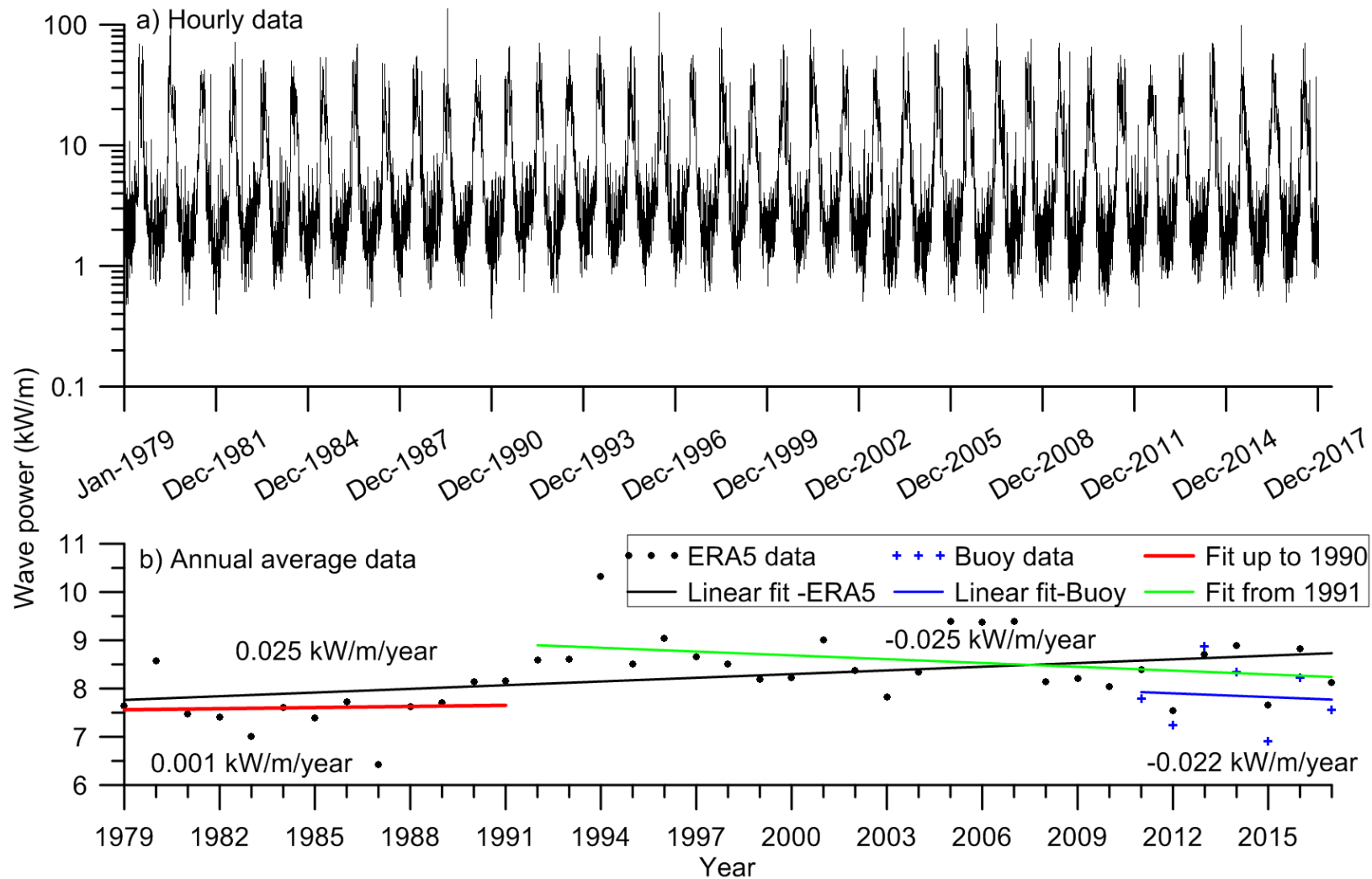


Figure 11. Variation of a) hourly wave power and b) annual average wave power at 50 m water depth off Ratnagiri based on ERA5 data. The blue dots are the values based on measured buoy data at 14 m water depth. The solid line is the linear fit

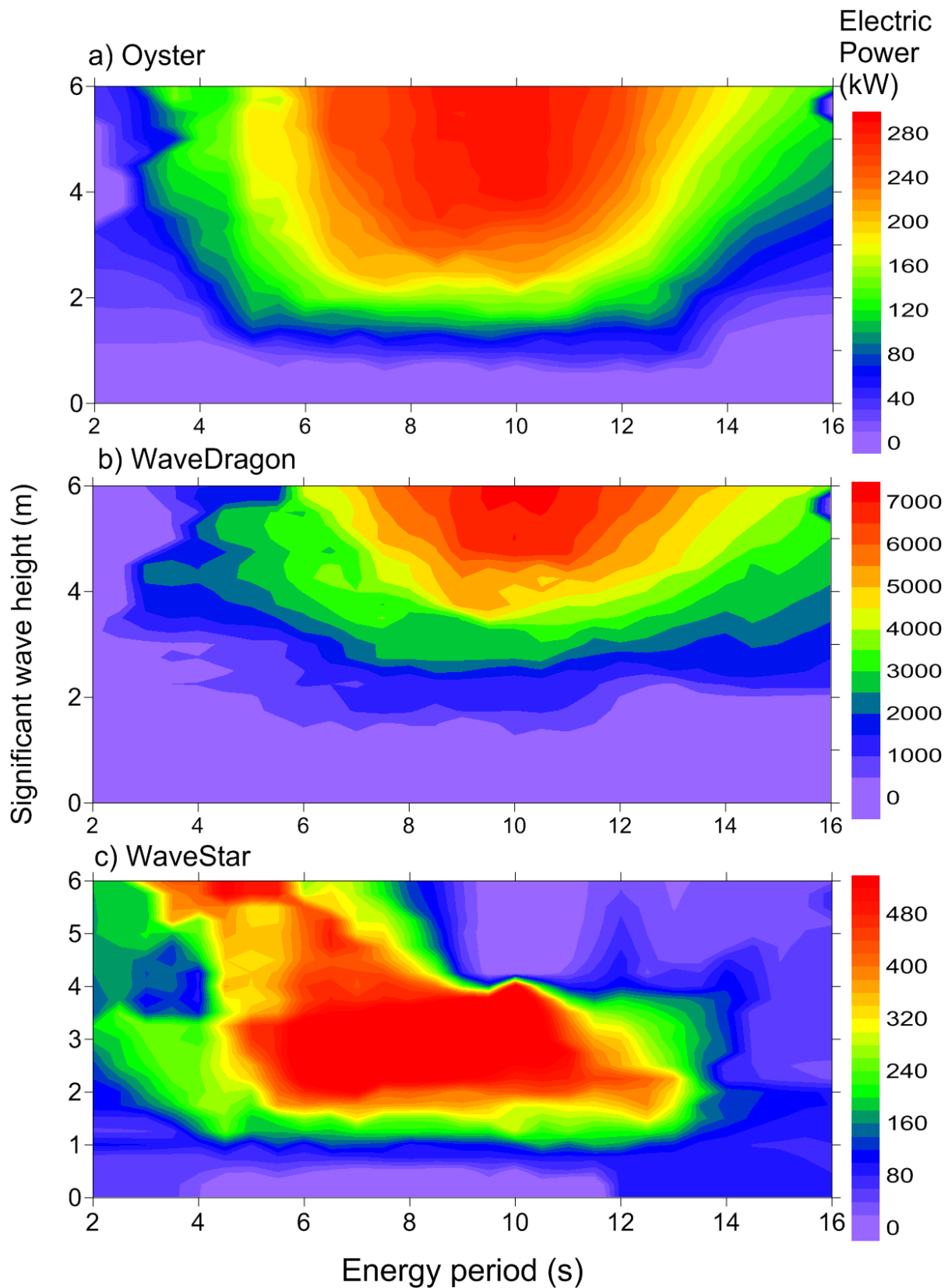


Figure 12. Joint distribution of electric power for different wave energy converters (a) 315 kW Oyster, (b) 7000 kW WaveDragon and (c) 600 kW WaveStar. The estimates are based on wave data for the year 2015